

DISS. ETH NO. 21660

# **WATER ECONOMICS AND GOVERNANCE IN THE KAFUE RIVER BASIN, ZAMBIA**

A THESIS SUBMITTED TO ATTAIN THE DEGREE OF  
DOCTOR OF SCIENCES OF ETH ZURICH  
(DR. SC. ETH ZURICH)

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2013



Follow the river  
and find the sea

*Zambian proverb*



## Summary

The Kafue River is the lifeblood of Zambia: it is host of the major urban centres of the country, it delivers water to two large dams and one hydropower station, it services major agricultural and industrial areas, and it ensures the health of a precious wetland ecosystem and of a rich fishery sector. Although Zambia is considered to have abundant water resources, major expansions in the irrigated agriculture and hydropower sectors coupled with a rising population and the uncertain developments in the mining sector are increasing competition for water resources across the country and, in particular, in the Kafue River basin.

The overall objective of the present research is to analyse the availability and allocation of the waters of the Kafue River within the boundaries given by the policy and legislative framework. One of the major challenges in water management is finding the optimal allocation of water resources for multiple uses in a catchment for which limited data is available. In a dynamic context where demands are increasingly competing, where a lack of knowledge on the amount of water withdrawals as well as on the basin's groundwater resources is manifest, and where uncoordinated policies and legislative frameworks on water resources management are in place, it is of utmost importance to adopt a multi-objective approach to water management. Only in this way the detrimental consequences of intersectoral competition for water in a weak institutional framework – such as environmental degradation, load shedding, urban water shortages, declines in overall welfare and productivity – can be avoided.

The first part of this PhD thesis presents a comprehensive analysis of the changing water governance system in Zambia. The revised Water Policy and the new Water Resources Management Act clearly sign a step towards the implementation of an Integrated Water Resources Management framework in Zambia. The country is moving towards a decentralised and participative governance framework, but concrete challenges to the implementation of the new governance system exist. The inadequate allocation of human and financial resources is the main constraint to the effective and timely implementation of the reform. This is aggravated by the strong resistance to change of government officials and key stakeholders, particularly in the agricultural sector, that might further delay the implementation process.

Decentralization, devolution of powers, and greater stakeholders' participation are the goals of the new governance structure. The second part of this study demonstrates that in the Kafue basin, a pilot case for the early implantation of the renovated governance structure, the water users' understanding of and level of participation in the governance institutions is worrisomely low. Only about 5.5 percent of the respondents of a rural household survey conducted as part of the study at hand declare to be aware of the institutions introduced with the recent Water Act, demonstrating that the institutional reforms have not yet been implemented on the ground. In clear contrast with the provision of the Water Policy and Water Act which strongly promote women's empowerment and participation in the water sector, women participate the least and generally do not contribute to decision making with regards to water.

The changing water governance structure presents invaluable opportunities for the Zambian society, as an improved management of water resources based on clear policy priorities and on the active interaction of stakeholders could foster the maximisation of societal net benefits derived from water allocation. The third part of this thesis describes a multi-objective hydro-economic optimization model as a tool to analyse the competing demands for water in the Kafue River basin and identify the trade-offs associated to different water allocation arrangements. The model addresses the linkages between water supply and the economic use of water at river basin scale and considers economic, social, and environmental objectives.

The hydro-economic model allows testing alternative development scenarios and comparing the respective frontiers of efficient solution. Using the hydro-economic framework, the fourth part of this dissertation describes ten scenarios that are based on the policy priorities and development plans indicated by the stakeholders and are tested on different hydrological conditions. Water demands for the urban, industrial, mining, energy, and agricultural sectors as well as environmental demands for water are analysed and trade-offs in terms of economic net benefits and water allocation between different water users are clearly outlined. In a context where population growth is to be expected and water supply from the mining areas might decrease, water use for agriculture and hydropower will increasingly trade-off, particularly in dry hydrological years. Various policy options to improve water management and reach optimal water allocations are analysed but it is ultimately the government and the stakeholders' task to set agreed upon development priorities considering a wider range of social and political variables.

The joint approach to assessing the economic and physical outcomes of different water allocations provides a best practice that could support a more holistic decision making, in line with the changes from a sectoral to an integrated approach for water management in Zambia and in the Zambezi. The fifth part of this study, therefore, broadens the view proposing a hydro-economic model for the whole Zambezi River basin, where Zambia plays a pivotal role. In May 2013, Zambia signed the Zambezi Commission (ZAMCOM) Agreement that provides the necessary framework to manage the Zambezi waters collectively for a shared long-term benefit (both social and economic). But also in the Zambezi often conflicting national and water-users objectives need to be accounted for and competition exists between, mainly, irrigated agriculture and hydropower generation. Scenarios analyse the future hydropower and irrigated agriculture development showing that the expansion of irrigation would be economically suboptimal while the future hydropower development might rise a concern of environmental degradation in the main wetlands of the basin.

The models and frameworks developed in the present study are expected to promote the search for efficient and sustainable water allocation options for the Kafue River basin within the broader context of the integrated management of the Zambezi River basin. The approach presented in this work is of direct use to decision makers as it supports the cross-sectoral analysis of a range of economic and environmental options for the Kafue and Zambezi basins considering not only the physical dimensions of alternative water allocations, but also the economic consequences associated with them.

# Sommarior

Il fiume Kafue è la linfa vitale dello Zambia: vi si trovano i maggiori centri urbani del Paese, alimenta due grandi dighe ed una stazione idroelettrica, fornisce acqua alle principali aree agricole ed industriali, e garantisce l'integrità di preziosi ecosistemi e di un ricco settore ittico. Sebbene in letteratura lo Zambia sia considerato un paese dotato di abbondanti risorse idriche, considerevoli espansioni nel settore agricolo e nella produzione di energia idroelettrica, assieme all'aumento della popolazione ed agli incerti sviluppi nel settore minerario, stanno incrementando la competizione per le risorse idriche del paese ed, in particolare, del fiume Kafue .

L'obiettivo complessivo della presente ricerca è quello di analizzare la disponibilità e la ripartizione delle acque del fiume Kafue entro i limiti indicati dal quadro politico e legislativo. Una delle principali sfide nella gestione delle acque è trovare l'allocazione ottimale delle risorse idriche per diversi usi in un bacino per il quale la disponibilità di dati è limitata. In un contesto dinamico in cui le i vari usi dell'acqua sono sempre più in competizione, dove la mancanza di informazioni sulla quantità dei prelievi d'acqua e sulle risorse idriche sotterranee è manifesta, e dove le politiche e i quadri legislativi in materia di gestione delle risorse non sono efficacemente coordinati, è estremamente importante adottare un approccio multi-obiettivo per la gestione delle acque. Solo in questo modo si possono evitare le conseguenze negative della concorrenza intersettoriale per l'acqua in un quadro istituzionale debole – per esempio il degrado ambientale, la scarsità idrica nelle regioni urbane, la riduzione della fornitura di energia elettrica come risposta ad insufficienti quantità di generazione idroelettrica, la generale riduzione del benessere economico e della produttività.

La prima parte di questa tesi di dottorato presenta un'analisi completa del sistema di governance dell'acqua cambia in Zambia. La Water Policy ed il Water Resources Management Act recentemente entrati in vigore denotano chiaramente un passo avanti verso la realizzazione di un quadro integrato di gestione delle risorse idriche in Zambia. Il paese si sta muovendo verso un sistema di governance decentrato e partecipativo, ma si trova a confrontarsi con sfide concrete all'implementazione del nuovo sistema di governance. L'inadeguata allocazione di risorse umane e finanziarie è l'ostacolo principale all'effettiva e tempestiva attuazione della riforma. Un ulteriore ritardo al processo di attuazione della riforma è costituito dalla forte resistenza al cambiamento riscontrata tra i funzionari governativi ed alcuni degli stakeholder principali, in particolare nel settore agricolo.

Decentralizzazione, devoluzione dei poteri, e maggiore partecipazione degli stakeholder sono gli obiettivi della nuova struttura di governance. La seconda parte di questo studio attesta che nel bacino del fiume Kafue, un caso pilota per l'introduzione della nuova struttura di governo delle acque, la maggior parte degli utilizzatori delle risorse idriche nelle aree rurali dimostra una scarsa conoscenza delle strutture di governance e non partecipa nelle decisioni concernenti la gestione dell'acqua. Infatti, soltanto circa il 5,5 per cento dei partecipanti ad un sondaggio condotto come parte del presente studio dichiara di essere a conoscenza delle istituzioni introdotte con la recente legge sulle acque, dimostrando che le riforme istituzionali non sono ancora state messe in atto sul campo. In netto contrasto con la disposizione della Water Poli-

cy e del Water Act che promuovono la partecipazione delle donne nelle decisioni riguardanti il settore idrico, le donne partecipano poco e in genere non contribuiscono al processo decisionale in merito alla gestione dell'acqua.

Il cambiamento della struttura di governance delle risorse idriche presenta preziose opportunità per lo Zambia, poiché una migliore gestione delle risorse idriche sulla base di chiare priorità e sulla interazione degli stakeholder potrebbe favorire la massimizzazione dei benefici netti sociali derivanti dall'allocazione delle risorse idriche. La terza parte di questa tesi descrive un modello idro-economico multi-obiettivo come strumento per analizzare nel bacino del fiume Kafue le varie domande idriche in competizione ed identificare i trade-off associati ai diversi tipi di allocazione delle risorse idriche. Il modello esamina le interconnessioni tra le quantità d'acqua a disposizione e l'uso economico della risorsa nel bacino idrico e considera simultaneamente gli obiettivi economici, sociali e ambientali.

Il modello idro-economico consente di testare scenari alternativi di sviluppo economico e confrontare le rispettive frontiere di soluzioni efficienti. Utilizzando la struttura del modello idro-economico, la quarta parte di questa tesi descrive dieci scenari basati sulle priorità politiche e sui piani di sviluppo indicati dagli stakeholder. Gli scenari vengono testati su varie condizioni idrologiche. Lo studio analizza le domande idriche dei settori urbano, industriale, minerario, energetico, e agricolo, nonché l'allocazione d'acqua necessaria per mantenere la salute ambientale e delinea i trade-off in termini di benefici netti e allocazione delle risorse idriche tra i diversi utilizzatori dell'acqua. In un contesto in cui è possibile prevedere la crescita della popolazione ed una possibile diminuzione della quantità di acqua sotterranea immessa nel sistema dalle zone minerarie, l'utilizzo di acqua per l'agricoltura e per la produzione idroelettrica saranno sempre più in competizione, in particolare negli anni secchi. Vengono analizzate varie opzioni politiche per migliorare la gestione delle acque e raggiungere allocazioni dell'acqua ottimali, ma è in ultima istanza il compito del governo e degli stakeholder quello di concordare priorità di sviluppo prendendo in considerazione una ancor più ampia gamma di variabili sociali e politiche.

La valutazione congiunta dei risultati economici e fisici derivanti da diverse allocazioni delle risorse idriche costituisce una buona norma atta a favorire decisioni olistiche e comprensive, in linea con i cambiamenti nella gestione delle acque in Zambia e nello Zambesi da un approccio settoriale ad uno integrato. La quinta parte di questo studio, pertanto, amplia la prospettiva proponendo un modello idro-economico per l'intero bacino del fiume Zambesi, in cui lo Zambia ha un ruolo fondamentale. Nel Maggio 2013, lo Zambia ha firmato l'accordo per la costituzione della Commissione dello Zambesi (ZAMCOM) che fornisce il quadro necessario per gestire le acque dello Zambesi collettivamente per un beneficio condiviso di lungo termine (sia sociale che economico). Ma anche nel contesto del bacino dello Zambesi gli interessi dei vari utilizzatori delle risorse idriche sono spesso contrastanti e già esiste una competizione per l'uso delle risorse soprattutto tra l'agricoltura irrigua e la produzione di energia idroelettrica. Una serie di scenari analizza i futuri sviluppi nei settori agricolo e idroelettrico dimostrando che l'espansione dell'irrigazione non sarebbe economicamente ottimale, ed la futura costruzione di dighe idroelettriche potrebbe creare un problema di degrado ambientale nelle principali zone umide del bacino.

I modelli e le analisi sviluppati nel presente studio sono capaci di favorire la ricerca di opzioni alternative per l'allocazione efficiente e sostenibile delle risorse idriche del fiume Kafue nel più ampio contesto della gestione integrata del bacino del fiume Zambesi. L'approccio presentato in questo lavoro è di utilità diretta per i responsabili delle decisioni in materia di risorse idriche poiché supporta l'analisi intersettoriale di una gamma di possibilità di gestione dei bacini Kafue e Zambesi, considerando non solo la dimensione fisica ma



anche le conseguenze in termini di sviluppo economico e benefici netti associati ad allocazioni alternative delle risorse.



# Acknowledgements

I have been a PhD student for almost five years. This means that I woke up every morning thinking of the day I would finalise my thesis, that I gave my mind and brain fully to research, that I was cuddled to sleep every night by the thought of the improvement to make to the new-born hydro-economic model. My PhD work has been my companion and my motivation for almost five years. The road that led to the compilation of this thesis was not without sharp bends, dead end roads, and very steep hills. But I was never alone in this journey.

I am most grateful to Andreas Grenacher who took my hand and stood with me the most difficult moments and who unconditionally supported me “through the good and the bad times”: I love you. I am deeply thankful to my parents for supporting me in this adventure: it might not have been exactly what they expected from me, it might have involved a few trips to Zambia too much but I always knew that my parents were rooting for me.

I would like to sincerely thank my dear friends, close and far: Alexandra, Beate, Elnaz, Janice, Leonardo, Marie-Laure, Nadia, Nalini, Raffaella, and Samia. Thanks for your words of encouragement, when I needed them; thanks for the light talks and jokes that made the thinking process easier; thanks for sharing many unforgettable moments and making this PhD time a really enjoyable trip.

The work that led to this thesis would not have been possible without the supervision and guidance offered by Prof. Rolf Kappel: I really appreciated the timely comments and the suggestions to improve my work in critical moments. The final version of my work also benefited from inputs, comments, and suggestions received from several colleagues. In this respect, I am particularly indebted to Prof. Amaury Tilmant, Florian Koch, Philip Meier, and Prof. Thomas Bernauer. I would also like to thank the African Dams Project members, in particular Dr. Jasmin Mertens, for the brainstorming sessions we often had, and the Zambian colleagues and Master students who contributed to this work.

Finally, I would like to thank the more than 200 water sector professionals I interviewed during my fieldwork in Zambia and each person I met in the villages and towns along the Kafue. I learnt a lot from them: without knowing, they led me to deeply understand their country and all its contradictions and gave me memories and impressions that I will carry with me throughout the journey of life. Shansha, be strong and carry on, they taught me, and so I did.

All these friends and colleagues morally wrote each single word of this thesis: we have all been PhD students for almost five long years, and to you I owe this little success story.

This project was mainly founded by the Competence Center for Environment and Sustainability (CCES) of the ETH domain. Funds for the household survey were provided by the North –South Centre of the ETH domain and by the Centre for Development and Cooperation (Nadel).



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# Chapter 1 Introduction

## 1.1 Background and motivation: working on the lifeblood of Zambia

Although Zambia is considered to have abundant water resources, development in the sectors of irrigated agriculture and hydropower generation coupled with a rising population is exerting heavy pressure on the available water resources base especially in the Kafue River basin. Under normal hydrological conditions, the water resource base might appear adequate; however, Zambia has experienced a recurrence of droughts in 1991/92 and 1994/95 and 2000/01 resulting in lower than average rainfall and severely reduced agricultural productivity and production. In this regard, it is recognized that the availability of water may not necessarily match the spatial pattern of current and future demand (GoZ, 2004).

The Kafue River is the second largest river in Zambia with a length of about 1,500 km and an average width of 25 meters and is one of the main tributaries to the Zambezi. The Kafue can be considered the lifeblood of Zambia: it comprises about 20% of the area of Zambia, it is host to more than 40% of the Zambian population, and it supplies water to the major industrial, commercial and agricultural areas of the country. The Kafue rises close to the borders with the Democratic Republic of the Congo, flows through the Copperbelt district and through the floodplain of the Lukanga swamp until it reaches the Itezhi-tezhi dam. Between this reservoir of 390 km<sup>2</sup> and the Kafue Gorge dam lies the Kafue National Park, which is recognized as a major wetland resource in ecological terms and also has a great importance in economic terms, supporting local industries, agriculture and fisheries.

Water from the Kafue River is abstracted for a variety of purposes, including municipal supplies, industrial use, mining in the Copperbelt, and irrigation of agricultural land - primarily sugar-cane growers, maize, and supplemental irrigation on winter wheat production. Moreover, the Kafue's waters are fundamental for the survival of the dense fishery activities as well as of other rich natural resources, including wildlife.

In Zambia water is allocated based on a system of water rights application which is managed by the central government. Nonetheless, water rights do not apply to all sectors and the monitoring system necessary to enforce the compliance with such rights' allocation is weak. Besides the water rights based allocation, a specific regulation of the dams is in place to ensure the preservation of Zambia's aquatic environment.

Until the water governance reform of 2010-2011, water has not been managed for the integrated benefits of the overall Zambian economy and all legislation and policies tended to reflect a sectoral bias. In this context hydropower generation has always been accorded the highest priority due to power requirements for copper mining activities and other local industries. The Zambian Government has recently embarked on the formulation of an integrated approach towards management of water resources in the country, which led to the approval of the 2010 Water Policy and the 2011 Water resources Management Bill. These documents are strongly characterised by decentralisation and stakeholders' participation, in the spirit of Integrated Water Resources Management (IWRM). Nonetheless, weak linkages between institutions managing water resources can be noticed. Moreover, local communities have neither been adequately organized nor sensitized in water management and planning while their participation is equally lacking.

In a moment when the IWRM strategies are being newly implemented in Zambia and when the competition among different uses of water is growing, it is necessary to thoroughly study the water governance system and the policy options for water management focusing on the trade-offs emerging from the stakeholders' multiple and conflicting objectives. What policymakers and stakeholders aim to achieve is a satisfactory set of options on the Pareto frontier that can be the basis for a multi-objective participatory optimization process which will lead to the selection of negotiated solutions (Marttunen and Suomalainen, 2005; Van Cauwenbergh et al., 2008; Soncini-Sessa, 2007a,b; Castelletti et al., 2004; Hofwegem and Jaspers 1999; Dinar et al. 1997).

The overall objective of the present research is to analyse the availability and allocation of the waters of the Kafue River within the boundaries given by the policy and legislative framework. One of the biggest challenges in water management is finding the optimal allocation of water resources for multiple uses, e.g. power generation, food production, and ecosystem functions in a catchment for which limited data is available. In a dynamic context where the competing demands for water are increasing, where a lack of knowledge on the amount of water withdrawals as well as on the basin's groundwater resources is manifest, and where uncoordinated policies and legislative frameworks on water resources management are in place, it is of utmost importance to adopt a multi-stakeholder and multi-objective approach to water management. Only in this way the detrimental consequences of intersectoral competition for water in a weak institutional framework – environmental degradation, load shedding, urban water shortages, declines in overall welfare and productivity – can be avoided.

The analysis presented in this PhD thesis integrates hydrological, economic, and governance aspects. The economic optimization framework provides the stakeholders with a set of possible optimal water allocations that could be achieved to obtain an efficient use of the Kafue's water resources, taking into consideration different stakeholders' and policy objectives. The governance analysis provides a clear synopsis of the current water governance system in Zambia and suggests institutional and policy options to be adopted in order to reach the optimal frontier.

The models developed in the present study are therefore expected to promote the search for efficient and sustainable water allocation options for the Kafue River basin within the broader context of the integrated management of the Zambezi River basin. Moreover, the approach adopted couples hydrological and economic models which will allow to dynamically examine the range of economic and environmental options for the Kafue basin in a truly cross-sectoral vision of the system.

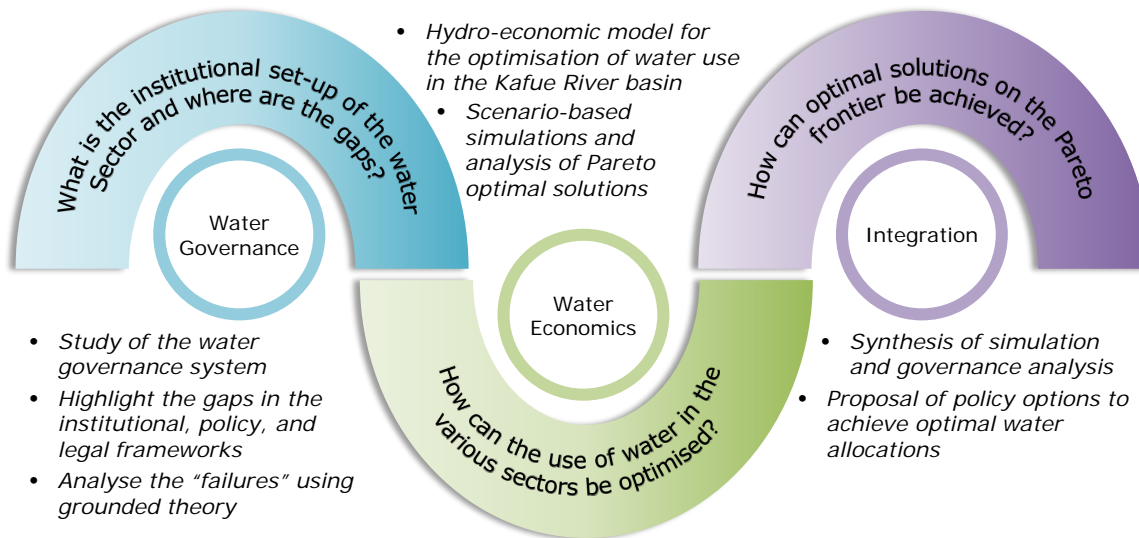
The development of such a multi-objective social optimization approach requires a close integration of economics, social sciences, hydrology, and environmental sciences. These requirements are met thanks to the collaboration with the team of researchers working on the African Dams Project (ADAPT), of which the present project is part. The ADAPT Project has as overarching goal the strengthening of the interdisciplinary science IWRM by creating new models for the real-time control and multi-objective optimization of large hydraulic structures. The focus of the project is on the Zambezi River basin at various scales, from sub-catchment to the entire river basin. In particular, a large extent of the research focuses on the Kafue River basin where a hydrological model has been developed and calibrated, biogeochemistry studies have been undertaken, and environmental and ecological studies have been conducted.

The research presented in the following Chapters is of immediate relevance to the policymaking process concerning economic development in the Kafue River basin, particularly when conflicting demands are considered and the effects of the expansion of the different economic sectors on the availability and quality of water are examined. In fact, a clear understanding of the interactions between water supply and demand can drive changes in water policy that improve society's use of limited water resources (Burke, 1994). This is particularly true in the Zambian context, where it is also necessary to consider how policies and legislation can be used as a tool for overall development. To this extent, the multi-objective model should be considered as an integrated and transparent tool for supporting decision making.

The present study also makes a contribution to the expansion of the research stream on multi-objective optimization techniques through a holistic approach that encompasses surface and groundwater hydrology, the estimation of crop-water functions, the integration of environmental considerations, and the incorporation of urban, industrial and mining water uses. Moreover, the adoption of a participatory approach since the early stage of the process, achieved through stakeholders' interviews and the execution of a complete rural household survey, and the readiness of the model to be adapted to the stakeholders' priorities constitute a great challenge and a novelty in the application of multi-objective modelling in integration with governance studies. Of course, this requires a thorough collection and analysis of data as well as a continuous interaction between stakeholders for the identification of goals, values, and priorities.

## 1.2 Methodological framework

The research project is structured into two complementary blocks – water governance and water economics, which are closely linked together.



The research conducts a grounded study of the water governance system in Zambia analysing the institutional, policy and legal frameworks. The governance research has been carried out in a transition phase from a legal and institutional framework based on the 1948 Water Act and on the 1994 National Water Policy (1994) to a renovated framework that stems from the IWRM principles. Pending the full enactment of the renewed legislation and policy, the governance study: 1) provides insights into the discrepancies between the laws and policies and their effective implementation on the ground as well as the mismatch between the water governance framework and the IWRM provisions; 2) suggests key areas of tension or, eventually, conflict among key users; and 3) identifies the main challenges to the implementation of an integrated governance of water resources, both at national and regional level.

The governance analysis is based on an intense involvement of all water sector stakeholders in order to understand the multiple sectoral objectives of water management and the specific policy directions that are being adopted to reach those objectives. This has been achieved through the execution of stakeholders' interviews with representatives of various water governance and water using actors. These interviews have been conducted with government officials at various governance level, fishermen and fish farmers, large and small scale farmers, managers of the a number of copper mines, NGOs and international organizations' representatives. In addition, a full survey of 428 rural households was conducted in the lower Kafue River basin with the objective to assess the perception of the changing governance system at end-users level.

The theoretical approach used to analyse the interviews data is based on grounded theory (Myers, 1997; Pandit, 1996; Strauss and Corbin, 1994; Glaser and Strauss, 1967). Interviews were carried out in subsequent rounds with the aim to each time broaden the scope of the research in terms of number and depth of analysis of the key concepts. The interviews were transcribed and the material was coded and categorised based on various conceptual levels. The categorisation of the material brought to the identification of key concepts, repeatedly being present in interviews, documents, and observations, and the explanatory linkages between them. The canons of grounded theory have been applied in this study trading a fine line between the formal rigor and the necessary flexibility required by the contingencies of an applied field research in a developing country.

Based on the governance set-up, the analysis of its weaknesses, and the different policy goals, a hydro-economic model is built taking into consideration all water using sectors in the Kafue River basin. Taking into consideration the complex web of competing demands over the Kafue's waters occurring at different

geographical coordinates in the river basin, the present study does not only consider the demand for water for all the various economic sectors as well as for the environment, but also focuses on the construction of an economic optimization model for water allocation in the Kafue River basin.

The hydro-economic model helps giving an answer to a key research question: how can the use of water resources in the various sectors be optimized? While answering this question, our research also studies in depth the demands for water that rely on the Kafue River basin, the trade-offs between the demands of different water users, and the impact of water scarcity on the various water users. Finally, the model supports the identification of a set of optimal solutions in terms of water resources allocation under different degrees of water stress (considering as baseline the actual conditions).

The hydro-economic model includes both a temporal and a spatial dimension – necessary for the integration with the hydrological supply side –, and is based on multiple objectives mirroring the variety of targets that are embedded in water management decisions. The model builds on the hydrological models developed within the ADAPT Project and their outputs in terms of water flows and dam operation. Such hydrological studies provided the water availability interface of the model. Though in literature there is no universal formulation for a multi-objective optimization model, our framework includes all the essential elements such as (Lollmun, C., 2009):

- Consistent accounting of flows, water storages, diversions etc.;
- Representation of demand for water and economic benefit for its use;
- Consideration of both instream and offstream uses;
- Network representation of the physical basin;
- Incorporation of institutional rules and policies.

Our model uses scenarios to simulate the adoption of the various policies proposed in the first stage by the stakeholders themselves and confirmed in analysis of the recent policy and legislative developments. The results of the scenarios also help understanding the trade-offs associated with the implementation of different policy measures as well as those associated with the adherence to IWRM principles.

The economic model is a powerful instrument to indicate a portfolio of economically feasible Pareto solutions. Nonetheless, social objectives might differ from economic considerations and socially optimal solutions necessarily have to emerge from the interaction and bargaining among the stakeholders. Based on the Pareto optimal solutions as well as on the analysis of the challenges and opportunities derived from the water governance structure, our study provides a set of policy and institutional suggestions that could be adopted in order to optimize the allocation of the water resources. Cooperation among stakeholders in the management of common water resources is, indeed, a leitmotiv identified by this thesis. At local, Kafue, and Zambezi level we identify the trade-offs emerging from different water allocations and we highlight the benefits derived from a comprehensive and coordinated management of water resources. An adequate water governance platform needs to be in place to harness all the benefits of cooperation and ensure the satisfaction of the societal objectives. The governance changes introduced in Zambia appear to lead to an increased awareness for the need to coordinate and integrate water management, but challenges to the implementation of such framework still exist and might pose a threat to future development plans for the Kafue region, the country and, ultimately, the Zambezi basin as a whole.

### 1.3 Outline of the thesis

The core of this PhD thesis consists of five chapters that illustrate the governance and economic aspects of the management of the Kafue River basin.

Chapter 2 presents a comprehensive study of the changing water governance system in Zambia. In February 2010, a revised water policy for Zambia was approved by the Cabinet. The revised National Water Policy 2010 aims to improve water resources management by establishing institutional coordination and by defining roles as well as responsibilities for various ministries. The challenges to the implementation of principles for water governance are analysed in relation to the legal and administrative changes and organizational requirements involved. The gaps in implementing good water governance and Integrated Water Resources Management in Zambia are identified, as well as the root causes of these gaps. But a changing governance system also provides a set of new opportunities, particularly considering the decentralisation and the possibility for a greater involvement of water users at grassroot level. I equally shared the data collection and analysis effort with Preetham Salian, the theoretical conceptualisation as well as the draft of the paper was carried out by three authors in equal shares, and the revision of the drafts was shared among all four authors.

Taking the moves from the challenges and opportunities analysed in Chapter 2, particularly the devolution of powers to the lowest level of authorities, the creation of new institutions acting at river basin level, and a greater involvement of all stakeholders in the decision making process, Chapter 3 studies the uptake of the governance system at household level, in the rural areas of the Kafue basin. We focus, in particular, on the role of women in water use and water governance. The recently ratified 2010 Water Policy and 2011 Water Resources Management Act fully recognize the pivotal role of women in the water realm, and foster women empowerment and full participation in issues and decisions related to sustainable development of water resources and, specifically, in the use of water. Our results are derived from a survey of 428 rural households conducted, *inter alia*, with the objective to assess the gender influences on water use, the current level of awareness and participation of smallholders and women in water institutions, the understanding of the roles and functions of these institutions, and the perception of their performance. I lead the data collection and was the main responsible for carrying out the econometric analyses and drafting the paper.

Chapter 4 describes the multi-objective hydro-economic optimization model which is proposed here as a tool to analyse the competing demands for water in the Kafue River basin. The model addresses the linkages between water supply and the economic use of water at river basin scale and considers economic, social, and environmental objectives. Competing demands for water in the urban, agricultural, industrial, mining, and environmental sector are addressed and supporting models are used to provide the hydrological inputs and the agricultural water-yield functions. I designed the hydro-economic model and drafted the paper. I acknowledge Prof. Amaury Tilmant's feedback on its mathematical formulation.

The hydro-economic model presented in Chapter 4 allows testing several development scenarios and comparing the respective frontiers of efficient solution. Applying our hydro-economic model, Chapter 5 analyses several future development scenarios and the implications on water demand, supply and optimal water allocation across sectors of the economy. Optimal solutions derived from the optimization process are presented with a focus on the trade-offs between different water users and underlining possible policy options to optimise the allocation of water resources in the Kafue River basin. The approach presented in this work is of direct use to decision makers as it allows considering not only the physical dimensions of



alternative water allocations, but also the economic consequences associated with it. I collected the water use and socio-economic input data, designed the scenarios, interpreted the results, and drafted the paper. This chapter benefited from the hydrological data provided by Philip Meier and Florian Koch.

Chapter 6 broadens the perspective to consider the whole Zambezi River basin. A hydro-economic model supports the identification of Zambezi-wide water allocation policies, considering both hydropower generation and agricultural production. The model analyses the changing economic value of water across the basin and identifies the scope to improve the integrated and cooperative management of the Zambezi waters through planning of large hydraulic infrastructures and agricultural schemes. I provided a critical amount of water use data, with particular reference to agricultural and urban withdrawals, and I contributed to the revision of the drafts.

In the final chapter of this thesis the main findings are summaries and some open questions are discussed in the context of current hydro-economic and governance research. Also, an outlook on possible future interdisciplinary research on the Kafue and Zambezi basins is presented.

## References

Burke, J. J. (1994). Approaches to integrated water resource development and management: the Kafue Basin, Zambia. *Natural Resources Forum* 18(3), 181–192.

Castelletti A, Soncini-Sessa R (2004). PIP: a participatory and integrated planning procedure for decision making in water resource systems. In: IFAC Workshop on Modelling and Control for Participatory Planning and Managing Water Systems, Sept 28–Oct 1 2004, Venice.

Dinar A, Rosegrant M, Meinzen-Dick R (1997). Water allocation mechanisms—principles and examples. *World Bank Policy Research Working Paper*, 1779, 48.

Glaser, B. & Strauss, A. (1967). *The Discovery of Grounded Theory*. Chicago: Aldine.

Government of Zambia (GoZ) (2004). Water resource action program, final report: technical component 1 – Legal and institutional framework. Ministry of Energy and Water Development, Government Printers, Lusaka.

Hofwegem P, Jaspers F (1999). Analytical framework for integrated water resources management. IHE Monograph 2, Delft, The Netherlands.

Marttunen, M & Suomalainen, M. (2005). Participatory and multiobjective development of water course regulation - Creation of regulation alternatives from stakeholders' preferences. *Journal of Multi-Criteria Decision Analysis* 13(1), 29-49.

Myers, M. D. (1997). Qualitative research in information systems'. *MIS Quarterly* 21(2), 241–242. <http://www.qual.auckland.ac.nz/>.

Pandit, N. R. (1996). The creation of theory: A recent application of the grounded theory method, *The Qualitative Report*. <http://www.nova.edu/ssss/QR/QR2-4/pandit.html>.

Soncini-Sessa, R. (2007a). Integrated and participatory water Resources Management. Part I: Theory. Oxford, Elsevier, 2007.

Soncini-Sessa, R. (2007b). Integrated and participatory water Resources Management. Part II: Practice. Oxford, Elsevier, 2007.

Strauss, A. L. & Corbin, J. (1998). Basic of qualitative research: Techniques and procedures for developing grounded theory, in N. K. Denzin & Y. S. Lincoln, eds, 'Handbook of Qualitative Research', Sage., Thousand Oaks, CA.

Van Cauwenbergh, N., Pinte, D, Tilmant, A., Frances, I., Pulido-Bosch, A., Vanclooster, M. (2008). Multi-objective, multiple participant decision support system for water management in the Andarax catchment, Almeria. Environmental Geology, 54, 478-489.

## Chapter 2

# Good water governance and IWRM in Zambia: challenges and chances

This chapter is based upon: Uhlendahl, T., Salian, P., Casarotto, C. and J. Doetsch, 2011. Good Water Governance and IWRM in Zambia - Challenges and Chances. *Water Policy*, 13 (2011) 845–862.

## Abstract

The implementation of principles for water governance is widely accepted but challenging for the whole water sector of a developing country like Zambia, because of the legal and administrative changes and organizational requirements involved. In February 2010, a revised water policy for Zambia was approved by the Cabinet. The revised National Water Policy 2010 aims to improve water resources management by establishing institutional coordination and by defining roles as well as responsibilities for various ministries. Taking into account the previous political and administration changes, this paper points out the problems and challenges of the implementation of good water governance mechanisms in Zambia. Focusing on the Kafue River basin, from which water is abstracted for a variety of conflicting purposes (like municipal supplies, industrial use, mining, irrigation of agricultural land, fishery activities, wetland reserves and hydropower production), the gaps in implementing good water governance and Integrated Water Resources Management (IWRM) in Zambia are identified, as well as the factors causing these gaps in the Zambian water sector. The paper finishes with a overview of the opportunities given by the new water policy through Water User Associations (WUAs) at a local level.

## 2.1 Introduction

The implementation of principles for water governance is widely accepted but challenging for the whole water sector of a country because of the legal and administrative changes and organizational requirements it entails (e.g. Lemon, 2001; Keeley & Scoones, 2003; Gupta, 2007). While the implementation of the European Water Framework Directive is a challenge to European countries (Commission of the European Communities, 2003) the implementation of Integrated Water Resources Management (IWRM) is a challenge for developing countries like Zambia. Such an implementation requires a set of administrative systems called Water Governance (Global Water Partnership, 2000, 2003).

This paper points out the problems and challenges of the implementation of good water governance mechanisms in Zambia. It is based on a research project in the Kafue River basin, which focused on identifying the gaps in implementing IWRM in Zambia, and the factors causing these gaps in the Zambian water sector. The conceptual analytical framework for IWRM by Hofwegen & Jaspers (1999) was adapted to conduct an institutional analysis.

A qualitative approach based on the Grounded Theory Methodology (GTM), comprising twenty-eight interviews with forty interviewees amongst six groups (Zambian ministries, water users, donor agencies, international organizations, non-governmental organizations, and independent consultants), was adopted (Salian, 2010). The interviews were collected based on theoretical sampling: the range and type of interviewees selected were determined when more information on a particular situation or issue arose from preceding interviews. In order to explore the broadest spectrum of water governance challenges, a semistructured format was chosen for the interviews which were then transcribed, coded, and analyzed using the ATLAS.ti software. The interviews were also kept anonymous. In line with the methods fostered by GTM, a constant comparative analysis was performed. This included recursive analysis of the data collected with each interview, categorization of the material through coding carried out by two independent researchers, and unification of the codes in order to answer the original and upcoming research questions.

Section 2 of this paper illustrates the main challenges facing the proper implementation of IWRM, with specific attention to the degree of decentralization in allocating decisional power and the role of stakeholder participation in decision making. Section 3 illustrates the area of the study and the main features of the water resources system in Zambia. This is functional to contextualise the current institutional framework adopted for the management of water resources in Zambia and the water sector reform process, both of which are explored in Section 4. Section 5 looks into the challenges to water governance in Zambia, whilst the final section draws concluding remarks and recommendations.

## 2.2 Challenges to IWRM and good water governance

The Global Water Partnership (GWP) defines IWRM as ‘a process that promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems’ (GWP, 2000).

One of the core concepts of IWRM is to promote coordination and integration of various interest groups to achieve a more holistic cross-sectorial water management (Jønch-Clausen & Fugl, 2001). The concept proposes to make a clearer link between and better understanding of interactions between human and environmental requirements (Wallace et al., 2003). In addition, it includes managing the actions of various interest groups in a manner that promotes sustainable development vis-à-vis improving their livelihoods without disrupting the water cycle (Jonker, 2002).

For a successful implementation of IWRM plans, effective governance strategies are crucial (Grigg, 1999; Keen, 2003; Wallace et al., 2003; Koudstaal et al., 1992, cited in Savenije & Van der Zaag, 2000). The GWP defines water governance as ‘the range of political, social, economic and administrative systems that are in place to develop and manage water resources and the delivery of water services at different levels of society’ (Rogers & Hall, 2003). The principles of good water governance are derived from those of good governance in general and are formulated around the concepts of equity, efficiency, decentralization, integrations, transparency and accountability (UN, 2003).

Changes in governance paradigms are always challenging for any nation, but for a developing country like Zambia the implementation of good water governance principles can face considerable obstacles. Although the principles of good water governance are widely accepted, critical issues regarding power and localization of authority in the field of water governance remain unaddressed and unelaborated (Gupta, 2007). The decentralization process, from a state-centred actor to non-state and state actors, requires many changes in institutional structures, as well as the reallocation of power and funds to provide the participation of various stakeholders in the governance of a country’s natural resources.

Consequently, the two main topics in implementing IWRM in a country’s policies are decentralization versus centralization, and the role of stakeholder participation in decision making.

### 2.2.1 Decentralization vs. centralization

The appropriate allocation of power to manage water resources has been widely discussed in literature (Rondinelli et al., 1984; WWDR, 2006; Gupta, 2007). The argument in favour of centralization is that water needs to be controlled and held in public trust for the country to have the power to own the re-

source to the nation state for the purpose of equity. The counterargument for centralization is that it does not take into consideration the local stakeholder knowledge and interests. Furthermore, centralization imposes a hierarchy of top down view, where benefits arising from such arrangements are only gained by very few and undermine the ones with less power in the process (Rondinelli et al., 1984).

According to this critique, a successful implementation of a new water governance system will only develop when the solutions are locally generated and implemented (World Water Vision, 2000). Locally generated solutions will ensure the higher ownership of the stakeholders involved in the process, rather than centralized technocratic institutions deriving solutions, which would be far from the actual issues on the ground.

But this view is not free from criticism. Decentralization is difficult to achieve due to power struggles and limited capacities to run such systems effectively. Often decentralized mechanisms tend to externalize upstream impacts that affect communities or regions downstream, which do not fall under its governance framework (Gupta, 2007).

### 2.2.2 Stakeholder participation

Modern discourses have emphasized the need to combat democratic deficit within societies (Gupta, 2007). These discourses promote the introduction of public participation in technocratic decision-making in IWRM. For example, public participation was established in Europe by implementing the European Water Framework Directive (European Community, 2000, preamble 13 and 46, Article 14). The need for public participation derives itself from the principles of good governance and IWRM (Commission of the European Communities, 2001). These have been elaborated by the GWP as (2003):

“The approach to achieve good water governance has to be open and transparent, coherent and integrative, inclusive and communicative as well as equitable and ethical. The performance of such arrangements must be accountable, efficient, responsive and sustainable”.

The above normative approaches to such principles are ideal for improved water governance. However, the critiques concerning stakeholder participation pose a number of challenges in its implementation. Gupta (2003) argues that the process of managing stakeholder participation leads to an increase in bureaucratization of existing systems and thus increases costs associated with planning processes. This argument is true for formal participation settings like hearings in the post-planning process but not for informal settings such as in the pre-planning process (Uhlendahl, 2009). The more important point of critique is that the true costs of public participation are still not easy to assess (Andersson et al., 2005). While stakeholder participation offers without doubt the easiest way of solving conflicts directly (Uhlendahl, 2009), it does not guarantee constructive and sustainable solutions. Nevertheless, the costs for stakeholder participation are much higher in the pre-planning process of measures. This can lead to much faster implementations of measures and to the reduction of costs in the post-planning process.

The involvement of stakeholders does not automatically lead to balanced solutions. The consideration of power play within the actors is important as well. State involvement often plays a big role in balancing the power play among stakeholders. Usually, poor or underprivileged stakeholders are marginalized and cannot participate effectively. This causes a loss in motivation wherein the stakeholders feel their inputs are sidelined against some powerful actors. The so-called ownership of such a process loses its

value and the outcome can be unbalanced. This is often the case in a joint process where actual formulation is concentrated in a few hands leading to the control and manipulation of such participatory processes. The introduction of participatory approaches tends to reduce these power vested in the state and would further accentuate the imbalance between stakeholders (Keeley and Scoones, 2003).

Additionally, the culture and economic context within which new policies are implemented can lead to uncertain and unintended outcomes. Such unpredictable outcomes could contradict the very objective of a participatory process (Lemon, 2001). Finally, this could result in different local policies, which can cause lack of their harmonization at regional and national levels (Stiglitz, 2000).

## 2.3 Country context and a focus on the Kafue River

After copper, its most important natural resource, water is the most crucial natural resource in Zambia. The Fifth National Development Plan (2006–2010) states that water is one of the core factors for the economic growth of the country, and a vital and central element in pro-poor economic development by improving small-scale irrigation (GoZ, 2006). To date, Zambia remains one of the least developed countries in the world with a Human Development Index (HDI) of 0.395 (ranked 150th out of 169), with a high incidence of poverty (63.7% of the population is poor) and a life expectancy at birth of about 47.3 years (UNDP, 2010). These numbers underline the importance of poverty reduction for Zambia.

Despite Zambia's economy being heavily based on mining activities, thanks to the rich endowment of copper, the agricultural and hydropower sector play a key role in the development of the country and are recognized by the government as priority sectors. Currently, about 70,000 hectares (World Bank, 2009) are developed under formal irrigation (excluding land in non-equipped cultivated lowlands and wetland irrigation) and substantial developments are expected, particularly in the Kafue River basin. The World Bank (2009) estimates that by 2012 about 15,000 more hectares will be irrigated (Table 2.1); moreover, the Sixth National Development Plan (SNDP) foresees the construction of thirty new irrigation schemes by 2015 that will increase the agricultural land under irrigation by 25,000 hectares. Also, the hydropower sector is considered to be the key to the Zambian economic development and the SNDP set the expansion of hydropower generation capacity as a national priority. In fact, the Zambian hydropower potential is widely untapped: the available capacity, recently increased to 1,890 MW after up-rating and rehabilitation of the Kariba North Bank, Kafue Gorge and Victoria Falls hydropower stations, falls short of meeting the current and future anticipated electricity demands. Therefore, massive developments are planned that could, in the long term, bring the total installed capacity in the country to 4,635 MW (GoZ, 2011).

Table 2. 1 Expected expansion of irrigated land

Province	2008 (ha)	Likely 2012 (ha)
Eastern	400	500
Lusaka	8,500	9,500
Southern	39,000	45,000
Western	100	250
Northern	1,500	3,500
Northwestern	300	300

Luapula	150	250
Copperbelt	4,400	6,800
Central	10,000	15,500
<b>Total</b>	<b>66,358</b>	<b>81,600</b>

*Source: World Bank, 2009*

Most of the Zambian surface water is found within the major rivers of the Zambezi, Kafue, Luangwa, Luapula and Chambeshi, and the lakes of Tanganyika, Bangweulu, Mweru, Mweru-wa-Ntipa, Kariba and Itezhi-tezhi. The Kafue, second longest Zambian river, is essential since it comprises about 20% of the country's area and hosts more than 40% of its population (GoZ, 2008). Water from the Kafue River is abstracted for a variety of purposes including municipal supplies, mining activities, and small- and large-scale irrigation, primarily for sugar cane growers, maize and supplemental irrigation on winter wheat production (GoZ, 2008). Furthermore, the Kafue's waters are fundamental for the survival of the dense fishery activities, which serve as a livelihood for the people living in the basin, and the river comprises the two most important wetland reserves and Ramsar sites in the country (WWF, 2005). Figure 2.1 and Table 2.2 provide an illustration of the Kafue River and the main activities that benefit from its waters.

Table 2. 2 Water related activities in the Kafue River basin

	<b>Opportunities</b>	<b>Challenges</b>
<b>Mining</b>	<ul style="list-style-type: none"> <li>- Most of the copper mining activities take place in the Northern part of the basin, in the Copperbelt Province.</li> <li>- This area is one of the most active economic zones in Zambia.</li> </ul>	<ul style="list-style-type: none"> <li>- High population density due to migratory workers.</li> <li>- Pollution of soils.</li> <li>- Water pollution linked to the heavy utilization of chemicals for the extraction of minerals and to the discharge of heavy metals from the tailing dams.</li> <li>- Runoff from open pit mines during rainy season.</li> <li>- High incidence of HIV.</li> </ul>
<b>Hydropower</b>	<ul style="list-style-type: none"> <li>- 990 MW out of the generation capacity is produced by the Kafue Gorge dam on the Kafue River.</li> <li>- Increasing demand for electricity drives the expansion plans for the hydropower sector.</li> <li>- The main hydropower projects are the Itezhi-tezhi and the Kafue Gorge Lower stations.</li> </ul>	<ul style="list-style-type: none"> <li>- The increased storage capacity will further hold more water for the production of electricity, thus essentially restricting water availability for other economic activities.</li> <li>- Environmental concerns related to the change in flooding pattern and associated change in vegetation cover and fauna.</li> </ul>
<b>Agriculture</b>	<ul style="list-style-type: none"> <li>- Though rainfed agriculture is dominant in Zambia, the Kafue waters are used to irrigate about 50,000 hectares of cropland.</li> <li>- In the lower Kafue, several commercial farms cultivate areas of about 33,000 ha (World Bank, 2009) to produce the majority of Zambia's sugar for local use</li> </ul>	<ul style="list-style-type: none"> <li>- The lower Kafue is reaching conditions of water stress.</li> <li>- The allocation of water between small-scale and commercial farmers appears to be more and more conflictual, mainly due to the massive water requirements needed for the irrigation of sugar cane by Zambia Sugar (GoZ, 2004b).</li> </ul>

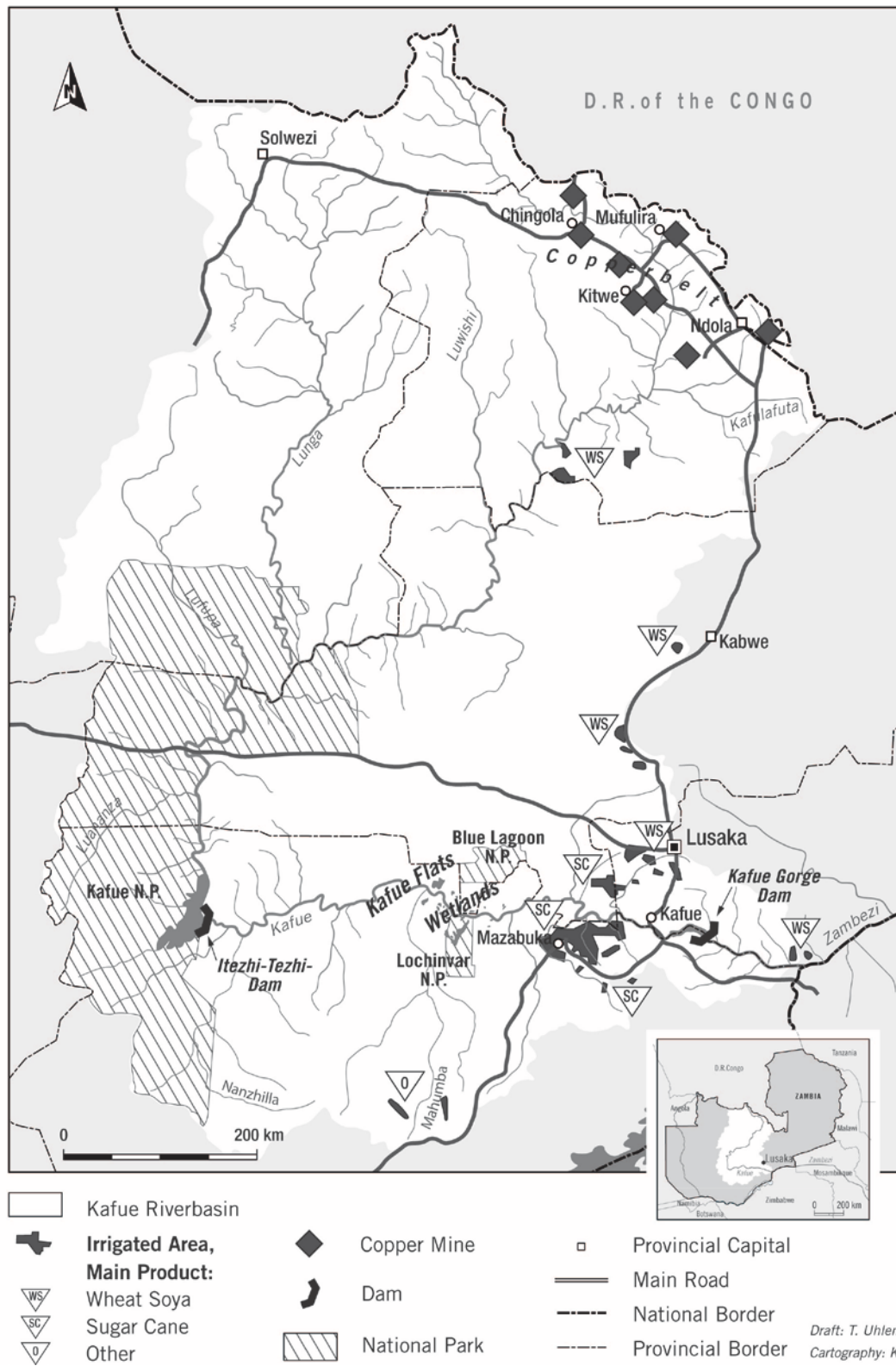


	and export.	- Nutrient-rich effluents are discharged back into the Kafue, contributing to the proliferation of many aquatic weeds.
<b>Wetlands</b>	<ul style="list-style-type: none"> <li>- The Kafue Flats cover around 6500 km<sup>2</sup> and are recognized as a major wetland resource in ecological terms of rare and endemic species.</li> <li>- The flats traditionally have supported the local population with land for cattle grazing, floodplain agriculture and fishing.</li> <li>- The flats include the two national parks of Lochinvar and Blue Lagoon.</li> </ul>	<ul style="list-style-type: none"> <li>- The impoundment of water for hydropower generation has lead to a reduction in the available surface area for grazing and for crop production.</li> <li>- A decline in the number of Kafue Lechwe (endemic antelope) has been registered since the construction of the Itezhi-tezhi dam, concurrently caused by a change in habitat and increased poaching.</li> </ul>

Recent independent studies (COWI, 2009; World Bank, 2009) concentrated on the water availability for two main economic activities in the basin, namely commercial agriculture and hydropower production, and concluded that the Kafue River will soon reach a state of economic water scarcity. Driven by a continuous economic growth and a steady increase in population, the pressure of different sectors on water resources is rising. Thus Zambia faces several challenges in harnessing the potential of the actually abundant water resources.

It is not only insufficient infrastructure investments to sustain the economic demand for water that are hindering the Zambian development but also a lack of proper governance in the water sector – the main factor causing a loss of the possible benefits that could be harnessed (Sievers, 2006; Chabwela & Haller, 2008).

Figure 2. 1 The Kafue River basin



## 2.4 Water resources management in Zambia

### 2.4.1 Institutional and legal framework

Water management in Zambia had always been managed on a sectorial basis. All legislation and policies in the past tended to reflect a sectorial bias (COWI, 2009) and there have been limited approaches so far to the development of a comprehensive strategy for water resources management. Recognizing the inefficiency of sectorial water management, the Zambian government opted for a water sector reform following the IWRM approach, under the auspices of the Water Resources Action Program (WRAP). Its implementation started in 2001 with the Ministry of Energy and Water Development (MEWD) in charge of the reform (GoZ, 2004a).

Currently the Zambian water sector involves many different organizations and authorities at various levels ranging from policy/legal formulation and implementation through service provision to consumption. Derived from the Water Act of 1949, the main ownership of the water resources is vested in the President of Zambia. Various ministries, departments and agencies are separately tasked to administer these resources. The MEWD, with the Department of Water Affairs (DWA) and the Water Board have the overall responsibility for water resources management and development in Zambia. The functions of the DWA and the Water Board are detailed in Table 2.3.

Table 2. 3 Functions of the Department of Water Affairs and Water Board

	Department of Water Affairs (DWA)	Water Board
<b>Water allocation</b>	Investigation on water rights and advice to Water Board.	<ul style="list-style-type: none"> <li>- Processes the water rights applications.</li> <li>- Decides on the water allocation based on a preliminary investigation by the DWA.</li> </ul>
<b>Water charges</b>	Provides advice to the Water Board on the determination of water charges in the lack of a proper pricing strategy document.	Provides advice to the Minister (MEWD) on the determination of water charges.
<b>Policy function</b>	Director of DWA has the role to advise and participate in the formulation of water-related policies. This function is carried out together with the Department of Planning and Information in the same Ministry.	The secretary of the Water Board provides advice on the formulation of water-related policies.
<b>Planning</b>	<ul style="list-style-type: none"> <li>- Planning the development of water resources.</li> <li>- Conduct surveys to explore water resources availability and facilitate the access to water.</li> <li>- This function is carried out together with the Department of Planning and Information in the same Ministry.</li> </ul>	Plans the issuance of water resources
<b>Quality</b>	Water resources quality monitoring and evaluation.	<ul style="list-style-type: none"> <li>- Can call upon polluters to take adequate steps to prevent the fouling or pollution of water.</li> </ul>

		- Can penalize polluters.
<b>Funding</b>	Provides funding – under general budget provision from the Ministry of Finance – to carry out WRM functions.	Can provide supplementary funds (derived from water right charges) for the investigation of water rights and other activities of the Water Board (Appropriation-in-Aid).
<b>Disputes solving</b>	Technical support function in case of disputes over water resources.	The secretary of the Water Board is called to testify over all issue of dispute over water resources in court.
<b>Information Management</b>	Assessment and surveying of water resources, both surface and groundwater.	Compiles the Water Rights Database.

The other institutions that are directly or indirectly involved in the water management are mentioned below in seven categories:

- Government ministries and departments:
  - The ministry of Agriculture and Cooperatives (MACO) has the responsibility to monitor the use of water for cropping activities;
  - The Ministry of Livestock and Fisheries has the responsibility to monitor the use of water for fishing, fish farming and livestock watering;
  - The Ministry of Local Government and Housing (MLGH) is the lead ministry in Water Supply and Sanitation and also responsible for policy development in this field and for the physical planning of water supply and sanitation services and resource mobilization;
  - The Ministry of Tourism, Environment and Natural Resources (MTENR) is mandated for the protection of water resources;
  - The Ministry of Health (MOH) is in charge of setting standards and monitoring the quality of drinking water.
  - The Office of the Vice-President coordinates disaster management;
  - The Ministry of Transport and Communication provides meteorological services and is responsible for inland waterways;
  - The Ministry of Mines is responsible for dewatering in mines.
- Local authorities (e. g. city, municipal, district councils) are mandated to provide, in an environmentally sustainable way, water supply and sanitation services to the areas under their jurisdiction. This mandate is carried out through nine commercial water utility companies.
- Parastatal companies, such as the Zambian Electricity Company ZESCO) with the functions of generation, transmission and distribution of electricity, and commercial water utilities that supply water and sanitation services under the general regulation of NWASCO.
- Regulatory authorities are statutory bodies established by Act of Parliament. The main authorities are, besides the Water Board, the National Water Supply and Sanitation Council (NWASCO), regu-

lating and setting standards for the urban and peri-urban water supply and sanitation services providers, and the Environmental Council of Zambia (ECZ), that establishes water quality and pollution control standards and determines conditions for the discharge of effluents. Another important body is the National Heritage and Conservation Commission which provides for the conservation of “natural heritage” such as waterfalls. Besides Zambia Wildlife Authority (ZAWA) controls, manages, conserves, protects and administers National Parks.

- Private sector companies that operate in the manufacturing, mining, food processing, agriculture and power generation fields (e. g. Mining companies, Zambia Sugar Company, industries).
- Bilateral and multi-lateral Cooperating Partners (e.g. European Commission, World Bank, African Development Bank, Germany, Denmark, Japan, UNICEF, etc.) that have been the main financiers of water-related projects and programmes in Zambia.
- Non-governmental organizations (NGOs) and Community Based Organizations (CBOs) (e.g. World Wildlife Fund, Care International, WaterAid, Residents/Ward Development Committees) that operate in a variety of fields related to water management, such as the promotion of community-based management of water supply schemes, gender related activities, sanitation and health education.

Sector Advisory Groups (SAGs) were introduced in 2003 by the Government of the Republic of Zambia through the Ministry of Finance and National Planning as a vehicle for contributing to the process of planning, implementation, monitoring and evaluation in the sectors. The SAGs comprise representatives from key institutions and stakeholders, which currently include the line ministries, statutory bodies, cooperating partners, academic and research institutions, NGOs and other stakeholder associations actively involved in the sectors. The Water Sector Advisory Group has four Sub-SAGs. These are Water Resources Management Sub-SAG, Water Resources Infrastructure Development Sub-SAG, Water Supply & Sanitation Sub-SAG and Capacity Building, Monitoring and Evaluation Sub-SAG. The main Water SAG advises the government on sector policy issues, performance of the various sub-sectors, efficient and effective water use, transparent management and sub-sectorial coordination. Furthermore, it provides a forum for sector wide approaches concerning planning, budgeting, delivery and implementation.

#### 2.4.2 The water sector reform process

The overall goal for the management of the Zambian water resources as explicitly stated in the IWRM and Water Efficiency Implementation Plan is “to achieve equitable and sustainable use, development and management of water resources for wealth creation, socio economic development and environmental sustainability by 2030” (GoZ, 2008). To realize this ambitious objective, institutional reforms have been started in various sectors.

In February 2010, a revised water policy for Zambia was approved by Cabinet. The revised National Water Policy 2010 aims at the improvement of water resources management by setting institutional coordination and defining roles as well as responsibilities of various ministries. Thus, the new policy is regarded as a document that covers all sectors and strives to address cross-sectorial interests with particular focus on water resources planning, development, management and utilisation. It encompasses the various sector policy objectives to be incorporated in one document and it is explicitly inspired by the principle of Integrated Water Resources Management with stakeholder participation and decentrali-

zation being two main thrusts. The policy underlines the following as major components of change with respect to the previous water policy of 1994:

- Decentralization in decision-making to the lowest possible level. This approach buoyed up by the Decentralisation Policy (GoZ, 2003) and by the long term government's vision of a fully decentralized system of governance, implies a marked shift from a heavily centralized system, as of today, to one based on hydrological boundaries that transcend provincial and district boundaries. Water management is thus the responsibility of a Water Resources Management Authority (WRMA) that delegates most of the activities to catchment and sub-catchment Councils and Water User Associations (WUAs).
- Promotion of active community and stakeholder participation in the design, implementation and management of water resources related programs and projects. It is, in fact, recognized that the views of stakeholders are valuable for influencing decisions that affect communities in water resources management and development.
- Promotion of regional cooperation in water resources management as well as in areas of research, data collection and information exchange.
- Assurance of resource efficiency and equity amongst all users, consistently with social, economic and environmental needs of present and future generations.

Although the Revised Water Policy refers to the normative aspect of water management, the question still remains on how these objectives would be fulfilled.

Nonetheless, first steps have been taken on the local level. WRAP together with DWA has supported two WUAs since 2008, namely Kamfinsa and Lunsemfwa. The Kamfinsa WUA lies within the Upper Kafue catchment while the Lunsemfwa catchment is situated in the Upper Lunsemfwa sub-catchment of the Luangwa catchment. The need to form such structures on the local level to manage water resources arose in the areas because of competing uses and disputes. Lessons learnt from the two pilot WUAs were fed back in the formulation of the Revised Water Policy and Water Resources Management Bill.

In the new Water Resource Management Bill, the WUA will play a crucial role in managing Zambia's water resources. While the pilot WUAs are financed through WRAP (EU and GIZ ), within the new structure with the Water Resource Management Authority, catchment Councils, and sub-catchment Councils the WUAs will finance themselves mainly through water permit charges and grants only when necessary. However, since the WUAs would consist of voluntary members, training and capacity building efforts should be conducted at catchment and sub-catchment Council level to support the proper functioning of the WUAs; but, at the same time, some capacity development must happen within the WUAs in order to ensure the sustainable operation of such institution. A detailed synoptic description of the functions of the Water Resource Management Authority, catchment Councils, sub-catchment Councils, and WUAs is provided in Table 2.4.

Despite the on-going reform process, the institutional set up is not yet completely aligned to the sector policies leaving 'grey zones' of responsibility and complex de facto arrangements. As emerged from the analysis of the empirical material, selected non-compliance in the current structure could be listed as follows and are further elaborated in section 2.5:

- Lack of integrated approach to water resource management;
- Inadequate institutional and legal framework (i.e., monitoring, regulatory and sanctioning);
- Lack of commitment by key stakeholders and staff in key institutions;
- Lack of decentralized structure to provide for stakeholder participation;
- Inadequate human and financial capacity for water resources management.

Table 2. 4 Functions of the main institutions as outlined in the draft Water Resources Management Bill (2010)

	<b>Water Resources Management Authority (WRMA)</b>	<b>Catchment Council</b>	<b>Sub-Catchment Council</b>	<b>Water User Association</b>
Water allocation	<ul style="list-style-type: none"> <li>- Approve allocation plans and determine the quantity of water to be allocated for the various uses as well as the purpose for which the water shall be used.</li> <li>- Identify potential sources of freshwater.</li> <li>- Planning the development of water resources.</li> <li>- Secure the provision of adequate safe water for various purposes.</li> <li>- Decide on the water allocation for various purposes.</li> <li>- Issue water permits and licenses for the use of water.</li> <li>- Carry out tasks of catchment Councils, sub-catchment Councils or Water Users Associations if none exists in specific catchment or sub-catchment.</li> </ul>	<ul style="list-style-type: none"> <li>- Regulate and supervise the use of water on catchment level.</li> <li>- Include sub-catchment allocation plans in catchment management plan and submits plan to Authority.</li> <li>- Carry out tasks of sub-catchment Council if no SCC exists in specific sub-catchment.</li> </ul>	<ul style="list-style-type: none"> <li>- Regulate the use of water in sub-catchment.</li> <li>- Undertake investigations and make recommendations on the applications for a water permit or license in sub-catchment.</li> <li>- Prepare an allocation plan for inclusion in a sub-catchment management plan and submits the plan to the Catchment Council.</li> <li>- Monitor permits, licenses, water works, water quantity and quality in sub-catchment.</li> </ul>	Facilitate and support inspections.
Water charges	<ul style="list-style-type: none"> <li>- Develop and revise water charges.</li> <li>- Carry out revenue collection in catchments where no catchment Council exists.</li> </ul>	Collect revenues through charges for the use of water in the catchment and sub-catchments and transmit these to the WRMA.		



Quality	<ul style="list-style-type: none"> <li>- Protect potential sources of freshwater.</li> <li>- Resource quality monitoring and evaluation.</li> <li>- Conserve, preserve and protect the environment.</li> </ul>	<ul style="list-style-type: none"> <li>- Resource quality monitoring and evaluation.</li> <li>- Undertake catchment protection.</li> </ul>	Monitor water quality and implement regulations and guidelines on catchment protection.	<ul style="list-style-type: none"> <li>- Monitor water quality and ensure water conservation.</li> <li>- Undertake projects that would ensure catchment protection.</li> </ul>
Policy function	Provides advice and recommends to the Minister policies for the management of water resources.			
Disputes solving	<ul style="list-style-type: none"> <li>- Investigate and deal with any dispute related to the use of water when the dispute does not fall in an area with catchment Council, sub-catchment Council or Water User Associations.</li> <li>- Encourage and facilitate the resolution of disputes over water by using alternative dispute resolution methods such as arbitration, mediation or conciliation.</li> </ul>	<ul style="list-style-type: none"> <li>- Investigate and deal with any dispute related to the use of water.</li> <li>- Play an important role in alternative dispute resolution.</li> </ul>	<ul style="list-style-type: none"> <li>- Investigate and deal with any dispute related to the use of water.</li> <li>- Play an important role in alternative dispute resolution.</li> </ul>	<ul style="list-style-type: none"> <li>- Investigate and deal with any dispute related to the use of water.</li> <li>- Play an important role in alternative dispute resolution.</li> </ul>
Information management	<ul style="list-style-type: none"> <li>- Establish and maintain a water resources information system.</li> <li>- Carry out functions of CC, SCC or WUA in areas those do not exist.</li> </ul>	<ul style="list-style-type: none"> <li>- Carry out hydrological and hydrogeological services.</li> <li>- Consolidate data forwarded by a sub-catchment Council or other entities.</li> <li>- Carry out functions of SCC and WUA in areas those do not exist.</li> </ul>	<ul style="list-style-type: none"> <li>- Collect hydrological, metrological, water quality and quantity, socio-economic and environmental data for submission to the catchment Council.</li> <li>- Maintain equipment for data capturing.</li> </ul>	<ul style="list-style-type: none"> <li>- Collect hydrological, metrological, water quality and quantity, socio-economic and environmental data for submission to the sub-catchment Council.</li> <li>- Maintain equipment for</li> </ul>

		ist.		data capturing.
Participation	Carry out advocacy programs.	Carry out public awareness campaigns in collaboration with sub-catchment Councils.	<ul style="list-style-type: none"> <li>- Carry out public awareness campaigns.</li> <li>- Promote the participation of the community in water management.</li> </ul>	Promote the participation of the community in water management.
Plans and reporting	<ul style="list-style-type: none"> <li>- Formulate and submit to the Minister a national water resources strategy and plan for the management, use, development, conservation, preservation, protection, control and regulation of water resources.</li> <li>- Recommend to the Minister what catchment management plan should contain.</li> <li>- Recommend to the Minister the constitution of a catchment Council.</li> <li>- Provide technical support and coordinate the activities of catchment and sub-catchment Councils and WUAs.</li> <li>- Approve catchment and sub-catchment management plans.</li> </ul>	<ul style="list-style-type: none"> <li>- Prepare and update, in collaboration with the WRMA, catchment management plans.</li> <li>- Harmonize sub-catchment management plans with catchment plans and facilitate their implementation.</li> <li>- Prepare catchment reports and report back to WRMA.</li> <li>- Provide technical support to sub-catchment Council and Water Users Association</li> </ul>	<ul style="list-style-type: none"> <li>- Develop sub-catchment management plans and facilitate their implementation.</li> <li>- Prepare an allocation plan for the sub-catchment.</li> <li>- Harmonize local management plans with sub-catchment management plans.</li> <li>- Provide technical support to WUAs.</li> <li>- Compile reports on activities in the sub-catchment and submit them to the catchment Council.</li> </ul>	Propose local water management plans to the sub-catchment Council and implement them.

## 2.5 Challenges to water governance in Zambia

The complex network of economic activities that draw their lifeblood from the Kafue's waters gave rise to an increasing competition for the resource basis and motivated the necessity to adopt a more integrated approach to water management. In fact, recognizing the sectorial and centralized basis of water management, the Zambian government formulated through the WRAP an integrated approach towards the management of water resources in the country. The WRAP noticed weak linkages between institutions, lack of legislation and policy in managing water resources (GoZ, 2008). Moreover, local communities have not been adequately organized nor sensitized to water management and planning while their participation is equally lacking (Sievers, 2006).

Amongst all the water uses, hydropower generation has always been awarded the highest priority due to power requirements for copper mining activities and other local industries. The construction of the Itezhi-tezhi reservoir has had many negative impacts primarily felt by the communities downstream of Itezhi-tezhi depending on the Kafue Flats for their livelihoods. Observed impacts include the reduction of the available surface area of grazing land and available land for crop production, a reduction in fisheries and a decline of rare endemic species due to the habitat loss (WWF, 2005). Besides the negative environmental impacts, ZESCO Limited has been approved to increase the height of the dam by 10 metres. An Environmental Impact Assessment (EIA) has been conducted by ZESCO Limited which shows no major impact to the Kafue Flats and its population, but an independent assessment to prove the same has not been carried out yet. Other hydropower projects like the Kafue Gorge Lower Hydropower Dam, which will be constructed at the confluence with the Zambezi, will have limited effects on the Kafue basin but have marked impacts on the Zambezi River.

The downstream part of the basin poses stiff competition for water resources between agricultural water use and use for hydropower generation. The expansion of agriculture over the last decade enforced the competition in this part of the basin. The agricultural production, especially sugar cane for export and regional markets, is now seen as a boosting sector and is getting a lot of attention in terms of future expansion (COWI, 2009). A developing economy and population growth coupled with the acute water demand to sustain all activities in the basin are expected to worsen the water resources utilisation. In addition, existing conflicts could become critical without appropriate governance mechanisms. These mechanisms are essential for introducing equitable and transparent allocation and accounting for illegal and unlawful activities in the use of water resources amongst all stakeholders within the basin (Burke, 1994; McCarthney, 1998; Scott Wilson Piésold, 2003; Nyambe and Fielberg, 2009).

All activities mentioned above are important to sustain Zambia's growth potential and thereby giving priority to an efficient and equitable water allocation. Therefore, in the sense of good water governance, the allocation of water has faced a number of challenges as well as conflicting interests for the available water resource. This is aggravated by the fact that there is lack of reliable information systems to provide accurate hydrological data for optimum allocation of water amongst all users.

The priority of the government focuses on specific economic sectors which earn valuable foreign exchange through export such as hydropower production and irrigated agriculture. It undermines the potential of other sectors related to development within the basin. Especially emerging farmers represent the larger population within the basin, and provide two thirds of the annual staple food harvest. Therefore they should be the prime beneficiaries of water according to the poverty alleviations and food security strategies

in Zambia, but these strategies have not been effectively adopted yet and still often small-scale farmers do not get the share of water they need.

Resulting from overlapping competences the inter-ministerial competition for control of important water resources affects the coordinated planning and implementation of policies that are paramount for the overall development of the water sector. The SAGs were formed as a platform where inter-ministerial coordination could occur, but the Water SAG is not utilized in the manner it was proposed to be. There is lack of commitment and ownership amongst the representatives of the coordination platform making this mechanism ineffective. Coordination and integration of various sector policies are still an unresolved issue. This has also created barriers in implementing policies supporting individual sectors using water resources.

Given the size of Zambia, decentralization in the water sector was advocated to induce greater reach and efficiency in the operations, but this has not been successfully achieved yet. Some constraints that have been identified are the lack of adequate human resources to support such decentralized structures. There is also a resistance to change the current centralized institutions as some ministries fear to lose their power and authority. This creates an uncertain future for the respective ministries who, at the moment, hold more power within the water sector.

Currently, the fragmented institutions in the water sector are unable to provide the emerging farmers with essential access to water. There is a clash between the land tenure under customary law, which follows traditional water management versus the system based on water rights linked to the ownership of land by title deeds. The emerging farmers without adequate resources and title deeds have no access to water for mechanized irrigation. Such an arrangement systematically undermines the development of a majority of the population living in the basin. Without further options the farmers have to abstract water, which is deemed illegal by authorities. This underlines the vulnerability of small- and medium-scale farmers due to the discrepancies in the current water sector.

Hence, the government supports stakeholders' participation in the water sector. Participation is only limited to consultation and decisions are still formalized behind closed doors creating mistrust in the system amongst stakeholders. Moreover, the interests of the commercial farmers, organized into lobby groups and associations, often overshadow the claims and interests of the peasant farmers.

Missing human and financial capacity in the Zambian water sector is paramount and institutions are unable to provide the necessary support and infrastructure for further development in the Kafue basin.

These identified gaps clearly indicate the lack of appropriate governance mechanisms causing impediments to successful implementation of IWRM in the Zambian water sector. This indirectly affects the strategies to fight against poverty and the vulnerability of the population's majority who rely on subsistence farming.

## 2.6 Conclusion

Zambia is now confronted with the challenge of implementing good water governance. The water governance system is highly sectorial and the institutional and legal frameworks are not yet sufficient to support the change towards Integrated Water Resources Management. Moreover, the governance structure is highly centralized and leaves a small room for effective stakeholders' participation and their influence in the decision making process is still limited. If these features are summed to the low resource base, in terms of human and financial resources and to the weak commitment by key stakeholders and staff in the water

institutions and their resistance to change, it is straightforward to understand the complexity of a transition towards IWRM-based governance practices.

The revised water policy approved by the cabinet in February 2010 is a big chance to support the change to good water governance in Zambia and first steps on the local level in form of WUAs have already started. However, it is questionable how these WUAs will function without adequate human and financial support. In fact, a massive number of well-trained professionals will be needed to manage such decentralised institutions at national, catchment and sub-catchment level as well as to assist the work of the WUAs. Without fulfilling this void of human and related financial capacity the success of the new water policy is at stake.

Though the Kafue River is the backbone of the Zambian economy, the country has abundant water resources from other river basins like the Zambezi Basin, Luangwa Basin and Luapula Basin. A possible solution to the problem could be promoting further economic development and required infrastructure in these basins to support the economic growth of other Zambian regions and to enforce the decentralisation process. This would considerably reduce the conflicts in the Kafue Basin. But such allocation of infrastructure in more remote parts of the country would also require large investments and long time-frameworks, which would pose a great challenge to such projects.

Some conflicts cannot be solved by replacing water users and need to rely on good water governance where all stakeholders participate to solve conflicts and find better solutions to secure the livelihoods of the rural population, mainly engaged in the production of the staple food. Good water governance will be a key issue for the sustainable development of Zambia.

## Declaration

This paper expresses the personal views of the authors.

## References

- Andersson, E., Warburton, D. & Wilson, R. (2005). The true costs of public participation. Available at: [http://www.sharedpractice.org.uk/Downloads/TC\\_Report.pdf](http://www.sharedpractice.org.uk/Downloads/TC_Report.pdf) (Accessed 26 October 2010).
- Burke, J. J. (1994). Approaches to integrated water resource development and management: the Kafue Basin, Zambia. *Natural Resources Forum* 18(3), 181–192.
- Chabwela, H. W. & Haller, T. (2008). Governance issues, potential and failures of participative collective action in the Kafue flats Zambia. *Political Geography* 16, 423–454.
- Commission of the European Communities (2001). European Governance: A white paper. Available at: [http://eur-lex.europa.eu/LexUriServ/site/en/com/2001/com2001\\_0428en01.pdf](http://eur-lex.europa.eu/LexUriServ/site/en/com/2001/com2001_0428en01.pdf) (Accessed 26 October 2010).
- Commission of the European Communities (2003). Common Implementation Strategy for the Water Framework Directive (2000/60/EC) Guidance Document No. 1: Economics and the environment – The implementation challenge of the Water Framework Directive. Produced by Working Group 2.6 (WATECO). Available at: [http://circa.europa.eu/Public/irc/env/wfd/library?l=/framework\\_directive/guidance\\_documents/guidancesnos1seconomicss/\\_EN\\_1.0\\_&a=d](http://circa.europa.eu/Public/irc/env/wfd/library?l=/framework_directive/guidance_documents/guidancesnos1seconomicss/_EN_1.0_&a=d) (Accessed 26 October 2010).
- Cosgrove, W. J. & Rijsberman, F. R. (2000). *World Water Vision*. Earthscan Publications Ltd, London.
- COWI (2009). Availability of water resources for sugar cane production expansion in Zambia in the context of competing hydropower and other users. Technical report no. 245. COWI, Lyngby, Denmark.
- European Community (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (Water Framework Directive). Available at: <http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2000:327:0001:0072:EN:PDF> (Accessed 26 October 2010).
- Global Water Partnership (GWP) (2000). *Integrated Water Resources Management*. TAC Background Paper No. 4. Global Water Partnership, Stockholm. Available at: <http://www.gwpcacena.net/en/pdf/tec04.pdf> (Accessed 26 October 2010).
- Global Water Partnership (GWP) (2003). *Effective Water Governance*. TAC Background Paper No. 7. Global Water Partnership, Stockholm.
- Government of Zambia (GoZ) (2003). *The National Decentralisation Policy: Towards Empowering the People*. Office of the President, Cabinet Office, Government Printers, Lusaka.
- Government of Zambia (GoZ) (2004a). *Water resource action program, final report: technical component 1 – Legal and institutional framework*. Ministry of Energy and Water Development, Government Printers, Lusaka.
- Government of Zambia (GoZ) (2004b). *National Agricultural Policy*. Ministry of Agriculture and Cooperatives, Government Printers, Lusaka.
- Government of Zambia (GoZ) (2006). *Fifth National Development Plan: 2006–2010*. Ministry of Energy and Water Development, Government Printers, Lusaka.

- Government of Zambia (GoZ) (2008). Integrated Water Resources Management and Water Efficiency (IWRM/WE) –Implementation Plan Volume 1: Main report (2007–2030). Ministry of Energy and Water Development, Government Printers, Lusaka.
- Government of Zambia (GoZ) (2011). Sixth National Development Plan. Government Printers, Lusaka.
- Grigg, N. S. (1999). Integrated water resources management: Who should lead, who should pay? *Journal of the American Water Resources Association* 35(3), 527–534.
- Uhlendahl, T., Salian, P., Casarotto, C. and J. Doetsch, 2011. Good Water Governance and IWRM in Zambia - Challenges and Chances. *Water Policy*, 13 (2011) 845–862.
- Gupta J. (2003). The role of non-state actors in international environmental affairs. *Heidelberg Journal of International Law* 63(2), 459–486.
- Gupta, J. (2007). ‘Glocal’ water governance: controversies and choices. Discussion Paper on Governance. UNESCO-IHE, Institute for Water Education, Delft.
- Hofwegen, P. J. & Jaspers, F. G. (1999). Analytical framework for Integrated Water Resources Management: Guidelines for assessment of institutional framework. A.A. Balkema, Rotterdam.
- Jønch-Clausen, T. & Fugl, J. (2001). Firming up the conceptual basis of integrated water resources management. *International Journal of Water Resources Development* 17(4), 501–511.
- Jonker, L. (2002). Integrated water resources management: theory, practice, cases. *Physics and Chemistry of the Earth* 27, 719–720.
- Keeley, J. & Scoones, I. (2003). Understanding Environmental Policy Processes: Cases from Africa. Earthscan, London.
- Keen, M. (2003). Integrated water management in the South Pacific: policy, institutional and socio-cultural dimensions. *Water Policy* 5(2), 147–164.
- Lemon, A. (2001). Gender and Forestry: integrated local knowledge into environmental planning and management. *International Journal of Sustainable Development* 4(3), 265–281.
- Nyambe, I. & Fielberg, M. (2009). Zambia: National Water Resources Report for WWDR3. Ministry of Energy and Water Development, Government of Zambia, Lusaka, Zambia.
- Rogers, P. & Hall, A. (2003). Effective water governance. TAC Background Papers, No. 7. Global Water Partnership, Stockholm, Sweden.
- Rondinelli, D. J. N. & Chemma, S. (1984). Decentralization in developing countries: A review of current experience. World Bank, Washington.
- Salian, P. (2010). Water governance in Zambia: Case study of the Kafue River basin. Thesis submitted in partial fulfilment of the requirements for the Degree of Master of Science in Environmental Governance, University of Freiburg, Germany, January 2010.
- Savenije, H. G. H. & van der Zaag, P. (2000). Conceptual framework for the management of shared river basins, with special reference to the SADC and EU. *Water Policy* 2(1), 9–45.

Scott Wilson Piésold (2003). State of Environment Report: Integrated Kafue River basin Assessment – Environmental Impact Assessment Study. Ministry of Energy and Water Development, Lusaka, Zambia.

Sievers, P. (2006). Zambia Water Sector: Challenges for integrated water resources management in Zambia. Danida Water Sector Seminar, January 2006. Accra, Ghana.

Uhlendahl, T. (2009). Public participation in river basin management on the local level within the context of the WFD. Available at: <http://www.freidok.uni-freiburg.de/volltexte/6263/> (Accessed 26 October 2010).

United Nations (2003). Water for People, Water for Life: The United Nations World Water Development Report. UN, New York.

United Nations Development Programme (UNDP) (2010). Human Development Report 2010: The real wealth of nations – Pathways to human development. Available at: <http://hdr.undp.org/en/reports/global/hdr2010/chapters/en/> (Accessed 2 March 2011).

Wallace, J. S., Acreman, M. C. & Sullivan, C. A. (2003). The sharing of water between society and ecosystems: from conflict to catchment-based co-management. Philosophical transactions of the Royal Society of London, Series B, Biological sciences 358(1440), 2011–2026.

World Bank (2009). Zambia – Managing Water for Sustainable Growth and Poverty Reduction: A Country Water Resources Assistance Strategy for Zambia. The World Bank, Washington, DC.

WWF (2005). Summary of Study Findings on Kafue Flats Communities' Livelihoods Options and the effect of a Changed Flooding Regime. World Wide Fund for Nature, Lusaka, Zambia.



## Chapter 3

### A half empty bucket: women's role in the governance of water resources in Zambia

This chapter is based upon: Casarotto, C., and Kappel, R., 2013. A half empty bucket: women's role in the governance of water resources in Zambia. *Journal of Gender and Water* 3: 26-33. The first person plural is used throughout this chapter.

## Abstract

The water governance system in Zambia has undergone major reforms that have fostered decentralization<sup>1</sup>, the devolution of powers to the lowest level of authorities<sup>2</sup>, the creation of new institutions acting at the river basin level, and a greater involvement of all stakeholders in the decision making process.

Currently, water use in Zambia's rural households is strongly determined by the work of women. Water collection, domestic water use decisions, irrigation of orchards and fields, and other practices are a primary responsibility of women.

The recently ratified 2010 Water Policy and 2011 Water Resources Management Act fully recognize the pivotal role of women in the water realm, and foster women empowerment and full participation in issues and decisions related to sustainable development of water resources, and specifically, in the use of water.

A survey of 428 rural households has been conducted in the Lower Kafue River basin, inter alia, with the objective to assess the gender influences on water use, the current level of awareness and participation of smallholders and women in water institutions, the understanding of the roles and functions of these institutions, and the perception of their performance.

The fundamental role of women in water use, in particular related to household consumption, is assessed through the use of a multiple regression analyses. Results show that women are key actors in water collection and use, and that they can significantly influence the water consumption at the household level. In fact, a positive and significant relationship between the number of women in the household and the total household water consumption is found in all of the examined regression models.

Although the findings support the emphasis given by Zambia's Water Policy and Water Act to empower and increase female participation in water issues, our empirical results show that, compared to men, women are less aware of the water sector institutions and do not seem to have an adequate knowledge of their exact functions. In addition, only about 5.5 percent of the respondents declared to be aware of the institutions that were introduced with the recent Water Act, demonstrating that the institutional reforms have not yet been implemented on the ground.

Women are also considerably less involved than men in the water governance participation mechanisms, particularly in the Water Users Associations. Moreover, only about 18 percent of the respondents believe in the influence that smallholders' participation can have on water-related decisions, and women, in general, have an even more pessimistic perception.

In order to implement an effective reform process with a strong decentralization focus that realizes the subsidiarity principle, it is of utmost necessity for the Government of Zambia to increase smallholders' and women's awareness and participation in the water sector, and to improve the capacity of women to act politically in the management of water resources at the grass-root level.

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<sup>1</sup> The decentralization theorem implies that "each public service should be provided by the jurisdiction having control over the minimum geographic area that would internalize benefits and costs of such provision" (Oates, 1972 p. 55).

<sup>2</sup> According to the subsidiarity principle, "taxing, spending, and regulatory functions should be exercised by lower levels of government unless a convincing case can be made for assigning them to higher levels of government" (Shah and Shah, 2006 p. 4).

### 3.1 Introduction

Water use in Zambia's rural households is strongly determined by the work of women. Women are primarily responsible for water collection, domestic water use decisions, irrigation of orchards and fields, and other practices. 79 percent of Zambian women live in rural settings and are employed in the agricultural sector; this is in comparison to the 64 percent of men that live in a similar setting (GoZ, 2006). Agriculture, still considered an important engine of development and growth in the Zambian economy (GoZ, 2011a), contributes 21.6 percent of the national gross domestic product (World Bank, 2011). In 2009, 74 percent of the urban population and only 53 percent of the rural population in Zambia had access to a safe water supply (GoZ, 2011a). Rural areas have not benefited so far from the commercial utilities' development of a piped water network. Instead, most of the rural areas in Zambia are served by wells and boreholes. Between 2005 and 2010, the Government of Zambia (GoZ) constructed 3,800 new boreholes in rural areas and it plans on constructing 6,000 more boreholes by 2015.

The Zambian water governance system has recently undergone major transformations with both a new Water Policy and a Water Resources Management Act, ratified by Parliament in 2010 and 2011 respectively. These measures stipulate the decentralization of the water sector and the devolution of power to the lowest level of authorities. One consequence is the creation of new institutions<sup>3</sup>, namely the Catchment Councils (CC) and Sub-catchment Councils (SCC), as well as the strengthening of the Water Users Associations (WUAs) under the overall coordination of the Water Resources Management Authority. Table 3.1 summarizes the main functions of the Zambian institutions in the water sector. In addition, the law fosters stronger participation of all water users, in particular smallholders, and among them, women (GoZ, 2010; GoZ, 2011(b2)). The National Water Policy adopts gender equity in accessing water resources as a guiding principle for water management<sup>4</sup>. This principle is reflected in several articles of the Water Resources Management Act that explicitly promote the role of local communities and the participation of women at all levels of the decision making process with regards to water use<sup>5</sup>.

<sup>3</sup> The definition of a water institution adopted in the present work is the broad definition proposed by Saleth and Dinar (2000, p. 176): a "water institution sets the rules and defines, thereby, the action sets for both individual and collective decision-making in the realm of water resource development, allocation, and utilization. Since these rules are often formalized in terms of three inter-related aspects, i.e., legal framework, policy environment, and administrative arrangement, water institution can be conceptualized as an entity defined interactively by its three main analytical components, i.e., water law, water policy, and water administration."

<sup>4</sup> The National Water Policy (2010, p. 19) stresses that "women shall be empowered and fully participate in issues and decisions related to sustainable development of water resources and, specifically, in the use of water."

<sup>5</sup> Art. 20.1.q and Art. 25.e mention that the Catchment Council and the WUA shall "promote the participation of the community in water resources management and ensure gender mainstreaming in the decision-making process relating to the management, development and use of water."

Art. 27.2.b mandates the Minister of Water with the "mainstreaming of gender into the policies, programmes and activities relating to water resource management, development and use."

Art. 31.3.d mandates the Water Resources Management Authority to "provide mechanisms [...] for enabling the public and communities, in particular women, to participate in managing the water resources within each catchment."

Table 3. 1 Functions of the Zambian institutions in the water sector

	<b>Water Resources Management Authority (WRMA)</b>	<b>Catchment Council (CC)</b>	<b>Sub-Catchment Council (SCC)</b>	<b>Water User Association (WUA)</b>
<b>Water Allocation</b>	<ul style="list-style-type: none"> <li>- Approve allocation plans and determine water allocation</li> <li>- Identify freshwater sources</li> <li>- Plan water development</li> <li>- Secure the provision of adequate safe water</li> <li>- Issue water permits</li> <li>- Carry out tasks of the CC, SCC or WUAs if none exist</li> </ul>	<ul style="list-style-type: none"> <li>- Regulate and supervise the use of water at the catchment level</li> <li>- Include sub-catchment allocation plans in the catchment management plan</li> <li>- Carry out the tasks of the sub-catchment Council if no SCC exists</li> </ul>	<ul style="list-style-type: none"> <li>- Regulate the use of water at the sub-catchment level</li> <li>- Investigations and recommendations on water permit or license applications in the sub-catchment</li> <li>- Prepare the allocation plan in a sub-catchment</li> <li>- Monitor permits, water works, water quantity in sub-catchment</li> </ul>	<ul style="list-style-type: none"> <li>- Facilitate and support inspections</li> </ul>
<b>Water Charging</b>	<ul style="list-style-type: none"> <li>- Develop and revise water charges</li> <li>- Revenue collection where no CC exists.</li> </ul>	<ul style="list-style-type: none"> <li>- Collect revenues</li> </ul>		
<b>Water Quality Monitoring</b>	<ul style="list-style-type: none"> <li>- Protect freshwater sources</li> <li>- Resource quality monitoring and evaluation</li> <li>- Conserve, preserve and protect the environment</li> </ul>	<ul style="list-style-type: none"> <li>- Resource quality monitoring and evaluation</li> <li>- Undertake catchment protection</li> </ul>	<ul style="list-style-type: none"> <li>- Monitor water quality and implement regulations and guidelines on catchment protection</li> </ul>	<ul style="list-style-type: none"> <li>- Monitor water quality and ensure water conservation</li> <li>- Undertake projects that would ensure catchment protection</li> </ul>
<b>Policy Function</b>	<ul style="list-style-type: none"> <li>- Advise and recommend policies for the management of water resources to the Minister</li> </ul>			
<b>Information Management</b>	<ul style="list-style-type: none"> <li>- Establish and maintain a water resources information system</li> </ul>	<ul style="list-style-type: none"> <li>- Hydrological and geological surveys</li> <li>- Consolidate data</li> </ul>	<ul style="list-style-type: none"> <li>- Collect hydrological, meteorological, water quality and quantity, socio-economic and environmental data for submission to the CC</li> </ul>	<ul style="list-style-type: none"> <li>- Collect hydrological, meteorological, water quality and quantity, socio-economic and environmental data for submission to the SCC</li> </ul>
<b>Participation</b>	<ul style="list-style-type: none"> <li>- Advocacy programs</li> </ul>	<ul style="list-style-type: none"> <li>- Public awareness campaigns</li> </ul>	<ul style="list-style-type: none"> <li>- Public awareness campaigns</li> <li>- Promote community participation</li> </ul>	<ul style="list-style-type: none"> <li>- Promote community participation</li> </ul>

Planning and Reporting	- National water resources strategy	- Develop catchment management plans	- Develop sub-catchment management plans	- Local water management plans
	- Recommend constitution of the CC	- Harmonize sub-catchment management plans	- Harmonize local plans	
	- Technical support	- Technical support	- Technical support to WUAs	
	- Approve catchment and sub-catchment plans			

*Source: author's elaboration of Uhlen Dahl et al. 2011*

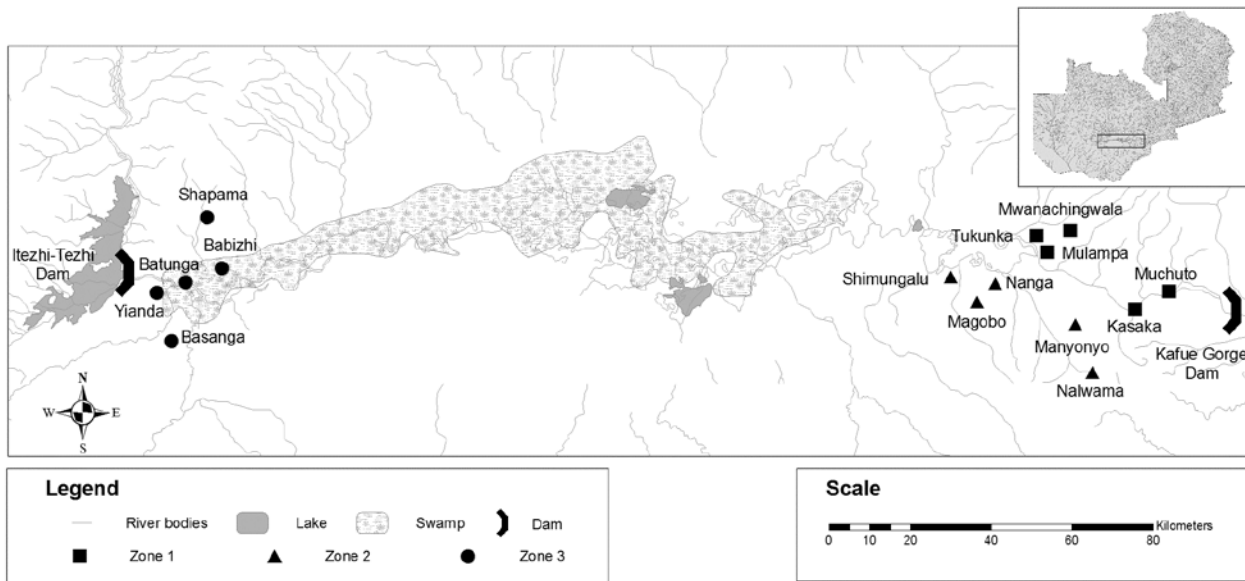
The central role of women in water management has been recognized by the international community (Wahaj and Hartl, 2007). Several studies describe rural water consumption patterns and the role of women in the collection and use of water (Nyong and Kanaroglou, 2001; Arouna and Dabbert, 2010; Potter and Darmane, 2010). However, few of these studies quantitatively assess the role of women in the collection and use of water. Moreover, no available study attempts to explore how women perceive the water governance system, how knowledgeable they are of the institutional setting, and how they actively participate in these institutions.

Other studies that try to assess some of these questions concentrate more generally on the role of rural women in connection to the strategic water use decisions at the household and farm level (Hawkins and Seager, 2010; Bennett, 2004; Makoni et al., 2004; Farmar-Bowers, 2001). Upadhyay (2003) attempts to investigate the gender aspects of participating in the management and governance of water resources; however, the study makes exclusive reference to irrigated agriculture. A handful of studies describe the legal and policy environment related to gender and natural resources management in developing countries (e.g. Manase et al., 2003; van Wijk et al., 1996). Studies related specifically to gender and water governance in rural areas are rare (Harris, 2009) and they are neither based on specific survey data nor do they target developing countries.

## 3.2 Methods

This study was conducted in Zambia in the lower Kafue River basin, the area lying between the Itezhi-tezhi Dam and the Kafue Gorge Dam. With the choice of this geographical location, we aimed at capturing the views of water stakeholders (smallholders) in one of the economically most active areas of the country. Large and small-scale agriculture, fishing, tourism, and hydropower generation are major economic activities carried out in the lower Kafue region.

Figure 3. 1 Sampled villages



*Source: Map constructed by authors with ArcMap, using data layers provided by the Zambian Ministry of Land*

A team of local enumerators conducted 428 interviews within the course of three weeks. Fifteen villages were sampled along the Kafue River (Figure 3.1), excluding the permanently flooded area (and protected national park) of the Kafue Flats where the population density is extremely low and economic activities are limited. The survey instrument was a formal questionnaire that comprised seven modules (identification, household information, domestic water use, agriculture, fisheries, income, and governance) for a total of 210 questions<sup>6</sup>. The survey was administered in the local languages. Zambia counts 72 languages (although many of them can be considered as dialects), but only four languages are currently spoken in the study area (namely Nyanja, Bemba, Tonga, and Ila) and these were used to administer the questionnaire.

The total number of 428 observations was reduced to 400 due to the elimination of two incomplete questionnaires and 26 outliers in the dependent variable. In the SPSS procedure that we used a household is considered as outlier if its anomaly index value is larger than or equal to 2. The anomaly index is the ratio of the group deviation index to its average over the cluster that the case belongs to. Before dropping observations we controlled the original questionnaires and concluded that in each case either reporting errors by interviewees or data entry errors by interviewers had occurred. The two most extreme outliers reported either a zero in total water used or more than 100'000 litres per day.

### 3.3 Results

The fundamental role of women in water use for household consumption is assessed through the use of regression analyses. The dependent variable is the logarithm of the total household water use measured in liters per day. The regression models control for the size of the villages, the position of the villages with respect to a main watercourse, the location (district) of the villages, and the level of education and age of the household heads. These control variables are never statistically significant and are not reported in the subsequent tables. We use hierarchical Ordinary Least Squares (OLS) regressions, i.e. in the first stage the

<sup>6</sup> The complete questionnaire is available from the authors upon request.

control variables were entered, then the regressors. Appendix 3.1 reports summary statistics for all variables included in the analysis.

First and foremost we hypothesize that water consumption is dependent upon the prosperity of households. We construct a wealth index based on assets owned by households. Observable assets are usually a more reliable indicator of prosperity than income or consumption data collected through household interviews. The wealth index is computed from weights obtained from a Principal Component Analysis, as suggested by Filmer and Pritchett (2001). Appendix 3.2 describes the method and data to construct the index.

Other explanatory variables comprise demographic and some occupational characteristics of households: the number of persons living in a household, the share of female household members (or, as an alternative, the ratio between female and male members), the gender and the main occupation of the household head, and whether the household members participate in a cooperative. Water source-specific explanatory variables include the water quality, the ownership of water sources, the level of water abstraction (surface or underground), the distance from the sources of water used, and the frequency of lacking water (due to mechanical problems, depletion of water resources by competing users, or drought). Expenditures for the use, operation, and maintenance of the water sources are also included, which cover both regular monetary contributions and irregular contributions in terms of labor or *una tantum* disbursements.

The two regression models presented in Table 3.2 differ in the way the gender composition of the household is represented. Model 1 uses the percentage of female persons as the indicator of gender composition, Model 2 the ratio of women to men. In addition, three specifications of each model are being tested in order to assess the functional relation between household water uses on the one hand and the wealth and household size on the other hand. The first specification assumes a log-linear relationship between household water use and wealth and a non-linear relationship between water use and household size (using a linear and a quadratic term). The second specification assumes a log-linear relationship between water use and wealth and a non-linear (log-log) relationship between water use and household size. Finally, the third specification, assumes a non-linear (log-log) relationship between water use and wealth as well as water use and household size.

Table 3. 2 Coefficients of the regression analysis<sup>7</sup>

	Model 1			Model 2		
	Specific. 1	Specific. 2	Specific. 3	Specific. 1	Specific. 2	Specific. 3
Constant	3.340*** .212	3.190*** .209	3.015*** .206	3.427*** .206	3.260*** .230	3.097*** .200
Wealth Index	0.011*** .003	0.011*** .003		0.011*** .003	0.011*** .003	
Wealth Index (Log)			0.205*** .037			0.201*** .037
Total contribution to water source	0.002** .001	0.002** .001	0.002** .001	0.002** .001	0.002** .001	0.002** .001
Gender of household head (male=0, female=1)	-0.102 .073	-0.099 .072	-0.068 .071	-0.101 .073	-0.098 .072	-0.067 .071
Occupation of the household head (other=0, agri=1)	0.152* .087	0.138 .086	0.115 .084	0.142 .087	0.130 .086	0.107 .084
Member of a cooperative (no=0, yes=1)	0.236** .067	0.237** .066	0.211** .065	0.243** .068	0.243** .066	0.218** .065
Frequency of lack of water	0.004 .005	0.004 .005	0.004 .004	0.004 .005	0.004 .005	0.005 .004
Water quality (bad=0, good=1)	0.100* .059	0.108* .058	0.113** .057	0.107* .059	0.115** .058	0.119** .057
Distance from main water source	0.029 .023	0.027 .022	0.031 .022	0.031 .023	0.028 .022	0.032 .022
Type of source (Ground=0, Surface=1)	0.068 .060	0.064 .060	0.054 .059	0.069 .061	0.066 .060	0.056 .059
Ownership of source (Public=0 Private=1)	-0.099 .070	-0.100 .069	-0.096 .068	-0.099 .070	-0.100 .069	-0.096 .068
Number of people in the household	0.098*** .020			0.100*** .020		
Square number of people in the household	-0.002*** .001			-0.002*** .001		
Number of people in the household (Log)		0.388*** .056	0.365*** .055		0.394*** .055	0.372*** .054
Percentage of women in the household	0.362** .142	0.303** .141	0.320** .138			
Ratio women to men				0.066** .030	0.056** .030	0.055** .029
R square	0.288	0.303	0.328	0.285	0.3	0.325
Observations	400	400	400	400	400	400

\*\*\* Significant at the 0.01 level

\*\* Significant at the 0.05 level

\* Significant at the 0.1 level

<sup>7</sup> The dependent variable is the logarithm of the total household daily water use; therefore, some of the regression coefficients cannot be directly interpreted as the expected change in value of the dependent variable subject to one unit change in the independent variable, *ceteris paribus*.



The results suggest a positive and highly significant effect of wealth on domestic water use. The slightly higher  $R^2$  of specification 3 compared to specifications 2 and 1 (of both models 1 and 2) indicates that the log-log relationships between water consumption and wealth and household size should be preferred.

The total amount of water consumed at household level increases, as expected, with the number of people in the household. Also, the level of users' payments allocated to the operation and maintenance of the water sources significantly contributes to an increase in water consumption. This result, if confirmed by more detailed studies, could suggest that user payments for the maintenance and operation of water sources contribute to improving the reliability of water supplies and consequently to an increase in the use of water.

A positive and significant relationship between gender and water consumption is found in all specifications of the two models. Thus, it is possible to conclude that an increase in the number of women in the household leads to higher water use. This result corroborates findings of descriptive analyses by Nyong and Kanaroglou (2001) and Makoni et al. (2004), where the authors find that women have a predominant role in household water management and hygiene. In fact, the presence of more women in the household implies that a larger amount of water is collected, since it is mainly the women's role to collect water. Additionally, water consumption increases with the number of women in the household due to a series of women-dominated activities, such as household cleaning, child and personal hygiene, and watering of small gardens. Results for the three versions of model 1 indicate that, in an average household with a daily consumption of 124 litres of water, a swap from a male member to a female member increases the total water consumption by amounts between 5.7 and 6.8 litres. For the three versions of model 2 the respective values vary between 6.6 and 8 litres<sup>8</sup>. Finally, water consumption appears not to be related to the gender of the household head.

Contrary to what could be expected, the distance from the water as well as the frequency of lacking water have no significant effect on water consumption. This might be due to the fact that the lower Kafue region, which, endowed with a sub-tropical climate, does not suffer from water scarcity. In fact, 50.3 percent of the households withdraw water from sources located not farther than 15 minutes away on foot, and 85 percent use sources located within 30 minutes. This result is in line with the findings of a survey conducted in 25 sub-Saharan countries that reports a mean time to collect water of approximately 30 minutes (UNICEF and WHO, 2012). Moreover, levels of water use for domestic purposes are still extremely low: in eight out of the 15 villages sampled, the average per capita daily use of water does not exceed the threshold of 20 liters<sup>9</sup>. With such low levels of consumption, mechanical breakdowns, competition for water, or temporary water scarcity at one source might not affect the total water used at the household level. In fact, in order to

<sup>8</sup> We calculate these changes by first multiplying the regression coefficients given in Table 2 with the mean values of the sample variables reported in Appendix 3.1. This gives us our "baseline" water consumption for the "average" household, described with the mean values of the sample observations. We then substitute one male household member by an additional female person, which changes the gender composition variable (from 0.47 to 0.61 for the share of female persons, from 1.1 to 2.05 for the ratio women to men). In the next step we calculate the water consumption after the swap and the relative difference to the baseline. Finally we multiply this relative change with the average water consumption of 124 liters.

<sup>9</sup> The World Health Organization (WHO) classifies the requirement for water service level to promote health into:

- No access: quantity collected often below 5 litres per capita per day (l/c/d) and more than 30 minutes total collection time;
- Basic access: average quantity unlikely to exceed 20 l/c/d and between 5 to 30 minutes collection time;
- Intermediate access: quantity about 50 l/c/d and water delivered through tap or within 5 minutes collection time;
- Optimal access: average quantity 100 l/c/d and Water supplied through multiple taps continuously.

maintain a minimum level of per capita water consumption, the collectors could travel longer distances and use secondary, often not clean, sources of water or queue longer at the primary source.

As expected, the quality of the water withdrawn has a positive and significant effect on water use, clearly underlining the importance of improved water sources to maintain sufficient levels of water use. While the main occupation of the household head is generally not significant to explain household water use, the participation of one or more of the household members in a cooperative is positively and significantly related to higher household water use. Usually the cooperatives (fishing or agricultural) are coordinated by government officials and include the participation of several households located in the same neighborhood. Therefore, this result could possibly indicate the importance of coordination at the household level to improve water use.

The results of our regression analyses corroborate the hypothesis that women have a key role in water management and consumption and that they markedly influence the total amount of water used at the household level. This finding supports the emphasis given by Zambia's Water Policy and Water Act to women's empowerment and participation in issues and decisions related to water resource use. In fact, one of the governance principles listed under paragraph 6 of the Water Act reads that "there shall be equity between both gender in accessing water resources and, in particular, women shall be empowered and fully participate in issues and decisions relating to the sustainable development of water resources and, specifically, the use of water" (GoZ 2011b).

In this context, we analyzed the current level of awareness and participation of smallholders and women in water institutions, the understanding of the roles and functions of these institutions, and the perception of their performance. Respondents were asked questions concerning nine institutions, which also include the Sub-Catchment Councils, the Catchment Councils and the WUAs that were newly introduced with the Water Act. Out of the 428 respondents, 279 were male, 148 female, and only one of the respondents refused to complete the interview.

A first striking result concerns the low level of declared awareness of each of the institutions. Not only was the share of respondents that declared to be aware of the 2011 Water Act institutions very low (only 5.9 percent of the whole sample knew about the Sub-Catchment Council and 5.4 percent were familiar with the Catchment Council), but female respondents in general showed a more limited awareness of all water institutions (Table 3.3). This finding is unexpected considering that since 2008, the Government of Zambia set up decentralized water resources management structures in the Kafue and Lunsemfwa Catchments as pilot projects to test the application of the National Water Policy and Water Act. At the same time, the drafting process of the Water Policy and Water Act involved an extensive series of consultations, also in the Kafue Basin. In particular, women are significantly less aware of the work that is conducted by the Ministry of Agriculture (MACO), Ministry of Livestock and Fisheries (MLF), Environmental Council (ECZ) and Zambia Wildlife Authority (ZAWA).

Table 3. 3 Awareness of institutions by gender

	Men	Women
Water Users Association	6.1%	6.1%
	17	9
Ministry of Energy and Water Development	12.5%	8.1%
	35	12
Ministry of Agriculture and Cooperatives	52.0%	40.5%

**	145	60
Ministry of Livestock and Fisheries **	48.0%	37.8%
	134	56
Sub-Catchment Council	5.7%	6.1%
	16	9
Catchment Council	5.0%	6.1%
	14	9
Zambia Wildlife Authority **	42.3%	31.1%
	118	46
Environmental Council of Zambia *	13.6%	8.1%
	38	12
Water Utilities	10.4%	8.1%
	29	12

\*\* Significant at the 0.05 level

\* Significant at the 0.1 level

The respondents' knowledge of the exact functions of the various institutions tends to corroborate this gender bias, indicating that women, even if they are aware of an institution, are less capable to precisely recognize its functions. In fact, only 25 percent of the women (compared to 89 percent of the men) who declared to be aware of the Ministry of Energy and Water Development (MEWD) exactly know the functions of the institution. Also, among the respondents aware of MACO and MLF, about 80 percent of women and over 90 percent of men are knowledgeable of the duties of the two institutions. Moreover, both men and women who declare to be aware of the New Water Act institutions fail to identify the functions of the Catchment Council, and only 25 percent of men can describe the functions of the Sub-Catchment Council.

To some extent, this result is also reflected in the lower degree of participation<sup>10</sup> of women in the water sector institutions compared to men. Although the majority of both men and women explain that they do not have any direct contact with the institutions, it is – at least for three of these institutions – evident that women's participation is significantly lower (Table 3.4).

Table 3. 4 Participation by gender (percentage of respondents aware of the institution)

	Men	Women
Water Users Association *	35.3	0
Ministry of Energy and Water Development	5.9	16.7
Ministry of Agriculture and Cooperatives	35.9	26.7
Ministry of Livestock and Fisheries **	32.4	14.3
Zambia Wildlife Authority **	23.9	8.9
Environmental Council of Zambia	5.7	18.2
Water Utilities	10.7	9.1

\*\* Significant at the 0.05 level

\* Significant at the 0.1 level

<sup>10</sup> A set of questions were asked to understand the type and frequency of participation within each of the analysed institutions. The respondents were first asked a generic question about their participation in the decision taken by each institution. Then they were asked to explain how and how often participation within each institution takes place. Finally the respondents were asked to express an opinion concerning how often their participation could influence the decisions taken by each institution (and in case this was "rarely" or "never" a follow-up questions addressed the possible reasons).

A similar result is obtained when inquiring if the participation of smallholders could influence the decisions taken by the institutions. Respondents exhibit a generally pessimistic perception of the efficacy of participation in influencing decisions. In fact, only 45 percent of the respondents who are aware of the institutions believe in the effectiveness of smallholders' participation in the Ministry of Livestock and Fisheries, and about 50 percent in MACO, ECZ and ZAWA. Moreover, women express a markedly negative judgment regarding MLF and ZAWA: only 33 and 44 percent of women believe in the possibility to influence the decisions of MLF and ZAWA, while men are more optimistic with 56 and 69 percent answering in the affirmative.

This is all in contrast to that there is no significant difference between men and women in the perception of the usefulness of the institutions to solve water related problems. Stakeholders are pessimistic regarding the problem-solving capacity of the Environmental Council and the Water Act (2011) institutions; more than 70 percent of the respondents aware of such institutions consider them to be unhelpful to the end users. This result is linked to the low awareness of these institutions, the uncertainty about their roles and mandates, and their scarce presence in the field. Surprisingly, though, MLF, MACO and ZAWA also did not pass the test of the smallholders and received a rather negative judgment. 52 percent of the respondents consider MLF and MACO as not useful in solving water related problems at the grass-root level, and 50 percent of the interviewees reported the same opinion with regards to ZAWA.

Interestingly, 44 percent of the men and 31 percent of the women explain that they have been helped by one or more institution in solving water related problems. For this purpose, the respondents were asked an open question that allowed them to also mention institutions other than the water sector institutions. However, the national water institutions are rarely named (Table 3.5), while 43.9 percent of the men and 45.7 percent of the women reported that donor agencies and non-governmental organizations (NGOs) are the main actors that intervene in the case of water-related problems at the village level.

Table 3. 5 Intervention for water related problems by institution (percentage of total respondents)

	Men	Women
Water Users Association	2.4	0
Ministry Energy and Water Development	0.8	2.2
Ministry of Agriculture and Cooperatives	3.3	2.2
Ministry of Livestock and Fisheries	0	0
Sub-Catchment Council	0.8	0
Catchment Council	0	0
Zambia Wildlife Authority	1.6	2.2
Environmental Council of Zambia	1.6	0
Water Utility	0	0
Donors and NGOs	43.9	45.7
District Council	7.3	6.5
Other Ministries	15.4	19.6
Zambia Sugar	4.1	2.2
Church	2.4	2.2
Other	5.7	4.3
Do not know	10.6	13.0

Moreover, in 77 percent of the cases, respondents are satisfied with the interventions of donors and NGOs. Taken together, these findings suggest that the awareness and the impact of the national water institutions

at the grass-root level is still very limited, and that international donor agencies and NGOs are the main source of direct support in the water sector.

### 3.4 Conclusions

The study at hand presents one of the few examples of water governance analysis linked to water use and gender considerations. The statistical analysis of the data from a formal household survey confirms the important role of women concerning household water use, and supports the conclusion that rural smallholders in general, and women in particular, are not sufficiently aware of the water institutions and their functioning. The water sector reform process in Zambia is unknown to rural women, and their participation is correspondingly scarce. With the caveat that the survey covers only one region of the country, these results ring alarm bells. If the objectives stated in the current Water Act and Water Policy are to be achieved, the ministries and water institutions should invest in deeper and broader awareness campaigns and strive to involve women at all levels of the decision making process. In the rural areas of Zambia, women are key actors in water collection and domestic water use, and specific education and sensitization campaigns targeted towards women might increase their participation in the water sector. This would improve the capacity of women to act politically in the management of water resources at the grass-root level, and would strengthen the declared aim of more decentralization and participation. The women's involvement would improve their relation with the water sector institutions as well as their knowledge and perception of the institutions' functions. It would also foster participatory decisions that would benefit rural communities overall. Rural women are key to Zambian development, and without their strong involvement, the implementation of the water sector reform process can only be a half empty bucket.

### Acknowledgments

The authors wish to acknowledge the support of Thomas Simfukwe in collecting the survey data. The authors would like to express especial gratitude to the excellent team of enumerators who, with their commitment and hard work, made the data collection possible: Mutinta Chaampita, Clera Moyo, Steven Moyo Munkombwe, Alice Mulenda, Jabes Ng'wane, and Tafara Zengeni. The authors also wish to thank Prof. Imasiku Nyambe, Dr. Thomson Kalinda, and Dr. Gelson Tembo, University of Zambia, for their support. This research would not have been possible without the cooperation of the Ministry of Agriculture and Cooperatives and the Ministry of Livestock and Fisheries whose officers assisted and facilitated the data collection.

## References

- Aminou, A. & Dabbert, S. (2010). Determinants of domestic water use by rural households without access to private improved water sources in Benin: a seemingly unrelated tobit approach. *Water Resources Management* 24: 1381-1398.
- Bennett, E. (2005). Gender, fisheries and development. *Marine Policy* 29: 451-459.
- Farmer-Bowers, Q. (2010). Understanding the strategic decisions women make in farming families." *Journal of Rural Studies* 26:141-151.
- Filmer, D. & Pritchett, L. H. (2011). Estimating Wealth Effect Without Expenditure Data or Tears: An Application to Educational Enrollments in States of India. *Demography* 38: 115-132.
- GoZ (2011a). Sixth National Development Plan 2011-2015. Sustained economic growth and poverty reduction.
- GoZ (2011b). Water Resources Management Act. No. 21 of 2011.
- GoZ (2006). Living Conditions Monitoring Survey Report, 2006.
- Harris, L. M. (2009). Gender and emergent water governance: comparative overview of neoliberalized natures and gender dimensions of privatization, devolution and marketization. *Gender, Place & Culture* 16, 4: 387-408.
- Hawkins, R. & Seager, J. (2010). Gender and Water in Mongolia. *The Professional Geographer* 62, 1: 16-31.
- IBM. IBM SPSS Statistics 22 Command Syntax Reference (2013). Accessed October 6, 2013 [ftp://public.dhe.ibm.com/software/analytics/spss/documentation/statistics/22.0/en/client/Manuals/IBM\\_SPSS\\_Statistics\\_Command\\_Syntax\\_Reference.pdf](ftp://public.dhe.ibm.com/software/analytics/spss/documentation/statistics/22.0/en/client/Manuals/IBM_SPSS_Statistics_Command_Syntax_Reference.pdf)
- Makoni, F. S., Manase, G. & Ndamba, J. (2004). Patterns of domestic water use in rural areas of Zimbabwe, gender roles and realities. *Physics and Chemistry of the Earth* 29: 1291-1294.
- Manase, G., Ndamba, J. & Makoni, F. (2003). Mainstreaming gender in integrated water resources management: the case of Zimbabwe. *Physics and Chemistry of the Earth* 28: 967-971.
- McKenzie, D. J. (2005). Measuring Inequality with Asset Indicators. *Journal of Population Economics* 18, 2: 229-60.
- Nyong, A. O. & Kanaroglou, P. S. (2001). A survey of household domestic water-use patterns in rural semi-arid Nigeria. *Journal of Arid Environments* 49: 387-400.
- Oates, W. (1972). *Fiscal Federalism*. New York: Harcourt Brace Jovanovich, 1972.
- Potter, R. B. & Darmane, K. (2010). Contemporary social variations in household water use, management strategies and awareness under conditions of "water stress": The case of Greater Amman, Jordan. *Habitat International* 34: 115-124.
- Saleth, R. M., & Dinar, A. (2000). Institutional changes in global water sector: trends, patterns, and implications. *Water Policy* 2: 175-199.

Shah, A. & Shah, S. (2006). The New Vision of Local Governance and the Evolving Roles of Local Governments, in *Local Governance in Developing Countries* ed. Anwar Shah (Washington, D.C.: The World Bank, 2006).

Uhlendahl, T., Salian, P., Casarotto, C., & Doetsch, J. (2011). Good Water Governance and IWRM in Zambia - Challenges and Chances. *Water Policy* 13: 845–862.

UNICEF and World Health Organization. Progress on Drinking Water and Sanitation: 2012 Update (WHO Press, 2012), accessed February 11, 2013, <http://www.unicef.org/media/files/JMPReport2012.pdf>

Upadhyay, B. (2003). "Water, poverty and gender: review of evidences from Nepal, India and South Africa. *Water Policy* 5: 503-511.

van Wijk, C., de Lang, E. & Saunders, D. (1996). Gender aspects in the management of water. *Natural Resources Forum* 20, 2: 91-103.

Wahaj, R. & Hartl, M. (2007). Gender and water: Securing water for improved rural livelihoods: The multiple-uses system approach. Rome: International Fund for Agricultural Development (IFAD), 2007.

World dataBank, 2011. World Development Indicators and Global Development Finance. Accessed July 24, 2012. <http://databank.worldbank.org/ddp/home.do>

## APPENDIX 3.1: Descriptive statistics

	Minimum	Maximum	Mean	Median	Standard Deviation
Dummy variable for Kafue (district 1)	0.00	1.00	0.33	0.00	0.47
Dummy variable for Mazabuka (district 2)	0.00	1.00	0.33	0.00	0.47
Size of village (small=0, large=1)	0.00	1.00	0.50	1.00	0.50
Location (close to river=0, far from river=1)	0.00	1.00	0.16	0.00	0.37
Age of the HH head	18.00	98.00	45.49	41.00	18.19
Level of education of the HH head	1.00	4.00	2.27	2.00	0.63
Wealth Index	1.00	100.00	9.72	6.96	9.30
Total contribution to water source	0.00	360.00	14.39	0.00	35.81
Gender of household head (male=0, female=1)	0.00	1.00	0.18	0.00	0.39
Occupation of the HH head (other=0, agri=1)	0.00	1.00	0.88	1.00	0.33
Member of a cooperative (no=0, yes=1)	0.00	1.00	0.30	0.00	0.46
Distance from water source	1.00	5.00	2.66	2.50	1.19
Type of source (Ground=0, Surface=1)	0.00	1.00	0.63	1.00	0.46
Ownership of source (Public=0 Private=1)	0.00	1.00	0.22	0.00	0.41
Frequency of lack of water	0.00	365.00	21.56	0.50	75.34
Water quality (bad=0, good=1)	0.00	1.00	0.33	0.00	0.47
Number of people in the HH	1.00	30.00	6.80	6.00	3.76
Square number of people in the HH	1.00	900.00	60.37	36.00	89.31
Percentage of women in the HH	0.00	1.00	0.47	0.50	0.19
Ratio women to men	0.00	6.00	1.10	1.00	0.90



## APPENDIX 3.2: Wealth Index

The estimation of the wealth index using Principal Component Analysis is based on the first principal component. By definition the first principal component variable across households or individuals has a mean of zero and a variance of  $\lambda$ , which corresponds to the largest eigenvalue of the correlation matrix of the  $j^{\text{th}}$  asset variable  $x$ . The first principal component yields a wealth index that assigns a larger weight to assets that vary the most across households so that an asset found in all households is given a weight of zero (McKenzie 2005).

Formally, the wealth index  $y$  for household  $i$  is

$$y_i = \sum_{j=1}^n \alpha_j \left( \frac{x_j - \bar{x}_j}{s_j} \right)$$

where  $\bar{x}_j$  and  $s_j$  are the mean and standard deviation of asset  $x_j$ , and  $\alpha_j$  represents the weight for each variable  $x_j$  for the first principal component. The  $x_j$  variables included in the analysis and the respective weights  $\alpha_j$  are:

	Maximum	Mean	Standard Deviation	$\alpha$
Heads of cattle	400	6.83	26.102	0.234
Heads of goats	55	1.68	5.111	0.48
Heads of sheep	17	0.04	0.850	0.16
Heads of poultry	99	9.04	12.613	0.357
Heads of pigs	12	0.22	1.177	0.134
Number of beds	11	1.63	1.427	0.558
Number of tables	5	1.08	1.018	0.573
Radio/stereo/tape/CD-player	4	0.76	0.762	0.562
Television	4	0.26	0.533	0.657
Mobile phone	7	1.02	1.116	0.654
Land phone	2	0.02	0.172	0.568
Watch/clock	4	0.25	0.497	0.599
Charcoal stove	10	0.73	0.874	0.382
Gas/electric stove	2	0.03	0.216	0.53
Refrigerator	2	0.03	0.204	0.509
Generator	2	0.04	0.215	0.467
Bycycle	10	0.81	1.025	0.463
Motorbike	2	0.05	0.283	0.408
Car/pick-up	2	0.02	0.186	0.525
Private toilet (yes=1, no=0)	2	0.66	0.485	0.370



## Chapter 4

# An integrated model for water resources management in developing countries: the case of the Kafue River basin. Part I: Concept and Theory

At the time of submitting this thesis, a version of this single-authored chapter is in preparation for publication with ETH Hochschulverlag.

## Abstract

A multi-objective hydro-economic optimization model is proposed here as a tool to analyse the competing demands for water in the context of developing countries. The model addresses the linkages between surface and groundwater supply and the economic use of water at river basin scale and considers economic, social, and environmental objectives. Competing demands for water in the urban, agricultural, industrial, mining, and environmental sector are addressed and supporting models are used to provide the hydrological inputs and the agricultural water-yield functions. The approach presented in this work is of direct use to decision makers as it allows considering not only the physical dimensions of alternative water allocations, but also the economic consequences associated with it. The model allows testing several development scenarios and comparing the respective frontiers of efficient solution. A companion paper presents the results of the application of the model for a case study of the Kafue River basin, in Zambia.

## 4.1 Introduction

Research on optimization of water resources began in the mid-1950s and developed rapidly in the 1960s. Optimization of water resources has been applied to single water using sectors as well as to multiple sectors in order to achieve an insight into the trade-offs emerging from the simultaneities in the use of water resources. Various optimization techniques are adopted, from simple linear optimization to complex non-linear optimizations based on the most recent mathematical techniques (genetic algorithms, fuzzy logic, hybrid algorithms). Most of the models integrate hydrology and economics, and relatively few models deal with the analysis of the environmental benefits of water use.

Most optimization problems naturally have several objectives to be achieved, normally conflicting with each other; but in order to simplify their solution, they are treated as if they have only one and the remaining objectives are normally handled as constraints.

Multi-objective analysis and large-scale system decomposition has been used by Peter et al. (1984) to address the problem of group decision-making for allocating water resources. Percia et al. (1997) used their model to maximise economic benefits, and developed a management model that relied on numerous water sources to meet the demands of different users for waters of different quality. Minsker et al. (2000) used genetic algorithms to develop a water resources multi-objective optimization model taking into consideration uncertainty. Wang and Zheng (1998) and Wang et al. (2009a, b) used a mixed algorithm (genetic algorithms and simulated annealing) to optimise the water use from different sources, also including environmental demands. Xevi and Khan (2005) developed a multi-criteria decision-making framework to analyse production targets under physical, biological, economic, and environmental constraints, and studied the optimum use of all water resources under conflicting demands. Raquel et al. (2007) introduced game theory to a multi-objective conflict problem for an irrigation district where economic benefits from agricultural production should be balanced against the associated negative environmental effects.

Hydro-economic models<sup>1</sup> have emerged as an effective tool for integrated water resources management. Such models systematically address the interconnectedness between water supply and economic use of the resource at river basin scale. When developed in collaboration with decision-makers, they serve as useful tools to guide the policy making process based on a clear understanding of trade-offs arising from conflicting stakeholders' objectives. Depending on the underlying water management questions of concern, and depending on the different uses of water that shall be analysed, different hydro-economic modelling approaches can be adopted. Hydro-economic simulation models can be used to answer specific "what if" scenarios consisting of particular management decisions. Optimization models, instead, can identify the most appropriate management decision based on the maximisation or minimization of a stated mathematical objective function subject to a series of constraints. Often, such as in the study at hand, simulation and optimization approaches are merged into one: the net benefits from water allocation in different sectors are maximised (optimization aspect) under varying constraints and other exogenous assumptions (what-if aspect). A hydro-economic optimization model is classified as linear when the objective functions and constraints are represented entirely by linear equations. At the same time, hydro-economic models can be classified as either stochastic or deterministic. In the latter, the model considers one specific set of initial conditions and boundary conditions and leads to one set of results. In stochastic models the probabilistic nature of some of the model inputs (e.g. inflows, rainfall) is explicitly considered. When deterministic models are run many times based on different input conditions they become intrinsically stochastic. A dynamic optimization hydro-economic model, compared to a static model, directly incorporates time into its structure and is usually solved through a system of differential equations.

Typical limits or weaknesses in the design and application of hydro-economic models have been broadly discussed in the literature and mainly relate to: i) the need to aggregate physical and economic processes that might be perceived by decision makers as not sufficiently detailed; ii) the necessity to reduce the model size for computational reasons when non-linear functions are employed; iii) the difficulty in analysing simultaneous changes in constraints and parameters; iv) the complexity of representing in a sufficiently accurate way political, social, and environmental constraints; v) the different time and spatial scale of the economic and the hydrological component of the model (e.g. McKinney et al., 2009; Pulido-Velázquez et al., 2008; Maneta et al., 2009; Harou et al., 2009). Despite these limitations, hydro-economic models have been widely used to address a large range of issues related to the optimal use of water across sectors and over time. As several authors have extensively reviewed the current hydro-economic literature (see Harou, 2009; Bower and Hofkes, 2008; Rosegrant et al., 2000; Ward, 2006; Heinz et al., 2009) we will address here only the most recent developments and a few additional key pieces of work relevant to our study. An overview of the most recent developments in hydro-economic modelling is provided in Table 4.1.

Few studies tackle the allocation problem in the Zambezi River basin, also including its main tributary, the Kafue, from a hydro-economic perspective. Tilmant et al. (2011) and Tilmant and Kinzelbach (2012) present a stochastic dual dynamic programming model with a net benefit function that includes the net benefit from energy generation, from irrigated agriculture, and penalties for not meeting system

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<sup>1</sup> In the definition provided by Harou (2009) "hydro-economic models represent spatially distributed water resource systems, infrastructure, management options and economic values in an integrated manner".

constraints (such as institutional, legal, operational, minimum water flows, etc.). A similar coupled hydro-economic model of the Zambezi River is developed by the World Bank (2012) where scenarios also illustrate future developments within the basin in order to assess trade-offs between the different water users and the possibilities for collaboration at the basin level. The latter aspects are the subject of investigation also for Beck and Bernauer (2011), who formulate a hydrological model and a demand model to analyse the potential implications of climate change and changes in water demand for water availability in the Zambezi River Basin. Gandolfi et al. (1997) also analyse the optimal allocation of the Zambezi waters across different sectors of the economy with a specific focus on the impacts of the Kafue Gorge dam on the ecosystem, hydropower production and on other water uses such as irrigation and fisheries. Studies that scale models down to analyse the hydrological and economic aspects of the Kafue River basin are rare. Tesini (2010) develops a hydrological model of the Kafue River with a focus on the daily conjunct operation of the Itzhi-tezhi and Kafue Gorge Dam; hydroelectric production is the main subject of the study, but crop-water requirements are also included to model agricultural abstractions. Meier (2012) formulates a real-time fully distributed hydrological model that can simulate the flooding patterns in the Kafue Flats under various conditions.

The paper at hand presents a modelling framework for the economic optimization of multiple surface and groundwater uses in the Kafue River basin that extends the scope of existing hydro-economic models. In rare cases models consider explicitly groundwater, above all in developing countries. Due to the large uncertainties and the scarcity of data, the model at hand adopts a simplified groundwater network that can be adapted to include new and more accurate groundwater measurements, when available. The model presented here develops optimization procedures that allow for understanding the trade-offs arising from competing demands for water as we optimise the weighted sum of the discounted net benefits of the different water using activities.

The hydro-economic model presented here also provides an accurate representation of the water demands for the largest water users through the use of location specific crop-water functions and the adoption of built-in elevation-storage curves for the reservoirs. The model also integrates environmental, social, and policy considerations through the analysis of the water demands for the safeguard of the wetlands and for the urban centres and industrial activities, and it considers limits related to the administration of water rights and permits. Environmental, urban, and mining water uses are thoroughly analysed based on a large amount of water balances and related data, and enter the hydro-economic models as constraints. In fact, despite the great relevance of these water uses, the magnitude of water withdrawn is marginal relative to the large amounts employed for hydropower and agricultural production. In order to avoid the need to place artificial weights on the net benefits functions for these sectors, we consider their water demands as minimum requirements in order to sustain basic water needs of the population, water-related environmental functions, and growing water demand through economic growth.

This study presents the first integrated hydro-economic model for the Kafue basin that derives its strength not only from the thorough study of the underlying demands for water and respective net benefit functions but also from the strong interdisciplinary approach adopted in the integration of the hydrologic and economic component. In fact, the node-link model aggregates the output of a complex

real-time hydrological model for the Kafue basin developed within the African Dams Project (ADAPT) and leads to a realistic representation of the hydrological component (Meier, 2012).

Table 4. 1 Overview of recent hydro-economic literature

	Model typology		Region					Environment			Agriculture		Agricultural water demand			Inclusion of Groundwater	Inclusion of policy considerations
	Dynamic VS Static	Deterministic VS Stochastic	Asia	Africa	North America	South and Central America	Europe	Env. Functions	Env. Flow	Env. Water Requirement	Multi-crop	Single crop or aggregate	Crop-water functions	Estimated Demand	Crop-water requirement		
Linear Programming																	
Kracman et al., 2006	Static	Stoc.			X							X			X		
Medellín-Azuara et al., 2009	Static	Determ.				X			X			X			X		
Gartley et al., 2009	Static	Determ.	X						X		X			X			X
World Bank, 2010	Static	Determ.		X					X		X				X		X
George et al., 2011a,b	Static	Determ.	X					X			X			X		X	X
Divakar et al., 2011	Static	Determ.	X							X	X				X	X	
Becker and Friedler, 2012	Dynamic	Determ.	X					X				X			X		
Non-linear Programming																	
Ward and Velázquez, 2008	Dynamic	Determ.			X			X				X			X		X
Wang et al., 2008	Static	Determ.			X				X			X		X			
Pena Haro, 2009	Static	Stoc.						X			X				X	X	
Maneta et al. 2009	Dynamic	Determ.				X					X		X				
Gutiérrez, 2010	Static	Determ.					X		X		X			X			X
Varela-Ortega, 2011	Static	Determ.					X			X		X			X	X	X
Hurd and Coonrod, 2011	Static	Determ.			X							X			X	X	
Pande et al. 2011	Dynamic	Determ.	X								X			X			
Tilmant et al., 2012	Static	Stoc.		X					X		X				X		
Torres et al., 2012	Static	Determ.				X					X			X			



## 4.2 Model Formulation

We formulate a non-linear, dynamic, spatially defined, deterministic hydro-economic model which is tested on different hydrologic conditions to analyse the competing demands for water in the Kafue River. The model is conceived as a comprehensive tool for optimising, under various constraints, water allocation between different uses across time and space and comprises three components: (1) a hydrological component, including the water balances in reservoirs, river reaches and aquifers within the river basin; (2) water demand or requirement functions, including water for agricultural production, mines dewatering, industrial production, and municipal water uses; and (3) monetary costs and revenues of agricultural production and hydropower generation, which allow for maximising net economic benefits under constraints.

Figure 4. 1 Scheme of the modelling framework

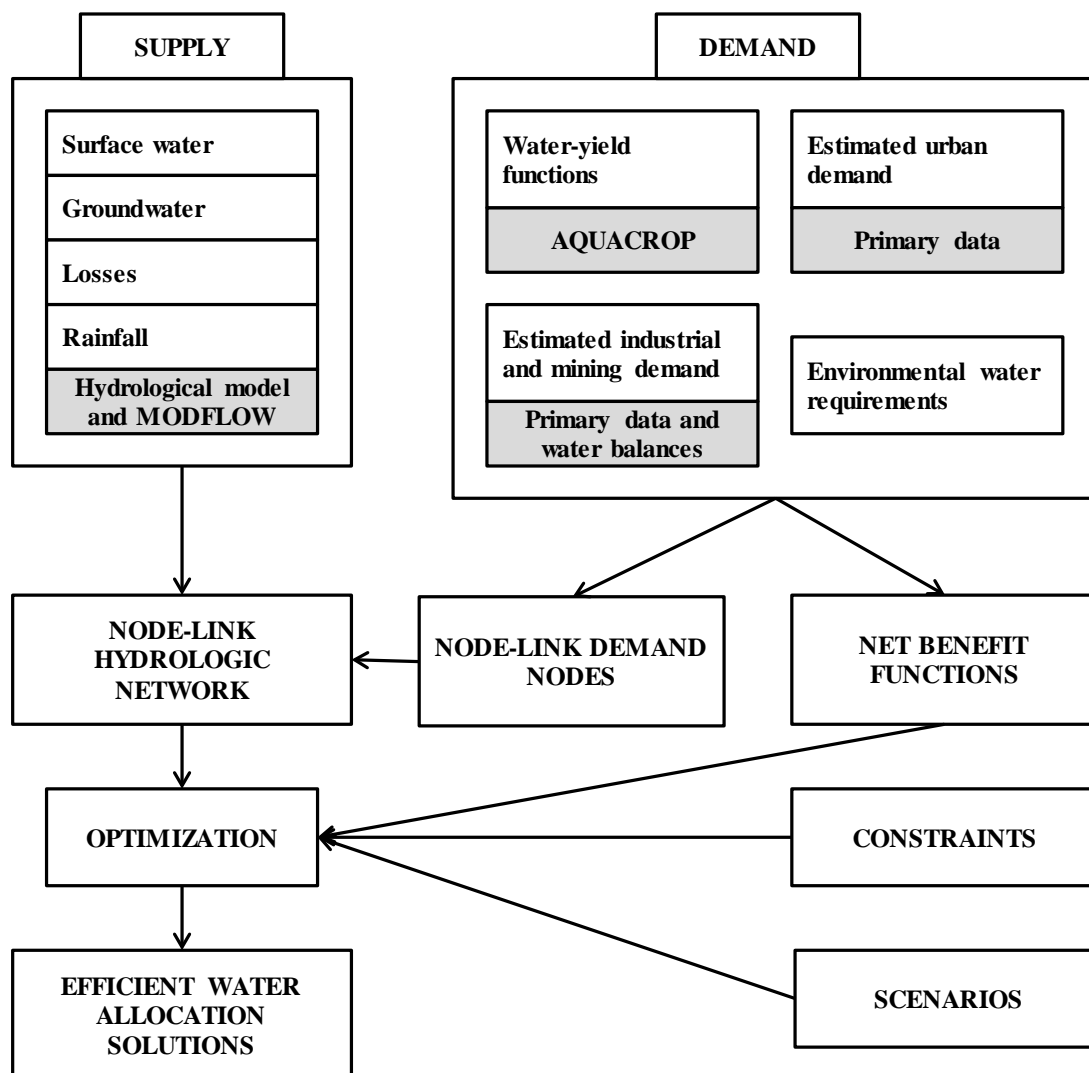


Figure 4.1 illustrates the modelling framework adopted for the present study, which is based on the integration of hydrological and economic components, and which is supported by two off-line models for the estimation of water supply inputs and agricultural water demands. Water supply information is derived from a hydrological model that predicts the inflows at Itezhi-tezhi, using rainfall and soil moisture data as inputs, and from a fully distributed floodplain model based on MODFLOW (Harbaugh, 2005). Similarly, also

agricultural water demands are derived from a separate model based on AquaCrop (FAO, 2011) and calibrated for the specific conditions of the Kafue River basin (a detailed explanation of the calibration procedure and the derivation of water demand and net benefit function is provided in Section 4.2.3). Other demand functions are derived within the main hydro-economic model and are based on primary data.

There is no universal formulation for a multi-objective optimization model, and the model should include all the essential elements such as:

- Network representation of the physical basin;
- Consistent accounting of flows, water storages, diversions etc.;
- Representation of requirements for water and economic benefits from its use, considering both in-stream and off-stream uses;
- Incorporation of institutional rules and policies.

In-stream uses include the environmental use of water and hydropower generation. Off-stream uses include water diversion for small and large-scale agriculture and municipal, mining, and industrial water uses. The water use for the mining activities requires special attention, as – in the case of open pit mines – it tends to increase the river flow through the mines’ dewatering operations.

It is possible to use several methods for water demand estimation (Table 4.2), but for the purpose of this study mathematical programming and the analysis of production functions are used to analyse the water requirements. The study at hand privileges the “engineering” approach to demand estimation – as opposed to the “statistical” approach, as defined by Kindler and Russell (1984) – due to the lower data requirements in terms of time series data. This choice is also justified by the fact that in the Zambian context, as in many other developing countries, it is often impossible to derive reliable estimates of the price elasticity of demand, and it therefore makes more sense to analyse water abstraction requirements calculated from known production practices. It should be explicitly underlined that this study uses the term “demand” as synonym of “requirement”. Nonetheless, the two concepts differ: “demand” is a concept used by economists to denote the willingness to purchase goods or services at a given price – and that willingness of course varies with the price of the purchased good or service. A “requirement” is, instead, an amount of a good or service which is required to achieve a specific target without considering the price of the specific good (Kindler and Russell, 1984).

Table 4. 2 Methods of demand estimation

	<b>Technique</b>	<b>Functionally Capable</b>	<b>Data/input Types</b>	<b>Sectoral Specialties</b>
Engineering approach	Mathematical programming	Yes	Output/prices for each activity to be considered	When water is a large input to production, especially irrigation and possibly industry
	Production function (estimation or simulation)	Yes	Experimental data or physical relationships	Irrigation, hydropower, individual manufacturing processes
Statistical approach	Statistical regression	Yes	Behaviour under administered prices; market transactions; metadata	Urban/residential, industrial/commercial
	Contingent evaluation	Yes	Survey data from consumers	Urban/residential, recreation

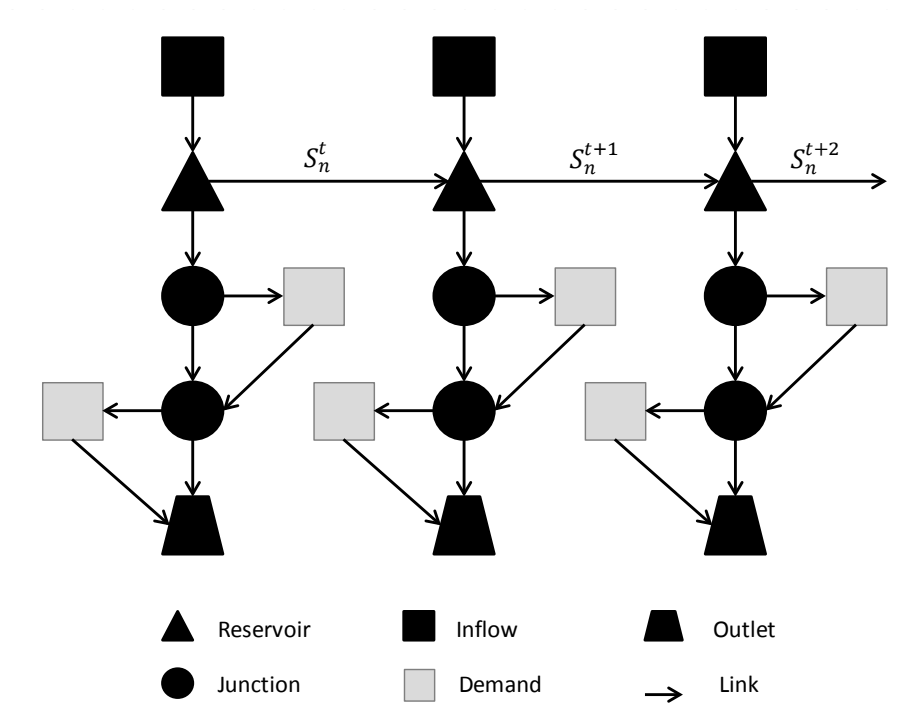
	ation		sumers	
	Travel costs	No	Survey data for recreation participants	Recreation
	Hedonic pricing	No	Market transactions of land/water	Recreation, irrigation
Other ap- proach	Point expansion	Yes	A known (w, p) and an exogenous elasticity	Potentially useful for all sectors but elasticity must be generated through another method
	Residential imputation (single-activity analysis)	No	Output amount and price, and a cost-of-production budget	When water is a large input to production, especially irrigation

*Adapted from Griffin, 2006*

#### 4.2.1 Network representation and hydrological component

The model has a basin-wide scale and is based on a node-link river basin network that can be schematically represented as a set of physical water demand nodes, in locations where water is abstracted for beneficial use, and links, which represent natural or man-made conjunctions between nodes (Figure 4.2) (Wang et.al, 2009; Rosegrant et al., 2000). For a regional planning problem over multiple time periods the network assumes a configuration where the different periods are connected by the reservoirs' storages, i.e. the end storage level at time  $t$  is identical to the initial storage level at time  $t+1$ , if no additional inflows are considered.

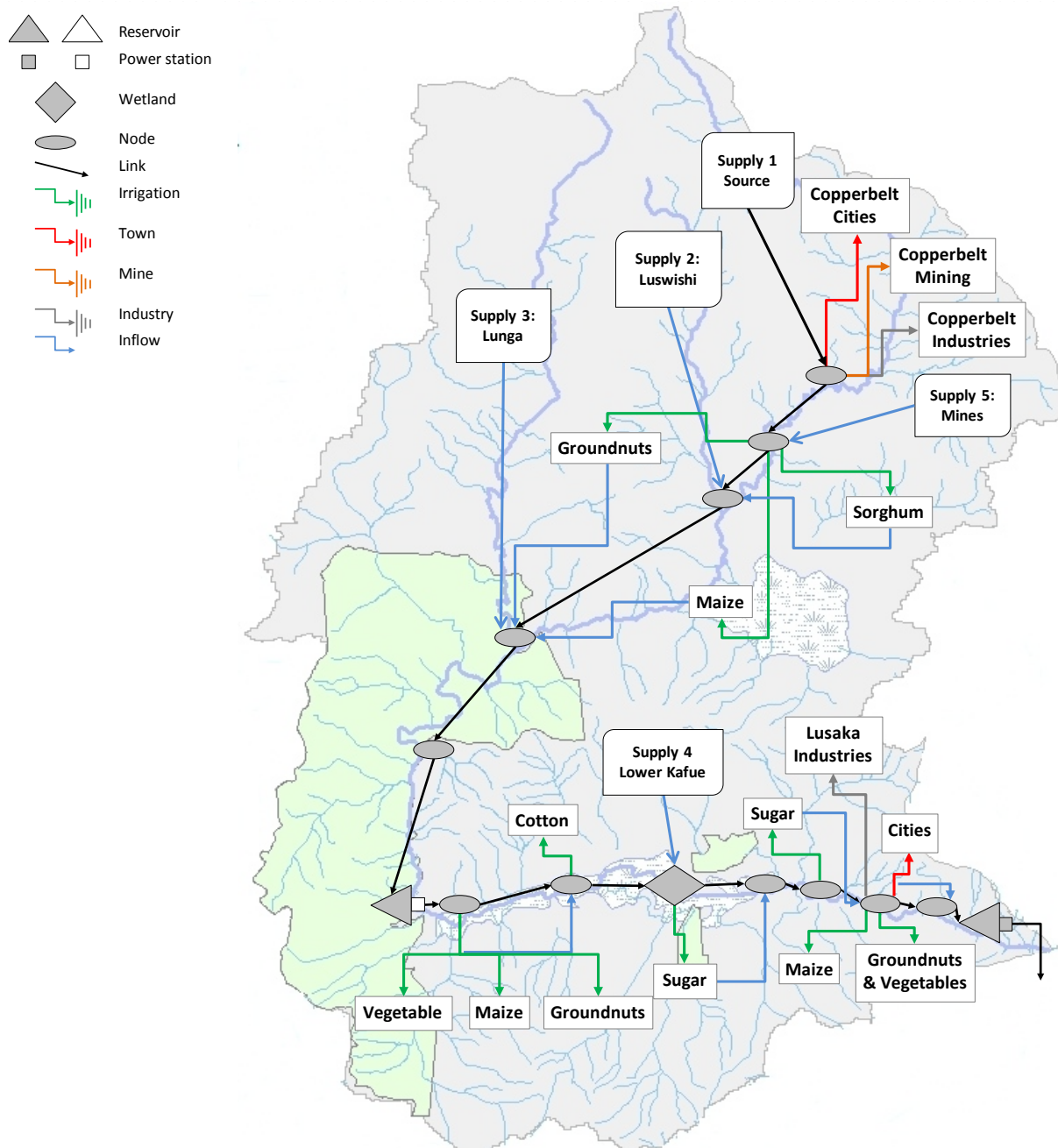
Figure 4. 2 Schematic representation of a node-link network



For the specific case of the Kafue River basin the full network includes two reservoirs, namely Itezhi-tezhi and Kafue Gorge (RES), two active hydropower stations, five supply nodes (SUP), 26 simple and diverting nodes (SIM and DIV, which comprise, inter alia, nine agricultural water diversions AG), and one unconfined groundwater storage divided into three cells (GRES). Figure 4.3 represents a simplified version of the

network, which, in order to improve the clarity of the graphical representation, excludes the groundwater storages and groups some of the agricultural areas. The hydrological input data is derived from an off-line model developed within the African Dams Project (ADAPT). The real-time hydrological model adopts daily time steps and is based on remote sensing data providing soil moisture and rainfall estimates (Meier, 2012).

Figure 4. 3 A simplified representation of the Kafue River network



The hydrological mass balance equation for the reservoirs can be drawn as<sup>12</sup>:

<sup>12</sup> The sequence of the n indices of the nodes indicate the direction of the flows.

$$S_n^t - S_n^{t-1} = \sum_{(n,n_1) \in N} Q_{n,n_1}^t - \sum_{(n_1,n) \in N} Q_{l_{n_1,n}}^t + Q_{ret_{n_1,n}}^t - \sum_{(n,n_2) \in N} R_{n,n_2}^t - D_n^t - Rc_n^t - Spill_n^t \quad \forall n \in RES \quad (1)$$

The reservoir operations are constrained by minimum and maximum releases, and minimum and maximum storage volume, reflecting the physical characteristics of the reservoirs studied.

$N$	set of nodes (-)
$T$	index of time periods (period length is $\Delta t$ ), $t \in T = (1, 2, \dots, T)$
$S_n^t$	storage volume for storage node (reservoir) $n$ at the end of period $t$ (million cubic meters, $Mm^3$ )
$Q_{n,n_1}^t$	net flow (excluding diversions to water using activities) from node $n_1$ to $n$ during period $t$ ( $Mm^3$ )
$Q_{l_{n_1,n}}^t$	conveyance losses because of evaporation, leakage, seepage of the flow from node $n_1$ to $n$ during period $t$ ( $Mm^3$ )
$Q_{ret_{n_1,n}}^t$	gain of inflow at node $n$ for return flows from other sources (losses in the water conveyance systems) during period $t$ ( $Mm^3$ )
$R_{n,n_2}^t$	release from node $n$ to node $n_2$ during period $t$ ( $Mm^3$ )
$D_n^t$	water diverted at node $n$ because of economic activities ( $Mm^3$ )
$Rc_n^t$	recharge from surface to groundwater, function of the total net flow ( $Mm^3$ )
$Spill_n^t$	residual variable indicating the possibility for node $n$ to release non-turbined water ( $Mm^3$ )

Also, additional operation rules, such as minimum releases in predefined periods to comply with environmental water requirements, are included in the model (see section 2.4).

At the source (or supply) node the mass balance equation implies that the releases equal the inflows:

$$R_n^t = Supply_n^t \quad \forall n \in SUP \quad (2)$$

$R_n^t$	release from node $n$ during period $t$ ( $Mm^3$ )
$Supply_n^t$	source of water at node $n \in$ source (or supply) node and for each time period $t$ ( $Mm^3$ )

For simple nodes, which include any junction node, the mass balance equation is:

$$\sum_{(n,n_2) \in N} R_{n,n_2}^t = \sum_{(n_1,n) \in N} Q_{n,n_1}^t + Dr_{n,n_1}^t - Rc_n^t \quad \forall n \in SIM \quad (3)$$

$R_{n,n_2}^t$	release from node $n$ to node $n_2$ during period $t$ ( $Mm^3$ )
$Q_{n,n_1}^t$	net flow (excluding diversions to water using activities) from node $n_1$ to $n$ during period $t$ ( $Mm^3$ )
$Rc_n^t$	recharge from surface to groundwater, function of the total net flow ( $Mm^3$ )
$Dr_{n,n_1}^t$	drainage to aquifer that increases with the amount of water diverted ( $Mm^3$ ):

$$Dr_{n,n_1}^t = rec_n^t \cdot \sum_{(n_1,n) \in N} Q_{n,n_1}^t \quad (4)$$

$rec_n^t > 0$  is the recharge coefficient indicating the share of water applied to the crops or used in the urban context that is not returning to the river directly but to groundwater

The generic equation that characterizes the diversion nodes, where water is abstracted for industrial use, urban consumption, mining operations, and agricultural purposes, is:

$$R_n^t = ret_n^t \cdot \sum_{(n_1,n) \in N} Q_{n,n_1}^t - D_n^t \quad \forall n \in DIV \quad (5)$$

$R_n^t$  release from node n during period t (Mm<sup>3</sup>)

$ret_n^t$  percentage of return flow to surface water from water using node n  $\in DIV$  and for each time period t (due to inefficiency of the supply system) (%)

$Q_{n,n_1}^t$  net flow (excluding diversions to water using activities) from node n1 to n during period t (Mm<sup>3</sup>)

$D_n^t$  water diverted at node n because of economic activities (Mm<sup>3</sup>)

The hydrological model is completed by a simplified groundwater network. The formulation of the groundwater schematic model was inspired by Sperow (2004) and translated into the node-link hydro-economic model concept. Agricultural and urban users have the possibility to withdraw water from both surface and groundwater, alternatively or jointly. In order to cope with the scarce data availability on groundwater in Zambia, and in order to match the node-link network, the aquifer is divided into three cells determined by varying depths. Each aquifer cell contains an amount of water dependent on its volume. Aquifer cells are recharged by inefficient use of water in agriculture and urban settings.

$$A_n^t - A_n^{t-1} = Dr_n^{t-1} - P_n^t + Rc_n^{t-1} \quad \forall n \in GRES \quad (6)$$

$A_n^t$  Water volume in aquifer cell n at time t (Mm<sup>3</sup>)

$Dr_n^{t-1}$  drainage to aquifer at time t-1 (Mm<sup>3</sup>) that increases with the amount of water diverted:  $Dr_n^{t-1} = \tau_1 D_n^t + \tau_1 P_n^{t-1}$  where  $\tau_1$  and  $\tau_1$  are irrigation efficiency coefficients for water application (surface or groundwater)

$P_n^t$  Water pumped from aquifer cell n at time t (Mm<sup>3</sup>)

$Rc_n^{t-1}$  recharge from surface to groundwater at time t-1, function of the total net flow (Mm<sup>3</sup>)

Surface and groundwater abstractions require water rights. The water rights are administrative measures often used in the context of developing countries to regulate abstractions of water in the irrigation sector, when volumetric charging systems cannot be applied. In the case of Zambia, the water rights are allocated by the Water Development Board, but due to inadequate financial and human resources the registry of water rights up to the new legal and policy reform was unreliable (Uhlendhal et al., 2011). For this reason, the model allows for the incorporation of surface water and groundwater rights whenever data are available. Otherwise, the model is unconstrained in this respect (see section 4.2.4).

#### 4.2.2 Hydropower

The use of water for hydropower generation is generally considered as an in-stream, non-consumptive water use, where non-consumptive water use is defined as any use of water that leaves the same quantity of water available for other uses (Pereira et al., 2009). Apart from hydropower production, this definition typically includes uses such as navigation or fishing. It goes without saying that non-consumptive uses of water are not entirely non-consumptive, as there are evaporation losses, for instance associated with maintaining a reservoir at a specified elevation to support fishery, recreation use, or hydropower production, and there are conveyance losses associated with maintaining a minimum flow in a river, canal, or ditch. Likewise, no typical consumptive use is fully efficient in the sense that there is always some return flow associated with such use, either in the form of a return to surface flows or as a ground water recharge.

The benefits of hydropower production are often defined by using the so-called “alternative cost technique”, calculating the cost savings of hydropower compared with the next less expensive energy production alternative (Gibbons, 1986; Booker and Young, 1994). The approach adopted here is to derive net benefit functions from the quantity of energy produced (determined by the technical characteristics of the dams) and its energy market price. The energy produced depends on the power plant discharge, the hydraulic head and the efficiency of the turbine-generator group. Hydraulic head is often represented as a linear function of reservoir storage, although this can produce inaccuracies (Diaz et al., 2000; Cai et al., 2003). The production function adopted in this study assumes that hydroelectric generation at time  $t$  depends on the water releases and on the dam head (Edwards, 2003). The head of the dam at time  $t$  is a function of the elevation of the reservoir in the same period, which, in turn, is a function of the volume of water contained in the reservoir in period  $t$ . The dynamic relation between elevation and reservoir storage is given by:

$$S_n^t = \gamma(h_n^t - h_n^0)^\delta \quad \forall n \in RES \quad (7)$$

$S_n^t$  storage volume for storage node (reservoir)  $n$  at the end of period  $t$  ( $Mm^3$ )

$h_n^t$  elevation of the water surface in the reservoir node  $n$  (m)

$h_n^0$  elevation of the tail-water at the outlet of the reservoir node  $n$  (m)

$\gamma$  and  $\delta$  coefficients (-)

The numerical value of the coefficients are estimated based on the least squares method:

$$\min \sum_{t=1}^T (e_n^t)^2 \quad (8)$$

where

$$e_n^t = S_n^t - \hat{S}_n^t = \gamma(\hat{h}_n^t - h_n^0)^\delta - \hat{S}_n^t \quad (9)$$

$e_n^t$  residual or difference between the actual value of storage and the predicted value ( $Mm^3$ )

$S_n^t$  storage volume for storage node (reservoir)  $n$  at the end of period  $t$  ( $Mm^3$ )

$\hat{S}_n^t$  is the observed storage volume in the reservoir  $n$  at time  $t$  ( $Mm^3$ )

$\hat{h}_n^t$  is the observed water elevation in the reservoir  $n$  at time  $t$  (m)

$h_n^0$  elevation of the tail-water at the outlet of the reservoir node  $n$  (m)

Given the derivation of the storage volume relationship, it is then possible to derive the amount of energy produced by each of the hydropower plants present in the system<sup>13</sup>:

$$E_n^t = g \cdot h_n^t \cdot r_n^t \cdot ef_n \quad (10)$$

$E_n^t$  Energy produced at node  $n$  ( $n \in RES$ ) at time  $t$  (kW)

$g$  gravitational acceleration, constant (9.81 m/sec<sup>2</sup>)

$h_n^t$  elevation of the water surface in the reservoir node  $n$  (m)

$r_n^t$  releases from the dam at time  $t$  (m<sup>3</sup>/sec)

$ef_n$  efficiency of the hydropower dam (%)

Based on this relation the net benefit function for the hydropower generation can be written as:

$$NB_{hp} = \sum_t^T \sum_n^N E_n^t \cdot ph_n^t(E_n^t) - ch^t \quad (11)$$

$NB_{hp}$  net benefits of hydropower generation for the overall system (million ZMK)

$E_n^t$  power produced at node  $n$  ( $n \in RES$ ) at time  $t$  (kW)

$ph_n^t$  price of energy, where  $E_t$  is the quantity of energy produced, and sold, during period  $t$  (million ZMK/kW)

$ch^t$  cost of hydropower production at time  $t$  (million ZMK). Costs are assumed to be fixed, but it is possible to assume costs increasing with the release rate, i.e.  $ch^t(r_n^t)$  with  $\partial ch / \partial r > 0$

#### 4.2.3 Agricultural water demands and net benefit functions

Agricultural water demands are primarily estimated in terms of each crop's production function, which builds a functional relation between a crop's yield or production and the amount of water, both rainfall and irrigation, applied to the plant. The approach adopted in the present study is designed to identify net benefit functions, which depend on revenues from the produced output, the costs of water used, and on all other production inputs' costs.

For many crops so-called "water-yield functions" are well-documented in the literature and are usually based on experiments. However, the conditions under which the experiments are carried out, the geographical location, the type of soils, and the frequency of water application greatly differ and can hardly lead to "generally valid" water-yield functions. Therefore, in our study the yield responses to water of most of the major field and vegetable crops are estimated with AquaCrop (FAO, 2011). AquaCrop, which evolves from the Doorenbos and Kassam (1979) approach to determine the yield response to water, is a water-driven simulation model that requires a relatively small number of parameters and input data. Its parame-

<sup>13</sup> Technically the equation should include the density of water which is constant at about 1,000 kg/m<sup>3</sup>. Omitting this constant gives values in kW instead of W.



ters are explicit and mostly intuitive, and the model maintains a good balance between accuracy, simplicity, and robustness. The model produces daily data, which can be aggregated into a monthly time-scale to match the hydro-economic modelling time-scale. The output of the program consists of key variables for crop development and production, for soil water balance, for soil water content, and for net irrigation requirement (particularly: evapotranspiration, crop transpiration, soil evaporation, and daily irrigation requirement).

Water-yield functions can be simulated for the specific region of interest when at least the following information is available (Steduto et al., 2012):

- Average historical time series of rainfall and evapotranspiration;
- Crop and soil characteristics.

With such input data, the yield response to different amounts of irrigation water applied is simulated by increasing the irrigation water application in stepwise intervals of two millimetres until the full irrigation requirement for the crop is reached (García-Vila and Fereres, 2012; Geerts et al., 2009)

Based on these simulated outputs, curve-linear relationships between crop yield and applied water are derived:

$$y_i = \sum_t^T (\alpha_1 + \alpha_2 W_i^t + \alpha_3 W_i^{t^2} + \alpha_4 W_i^{t^3}) \quad \forall n \in AG \quad (12)$$

$y_i$  yield of crop  $i$ ,  $i \in I$  (ton/ha)

$\alpha$  parameters of the yield-water function (-)

$W_i^t$  is the total water applied to crop  $i$ ,  $i \in I$ , at time  $t$  consisting of irrigation water applied (surface and groundwater) and rainfall,  $r$  (Mm<sup>3</sup>/ha):

$$W_i^t = \tau_1 D_i^t + \tau_1 P_i^t + r^t \quad (13)$$

$\tau_1$  and  $\tau_1$  irrigation efficiency coefficients (-) for water application to crop  $i$  depending on the irrigation method (surface or groundwater). The irrigation efficiency coefficients are supposed to be constant over time and characterise each farming area.

$D_i^t$  surface water diverted for crop  $i$  at node  $n$  (Mm<sup>3</sup>/ha)

$P_i^t$  groundwater diverted for crop  $i$  at node  $n$  (Mm<sup>3</sup>/ha)

Yields are calculated on a yearly basis for all crops. Sugarcane deserves a specific treatment as it is grown on a three-year cropping cycle with a main harvest after the first 12 months and two subsequent “ratoon”<sup>14</sup> harvests, with lower yields (Steduto et al., 2012). In order to model this feature the parameters of the yield-water function for sugarcane are not constant over time but change for the ratoon crop in order to reflect the lower productivity. The use of water-yield functions allows for the adoption of deficit irrigation, which

<sup>14</sup> Sugarcane plants provide more than one harvest: after the first harvest is made and the plant cut at ground level a new stalk (“ratoon”) grows. Technically, a sugarcane plant can provide up to 20 ratoons, but after two to three ratoons, harvested every year, the sugar yield is considerably lower with respect to the first crop and the stalks should be removed and new plants planted (Steduto et al., 2012).

may be warranted for attaining the overall net benefit maximisation. Deficit irrigation, i.e. the application of water below full crop-water requirement, is often practiced in developing countries, including Zambia, also in the sugar industry (Jumman, 2008), as a strategy to maximise profits as opposed to yields.

The net income is determined as proportional to the yield, while the costs are composed of a fixed (production costs not associated to the irrigation depth) and a variable component (Tsur et al., 2004; Hart et al., 1980; Mannocchi and Mecarelli, 1994).

$$NB_{ag}^i = \sum_{t=1}^T p_i y_i^t (W_i^t) x_i - c_i x_i - \sum_{t=1}^T c_w^s D_i^t x_i^s - \sum_{t=1}^T c_w^g P_i^t x_i^g - cr \quad (14)$$

$NB_{ag}^i$	net benefit derived from the agricultural production of crop $i$ , $i \in I$ (million ZMK)
$p_i$	farm-gate price of crop $i$ , $i \in I$ (million ZMK/ton)
$y_i$	yield of crop $i$ (ton/ha)
$x_i = x_i^s + x_i^g$	cropped and irrigated area with crop $i$ , $i \in I$ , where the irrigated area is composed of surface irrigated areas, $x_i^s$ (ha), and groundwater irrigated areas, $x_i^g$ (ha).
$W_i^t$	surface and groundwater applied to crop $i$ ( $Mm^3/ha$ )
$c_i$	crop production cost for crop $i$ , $i \in I$ , excluding irrigation-related costs (million ZMK/ha)
$c_w^s$	unit cost for surface water (million ZMK/ $Mm^3$ )
$D_i^t$	surface water diverted for crop $i$ at node $n$ ( $Mm^3/ha$ )
$c_w^g$	unit cost for groundwater (million ZMK/ $Mm^3$ )
$P_i^t$	groundwater diverted for crop $i$ at node $n$ ( $Mm^3/ha$ )
$cr$	connection cost or water right cost (million ZMK)

Following the same rationale adopted for the crop yields, also the net benefit function is calculated for every cropping year and for each crop, and can then be aggregated at farming area level (the model allows for multi-cropping in all farming areas). The net benefit function for agriculture can reflect different water charging systems. The parameters  $c_w^s$  and  $c_w^g$  imply the existence of a volumetric charging system, possibly an efficient marginal cost charge. The parameter  $cr$  implies the existence of a fixed cost or connection fee independent from the effective water consumption. The use of the latter parameter alone suggests the use of a uniform charging system or the presence of a water right administratively allocated. In such a case, the charge is computed as the total yearly fee to be paid in order to receive the respective water right. The conjunct use of  $c_r$  and  $c_w$  indicates the adoption of a two-part tariff that consists of a constant marginal price per unit of water applied to the field (volumetric marginal cost pricing) and a fixed annual (or admission) charge for the right to purchase the water. With a small modification of the net benefit equation already implemented in the code for the hydro-economic model, it is possible to include the provision of a block rate tariff<sup>15</sup>. Other charging systems such as area charging or input or output charging are not taken

<sup>15</sup> Block-tariffs are a multi-rate volumetric method, in which rates vary as the amount of water consumed exceeds certain threshold values. The agricultural net benefit function defined for a two-blocks tariffs is:

into consideration because not implemented in the Kafue Basin due to the complex assessment of the exact charge and because they provide an undesirably high incentive for an inefficient application of irrigation water.

#### 4.2.4 Constraints

Constraints are used to characterize the basin's hydrology and its institutions. The main constraints for the model are described below, along with the corresponding equations where necessary to clarify the exact mathematical formulation.

- Mass balance for each reservoir (see section 2.1)
- Minimum and maximum storage levels for the reservoirs:

$$S_{min} \leq S_n^t \leq S_{max} \quad (15)$$

$S_n^t$  storage volume for storage node (reservoir) n at the end of period t (Mm<sup>3</sup>)

$S_{min}$  minimum storage volume (Mm<sup>3</sup>)

$S_{max}$  maximum storage volume (Mm<sup>3</sup>)

- Minimum and maximum release flows for the reservoirs:

$$R_{min} \leq R_n^t \leq R_{max} \quad (16)$$

$R_n^t$  release from node n during period t (Mm<sup>3</sup>)

$R_{min}$  minimum release flow (Mm<sup>3</sup>)

$R_{max}$  maximum release flow (Mm<sup>3</sup>)

- It is common practice for many countries to allow predefined water flows to be released from water storage infrastructures at regular time intervals in order to maintain the downstream ecosystem. The environmental flows have been practiced as a strategy to mitigate some of the negative impacts of large dams, thus offering the possibility to protect, within certain limits, the ecosystem as well as the livelihoods that depend on it. In the context of the Kafue River, the Zambian electricity company (ZESCO), is bound to release from the Itezhi-tezhi reservoir a daily minimum flow of 300 m<sup>3</sup>s<sup>-1</sup>, over a

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$NB_{ag}^i$

$$= \sum_{t=1}^T p_i y_i^t (W_i^t) x_i - c_i x_i - \sum_{t=1}^T c_w^{s1} \bar{D}_i^t x_i^{s1} - \sum_{t=1}^T c_w^{s2} (D_i^t - \bar{D}_i)(x_i^s - x_i^{s1}) - \sum_{t=1}^T c_w^{g1} \bar{P}_i^t x_i^{g1} - \sum_{t=1}^T c_w^{g2} (P_i^t - \bar{P}_i)(x_i^g - x_i^{g1}) \quad (14bis)$$

$c_w^{s1}$  unit cost for surface water for the first block of water consumed (million ZMK/Mm<sup>3</sup>)

$c_w^{s2}$  unit cost for surface water for the second block of water consumed (million ZMK/Mm<sup>3</sup>)

$c_w^{g1}$  unit cost for groundwater for the first block of water consumed (million ZMK/Mm<sup>3</sup>)

$c_w^{g2}$  unit cost for groundwater for the first block of water consumed (million ZMK/Mm<sup>3</sup>)

$\bar{D}_i^t$  first block of surface water consumed for crop i, administratively assigned (Mm<sup>3</sup>/ha)

$\bar{P}_i^t$  first block of surface water consumed for crop i, administratively assigned (Mm<sup>3</sup>/ha)

four-week period, usually in March each year in order to simulate the natural flooding regime downstream of the dam. For this reason, the environmental flow constraint is formulated as:

$$R_{RES_1, n_2}^{t=March} \geq \overline{R^{t=March}} \quad (17)$$

$R_{RES_1, n_2}^{t=March}$  releases from the Itezhi-tezhi reservoir during the month of March (Mm<sup>3</sup>)

$R^{t=March}$  fixed releases from the Itezhi-tezhi reservoir in March (778 Mm<sup>3</sup>)

- Separation of reservoir turbine  $R_n^t$  and spill flows,  $Spill_n^t$ .

- Upper limit to the aquifer volume:

$$0 \leq A_n^t \leq \theta A_n^{t-1}, \theta \geq 1 \quad (18)$$

$A_n^t$  Water volume in aquifer cell n at time t

- Upper and lower bound on diversions for municipal and industrial water use:

$$D_{min} \leq D_n^t \leq D_{max} \\ \forall n \in DIV_{urban} \text{ and } \forall n \in DIV_{ind} \quad (19)$$

$D_n^t$  water diverted at node n because of economic activities (Mm<sup>3</sup>)

$D_{min}$  minimum diversions at node n (Mm<sup>3</sup>)

$D_{max}$  maximum diversions at node n (Mm<sup>3</sup>)

- Upper limit for agricultural run-of-river diversions which shall not exceed the amount specified in the respective water rights. This constraint is adopted only when sufficient and reliable information can be retrieved from the local water regulators.

$$\sum_i^I (D_i^t)_n \leq Ri_n^t \quad \forall n \in AG \quad (20)$$

$D_i^t$  surface water diverted for crop i at node n (Mm<sup>3</sup>)

$Ri_n^t$  amount of surface water right administratively allocated to agricultural node n at time t (Mm<sup>3</sup>)

- Upper limit for agricultural groundwater diversions which shall not exceed the amount specified in the respective water rights. As mentioned above, this constraint is optional and its use depends on the data availability at national level.

$$\sum_i^I (P_i^t)_n \leq GRi_n^t \quad \forall n \in AG \quad (21)$$

$P_i^t$  groundwater diverted for crop i at node n (Mm<sup>3</sup>)

$GRi_n^t$  amount of groundwater right administratively allocated to agricultural node n at time t (Mm<sup>3</sup>)

- Upper limit to groundwater diversions which shall not exceed the maximum pumping capacity,  $\overline{P}_i^t$ , nor the total aquifer capacity:

$$\sum_{i \in n_{ag,n}} P_i^t \leq \min \left( A_n^t, \sum_{i \in n_{ag,n}} \overline{P}_i^t \right) \forall n \in GRES \quad (22)$$

$P_i^t$  groundwater diverted for crop  $i$  at node  $n$  (Mm<sup>3</sup>)

$\overline{P}_i^t$  pumping capacity (Mm<sup>3</sup>)

$A_n^t$  water volume in aquifer cell  $n$  at time  $t$  (Mm<sup>3</sup>)

- Minimum and maximum irrigated land area:

$$x_{i_{min}} \leq x_i \leq x_{i_{max}} \quad (23)$$

$x_i$  area cropped with crop  $i$  (ha)

$x_{i_{min}}$  minimum cropped area with crop  $i$ , generally considered as the historical minimum irrigated land size in the past 10 years (ha)

$x_{i_{max}}$  maximum cropped area with crop  $i$  in each farming area (ha)

- Non-negativity constraints are imposed on several variables: river flow, releases, storage volume of the surface reservoirs, storage volume of the groundwater reservoirs, surface and groundwater applied to crops, diversions, cropped hectares, and crop yields.

#### 4.2.5 Objective function and solution algorithm

The model presented above is a highly non-linear multi-objective water management problem that involves of about 19,000 equations and about 26,500 single variables. The model consists of 54 blocks of equations, each of them adapted to the specific conditions of the node of interest. For example, a formally identical equation is calculated for each of the crops considered, for each agricultural node, and for each year, but different parameters are adopted each time in order to account for different soil characteristics, return flows, and plant growth stages. To solve such a complex large size model we used the General Algebraic Modeling System (GAMS) because of its versatility, the ease to adopt node-link hydro-economic networks, the possibility to include non-linear equations, and the computational speed (Brooke et al., 1998).

The objective of the model is to maximise the discounted value of net economic benefits over a three year time horizon (Becker and Friedler, 2012; George et al., 2011; Ward and Pulido Velazquez, 2008). Hydro-power production, water use patterns, pumping levels, and on-farm irrigation strategies are optimised over the model's time horizon. The model accounts for interactions among water users, storage (surface and groundwater), flows (diversions from surface and groundwater and return flows), and losses (conveyance, agricultural inefficiencies, and reservoir evaporation). The optimization time horizon of three years is chosen to be able to simulate a full cropping cycle for sugarcane and to allow the possibility to take into account a varied range of hydrological scenarios. In addition, the three year optimization time frame is also chosen to avoid that starting and ending conditions, particularly related to reservoir storage, influence first-stage decisions in the model. Adopting a three-year time frame allows the hydro-economic model to be dynamic, within that period, while it allows for assessing the comparative static of various scenarios. The

scenarios tested, in fact, are projected over a longer time-frame (ten years from the moment of writing or longer) that allows considering likely long-term developments such as the construction of additional dams and hydropower stations, the increase in irrigated agriculture, the growth in population, and the future closure of the mining operations. The detailed scenarios are described in part 2 of this paper.

The model runs on monthly time steps. As opposed to daily time steps, monthly intervals allow simulating irrigation decisions: due to technical constraints, farmers cannot adapt the irrigation schedule or the positioning of the irrigation system in response to daily changes in terms of rainfall or water availability, while the monthly time frame more accurately reflects the farmers' decision horizon. Moreover, a monthly time-step is convenient when considering water withdrawals for urban, industrial, and mining use of water because the Water Supply Councils collect water use data on monthly time steps. The time definition adopted implies the aggregation at a monthly level of the further disaggregated hydrological input data (daily basis). Despite a loss in accuracy, this solution is considered best in order to effectively assess a large multi-objective planning problem while ensuring enough hydrological variability to influence stakeholders' water using behaviours.

GAMS is capable of using a wide variety of solvers for the optimization process, including OSL, CONOPT, Cplex and MINOS. Among the available solvers, MINOS is chosen as the most suitable because of the possibility to use non-linearity in both the objective functions and the constraints and because of the efficient algorithms used. Nonetheless, when using MINOS the modeller must pay additional attention to the scale of the problem in order to keep the equations in the most natural form and avoid computation errors.

The objective function adopted with the MINOS solver can be represented in a generic form as:

$$OBJ = \text{Max} \left( \sum_{T=1}^3 \sum_i^I \varphi \frac{NB_{ag}^{iT}}{(1+r)^T} + \sum_{T=1}^3 \omega \frac{NB_{hp}^T}{(1+r)^T} \right) \quad (24)$$

where  $NB_{ag}^{iT}$  and  $NB_{hp}^T$  are, respectively, the net benefits generated by the  $i^{\text{th}}$  crop in year  $T$  and by hydro-power generation in year  $T$ ,  $r$  is the discount rate<sup>16</sup> and  $\varphi$  and  $\omega$  are weighting parameters that can be assigned based on the stakeholders' assessment of the relative importance of the different water using sectors. The objective function is subject to the constraints illustrated in Section

### 4.3 Conclusion and further explorations

The previous sections describe the concept of a hydro-economic model to support integrated water management in developing countries. The hydro-economic approach is an effective tool to analyse the compet-

<sup>16</sup> The selection of the appropriate discount rate strongly depends on the country information and on the details provided in previous studies. For the case of Zambia, World Bank (2009) adopts a discount rate of 12 percent for agricultural expansion. Seyam et al. (2001) use 5 percent as a discount rate to assess the future value of biodiversity. IFAD (2011), instead, uses a 10 percent discount rate to calculate the net present value of agricultural projects in Zambia. Broadening the scope of the analysis to other developing countries, the World Bank tends to adopt discount rates between 8 and 12 percent for the evaluation of the economic benefits derived by various water using sectors (World Bank, 2012, 2007). Other authors also apply discount rates in hydro-economic modelling: a discount factor of 3 percent for the Alexander-Zeimar River (Israel) system net benefit is used by Becker and Freidler (2012) while George et al. (2008) adopt 8 percent for their Musi Basin (India) model.

Due to the uncertainty in assessing the discount rate, for the present study the authors decided to adopt a cautious approach. Given the low interest rate environment that Zambia is facing at the moment and considered that the real interest rate of a one year maturity Zambian Treasury Bill, which can be defined as the risk free interest rate, is 1.42 percent, we decided to consider 5 percent as a good approximation for the discount rate. Sensitivity analyses are performed on this value.

ing water demands within a watershed and to provide clear indications on the trade-offs arising from the different and often conflicting stakeholders' objectives. The optimization model suggests a range of efficient solutions of the water allocation problem for agricultural production on the one hand and hydropower generation on the other hand. At the same time the model also takes into consideration normative fairness aspects in the distribution of water resources: this is reflected in the constraints for the allocation of water to the urban centres (water consumption of households, industry and mines) and through the binding environmental flow constraints to the dams operations that determine water flows for environmental purposes. The possibility to vary the weights assigned to the hydropower and agriculture components of the net benefit optimization function also provides the flexibility to adapt the model to changing policy and societal priorities and integrate fairness considerations. The quantitative representation of the hydro-economic network requires a large amount of input data. Moreover, two off-line supporting models are applied to generate hydrological flow data and irrigation schedules and crop growth to derive water-yield functions. The validation of the model is described in part 2 of this paper. The model is optimised using a general-purpose non-linear programming algorithm.

The mathematical formulation presented above already accommodates the possibility to enhance selected sections of the model depending on additional data availability. For the specific case of the Kafue River basin reliable groundwater data for the whole watershed were not available at the time of the study. Despite the scarce data availability, the groundwater cells are implemented in the model and are linked with the rest of the hydro-economic network. In other words, the model functions with a rather crude representation of the supply and use of groundwater, and it would allow for the inclusion of more accurate groundwater input data whenever that was available. The derivation of appropriate environmental functions could also be the subject of a further improvement of the hydro-economic model. Scientific studies are being carried out in the wetlands of the Kafue Basin to assess the relation between water levels, vegetation cover, and density of endemic fauna. Based on the results of such studies it would be possible to estimate appropriate ecological "water-yield" functions. At the same time, the availability of information regarding the relation between water levels and fish catch across the basin could further enrich the correct understanding of the environmental demand for water. Finally, water pollution is not explicitly included in the model but GAMS is a versatile platform that could accommodate a complete pollution transport model. Considering the characteristics of the Kafue River and the large scale mining and agricultural operations taking place across the basin, a complete assessment of the risks of pollution and their environmental and economic impacts would be desirable.

## Acknowledgements

This study greatly benefited from Prof. Amaury Tilmant's introduction to hydro-economic modelling and from his precious feedback on the mathematical formulation of the model. This chapter would not have been possible without Prof. Rolf Kappel's comments and suggestions.

## References

- Beck, L. & Bernauer, T. (2011). How will combined changes in water demand and climate affect water availability in the Zambezi River basin? *Global Environmental Change*, 21: 1061-1072.
- Becker, N. & Friedler, E. (2012). Integrated hydro-economic assessment of restoration of the Alexander-Zeimar River (Israel-Palestinian Authority). *Regional Environmental Change*, 1-12.
- Booker, J.F. & Young, R.A. (1994). Modeling intrastate and interstate markets for Colorado River water-resources. *Journal of Environmental Economics and Management*, 26 (1), 66–87.
- Bower, R. & Hofkes, M. (2008). Integrated hydro-economic modelling: Approaches, key issues and future research directions. *Ecological Economics*, 66, 16-22.
- Brooke, A., Kendrick, D., Meeraus, A., and R. Raman, (1998). *GAMS: A User's Guide*. GAMS Development Corporation, Washington, DC, December 1998.
- Cai, X.M., McKinney, D.C., and Lasdon, L.S. (2003). Integrated hydrologic–agronomic– economic model for river basin management. *Journal of Water Resources Planning and Management*, 129 (1): 4–17.
- Diaz, G.E., Brown, T.C., and Sveinsson, O. (1997). AQUARIUS: A modeling system for river basin water allocation. General Technical Report RM-GTR-299, Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Fort Collins, CO. Available from: <http://www.engr.colostate.edu/depts/ce/research/aquarius/index.html>.
- Divakar, L., Babel, M.S., Perret, S.R, and Gupta, A.D. (2011). Optimal allocation of bulk water supplies to competing use sectors based on economic criterion – An application to the Chao Phraya River Basin, Thailand. *Journal of Hydrology*, 401 (1–2), 22–35.
- Doorenbos, J. & Kassam, A.H. (1979). *Yield response to water*. FAO Irrigation and Drainage Paper No. 33, FAO, Rome, Italy, 193 pp.
- FAO (2011). AquaCrop version 3.1 – The FAO crop model to simulate yield response to water.
- García-Vila and Fereres (2012). Combining the simulation crop model AquaCrop Model with an economic model for the optimization of irrigation management at farm level. *European Journal of Agronomy*, 36: 21-31.
- Gartley, M.L., George, B., Davidson, B., Malano, H.M., and Garg, K.K. (2009). Hydro-economic modelling of the Upper Bhima Catchment, India. 18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009.
- Geerts, S., Raes, D., Garcia, M., Taboada, C., Miranda, R., Cusicanqui, J., Mhizha, T., and Vacher, J. (2009). Modelling the potential for closing quinoa yield gaps under varying water availability in the Bolivian Altipiano. *Agricultural Water Management*, 96: 1652-1658.
- George, B., Malano, H., Davidson, B., Hellegers, P., Bharati, L., and Massuel, S. (2011a). An integrated hydro-economic modelling framework to evaluate water allocation strategies I: Model development. *Agricultural Water Management*, 98: 733–746.



- George, B., Malano, H., Davidson, B., Hellegers, P., Bharati, L., and Massuel, S. (2011b). An integrated hydro-economic modelling framework to evaluate water allocation strategies II: Scenario assessment. *Agricultural Water Management*, 98: 747–758.
- Gibbons, D.C. (1986). *The economic value of water*. Resources for the Future, Washington, DC.
- Griffin, R. C. (2006). *Water Resource Economics: The Analysis of Scarcity, Policies and Projects*. The MIT Press Cambridge, Massachusetts.
- Gutiérrez, I. B. (2010). Economic-hydrologic analysis of water management strategies for balancing water for nature and water for food – Implications for the Guadiana River Basin, in Spain. Doctoral Thesis, Polytechnic University of Madrid.
- Harbaugh, A. W. (2005). MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process. Techniques and Methods 6–A16. U.S. Geological Survey.
- Harou, J. J., Pulido-Velazquez, M., Rosenberg, D. E., Medellín-Azuara, J., Lund, J. R., and Howitt, R.E. (2009). Hydro-economic models: Concepts, design, applications, and future prospects. *Journal of Hydrology*, 375: 627–643.
- Hart, W.E., Woodward G., and Humpherys, A.S. (1980). Design and operation of gravity or surface system. In: M.E. Jensen, Editor, Design and Operation of On-farm Irrigation Systems ASAE Monograph, No. 3 (1980) USA.
- Heinz, I., Pulido-Velazquez, M., Lund, J. R., and Andreu, J. (2007). Hydro-economic modelling in river basin management: implications and applications for the European Framework Directive. *Water Resources Management*, 21: 1103-1125.
- Hurd, B. H. & Coonrod, J. (2012). Hydro-economic consequences of climate change in the upper Rio Grande. *Climate Research*, 53: 103-118.
- IFAD (2011). Smallholder productivity promotion programme (S3P). Programme Design Report. Volume 1 – Main Report. Available on <http://www.ifad.org/operations/projects/design/103/zambia.pdf>
- Jumman, A. (2008). Deficit irrigation: a strategy to improve profitability in sugarcane irrigation. Master Thesis, University of KwaZulu-Natal, South Africa.
- Kindler, J. & C.S. Russell (editors) (1984). *Modeling water demands*. Academic Press Inc., Publishers, Florida, 1984, 248 pp.
- Kracman, D. R., McKinney, D. C., Watkins, D. W., and Lasdon, S. (2006). Stochastic optimization of the Highland Lakes System in Texas. *Journal of Water Resources Planning and Management*, 132(2): 62-70.
- Maneta, M. P., Torres, M.O., Wallender, W.W., Vosti, S.A., Howitt, R., Rodrigues, L.N., Basso, L.H., and Panday, S. (2009). A spatially distributed hydroeconomic model to assess the effects of drought on land use, farm profits, and agricultural employment. *Water Resources Research*, 45.
- Mannocchi, F. & Mecarelli, P. (1994). Optimization analysis of deficit irrigation systems. *Journal of Irrigation and Drainage Engineering*, 120 (3): 484-503.

- Mavrotas, G. (2009). Effective implementation of the e-constraint method in Multi-Objective Mathematical Programming problems. *Applied Mathematics and Computation*, 213: 455–465
- McCartney, M. P., Chabwela, H. N., and Mwelwa, E. (2001). Managed flood releases in practise: the Kafue Flats case study.
- Medellín-Azuara, J., Mendoza-Espinosa, L.G., Lund, J.R., Harou, J.J., and Howitt, R.E: (2009). Virtues of simple hydro-economic optimization: Baja California, Mexico. *Journal of Environmental Management*, 90: 3470–3478.
- Meier, P. (2012). Real-time hydrologic modelling and floodplain modelling in the Kafue River basin, Zambia, Doctoral thesis, ETH Zürich.
- Minsker, B.S., Padera, B., and Smalley, J.B. (2000). Efficient methods for including uncertainty and multiple objectives in water resources management models using genetic algorithms. In: Proceedings of the XIII International Conference on Computational Methods in Water Resources, Calgary, Alberta, Canada. Balkema Publishers, Rotterdam, ISBN 90-5809-123-6, pp. 541–545.
- Pande, S., van den Boom, B., Savenije, H.H.G., and Gosain, A.K. (2011). Water valuation at basin scale with application to western India. *Ecological Economics*, 70: 2416–2428.
- Pereira, L.S., Cordery, I., and Iacovides, I. (2009). *Water Conservation and Saving: Concepts and Performance*. Springer Netherlands.
- Peña Haro, S. (2009). A hydro-economic modeling framework for optimal management of groundwater nitrate pollution from agriculture. Doctoral Thesis, Polytechnic University of Valencia.
- Percia, C., Oron, G., and Mehrez, A. (1997). Optimal operation of regional system with diverse water quality sources. *Journal of Water Resources Planning and Management*, 123 (2): 105–115.
- Peter, W.F.L., William, W.G., and Yeh, M., et al. (1984). Multiobjective water resources management planning. *Journal of Water Resources Planning and Management*, 110 (1): 39–56.
- Pulido-Velazquez, M., Andreu, J., Sahuquillo, A., Pulido-Velazquez, D. (2008). Hydro-economic river basin modelling: The application of a holistic surface–groundwater model to assess opportunity costs of water use in Spain. *Ecological Economics*, 66: 51-65.
- Raquel, S., Ferenc, S., Emery Jr., C., and Abraham, R. (2007). Application of game theory for a groundwater conflict in Mexico. *Journal of Environmental Management*, 84 (4): 560–571.
- Rosegrant, M.W., Ringler, C., McKinney, D.C., Cai, X., Keller, A., and Donoso, G. (2000). Integrated economic-hydrologic water modeling at the basin scale: the Maipo river basin. *Agricultural Economics*, 24 (1): 33 – 46.
- Seyam, I. M., Hoekstra, G. S., Ngabirano, G. S., and Savenije, H. H. G. (2001). The value of freshwater wetlands in the Zambezi Basin. Globalization and Water Resources Management: The Changing Value of Water. August 6-8 AWRA/IWLRI-University of Dundee International Specialty Conference 2001.

- Sperow, M. (2004). An Analysis of the Economic Impact of Water Transfers from Agricultural to Urban Uses. Presented at the American Agricultural Economics Association, Denver, Colorado, August 1-4 2004.
- Steduto, P., Hsiao, T. C., Fereres, E., and Raes, D. (2012). *Crop Yield Response to Water*. FAO Irrigation and Drainage Paper 66. FAO, Rome.
- Tesini, P. (2010). Gestione integrata della produzione idroelettrica e dei servizi ecosistemici nel Bacino del Kafue. Master Thesis, Politecnico di Milano.
- Tilmant, A., & Kinzelbach, W. (2012). The cost of noncooperation in international river basins. *Water Resources Research*, 48.
- Tilmant, A., Kinzelbach, W., Juizo, D., Beevers, L., Senn, D. and Casarotto, C. (2011). Economic valuation of benefits and costs associated with the coordinated development and management of the Zambezi River basin. *Water Policy*, 14: 490–508.
- Torres, M.O., Maneta, M.P., Howitt, R., Vosti, S.A., Wallender, W.W., Basso, L.H. and Rodrigues, L.N. (2012). Economic impacts of regional water scarcity in the São Francisco River Basin, Brazil: an application of a linked hydroeconomic model. *Environment and Development Economics*, 17: 227–248.
- Tsur, Y., Roes, T., Doukkali, R., and Dinar, A. (2004). *Pricing irrigation water – Principles and cases from developing countries*. Resources for the Future, Washington, D.C., USA.
- Uhlendahl, T., Salian, P., Casarotto, C. and Doetsch, J. (2011). Good Water Governance and IWRM in Zambia - Challenges and Chances. *Water Policy*, 13: 845–862.
- Varela-Ortega, C., Blanco-Gutierrez, I., Swartz, C.H., and Downing, T.E. (2011). Balancing groundwater conservation and rural livelihoods under water and climate uncertainties: An integrated hydro-economic modeling framework. *Global Environmental Change*, 21: 604–619.
- Wang, L., Fang, L., and Hipel K. W. (2008). Basin-wide cooperative water resources allocation. *European Journal of Operational Research*, 190 (3): 798–817.
- Wang, M. & Zheng, C. (1998). Ground water management optimization using genetic algorithms and simulated annealing: formulation and comparison. *Journal of the American Water Resources Association*, 34 (3): 519–530.
- Wang, X., Sun, Y., Song, L., and Mei, C. (2009a). An eco-environmental water demand based model for optimising water resources using hybrid genetic simulated annealing algorithms. Part I. Model development. *Journal of Environmental Management*, 90 (8): 2628–2635.
- Wang, X., Sun, Y., Song, L., and Mei, C. (2009b). An eco-environmental water demand based model for optimising water resources using hybrid genetic simulated annealing algorithms. Part II. Model application and results. *Journal of Environmental Management*, 90 (8): 2612–2619.
- Ward, F. A. & Pulido-Velázquez, M. (2008). Efficiency, equity, and sustainability in a water quantity–quality optimization model in the Rio Grande basin. *Ecological Economics*, 66: 23–37.
- World Bank (2012). Project appraisal document for a commercial agriculture project. Report No: 66499-GH.

World Bank (2010). *The Zambezi River Basin: a Multi-Sector Investment Opportunities Analysis*. The World Bank, Washington D. C., USA.

World Bank (2009). *Zambia: Managing Water for Sustainable Growth and Poverty Reduction - A Country Water Resources Assistance Strategy for Zambia*. Washington DC.

World Bank (2007). *Mozambique Country Water Resources Assistance Strategy - Making Water Work for Sustainable Growth and Poverty Reduction*. Washington DC.

Xevi, E. & Khan, S. (2005). A multi-objective optimization approach to water management. *Journal of Environmental Management*, 77 (4): 269–277.

# Chapter 5

## An integrated model for water resources management in developing countries: the case of the Kafue River basin. Part II: Practical Application

At the time of submitting this thesis, a version of this single-authored chapter is in preparation for publication with ETH Hochschulverlag.

## Abstract

Although Zambia is considered to have abundant water resources, development in the sectors of irrigated agriculture, hydropower generation, industry, and drinking water supply coupled with a rising and predominantly urban population is exerting heavy pressure on the available water resources base, especially in the Kafue River basin.

This study assesses the allocation of water resources to satisfy urban, agricultural, industrial, mining, and environmental water demand in the Kafue River basin. The overall water use patterns in the Kafue River basin are analysed with a focus on both consumptive and non-consumptive water uses. Applying the hydro-economic model developed in Part I of this study, future development scenarios are analysed and the implications on water demand, supply and optimal water allocation across sectors of the economy are examined.

Although the Kafue River basin is endowed with abundant water resources, tensions between different water using sectors are already evident and will be exacerbated by irrigated agriculture and hydropower developments throughout the basin. Our analysis shows that the Kafue Basin could sustain the planned future hydropower development while maintaining the current level of agricultural production. However, not all of the future agricultural developments are economically feasible, particularly in a dry year scenario: partial irrigation of sugarcane and the derived lower profits or a decrease in hydropower generation need to be taken into account. Population growth across the basin will by itself put a strain on water resources: would the actual irrigated agriculture be maintained, overall net benefits would be reduced by about 26 percent compared to a baseline scenario in the occurrence of a dry hydrological year. Reduced water inputs due to the termination of mining activities would lead to an overall reduction, on average, of about 20 percent of the net benefits with respect to the baseline scenario. This will also have a direct impact on agricultural activities and urban water supply in the upper Kafue.

## 5.1 Introduction and modelling framework

Although Zambia is considered to have abundant water resources, development in the sectors of irrigated agriculture, hydropower generation, industry, and drinking water supply coupled with a rising and predominantly urban population is exerting heavy pressure on the available water resources base, especially in the Kafue River basin.

Under normal hydrological conditions, the water resource base might appear adequate; however, Zambia has experienced a recurrence of droughts in 1991/92 and 1994/95 and 2000/01 due to lower than average rainfall, which resulted in severely reduced agricultural productivity and production. In this regard, it is recognized that the availability of water may not necessarily match the spatial pattern of demand (GoZ, 2004; GoZ, 2005).

The water governance system in Zambia underwent massive transformation between 2010 and 2011 with the enactment of a Water Policy and a new Water Resources Management Act (GoZ, 2010; GoZ, 2011b). These new regulations stipulate the decentralization of the water sector on the basis of water basin boundaries, not anymore administrative demarcations, and the devolution of power to the lowest level of authorities (Uhlendahl et al., 2011). Moreover, for the first time the new water governance

system provides for the control, regulation, and management of groundwater, filling a legislative gap that favoured the indiscriminate exploitation of the groundwater aquifers. Current estimates of water resources indicate a huge potential (49.6 Km<sup>3</sup> per year; YEC, 1995) for groundwater in addition to surface water which is readily available and can be reasonably exploited to warrant any additional irrigation expansion programmes.

In a moment when the competition among different uses of water is growing and the new water governance system is pending concrete implementation, this study aims at analysing the allocation of the Kafue waters and assessing the policy options for its management focusing on the trade-offs emerging from the stakeholders' multiple and conflicting objectives. What policymakers and stakeholders aim indeed to achieve is a satisfactory set of options on the Pareto frontier that can be the basis for a multi-objective participatory optimization process which will lead to the selection of negotiated solutions (Van Cauwenbergh et al., 2008; Soncini-Sessa, 2007a,b; Marttunen and Suomalainen, 2005; Castelletti et al., 2004; Hofwegem and Jaspers 1999; Dinar et al. 1997; Dinar and Letey, 1996).

The challenge in water resources management is to balance the demand and supply of water resources and to regulate water use to ensure sustained availability and an optimum use among various groups (GWP, 2000a,b). All interests and needs of stakeholders have to be simultaneously considered leading to the analysis of all trade-offs and, eventually, conflicts that emerge from their preferences. Multicriteria decision making (MCDM) methods evaluate the coupling among these objectives (Wright et al., 2002; Miettinen, 1999).

The key challenge of the present study is to provide a modelling framework to couple a physical model for water supply with an economic optimization model that includes an accurate representation of all demands for water and all stakeholders' objectives.

The model is conceived as a comprehensive hydro-economic tool for optimizing water allocation between different uses across space and over different hydrologic scenarios and includes three components: (1) a hydrologic component, including the water balances in reservoirs and river reaches within the basin; (2) water requirement functions, including water for agriculture use, mines dewatering, industrial use, and municipal water use complemented by constraints for other water uses, and (3) economic components (optimization), including the calculation of benefits from each water using sector.

The paper is organised in three sections. Firstly, the overall water use patterns in the Kafue River basin are presented with a focus on both consumptive and non-consumptive water uses. Secondly, a set of scenarios is defined to analyse future development scenarios and their implications on water demand, supply and optimal allocation. Finally, the study describes in detail the results of the scenario.

## 5.2 Water uses on the Kafue River basin

The Kafue River basin plays an important role in Zambia's economic development: it comprises about 20% of the area of Zambia, it is host to more than 40% of the Zambian population, and it supplies water to the major industrial, commercial and agricultural areas of Zambia (WWF, 2005). The Kafue catchment area covers the major urban centres of the country. The river, which rises close to the borders with the Democratic Republic of the Congo, flows through the Copperbelt district and through the floodplain of

the Lukanga swamp until it reaches the Itezhi-tezhi (ITT) dam. Between this reservoir of 390 km<sup>2</sup> and the Kafue Gorge (KG) dam lie the Kafue Flats, which are recognized as a major Ramsar protected wetland resource in ecological terms, and are also of great importance in economic terms, supporting local industries, agriculture and fishery. The Kafue River hosts two main dams, the Itezhi-tezhi dam and the Kafue Gorge dam. The Kafue Gorge dam has an installed hydropower capacity of 990 Megawatts (MW), while works at the Itezhi-tezhi dam will ensure by 2013 an installed capacity of 120 MW.

Water from the Kafue River is abstracted for a variety of purposes, including municipal supply, industrial use, mining in the Copperbelt, and irrigation of agricultural land, primarily for sugar-cane and maize production, and supplemental irrigation for winter wheat production. Moreover, the Kafue's waters are fundamental for the survival of intensive fishery activities as well as of rich natural resources, including wildlife. Most of these are consumptive water uses, which reduce the flow reaching Kafue Gorge, where the Zambian Electricity Supply Corporation (ZESCO) is interested in a maximum river flow to generate electricity.

This complex web of consumptive and non-consumptive uses is causing inter-sectoral competitions. Although at the moment the Kafue Basin is not under conditions of physical scarcity, the lack of good governance mechanisms in the basin, which affects the allocation and use of the common water resources, may exacerbate water use conflicts (Burke, 1994; McCartney and Houghton-Carr, 1998; Piésold, 2003).

### 5.2.1 Urban, industrial and mining water supply

Urban water use is generally considered a minor use of water compared to irrigated agriculture. FAO (2005) reports total yearly water withdrawals for Zambia of about 1,737 million cubic meters (MCM), with agriculture accounting for about 77 percent of the total. Domestic water use is recorded to claim 286 MCM, while industrial water use accounts for the remaining 131 MCM.

Urban and industrial water withdrawals across Zambia and in the Kafue catchment are affected by water losses often above 50 percent of the total water distributed (NWASCO and GoZ, 2009), due to leaking and vandalized pipes. Over time, yearly urban water withdrawals in the Kafue region markedly increased, from about 245 MCM in the period 2006/07 to about 315 MCM in the period 2008/09. Different water utilities are responsible for the distribution of urban and industrial water across the Kafue River basin. Nonetheless, most of the largest Zambian cities, namely Ndola and Kitwe in the Copperbelt, Mazabuka in the Southern Province, and Kafue and Lusaka in the Lusaka province, draw water for industrial and household use activities from the Kafue River (Figure 5.1). A detailed assessment of the gross water withdrawals, including surface water, groundwater, and losses from both sources, for each of the urban settlements in the basin is shown in Table 5.1.



Table 5. 1 Urban and industrial water use in the water supply councils of the Kafue region (MCM)

Water Supply Council	Region/City	2006/07	2007/08	2008/09
Kafubu and Nkana WSC <sup>1</sup>	Luanshya	15.36	21.4	14.5
Kafubu WSC	Masaiti	0.3	0.42	0.46
	Ndola	45.7	40.37	47.8
Lukanga WSC	Mumbwa	0.76	2.16	0.95
Lusaka WSC	Lusaka&Kafue	78.88	79.98	94.49
Mulonga and Nkana WSC	Chililabombwe	13.73	15.35	23.09
	Chingola	15.97	26.78	41.03
	Mufulira	12.29	17.74	26.16
Nkana WSC	Chambishi	1.74	0.98	na
	Kitwe	57.19	28.39	63.71
Southern WSC	Chisekesi	na	na	0.03
	Mazabuka	1.88	1.79	1.65
	Mbabala	0.02	0.02	0.02
	Monze	1.12	0.9	0.99
	Namwala	0.4	0.27	0.29
	Nega-nega	0.06	na	0.05
<b>Total</b>		<b>245.4</b>	<b>236.55</b>	<b>315.22</b>

Source: National Water Supply and Sanitation Council (NWASCO)

Figure 5. 1 Map of the municipalities

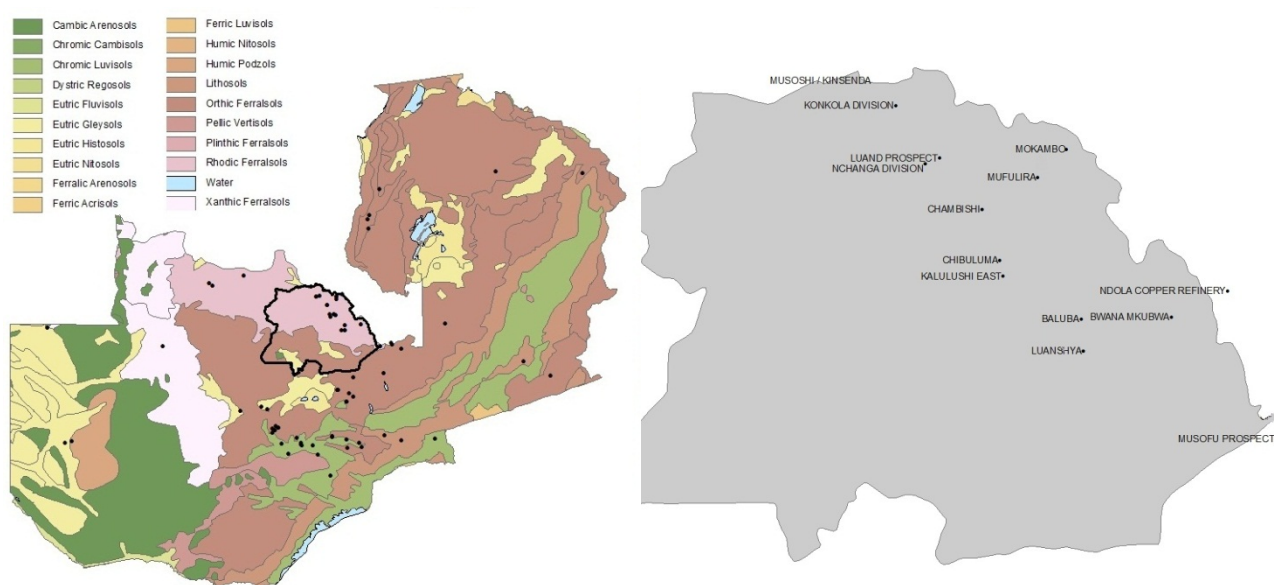


<sup>1</sup> Water Supply Council

The comprehensive data collected from the water utilities allows separating the amount of water delivered to the industrial sector from the total volume of water withdrawn by the various Water Supply Councils. On average, 27 percent of the water abstracted is delivered to commercial users, i.e. industries and other productive activities.

A separate consideration is given to the mining sector. In fact, the water required for the mining operations is generally not provided by the water utilities. Mines tend to use part of the groundwater abstracted from the surface or underground pits to carry out their daily operations. Water balances were collected from three large mining companies (Kansanshi, Konkola, Luanshya) to estimate the amount of groundwater abstracted and used by the mines. For the other mining companies data were retrieved from literature (ECZ, 2007a; ECZ, 2007b; CSMA Consultants Ltd. and ACA Howe International Ltd., 2001; de Vente, 1993). Figure 5.2 illustrates the location of the major Zambian mines, the type of soils and metals extracted, and provides a focus on the Copperbelt mines.

Figure 5. 2 Soil map and mines concentration



The monthly water requirements for each city, industrial area and the mining area are modelled within the hydro-economic node-link network. The urban water demands enter the model as constraints to other uses of water. This approach has been chosen to indicate the fundamental right to water provision for the population. Population growth is accounted for in the two of the scenarios analysed below.

### 5.2.2 Agricultural Water Use

Most of the Zambian crop production is rain-fed, and the Kafue River basin is no exception. Maize, groundnuts, and other cereals, such as sorghum and millet, are the main non-irrigated crops. Maize is certainly the staple food crop for most Zambians: about 600,000 hectares are cropped with maize across the country, above all in the South, Center and East, while the North and North-West rely on cassava and millet (grown on about 360,000 ha). Rice is predominantly grown in the wet area of the West. Most of

these food crops are grown by smallholders. Out of an estimated 600,000 farmers in the country, 76% are small-scale subsistence farmers and less than 1% are large-scale commercial farmers (Table 5.2). Commercial farmers play an important role in maize production inter alia due to the application, of supplementary irrigation to ensure better yields in dry years. Typical commercial crops are also coffee, horticulture and floriculture, mainly destined to export markets. Soy beans and sugar are also grown by large scale farmers and constitute a considerable part of the irrigation requirements in the southern part of the Kafue River basin, with two large sugar estates in the region of Mazabuka and Kafue, and a significant soy bean operation not far from Lusaka.

Table 5. 2 Zambian farming systems

	Small Scale	Emergent	Medium Scale	Large Scale
Number of Farmers	459,000	119,200	25,320	740
Total Area (ha/farm)	0.5 – 9.0	10 – 20	20 – 60	> 60
Crops Grown	Food Crops	Food/Cash Crops Commercial/Subsistence		Cash Crops
Type of Production	Subsistence			Commercial

Source: Ministry of Agriculture and Cooperatives (2005) and FAO (2005)

Of Zambia's total land area of 752,614 km<sup>2</sup>, 23.09 million hectares are classified as agricultural land of which 58% have medium to high potential for agricultural production and are suitable for the production of a broad range of crops and livestock., with rainfall ranging between 750 mm to 1,400 mm annually It is estimated that only 14% of total agricultural land, or 3.23 million hectares, is currently being utilized (GoZ, 2004). Currently 155,912 hectares, out of the available 2.75 million hectares of irrigable land<sup>2</sup>, is effectively irrigated, excluding about 100,000 ha of low laying dambos<sup>3</sup> used by traditional farmers to grow winter vegetables and maize (FAO, 2005).

On the south-eastern side of the Kafue Flats, near the town of Mazabuka, there are several sugarcane farms, each of which cultivates large areas of land to produce the majority of Zambia's sugar for local use and export. The farmers rely heavily on water from the Kafue River for irrigation, while nutrient-rich effluent is discharged back into the river, contributing to the proliferation of many aquatic plants, including the problematic water hyacinth.

Table 5.3 and Figure 5.3 illustrate the cultivated areas in the Kafue region for the main crops and the geographical distribution of the main cash crops (sugarcane, soya and cotton) and staple crops (maize, sorghum and groundnuts). Table 5.4 illustrates the surface and groundwater irrigated areas in the Kafue River basin.

<sup>2</sup> This is defined as the physical irrigation potential, i.e. the area which can potentially be irrigated based on the physical resources 'soil' and 'water', combined with the irrigation water requirements as determined by the cropping patterns and climate (FAO; 2005).

<sup>3</sup> A dambo can be defined as a "wide and low lying gently sloping treeless grass covered depression, which is seasonally water-logged by seepage from surrounding high ground assisted by rainfall and has water tables for most part of the year in the upper 50-100 cm of the soil profile from which they drain into streams" (FAO, 1998). The area covered by dambos in Zambia amounts to about 3.6 million hectares or 4.8 percent of the national area (FAO, 2005).

Table 5. 3 Cultivated areas in the Kafue River basin (ha)

Crop	Province				Total
	Copperbelt	Central	Southern	Lusaka	
Maize	74,498	190,048	232,495	32,726	529,767
Sorghum	1,425	3,674	15,797	138	21,034
Millet	486	5,079	3,837	29	9,431
Rice	38	212	12	89	351
Soya	374	7,718	662	241	8,995
Groundnuts	11,117	33,743	19,205	2,636	66,701
Beans	3,562	9,006	377	1,088	14,033
Sweet potatoes	8,676	16,443	13,647	1,749	40,515
Potato	35	92	151	25	303
Cowpeas	193	1,048	9,238	225	10,704
Paprika	17	102	13		132
Sunflower	40	5,904	11,373	130	17,447
Cotton	10	17,108	12,116	502	29,736
Sugarcane			33,068		33,068
<i>Total</i>	<i>100,471</i>	<i>290,177</i>	<i>351,991</i>	<i>39,578</i>	<i>782,217</i>

*Source: Elaborated from MACO Crop Harvest Survey (2009/10), World Bank (2008)  
and farm visits*

Figure 5. 3 Geographical distribution of staple and cash crops (area harvested, ha)

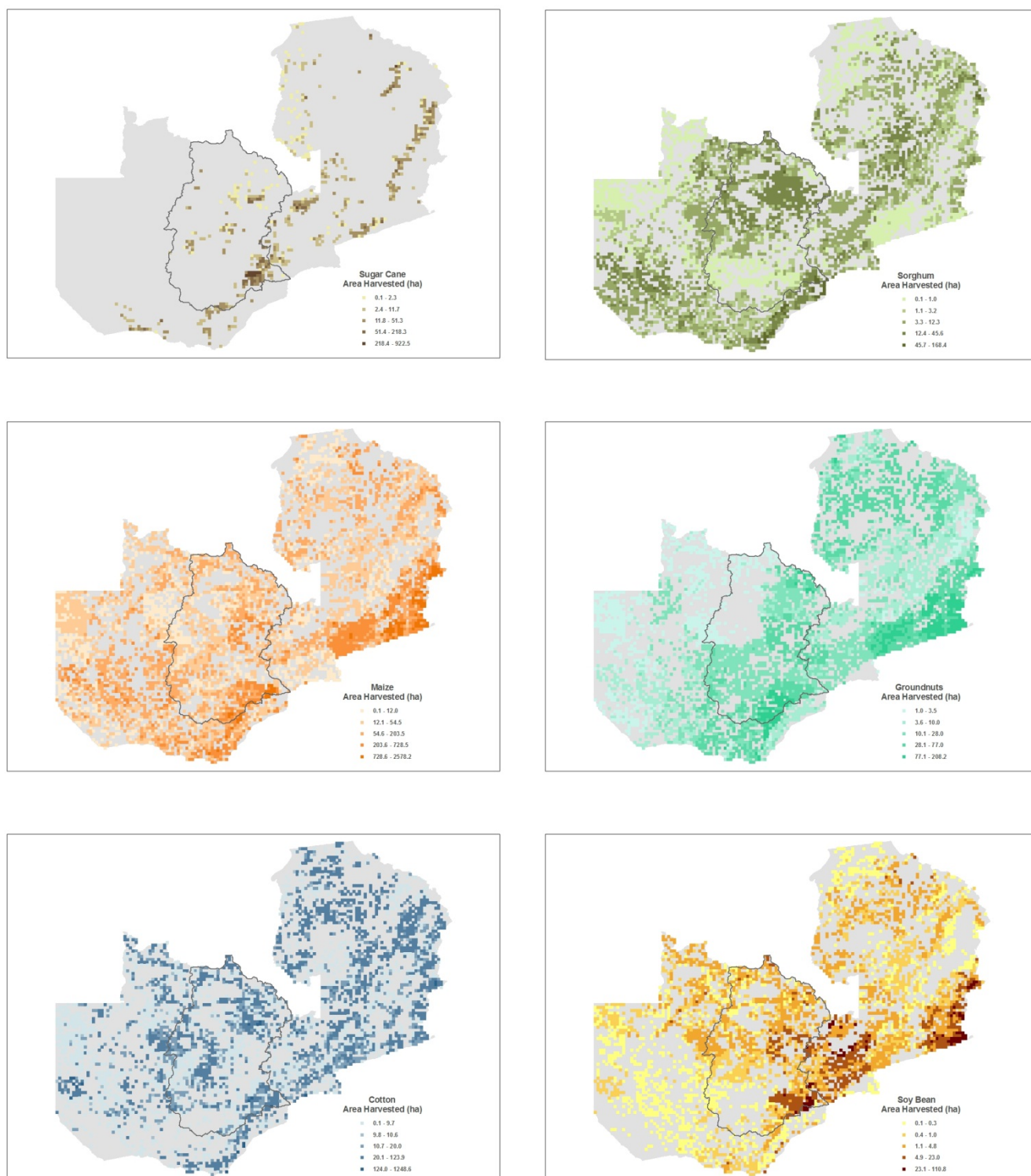


Table 5. 4 Irrigated areas in the Kafue River basin (ha)

Zone	Surface Water Irrigated Area						Groundwater Irrigated Area			Total Irrigated Area
	Bananas	Coffee	Sugarcane	Sugarcane ratoon	Cereals and Soya	Tobacco	Coffee	Horticulture	Cereals and Soya	
Upper Kafue	42				608					650
Mpongwe									1,938	1,938
Kampemba					1,015					1,015
Munkumpu					2,512					2,512
Kabwe							127		338	465
Chisamba							73	85	2,099	2,257
Choma						502				502
Mazabuka	82	596	25,487	1,153	1,275					28,593
Kafue Sugar			4,573	1,855						6,428
Lusaka West							80	667	3,585	4,332
Chiowa					960					960
<b>Total</b>	<b>124</b>	<b>596</b>	<b>30,060</b>	<b>3,008</b>	<b>6,370</b>	<b>502</b>	<b>280</b>	<b>752</b>	<b>7,960</b>	<b>49,652</b>

Source: World Bank, 2008

Water is one of the main inputs to crop production, together with soil, seeds, fertilizers, pesticides, labour, and machinery. Any discussion of demand for these inputs must be based on some knowledge of input-output relationships. However, these relationships are often not precisely known, especially for crop production involving several inputs. Therefore, water-yield relationships are rarely available for all crops under the conditions of the region where the demands are to be estimated.

To some extent it would be possible to derive yield functions for the main crops grown in Zambia from literature: studies have been conducted either in Zambia or in other Southern African countries where the cropping conditions are similar (Lecler and Jumman, 2009; Dehghanisanij, 2008; Igabadun, 2007; Lange and Kassam, 2006; Gomes and Carr, 2003; Nielsen, 2001; Andr  n, 1993; Russo, 1987). Nonetheless, in order to achieve uniformity of simulated soil, temperature, and water availability conditions, data generated with AquaCrop<sup>1</sup> (FAO, 2011; Doorenbos and Kassam, 1979) to simulate the yield response to water of most of the major field and vegetable crops.

### 5.2.3 Non-consumptive water uses: hydropower, environment, and fishery

Zambia's endowment of water resources and the country's topography provide significant hydropower resource potential, estimated at 6,000 MW. The installed hydropower capacity represents only 27 percent of the country's hydropower potential and accounts for 99 percent of all electricity production in Zambia (ERB, 2008). Most of the energy produced is consumed by the mining sector (Table 5.5), followed by the residential sector. The Zambian Electricity Supply Corporation (ZESCO) reports a deficit of electricity production, though Zambia figures as a net energy exporter since, over time, it continued exporting high voltage electricity mainly to Zimbabwe and South Africa and low voltage electricity to border towns. On the domestic side, ZESCO faces the challenge of increased energy demand, driven by population pressure and income growth in the urban centres, and the need to increase energy supply coverage also in rural areas. Currently, in fact only 18.8 percent of the population have access to electricity (World dataBank, 2012), 40 percent in the urban areas and only 2 percent in the rural areas. Therefore any increase in coverage would mean more pressure on ZESCO to meet the rise in demand due to income growth and the current population growth of 2.6 percent per year (GoZ, 2011c).

Table 5. 5 Energy use by sector

Economic Sector	Average Number of Active Consumer	Units Consumed (GWh)	% Contribution Total
Mining	74	4,005.43	54.5%
Residential	277,043	2,021.85	27.5%
Manufacturing	1,411	482.77	6.6%
Finance and Property	4,648	259.38	3.5%
Agriculture	1,294	166.42	2.3%
Trade	9,249	159.38	2.2%
Energy and Water	264	72.18	1%

<sup>1</sup> AquaCrop is a Windows-based software programme designed to simulate biomass and yield responses of field crops to various degrees of water availability. The output of the program consists of key variables for crop development and production, for soil water balance, for soil water content, and for net irrigation requirement (particularly: evapotranspiration, crop transpiration, soil evaporation, and daily irrigation requirement)

Transport	273	18.02	0.2%
Construction	89	6.53	0.09%
Other	5,693	165.13	2.2%
<b>Total</b>	<b>300,038</b>	<b>7,357.096</b>	<b>100 %</b>

Source: ERB, 2008

Two major storage structures have been constructed on the Kafue River: the Kafue Gorge Dam and Itezhi-tezhi Dam (Table 5.6). The Kafue Gorge hydroelectric power plant is the country's largest power station, providing more than 50 per cent of Zambia's electricity supply. To keep pace with demand, the Kafue Gorge power plant has needed more water than was available from the Kafue Gorge Dam. Consequently, a second storage reservoir (the Itezhi-tezhi Dam) was constructed at the western end of the Kafue Flats with a mere regulatory purpose. This allows for the release of sufficient water to maintain maximum power generation of the Kafue Gorge power plant throughout the year. Currently, the government of Zambia is finalising the construction of a hydropower station at Itezhi-tezhi that will have an installed capacity of 120MW. At the same time, the government is exploring the construction of a second large hydropower dam, the Kafue Gorge Lower project, and the implementation of mini-hydropower stations in areas of Northern, Luapula, Copperbelt and North-Western provinces where natural water falls are available.

Table 5. 6 Main dams of the Kafue River

	<b>Itezhi-tezhi</b>	<b>Kafue Gorge Dam</b>
Maximum Active Storage Volume (MCM)	6,013	1,178
Surface area (km <sup>2</sup> )	390	1,175
Catchment Area (km <sup>2</sup> )	106,579	162,564
Altitude (m ASL)	1031.5	977
Hydropower generation capacity MW	120	990

The construction of the Itezhi-tezhi reservoir had both positive and negative impacts on the economy and environment of the Kafue Flats (Blaser, 2013). On the positive side there have been benefits for the urban population who received additional electricity supply as well as for commercial farmers for whom river regulation ensures a steady supply of water for irrigation. However, negative impacts result from the increase of permanently flooded areas that caused a reduction of the available grazing land, a loss of potentially cultivable land, a reduction in fishery and a decline in the population of Kafue Lechwe (Schelle and Pittock, 2005). In order to minimise the negative impacts on the environment and preserve some of the natural flooding variation of the Kafue Flats, ZESCO's Water Right for Itezhi-tezhi is linked to a condition of releasing a "freshet" (environmental flow) of 300 m<sup>3</sup>/s for four weeks during the end of the wet season. Furthermore, the Water Right stipulates a minimum flow of 25 m<sup>3</sup>/s downstream of the Itezhi-tezhi reservoir.

The main fishing areas in the Kafue River basin are the Upper Kafue, the Itezhi-tezhi lake and the Kafue Flats that account for about 11,000 tons of yearly fish catch, equal to about 13 percent of the overall yearly fish catch in Zambia. The most active fishery in the Kafue basin is the Kafue Flats fishery. 63



percent of the regional catch originates from the Flats, particularly from the seven major lagoons<sup>2</sup> that provide favourable fish breeding areas. Most of the fishing in the Kafue basin is carried out in a regime of open access to the resource: any person is allowed to obtain a fishing licence and harvest fish in any location of the river, which leads to overcrowding and depletion of fish stock. This situation is aggravated by the poor monitoring of the licencing system and the seasonal migration of fishermen from different regions within the country. In addition, fisheries in the upper stretch of the Kafue are at risk due to the contamination of water caused by the discharges from the mining tailing ponds. In the lower Kafue there is less evidence of pollution, but it exists as well – mainly caused by the industry Nitrogen Chemicals of Zambia, located in Kafue town. At the same time the flooding pattern, determined by the releases from Itezhi-tezhi, increases the costs and efforts to catch fish: larger areas are permanently flooded, and grass and invasive plants grow on the water surface making the low water areas, where fish tends to live, difficult to reach.

## 5.3 Discussion of results

### 5.3.1 Scenario definition

The current supply of water resources is evaluated against the current and future needs of the various stakeholders, based on a set of development scenarios. The chosen development scenarios focus above all on the stakeholders with the largest demand for water, namely hydropower and irrigated agriculture, which are also the focus for the major investments and future developments in Zambia (GoZ, 2011a; World Bank, 2009). The environmental uses of water and the water needs for urban and industrial and mining areas are included as constraints.

Table 5.7 provides an overview of the scenarios, including an indication of the dimensions analysed (urban and rural water demand, mining and industrial water use, environment, hydropower and, irrigation) and the specific characteristics of the scenarios with reference to each dimension (e.g. current population or population growth; presence or absence of the environmental flows; operation of the mining companies or mine closure; etc.). Each of the scenarios is evaluated for two alternative hydrological assumptions (Figure 5.4 and 5.5): water flows in the Kafue basin in an average year and a dry year. Water inflows to the Kafue River comprise the various tributaries (permanent and seasonal) in the Copperbelt region, the Luswishi River, the Lunga and Lufupa Rivers, the various tributaries in the Kafue Flats, and the dewatered quantities from the mining operations. Average and dry year values of water inflows refer to observed discharges for a year with average and minimum cumulated discharge over the complete hydrological year. This implies that a dry year does not necessarily report inflows lower than an average year in each of the months. This approach was chosen to avoid the assumption of an unrealistically dry scenario instead assuming a historically recorded dry year.

Trade-offs with the other stakeholders' demand for water are shown in the simulation results to facilitate a comprehensive view on the overall costs and benefits of the scenarios, and provide guidance to policy makers. In all scenarios, environmental water requirements and water demands for domestic and industrial use are considered as constraints to the overall optimisation procedure. In other words,

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<sup>2</sup> Lukwato, Namwala, Kabulungwe, Chunga, Luwato, Chanyanya and Chansi

the scenario analysis is carried out with the primary objective of determining and maximizing economic benefits while meeting water supply, social demands (in the sense of people's most immediate water needs), and environmental sustainability requirements. The scenarios simulate different degrees of development that could occur in Zambia in ten years from the moment of writing and the simulation results are carried out over a three year period where homogeneous hydrological conditions are considered.

Figure 5. 4 Water flows in the basin, average hydrological scenario

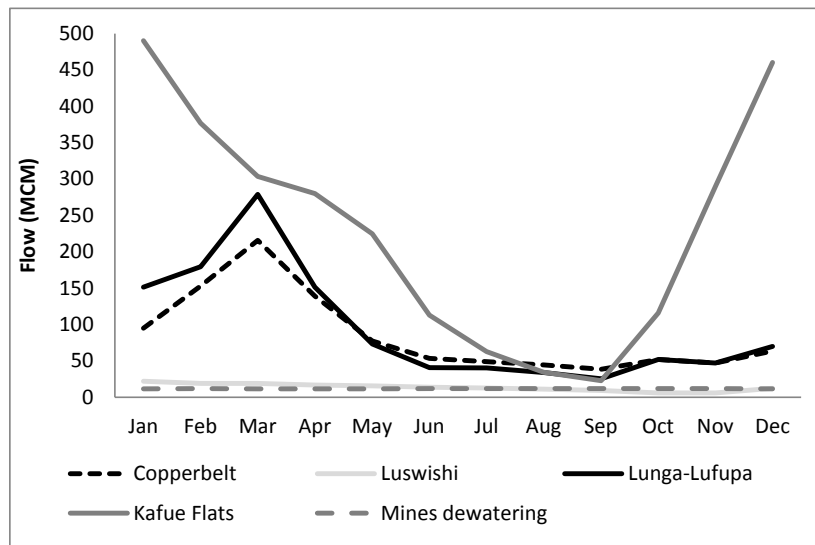


Figure 5. 5 Water flows in the basin, dry hydrological scenario

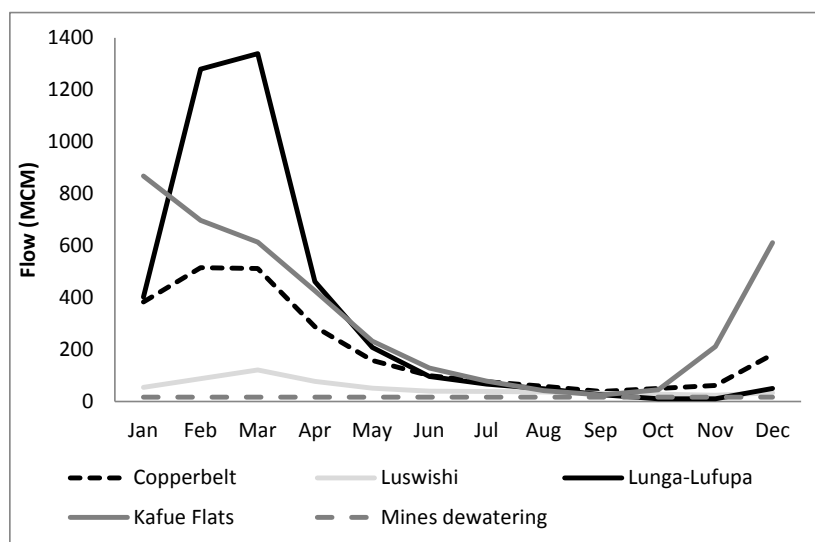


Table 5. 7 Summary of development scenarios

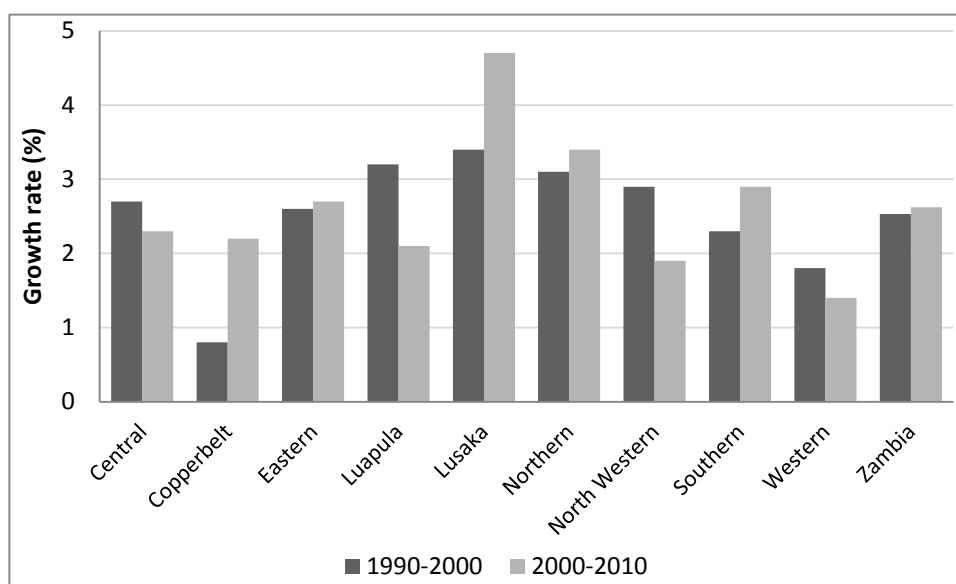
Scenarios		Water Demands												
		Urban and rural de- mand		Environmental flows		Mining			Hydropower			Irrigation		
		Current situation	Popula- tion growth	Yes	No	Current situation	Closure of mines		Current situation	Kafue Lower added	Gorge dam	Minimum Irrigation	Current situation	Development of new projects
1Base case	1.1 Baseline													
	1.2 Population growth													
2 Hydropower production expansion	2.1 Hydropower develop- ment with agriculture sta- tus quo													
	2.2 Hydropower develop- ment (high priority)													
	2.3 Hydropower develop- ment w/o E-Flow													
3 Irrigation Expansion	3.1 Agricultural develop- ment													
	3.2 Agricultural develop- ment w/o E-Flow													
	3.3 Irrigation and hydro- power development													
4 Mines De- commission- ing	4.1 Mines closure													
	4.2 Mines closure and ex- pansion of irrigation													

### 5.3.2 Baseline and population growth

The baseline scenario reflects the status quo in the Kafue River basin: the current urban and industrial water demand is satisfied, the operation of the mining activities is ensured, hydropower generation is taking place both at Itzhi-tezhi and Kafue Gorge, current irrigation demand is satisfied, and the health of the ecosystem is guaranteed by the implementation of environmental flows (in the month of March releases from the Itzhi-tezhi reservoir are bound to a daily minimum flow of  $300 \text{ m}^3 \text{ s}^{-1}$ ).

The population growth scenario differs from the baseline only by considering population growth over the scenario time horizon of ten years. 61 percent of the Zambian population today reside in rural areas and 39 percent in urban areas. At provincial level, Lusaka has the largest population (about 2.2 million), followed by the Copperbelt (1.96 million), Northern (1.76 million), Eastern (1.7 million) and Southern (1.6 million). Zambia's population grew at an average annual rate of 2.6 percent in the 2000 – 2010 inter-censal period compared to a growth of 2.5 percent in the 1990 – 2000 period (Figure 5.6). The fastest growing provinces are Lusaka, Northern, and Southern, while the Copperbelt and Lusaka provinces showed the largest increase in the growth rate between the two inter-censal periods. Considering only the Kafue River basin, the annual growth rate is about 3 percent, larger than the national average.

Figure 5. 6 Average annual population growth rate by Province



Source: Central Statistical Office, 2011

Table 5.8 depicts the main constraints used for the formulation of the baseline and population growth scenarios and Table 5.9 summarizes the most important results. The details of the mathematical formulation for all constraints, including the explanation of the formulas, variables, and constants are reported in Part I of this paper.

Table 5. 8 Baseline and population growth scenario: assumptions and inputs

	1.1 Baseline	1.2 Population growth
Urban and rural water demand	$D_{min}^U \leq D_n^t \leq D_{max}^U$ $D_{min}^U = 0.9 * D_{current}^U$ $D_{max}^U = 1.2 * D_{current}^U$ $D_{current}^U = 230.33 MCM$	$D_{min}^U \leq D_n^t \leq D_{max}^U$ $D_{min}^U = 0.9 * D_g^U$ $D_{max}^U = 1.2 * D_g^U$ $D_g^U = 230.33 * (1 + g)^T MCM$ $g = 3\% \text{ annual}$ $T = 10 \text{ years}$
Industrial water demand	$D_{min}^I \leq D_n^t \leq D_{max}^I$ $D_{min}^I = 0.9 * D_{current}^I$ $D_{max}^I = 1.5 * D_{current}^I$ $D_{current}^I = 84.89 MCM$	
Mining water demand	$D_{min}^M \leq D_n^t \leq D_{max}^M$ $D_{min}^M = 0.9 * D_{current}^M$ $D_{max}^M = 1.5 * D_{current}^M$ $D_{current}^M = 30.24 MCM$	
Environmental flow	$R_{RES_1, n_2}^{t=March} \geq \overline{R}^{t=March}$ $\overline{R}^{t=March} = 778 MCM$	
Hydropower	<p>Head-storage relation:</p> $h_n^t - h_n^0 = \gamma_n S_n^{\delta_n} \quad \forall n \in RES$ $\gamma_{ITT} = 0.00822, \gamma_{KG} = 0.51342$ $\delta_{ITT} = 0.92698, \delta_{KG} = 0.30978$ <p>Hydrological mass balance for the reservoirs:</p> $S_n^t - S_n^{t-1} = \sum_{(n_1, n) \in N} Q_{n, n_1}^t - \sum_{(n_1, n) \in N} Q_{l_{n1, n}}^t + Q_{ret_{n1, n}}^t - \sum_{(n, n_2) \in N} R_{n, n_2}^t - D_n^t - R_{c_n}^t - Spill_n^t \quad \forall n \in RES$ <p>Minimum and maximum storage levels for the reservoirs:</p> $S_{min}^n \leq S_t^n \leq S_{max}^n$ $S_{min}^{ITT} = 2894 \text{ MCM}, S_{min}^{KG} = 745 \text{ MCM}$ $S_{max}^{ITT} = 5624 \text{ MCM}, S_{max}^{KG} = 2845 \text{ MCM}$ <p>Minimum and maximum release flows for the reservoirs:</p> $R_{min}^n \leq R_t^n \leq R_{max}^n$ $R_{min}^{ITT} = 65 \text{ MCM}, R_{min}^{KG} = 90 \text{ MCM}$ $R_{max}^{ITT} = 808 \text{ MCM}, R_{max}^{KG} = 1430 \text{ MCM}$	
Irrigation	$x_{i_{min}} \leq x_i \leq x_{i_{max}}$ $\sum_i x_{i_{min}} = 1 * X_i$ $\sum_i x_{i_{max}} = 1.2 * X_i$ $X_i = 47,400 ha$	

Table 5. 9 Baseline scenario – Main average yearly results

		1.1 Baseline	1.2 Population growth
Average water supplied to urban, rural, industrial, mining use (MCM/year)	Dry	336.37	414.66
	Average	342.06	424.77
Average annual energy generation (TWh/year)	Dry	2.86 (ITT) 6.20 (KG)	2.297 (ITT) 5.75 (KG)
	Average	9.84 (ITT) 14.17 (KG)	9.68 (ITT) 13.82 (KG)
Average water use for agriculture (MCM/year)	Dry	341.46 (water applied) 444.22 (water abstracted, incl. system losses)	341.46 (water applied) 444.22 (water abstracted, incl. system losses)
	Average	376.79 (water applied) 490.75 (water abstracted, incl. system losses)	376.79 (water applied) 490.75 (water abstracted, incl. system losses)
Net benefits (million ZMK/year)	Dry	3,676,643 (Hydropower) 148,678 (Agriculture)	3,227,337 (Hydropower) 148,678 (Agriculture)
	Average	9,745,771 (Hydropower) 153,358 (Agriculture)	9,533,997 (Hydropower) 153,358 (Agriculture)

The optimization results of the baseline scenario (Table 5.9, scenario 1.1) highlight that the current water demands for mining, industrial, and agricultural activities together with the need to maintain a healthy ecosystem, hydropower production, and urban and rural water supply can be fully satisfied in the Kafue River basin during an average hydrological year. More than minimum water requirements can be allocated to industrial and mining activities (also including system losses) across the river basin. The Copperbelt region stands out, because in the dry months, particularly October and November, only the minimum urban water demands can be satisfied. In a dry hydrological scenario minimum requirements can always be satisfied, but we recognize a lower water supply for the mining and industrial sectors across the basin, above all during the period ranging from September to November.

During an average hydrological year all the currently irrigated land can be fully irrigated, i.e. each crop's average yearly water requirement is entirely satisfied. No additional sugarcane capacity is developed upstream, sugarcane yields in the Mazabuka area are close to the maximum potential, and the crop-water demand that is satisfied is about 9,300 m<sup>3</sup>/ha/year. Supplemental irrigation of maize and soya takes place between June and July, while sugarcane is irrigated throughout the dry season with particularly high amounts of water applied in the driest month of October. Total hydropower production is around 24 TWh/year, with the Kafue Gorge power station providing for about 60 percent of the total generation. During a dry year the total hydropower generated falls to 10 TWh/year, about 65 percent generated at Kafue Gorge. This indicates that the decreased water availability particularly affects the lower stretch of the Kafue River, after the Itezhi-tezhi reservoir. At the same time, agricultural production declines: water is applied throughout the traditionally irrigated area, but crop-water requirements are not fully satisfied. This is reflected in an overall lower amount of water abstracted for sugarcane irrigation, and in a corresponding decrease in production. In detail, a possible decision during a dry year would be the reduction of the irrigation water supply for sugarcane from about 9,300 m<sup>3</sup>/ha/year to only 8,440 m<sup>3</sup>/ha/year, bearing a reduction in yield of about 20 percent.

In scenario 1.2 we hypothesize that a population growth rate of 3 percent (equal to the past ten year average population growth rate) is consistently maintained over time for the coming ten years. The population growth scenario gives the highest importance to satisfying urban water demands: the lower and upper limits we set for urban, rural, mining and industrial water supply in such scenario are 381MCM/year and 508 MCM/year. In the average hydrologic scenario such demands can be satisfied with the supply of 425 MCM/year while during a dry scenario only 415 MCM/year can be supplied. It is interesting to notice that during a dry year, similarly to what we observed in the baseline scenario, industrial supply in the lower Kafue can be more than satisfied, while the northern stretch of the river is under pressure, particularly during the driest months. Similarly, increased urban water demand can be just satisfied both in an average and dry scenario, except during the rainy months of February, March and April, when more than the minimum requirements can be supplied. Results for agricultural water consumption are similar to the findings of the baseline scenario, while hydropower production is lower: in the dry hydrological scenario, hydropower production decreases by about 1.1 TWh/year while in the average scenario the reduction is about 0.51 TWh/year.

Our results indicate that in a dry year considerable benefits could arise from increased efficiency in the water supply system, since additional quantities of water could be allocated to other productive sectors of the economy. As mentioned before, system losses in the average account for about 10 percent of the overall water abstracted for domestic and industrial consumption. Nonetheless, a number of Water Supply Councils record larger system losses that can account for up to 50 percent of the overall water withdrawn (NWASCO database). At the same time, only about 55 percent of the water supplied to end users, including commercial users, is paid for. The Nkana and Southern Water Supply Councils, in particular, receive payments for less than 40 percent of the water supplied. A reduction of losses in the delivery network and an increase of the currently low tariff collection rate could significantly contribute to satisfying future water demands in the domestic and industrial sector while minimizing the negative effect on hydropower production. This is made even more urgent considering the policy objective declared by the Government (GoZ, 2011a) to expand water supply to the rural areas: population growth on one side, and extended supply to the rural areas on the other side call for efficiency gains and improved tariff collection rates to ensure the sustainable management of the domestic water supply service.

### 5.3.3 Increased hydropower production

The Kafue River basin is the target of future hydropower developments that are expected to increase the generating capacity of the country in order to ensure full electricity supply to Zambia and allow exports within the Southern African Power Pool. Besides the development of the Itezhi-tezhi power station (almost concluded at the time of the study), another major development concerns the Kafue Gorge Lower dam. The rationale for the development of additional storage capacity at Kafue Gorge Lower dam lies also in the need to capture the “freshet” release that cannot be stored at Kafue Gorge Upper dam. Three sites have been investigated for the location of the project. The sites lie about 60 to 65 km upstream from the confluence of the Kafue River and the Zambezi River and about 3 to 8 km downstream from the existing release of the Kafue Gorge Upper hydropower project. Based on engineering and economic considerations, it was recommended to construct a reservoir with the characteristics outlined in Table 5.10, with a generating capacity of up to 750MW.

Table 5. 10 Characteristics of the proposed Kafue Gorge Lower dam

Elevation (m)	Total Volume (MCM)	Area (km2)
520	0.02	0
525	0.07	0.01
530	0.17	0.03
535	0.36	0.05
540	0.72	0.09
545	1.25	0.12
550	1.94	0.16
555	2.86	0.21
560	4.08	0.29
565	5.75	0.38
570	7.93	0.49
575	10.66	0.61
580	14.14	0.79
585	15.89	0.9

Source: ZESCO, 2006 (field measurements)

Table 5.11 illustrates the key assumptions and constraints adopted in the scenario for the expansion of hydropower generation. Scenario 2.1 builds on the constraints of scenario 1.1, but includes additional hydrological constraints to simulate the existence of the new Kafue Gorge Lower dam (for the hydrological constraints for the Itezhi-tezhi and Kafue Gorge dams see Table 8). Scenario 2.2 relaxes the irrigation constraint, allowing for the decrease in irrigated area with respect to the baseline situation. Scenario 2.3, similarly to scenario 1.2, excludes the freshet releases from the Itezhi-tezhi reservoir.

Table 5. 11 Hydropower development scenario: assumptions and inputs

	2.1 Hydropower development with agriculture status quo	2.2 Hydropower development (high priority)	2.3 Hydropower development w/o E-Flow
Urban and rural water demand	$D_{min}^U \leq D_n^t \leq D_{max}^U$ $D_{min}^U = 0.9 * D_{current}^U$ $D_{max}^U = 1.2 * D_{current}^U$ $D_{current}^U = 230.33 MCM$		
Industrial water demand	$D_{min}^I \leq D_n^t \leq D_{max}^I$ $D_{min}^I = 0.9 * D_{current}^I$ $D_{max}^I = 1.5 * D_{current}^I$ $D_{current}^I = 84.89 MCM$		
Mining water demand	$D_{min}^M \leq D_n^t \leq D_{max}^M$ $D_{min}^M = 0.9 * D_{current}^M$ $D_{max}^M = 1.5 * D_{current}^M$ $D_{current}^M = 30.24 MCM$		
Environmental flow	$\frac{R_{ITT1,n2}^{t=March}}{R^{t=March}} \geq \frac{R^{t=March}}{R^{t=March}}$ $R^{t=March} = 778 MCM$		$R_{min}^{ITT} \leq R_{ITT1,n2}^{t=March}$ $\leq R_{max}^{ITT}$ $R_{min}^{ITT} = 65 MCM,$ $R_{min}^{KG} = 90 MCM$



Hydropower	<p>Itezhi-tezhi and Kafue Gorge constraints as in Scenario 1.  Hydrological mass balance for Kafue Gorge Lower identical to other reservoirs.  Kafue Gorge Lower head-storage relation:  <math display="block">h_n^t - h_n^0 = \gamma_n S_n^{t \delta_n} \quad n = KGL</math> <math display="block">\gamma_{KGL} = 21.22</math> <math display="block">\delta_{KGL} = 0.456</math> Minimum and maximum storage levels for Kafue Gorge Lower:  <math display="block">S_{min}^n \leq S_t^n \leq S_{max}^n \quad n = KGL</math> <math display="block">S_{min}^{ITT} = 0.07 \text{ MCM}</math> <math display="block">S_{max}^{ITT} = 15.89 \text{ MCM}</math> Minimum and maximum release flows for Kafue Gorge Lower:  <math display="block">R_{min}^n \leq R_t^n \leq R_{max}^n \quad n = KGL</math> <math display="block">R_{min}^{ITT} = 0 \text{ MCM}</math> <math display="block">R_{max}^{ITT} = 1498.18 \text{ MCM}</math> </p>		
Irrigation	$x_{i_{min}} \leq x_i \leq x_{i_{max}}$ $\sum_i x_{i_{min}} = 1 * X_i$ $\sum_i x_{i_{max}} = 1.2 * X_i$ $X_i = 47,400ha$	$x_{i_{min}} \leq x_i \leq x_{i_{max}}$ $\sum_i x_{i_{min}} = 0 * X_i$ $\sum_i x_{i_{max}} = 1 * X_i$ $X_i = 47,400ha$	$x_{i_{min}} \leq x_i \leq x_{i_{max}}$ $\sum_i x_{i_{min}} = 1 * X_i$ $\sum_i x_{i_{max}} = 1.2 * X_i$ $X_i = 47,400ha$

Table 5.12 summarizes the main results of the scenario.

Table 5. 12 Hydropower development scenario – Main average yearly results

		2.1 Hydropower development with agriculture status quo	2.2 Hydropower development (high priority)	2.3 Hydropower development w/o E-Flow
Average water supplied to urban, rural, industrial, mining use (MCM/year)	Dry	331.97	337.78	332.18
	Average	341.29	341.29	341.29
Average annual energy generation (TWh/year)	Dry	2.84 (ITT) 5.85 (KG) 3.26 (KGL)	3.26 (ITT) 6.76 (KG) 3.76 (KGL)	3.23 (ITT) 6.70 (KG) 3.40 (KGL)
	Average	7.92(ITT) 12.61 (KG) 7.01 (KGL)	7.92(ITT) 12.61 (KG) 7.01 (KGL)	7.92(ITT) 12.61 (KG) 7.01 (KGL)
Average water use for agriculture (MCM/year)	Dry	337.023 (438.44)	37.59 (48.85)	337.023 (438.44)
	Average	376.79 (water applied) 490.75 (water abstracted, incl. system losses)	376.79 (water applied) 490.75 (water abstracted, incl. system losses)	376.79 (water applied) 490.75 (water abstracted, incl. system losses)
Net benefits (million ZMK/year)	Dry	5,191,380 (Hydropower) 147,665 (Agriculture)	5,628,459(Hydropower) 6,095 (Agriculture)	5,424,651(Hydropower) 147,665 (Agriculture)
	Average	11,179,310(Hydropower) 153,358 (Agriculture)	11,179,310(Hydropower) 153,358 (Agriculture)	11,179,310(Hydropower) 153,358 (Agriculture)

If hydropower growth occurs while the current level of agricultural development is maintained, basic urban water consumption is ensured both in a dry and average hydrological year. During a dry hydrological year, industrial water withdrawals are almost identical to scenario 1.1. However, the additional water requirements necessary to fill the Kafue Gorge Lower dam put increasing pressure on domestic water use and on the mining sector where water allocation slightly decreases compared to the baseline scenario. Only the minimum water demands for the mining sector and the domestic sector in the Copperbelt province can be satisfied during the driest months (from May until November). In an average hydrological scenario all water demands can be satisfied to levels similar to those shown in Scenario 1.1.

After the construction of the Kafue Gorge Lower hydropower project and under average hydrological conditions, the current agricultural water demand is satisfied, similarly to scenario 1.1. Hydropower production at Itezhi-tezhi is 20% lower than in the baseline scenario and Kafue Gorge produces 11% less power. This can be explained by the need to further supply water to exploit the generating power of the Kafue Gorge Lower station. The latter, in fact, produces 7 TWh/year, contributing about 24% of the Kafue system hydropower production. In the occurrence of a dry year, the water stress situation is slightly more acute than in scenario 1.1: supplemental irrigation of soya is maintained, supplemental irrigation of maize is almost fully maintained, satisfying 87% of the crop-water requirement; the full irrigation of sugarcane cannot be sustained, and the yearly irrigation water supply decreases to 8230 m<sup>3</sup>/ha/year. Hydropower production for Itezhi-tezhi is similar to the baseline scenario with a generation of about 2.85 TWh/year. Kafue Gorge, instead, produces about 6% less energy than in the baseline scenario. This loss is more than compensated by the additional energy generated at Kafue Gorge Lower: with a production of 3.26 TWh/year, it contributes to 27% of the Kafue system hydropower production.

Scenario 2.2 gives a higher priority to hydropower development by allowing a decrease of agricultural production below the current level. This is to be considered a “theoretical” scenario, to illustrate the hydropower gains related to an extreme reduction of irrigated agriculture in dry years: the results help to better grasp the trade-off between electricity generation and agricultural production. In a dry hydrological year, no irrigation of sugarcane takes place; groundnuts and maize are irrigated, although the crop-water requirements are not fully satisfied. The possibility to decrease irrigated agriculture would allow an increase in hydropower production of 13 percent. In particular, the optimisation results show that the benefits from sugarcane irrigation both in the Mazabuka and Kafue schemes can be traded off with the larger benefits derived from increased hydropower production. In fact, overall net benefits for scenario 2.2 are larger than those for scenario 2.1: 140 billion ZMK are lost from agricultural production, but 400 billion ZMK are gained from increased hydropower generation. On the other side, the obvious result of such an extreme scenario would be the need to disinvest from sugarcane production and provide alternative sources of income and livelihood for a substantial part of the population; it would also imply the loss of foreign direct investments, jobs and infrastructures and technology, the loss of significant foreign trade and currency, and the loss of Zambia’s competitive position in the world’s sugar market.

The effect of omitting the environmental flows or freshet that regulate the Itezhi-tezhi dam to satisfy environmental water requirements can be recognised only in the occurrence of the dry hydrological scenario. When no environmental flow is guaranteed (scenario 2.3), the optimal release pattern from Itezhi-tezhi suggests releases in the month of March lower than the 300m<sup>3</sup>/sec freshet currently secured by ZESCO. Overall, the different time distribution of the release allows for a larger hydropower production at Itezhi-tezhi, about 13 percent larger than in the case with status quo agricultural production. Hydropower pro-

duction at the upper and lower Kafue Gorge stations benefits from the releases optimised for hydropower generation too, with increases in energy production of 13 and 4 percent respectively.

#### 5.3.4 Agricultural growth

The Zambian government has ambitious plans regarding agricultural development throughout the country and, particularly, in the Kafue River basin (GoZ and FAO, 2012 and GoZ, 2011a). Considerable governmental and donor investments are being allocated to the rehabilitation, modernization and development of irrigation schemes in order to reduce the vulnerability to seasonal rainfall variability and to mitigate the impact of adverse climatic events such as droughts and floods. As mentioned before, theoretically more than 2.75 million hectares of agricultural land could be used for irrigation to increase food production. The main policy focus for the future irrigation development lies on promoting small scale farming to gradually introduce commercial irrigation practices, particularly through the promotion of outgrower schemes.

One of the main avenues chosen by the Government of Zambia to promote agricultural development is through the so-called farm blocks (Table 5.13), extensions of land designated to the expansion of both rain-fed and irrigated agriculture, including small- and large-scale irrigation. The government's expectations from the development of the farm blocks are not only increased food production to satisfy internal and Southern African Development Community's (SADC) demand, but also the possibility to boost export of high value crops and attract foreign investments for the development of agro-industries and food processing plants. The timeframe for the development of the farm blocks is long term and these projects strongly depend on the government's initial investment to open up agricultural lands by providing basic infrastructures including roads, water supply, and electricity.

Table 5. 13 Farm blocks development in Zambia

Name of Farm Block	District	Province	Area (ha)
Nansanga	Serenje	Central	155,000
Kalumwange	Kaoma	Western	100,000
Luena	Kawambwa	Luapula	100,000
Manshya	Kasama	Northern	147,750
Solwezi	Solwezi	North-western	100,000
Simango	Kazungula	Southern	100,000
Machiya	Mpongwe	Copperbelt	100,000
Mungu	Kafue	Lusaka	100,000
Mwase-Mphangwe	Chipata	Eastern	100,000
Total area			1,002,750

Source: GoZ (2004b)

To simulate irrigated agriculture over the next ten years, we consider a list of on-going and pipeline projects carried out in Zambia by the government or by cooperating partners (GoZ and FAO, 2012). Based on the Zambia-wide list of projects, we account exclusively for the areas lying within the Kafue River basin. Appendix 5.1 includes a detailed overview of the on-going and planned irrigation projects, both small- and large-scale, throughout the Kafue River basin. Some of the pipeline projects do not include exact information regarding the cropping pattern or the funding sources. Other projects, still at an early stage of

planning, do not provide accurate information regarding the total number of hectares to be developed (or rehabilitated) under irrigation. Only those projects reporting sufficient information in terms of total number of hectares and location of the agricultural development or rehabilitation are taken into consideration. When the cropping pattern is not available (20 percent of the cases) we adopt a typical cropping pattern for the region of interest based on FAO (2005) and GoZ (2005). Table 5.14 synthesises the expected future agricultural development on the Kafue River basin by 2022.

Table 5. 14 Desired irrigation development in the Kafue River basin (ha)

Crop	Region			
	Southern	Copperbelt	Central	All Regions
Maize	42,240	50,250	55,250	147,740
Wheat	15,920	50	50	16,020
Rice	10,000	20,000	10,000	40,000
Millet	15,550	-	-	15,550
Groundnuts	15,550	-	-	15,550
Soy beans	400	-	10,000	10,400
Sugar	30,320	5,000	-	35,320
Cotton	80	-	-	80
<i>Total</i>	<i>120,060</i>	<i>75,300</i>	<i>75,300</i>	<i>270,660</i>

Source: author's elaboration from GoZ and FAO, 2012

We analyse three sub-scenarios to shed light on different aspects of future agricultural development. Scenario 4.1 considers agricultural expansion, as described in Table 5.14, with all other conditions the same as in the baseline scenario. Scenario 4.2 differs from Scenario 4.1 only in the exclusion of environmental flows. The last scenario (4.3) comprehensively considers all growth aspects, namely population growth, agricultural growth and growth in hydropower generation. This scenario also includes environmental flows. The agricultural scenarios include the additional assumption that stakeholders assign a higher priority to the objective of increasing the area under irrigation. This is reflected on the weighting parameters of the net benefit maximization objective functions: instead of equal weights as in the other scenarios, the weight  $\phi$  that reflects the relative importance of the agricultural objective is set to 0.55 and the weight  $\omega$  that reflects the relative importance of the hydropower objective is set to 0.45. Table 5.15 depicts the main assumptions and constraints used for the formulation of the irrigation development scenarios and Table 5.16 summarizes the main results.

Table 5. 15 Irrigation expansion scenario: assumptions and inputs

	4.1 Agricultural Development	4.2 Agricultural development w/o E-Flow	4.3 Irrigation and hydropower development
Urban and rural water demand	$D_{min}^U \leq D_n^t \leq D_{max}^U$ $D_{min}^U = 0.9 * D_{current}^U$ $D_{max}^U = 1.2 * D_{current}^U$ $D_{current}^U = 230.33MCM$	$D_{min}^U \leq D_n^t \leq D_{max}^U$ $D_{min}^U = 0.9 * D_{current}^U$ $D_{max}^U = 1.2 * D_{current}^U$ $D_{current}^U = 230.33MCM$	$D_{min}^U \leq D_n^t \leq D_{max}^U$ $D_{min}^U = 0.9 * D_g^U$ $D_{max}^U = 1.2 * D_g^U$ $D_g^U$ $= 230.33 * (1 + g)^T MCM$ $g = 3\% \text{ annual}$

		T=10 years	
Industrial demand	water	$D_{min}^I \leq D_n^t \leq D_{max}^I$ $D_{min}^I = 0.9 * D_{current}^I$ $D_{max}^I = 1.5 * D_{current}^I$ $D_{current}^I = 84.89 MCM$	
Mining demand	water	$D_{min}^M \leq D_n^t \leq D_{max}^M$ $D_{min}^M = 0.9 * D_{current}^M$ $D_{max}^M = 1.5 * D_{current}^M$ $D_{current}^M = 30.24 MCM$	
Environmental flow		$\frac{R_{RES1,n2}^{t=March}}{R^{t=March}} \geq \overline{R^{t=March}}$ $\frac{R_{RES1,n2}^{t=March}}{R^{t=March}} = 778 MCM$	$R_{min}^{ITT} \leq R_{ITT1,n2}^{t=March} \leq R_{max}^{ITT}$ $R_{min}^{ITT} = 65 MCM, R_{min}^{KG} = 90 MCM$
Hydropower		Head-storage relation, Hydrological mass balance for the reservoirs, Minimum and maximum storage levels for the reservoirs, Minimum and maximum release flows for the reservoirs as in Scenario 1.	Itezhi-tezhi and Kafue Gorge constraints as in Scenario 1. Hydrological mass balance for Kafue Gorge Lower identical to other reservoirs. Kafue-Gorge Lower constraints as in Scenario 2.
Irrigation		$x_{i,min} \leq x_i \leq x_{i,max}$ $\sum_I x_{i,min} = 47,400 ha$ $\sum_i x_{i,max} = 1.2 * X_i^e$ $X_i^e = 240,580 ha$ Note: expansion in cotton and rice is not considered in our analysis	$x_{i,min} \leq x_i \leq x_{i,max}$ $\sum_I x_{i,min} = 47,400 ha$ $\sum_i x_{i,max} = 1.2 * X_i^e$ $X_i^e = 240,580 ha$ Note: expansion in cotton and rice is not considered in our analysis

Table 5. 16 Irrigation expansion scenario – Main average yearly results

		3.1 Agricultural Development	3.2 Agricultural development w/o E-Flow	3.3 Agricultural and hydropower development
Average water supplied to urban, rural, industrial, mining use (MCM/year)	Dry	326.65	328.33	406.02
	Average	334.09	342.33	413.49
Average annual energy generation (TWh/year)	Dry	1.53 (ITT) 4.56 (KG)	1.55 (ITT) 4.56 (KG)	1.32 (ITT) 4.15 (KG) 2.37 (KGL)
	Average	8.35 (ITT) 12.34 (KG)	8.33 (ITT) 12.63 (KG)	7.51 (ITT) 11.89 (KG)

				6.80 (KGL)
Average water use for agriculture (MCM/year)	Dry	1,254.86 (1,596.06)	1,254.86 (1,596.06)	1,242.18 (1,586.06)
	Average	1,297.99 (water applied) 1,652.65 (water abstracted, incl. system losses)	1,297.99 (water applied) 1,652.65 (water abstracted, incl. system losses)	1,266.59 (water applied) 1,618.31 (water abstracted, incl. system losses)
Net benefits (million ZMK/year)	Dry	2,473,858 (Hydropower) 317,328 (Agriculture)	2,469,746 (Hydropower) 317,328 (Agriculture)	3,966,428 (Hydropower) 251,308 (Agriculture)
	Average	8,399,670 (Hydropower) 258,386 (Agriculture)	8,509,958 (Hydropower) 258,386 (Agriculture)	10,901,520 (Hydropower) 256,217 (Agriculture)

The optimization results of the agricultural development scenario (Scenario 3.1) show that in an average hydrological year the net irrigation water supply for sugarcane drops to about 8,800 m<sup>3</sup>/year/ha (against the requirement for the baseline scenario of about 9,300 m<sup>3</sup>/year/ha) with a corresponding decrease in yield of about 10 percent. In the dry year scenario, the applicable irrigation water is reduced to about 8,100 m<sup>3</sup>/year/ha in order to implement the full development of the additional irrigated areas. The corresponding 14 percent decrease in yield would make sugarcane farming still profitable, but the considerable decrease in produce of about 25 ton/ha could affect the viable operation of the sugarcane processing plants. In addition irrigated sugarcane in the Copperbelt appears not to be a feasible option from an economic point of view. Urban, industry and mining water supply is considerably affected by the additional farming requirements. When a dry hydrological scenario is considered, it is possible to satisfy only the minimum water demands in the upper stretch of the Kafue. In an average hydrological scenario, total water availability for the urban and industrial centres is reduced by about 8 million cubic meters per year relative to the baseline scenario, and the pressure on water resources would be particularly severe in the dry months and in the Copperbelt region. Hydropower production is affected the most by the increased agricultural developments. In a dry year scenario power production declines, by 47 percent at Itezhi-tezhi and by 26 percent at Kafue Gorge compared to the baseline scenario. In case of an average hydrological scenario, hydropower output decreases by 15 percent at Itezhi-tezhi and 13 percent at Kafue Gorge.

The elimination of the environmental flow regulation (scenario 3.2) does not have a significant impact on the hydropower generation in a dry year, but significantly decreases the loss in power output at Kafue Gorge during an average hydrological year. The main impact of the altered environmental flow regulation is the availability of additional water that can be supplied to the urban centres of the lower Kafue, particularly during an average hydrological year.

The overall economic growth scenario (scenario 3.3) in the Kafue basin assumes the conjoint development of additional hydropower generation, population growth, and irrigated agriculture growth. This scenario's constraints require to: 1) supply water to a population growing at a 3 percent yearly rate; 2) provide irrigation water to additional agricultural areas, as planned by the Government of Zambia, in order to maximise agricultural net benefits; 3) include additional energy generation capacity at Kafue Gorge Lower, considering the minimum and maximum releases and storage level for the reservoir. In an average hydrological year urban, rural, industrial and mining water demands can be satisfied with 414 MCM/year, 3 percent lower than the optimal level of supply generated in scenario 1.2. A similar decrease in supply,

compared to scenario 1.2, is recorded for a dry hydrological year. Irrigation water supply is significantly reduced with respect to scenario 3.1: in an average hydrological year, crop water application for sugarcane is reduced to 8,560 m<sup>3</sup>/ha/year and in a dry hydrological year crop water application for sugarcane and soya decrease respectively to 8030 m<sup>3</sup>/ha/year and 3,250 m<sup>3</sup>/ha/year (from an optimal crop water requirement of 4,500 m<sup>3</sup>/ha/year). In addition, only about 82 percent of the planned agricultural expansion can be realised under irrigation. Compared to scenario 3.1, this implies a reduction in total agricultural net benefits of about 66 billion ZMK in a dry hydrological year and 2 billion ZMK in a wet hydrological year. The decrease in the irrigation rate in this scenario allows for maximising net benefits with an increase of hydropower production in the system. Overall hydropower generation in a dry hydrological year is about 7.9 TWh/year and in an average hydrological scenario is about 26.2 TWh/year. Though power generation is considerably higher than in scenarios 3.1 and 3.2, when compared to scenario 2.1 we notice a loss in power output of about 34% in a dry hydrological year and 5% in an average hydrological year.

Our results in Table 5.16 confirm that a substantial reduction of system losses from both urban and industrial water supply and irrigation water use through increased efficiency could significantly benefit hydropower production and overall net benefits. If efficiency gains in the water distribution system and in the agricultural water application do not materialise and the assumed growth patterns in irrigation and population come true, the country will not be able to fully harness the potential of the future hydropower development at Kafue Gorge Lower. Overall net benefits in scenario 3.3 are between 9% (dry year) and 11% (average year) larger than the baseline scenario but these account also for the benefits accrued from the energy generated by the additional power station constructed at Kafue Gorge Lower. Instead, overall net benefits derived from the development of hydropower, without considering population growth and agricultural expansion (scenario 2.1), are between 13% and 28% larger than in the baseline scenario. It is of utmost importance for the Government of Zambia, in consultation with all stakeholders, to set attainable development objectives and prioritise projects based on the national goals. Trade-offs between irrigation, hydropower generation, environmental protection, and population growth exist and are reflected in the change in overall net benefits. The analysis of our scenarios can support the understanding of trade-offs that, when assessed based on national priorities and objectives, can guide the government in the choice of alternative Pareto optimal solutions.

#### 5.3.5 Mines closure

The mining sector has often been disregarded in studies related to water allocation and most of the public and scientific discussion focuses only on the quality of the effluents from the mining operations. However, mines in Zambia are not only large users of water, but they also have an important role, due to their dewatering operations, in increasing the water supply in the upper stretches of the Kafue River. For example, a large share of the freshwater supply for the city of Luanshya is ensured by the dewatering operations of Luanshya Copper Mines, subsidiary of the China Non-Ferrous Metal Company; the same is true for Konkola Copper Mines, a subsidiary of Vedanta Resources Plc. Overall, Konkola Copper Mines dewateres the largest volumes, with 300,000 m<sup>3</sup>/day, followed by Mopani Copper Mines with 110,000 m<sup>3</sup>/day, Chambishi Metals with 88,000 m<sup>3</sup>/day, Kansanshi Mining with 45,000 m<sup>3</sup>/day, and Luanshya Copper Mines with 23,400 m<sup>3</sup>/day.

Many of the mining operations will be closed between 15 and 30 years from the time being, unless new ore is being tapped on or more economic methods for metals extraction are being used. If such a scenario

would take place without opening up new mining operations not only the economy would suffer in terms of income and employment losses, but no more dewatering activities would be undertaken and the pits would be simply flooded with groundwater. In order to mitigate these negative impacts, the government seems to plan the development of new mines, but the constraints in terms of power availability limit the uptake of such plans at the time being. Mining, in fact, is an extremely energy intensive sector: as mentioned before 54 percent of the Zambian power is consumed by the mining companies, mainly located in the Copperbelt (Table 5.6).

Table 5.17 illustrates the assumptions and constraints that characterise the mines decommissioning scenario. The assumptions constraints for urban and industrial water demand, environmental flows, and hydropower are the same as in scenario 1.1. Mining water demand is set to zero as well as the inflow from dewatering operations. Scenario 4.2 allows for increased agricultural land to be irrigated, in line with the constraints applied to scenario 3.1. Table 5.18 summarizes the main results of these scenarios.

Table 5. 17 Mines decommissioning scenario: assumptions and inputs

	4.1 Mines closure	4.2 Mines closure and expansion of irrigation
Urban and rural water demand	$D_{min}^U \leq D_n^t \leq D_{max}^U$ $D_{min}^U = 0.9 * D_{current}^U$ $D_{max}^U = 1.2 * D_{current}^U$ $D_{current}^U = 230.33MCM$	
Industrial water demand	$D_{min}^I \leq D_n^t \leq D_{max}^I$ $D_{min}^I = 0.9 * D_{current}^I$ $D_{max}^I = 1.5 * D_{current}^I$ $D_{current}^I = 84.89MCM$	
Mining water demand	$D_t^M = 0$	
Environmental flow	$\frac{R_{RES1,n2}^{t=March}}{R^{t=March}} \geq \frac{R^{t=March}}{R^{t=March}}$ $\frac{R_{RES1,n2}^{t=March}}{R^{t=March}} = 778MCM$	
Hydropower	Head-storage relation, Hydrological mass balance for the reservoirs, Minimum and maximum storage levels for the reservoirs, Minimum and maximum release flows for the reservoirs as in Scenario 1.	
Irrigation	$x_{i_{min}} \leq x_i \leq x_{i_{max}}$ $\sum_i x_{i_{min}} = 1 * X_i$ $\sum_i x_{i_{max}} = 1.2 * X_i$ $X_i = 47,400ha$	$x_{i_{min}} \leq x_i \leq x_{i_{max}}$ $\sum_i x_{i_{min}} = 47,400ha$ $\sum_i x_{i_{max}} = 1.2 * X_i^e$ $X_i^e = 240,580ha$ Note: expansion in cotton and rice is not considered in our analysis



Table 5. 18 Mines decommissioning scenarios – Main average yearly results

		4.1 Mines closure	4.2 Mines closure and expansion of irrigation
Average water supplied to urban, rural, industrial, mining use (MCM/year)	Dry	302.18	289.72
	Average	322.25	317.72
Average annual energy generation (TWh/year)	Dry	2.187 (ITT) 4.408 (KG)	2.01 (ITT) 3.69 (KG)
	Average	7.139 (ITT) 10.535 (KG)	6.19 (ITT) 10.04 (KG)
Average water use for agriculture (MCM/year)	Dry	341.46 (water applied) 444.22 (water abstracted, incl. system losses)	1,254.86 (water applied) 1,596.06 (water abstracted, incl. system losses)
	Average	376.7 (water applied) 490.75 (water abstracted, incl. system losses)	1,385.21 (water applied) 1,766.48 (water abstracted, incl. system losses)
Net benefits (million ZMK/year)	Dry	2,758,333 (Hydropower) 148,678 (Agriculture)	2,065,788 (Hydropower) 252,670 (Agriculture)
	Average	7,573,759 (Hydropower) 153,358 (Agriculture)	7,469,925 (Hydropower) 260,827 (Agriculture)

Even for the case of current levels of economic activities, i. e. without population growth and expanded irrigated agriculture (scenario 4.1), the closure of the mines would have a direct impact on all other sectors, both in a dry and average hydrological scenario. Compared to the baseline scenario, hydropower production at Itezhi-tezhi decreases by more than 12 percent in a dry hydrological year and by 3.1 percent in an average year. The effect on the Kafue Gorge power production is moderate, with a decrease in production between 3.8 and 3.3 percent in a dry and average hydrological year respectively. Also urban water supply is affected, particularly in the Copperbelt where a number of cities depend on the dewatered resources. Interestingly, the effect of the mine closure on urban water supply downstream of Itezhi-tezhi is almost insignificant. In a dry year, overall yearly water supply decreases by about 10 percent. In an average hydrological year the urban and industrial areas would suffer from a 5.8 percent decrease in water supply. Our analysis takes into account the drop in water consumption at the mining sites, but it does not consider secondary effects of income losses in the region and the possibility of migrations from the Copperbelt, which would further decrease urban water demands in the region.

If agricultural investments, as described in Section 3.4, are implemented and the agricultural area under irrigation is increased (scenario 4.2), a mine closure scenario would further intensify the pressure on water resources. In a dry year, hydropower production decreases, compared to the baseline scenario, by about 20 percent, both at Itezhi-tezhi and Kafue Gorge. In case of average hydrological conditions the decrease is less marked, with power production at Itezhi-tezhi declining by about 16 percent and 8 percent at Kafue Gorge. As outlined in scenario 4.2, also urban and industrial water demand would be compromised: compared to the baseline scenario, water allocation to urban centres would be decreased by 14 percent in a dry year and 4.2 percent in an average hydrological year. Also in this case, it is in the Copperbelt where the water resources stress is most evident and where only the minimum water requirements can be satisfied for ten months a year (only the months of February and March allow for an allocation of water to domestic consumption larger than the minimum demand).

Considering the significant implications of a mines decommissioning scenario on domestic water consumption, agricultural production, and hydropower generation, it is important that decision makers adopt forward-looking approaches to manage alternative sources of livelihood in the Copperbelt. Mines decommissioning plans exist and the environmental impacts are assessed, but the government does not have a strategy in place to cope with the future closure of the mines. In addition, the Zambian government through Zambia Consolidated Copper Mines (ZCCM) retains a low share of the royalties from mining and the infrastructural investments outside the mining sector have not been substantial in the past. The impact of the mines closure on employment and other secondary effects on the regional economy could be significant: about 10 percent of the Copperbelt's population is employed by the mines (Central Statistical Office, 2005) and a considerable percentage is immigrants coming from other regions in Zambia or from neighbouring countries (Simatele, 2007). Would no alternative source of livelihood be possible, these workers might migrate to other urban centres generating further demand for jobs, housing, and services. Ultimately, increased poverty in the Copperbelt area together with additional pressure on existing urban centres could be foreseen. It is thus paramount that policy makers adopt a long-term and holistic view that incorporates possible scenarios for the mines post-closure phase. These scenarios should specifically take into account: the provision of alternative sources of livelihood, including the necessary infrastructural investments; the provision of adequate supplies of water of sufficient quality for the Copperbelt urban centres; the need to limit the impoverishment of the region and large-scale migrations.

## 5.4 Conclusions

Water as a natural resource plays a critical role in the future economic development of Zambia. However, despite having abundant water resources, the country's overall potential has not been fully tapped, and plans exist to further develop both irrigated agriculture and hydropower production, particularly in the Kafue River basin.

Due to a changing and not yet fully implemented water governance framework (Uhlendahl et al., 2010), inter-sectoral competition already exists in the Kafue Basin, particularly in dry hydrological years. By 2022, the Zambian government plans to develop additional 240,000 hectares under irrigation. Moreover, concrete plans exist for the construction a new hydropower station at Kafue Gorge Lower, while the Itezhi-tezhi power station is reaching the operational phase in 2013/14.

Using a hydro-economic model, this study attempts to estimate the hydrological and economic impacts of different socio-economic developments on the Kafue River basin. The optimization model employed in this study is capable of assessing a number of scenarios derived from concrete policy priorities and development options facing the Zambian water sector, and provides relevant hydrological and economic information that can be compared to a baseline scenario and facilitates the decision making process. Table 5.19 summarizes the results of the study at hand.

Table 5. 19 Summary of results

			Average annual energy genera- tion (TWh/year)	Average water supply for urban use (MCM/year)	Average water use for agricul- ture (MCM/year) <sup>22</sup>
1 Base case	1.1 Baseline	Dry	2.86 (ITT) 6.20 (KG)	336.37	341.46 (444.22)
		Average	9.84 (ITT) 14.17 (KG)	342.06	376.79 (490.75)
	1.2 Population growth	Dry	2.297 (ITT) 5.75 (KG)	414.66	341.46 (444.22)
		Average	9.68 (ITT) 13.82 (KG)	424.77	376.79 (490.75)
2 Hydropower investments	2.1 Hydropower devel- opment with agriculture status quo	Dry	2.84 (ITT) 5.85 (KG) 3.26 (KGL)	331.97	337.023 (438.44)
		Average	7.92(ITT) 12.61 (KG) 7.01 (KGL)	341.29	376.79 (490.75)
	2.2 Hydropower devel- opment (high priority)	Dry	3.26(ITT) 6.76 (KG) 3.76 (KGL)	337.78	37.59 (48.85)
		Average	7.92(ITT) 12.61 (KG) 7.01 (KGL)	341.29	376.79 (490.75)
	2.3 Hydropower devel- opment without Envi- ronmental Flow	Dry	3.23 (ITT) 6.70 (KG) 3.40 (KGL)	332.18	337.023 (438.44)
		Average	7.92(ITT) 12.61 (KG) 7.01 (KGL)	341.29	376.79 (490.75)
	3.1 Agricultural devel- opment	Dry	1.53 (ITT) 4.56 (KG)	326.65	1,254.86 (1,596.06)
		Average	8.35 (ITT) 12.34 (KG)	334.09	1,297.99 (1,652.65)
3 Agricultural growth	3.2 Agricultural devel- opment without Envi- ronmental Flow	Dry	1.55 (ITT) 4.56(KG)	328.33	1,254.86 (1,596.06)
		Average	8.33 (ITT) 12.63 (KG)	342.33	1,297.99 (1,652.65)
	3.3 Agricultural and hy- dropower development	Dry	1.32 (ITT) 4.15 (KG) 2.37 (KGL)	406.02	1,242.18 (1,586.06)
		Average	7.51 (ITT) 11.89 (KG) 6.80 (KGL)	413.49	1,266.59 (1,618.31)
	4.1 Mine closure	Dry	2.187 (ITT) 4.408 (KG)	302.18	341.46 (444.22)

<sup>22</sup> In parentheses we report the total amount of water abstracted as the sum of total water applied and conveyance losses.

		Average	7.139 (ITT) 10.535 (KG)	322.25	376.79 (490.75)
	4.2 Mine closure and agricultural growth	Dry	2.01 (ITT) 3.69 (KG)	289.72	1,254.86 (1,596.06)
		Average	6.19 (ITT) 10.04 (KG)	317.72	1,385.21 (1,766.48)

A central theme that emerges from the work is the necessity for policy makers to consider the impacts of development scenarios on all water using sectors. Among other things, this requires a holistic assessment of the consequences of different water allocation scenarios and of the trade-offs between users' objectives. The detailed hydrological and economic information derived for each of the scenarios allows policy makers to identify the trade-offs among various sectors of the economy and make informed choices in terms of water allocation. Our analysis also provides decision makers with the net benefits of undertaking some desired changes with respect to the baseline scenario. Figure 5.7 illustrates the change in net benefits for each scenario, in a dry and average hydrological year, compared to the baseline scenario (1.1).

Figure 5. 7 Change in net benefits with respect to the baseline scenario

	DRY		AVERAGE	
	Hydropower	Agriculture	Hydropower	Agriculture
Scenario 1.1	→ 0.00%	→ 0.00%	→ 0.00%	→ 0.00%
Scenario 1.2	↓ -12.22%	→ 0.00%	↓ -2.17%	→ 0.00%
Scenario 2.1	↑ 41.20%	↓ -0.68%	↑ 14.71%	→ 0.00%
Scenario 2.2	↑ 53.09%	↓ -95.90%	↑ 14.71%	→ 0.00%
Scenario 2.3	↑ 47.54%	↓ -0.68%	↑ 14.71%	→ 0.00%
Scenario 3.1	↓ -32.71%	↑ 113.43%	↓ -13.81%	↑ 68.49%
Scenario 3.2	↓ -32.83%	↑ 113.43%	↓ -12.68%	↑ 68.49%
Scenario 3.3	↑ 7.88%	↑ 69.03%	↑ 11.86%	↑ 67.07%
Scenario 4.1	↓ -24.98%	→ 0.00%	↓ -22.29%	→ 0.00%
Scenario 4.2	↓ -43.81%	↑ 69.94%	↓ -23.35%	↑ 70.08%

While agriculture on average accounts for less than 20 percent of the Zambian GDP, it is to be noted that, on one hand the sector employs a large share of the population and, on the other hand that the Government of Zambia gives high priority to the food security objective (GoZ, 2004a) to be achieved through the development of both large and small-scale farming and the creation of additional job opportunities. Our analysis shows that the Kafue River basin could afford the planned future hydropower development while maintaining the current level of agricultural production. However, not all of the planned future agricultural developments are feasible, particularly in a dry year scenario, and the optimal allocation of water resources depends on the policy priorities of the stakeholders. It would be possible to fully expand the irrigated area allowing for partial irrigation on, particularly, sugarcane only if part of the net benefits derived from hydropower production is sacrificed. This trade-off illustrates the effects of different timing of water releases from the dams necessary to optimise agricultural production with

compared to the optimal releases that would maximise hydropower production only. Would the policy priority be the maximisation of hydropower production to satisfy the internal demand and exploit the energy export opportunities within the region, existing irrigated agriculture would be compromised in a dry hydrological year with severe consequences for agricultural production in general and sugarcane production in particular. Would the Government of Zambia and the cooperating partners allocate enough resources for the desired agricultural expansion as well as for the construction and operation of the Kafue Gorge Lower power station, the overall system net benefits would increase, but proportionally less than if one development strategy only was pursued. In fact, in a dry year, the net benefits derived from the construction of the Kafue Gorge Lower power station would be only about 8 percent larger than in the baseline scenario. Considering that in scenario 2.1 the hydropower net benefits in a dry year are 41 percent larger than in the baseline case, the loss of about 33 percent of the potential net benefits cannot be compensated by the additional benefits derived from increased irrigation. It is here important to recall that net benefits maximisation might not be the only driver of decision maker's choice of the desired development scenario. Though the hydropower sector generates larger net benefits, the role of the Zambian agricultural sector in terms of employment of the rural population and food security is indisputable. Would only net benefit maximization be the choice criterion, the Zambian policy makers would also need to account for increased rural unemployment and loss of traditional sources of livelihoods. This might lead to, on one side, migration to the urban centres with a risk of impoverishment of large share of the population and, on the other side, decreased production of a number of key commodities with a negative impact on the food trade balance and risks of increased food prices or food insecurity.

It is also important to notice that a mining closure scenario, which in Zambia could occur in the next 15 to 30 years, would have a significant effect on the net benefits gained in the agriculture and hydropower sector. In fact overall net benefits would be reduced by, on average, 20 percent relative to the baseline scenario. This is mainly due to the lower water availability in the Copperbelt that would make full irrigation uneconomical and to the lower water supply to the Itzhi-tezhi dam. Decision makers must urgently consider such a scenario and adopt forward-looking approaches to manage either new mining operations or provide alternative sources of livelihood in the Copperbelt, together with planning ahead alternative supplies of water of sufficient quality for the growing cities. The dialogue between the government and the mining companies' representatives should be enhanced and a joint long-term planning of the future operations and decommissioning of the mining sites should be fostered. In particular, the impact of mines' decommissioning on water availability is an important topic to be assessed by decision makers and more detailed studies for the Copperbelt region could be important to shape and prioritize future policy decisions and investments in the region.

Population growth across the basin will alone put a strain on water resources. Considering only the Kafue River basin, the annual population growth rate is about 3 percent, larger than the national average. Would such growth rate be upheld for the coming 10 years, while maintaining the baseline irrigated agriculture, overall net benefits would be reduced by about 12 percentage points in a dry year. Also considering the national policies that foster the increased access to water and sanitation, including the rural areas, our results suggest that the reduction of system losses and the optimisation of the water supply services will gain increasing relevance. The Zambian government already called on NWASCO to introduce measure aimed at reducing water losses in the supply system and institutional audit teams have been created to implement strategies to address the issue. Progress has remained slow so far and an additional challenges

arise from the continuous increase in urban and rural water supply coverage. Water supply, together with sanitation, should be and is a priority for the Zambian government. This is also indicated by the increasing allocation of financial resources to these sectors. Nonetheless, it is paramount that these funds are not only directed to increase water supply coverage, but to the rehabilitation of the water network infrastructure, the integration of urban planning and delivery of water supply services, and the increase of the share of metered users and the water supply revenue collection rate (at the moment still below 50% in the Kafue region).

The joint approach to assessing the economic and physical outcomes of different water allocations provides a best practice that could support a more holistic decision making, in line with the changes from a sectoral to an integrated approach for water management in Zambia. Nonetheless, it should be noticed that policy makers need to be aware of a wider range of social and political considerations. In fact, equity concerns and policy and strategic priorities may have a greater impact than economic optimisation results. Similarly, the scenarios presented here provide an initial set of possible future developments and an initial answer to water development questions. But without doubt the scenarios analysed here to simulate the adoption of the various policies are not exhaustive and a participatory discussion among stakeholders based on these preliminary Pareto-optimal results would be needed to identify the socially optimal solution. While the economic model is a powerful instrument to indicate a portfolio of feasible Pareto solutions, only the interaction and constructive negotiation among stakeholders and decision makers can suggest the socially optimal solution.

## Acknowledgements

This study builds on the hydrological data provided by Philip Meier and Florian Koch and greatly benefited from Prof. Amaury Tilmant's and Prof. Rolf Kappel's advice.

## References

- Andrén, U. (1993). Breed and Seed Production in Zambia, Department of Agriculture, Ministry of Agriculture, Food and Fisheries and the Zambia Seed Company Limited, Lusaka (1993) 43 pp.
- Blaser, W. (2013). Impact of woody encroachment on soil-plant herbivore interactions in the Kafue Flats floodplain ecosystem. Dissertation ETH No. 21068.
- Burke, J. J. (1994). Approaches to integrated water resource development and management. The Kafue Basin, Zambia. *Natural Resources Forum*, 18 (3), 181-192.
- Castelletti A. & Soncini-Sessa, R. (2004). PIP: a participatory and integrated planning procedure for decision making in water resource systems. In: IFAC Workshop on Modelling and Control for Participatory Planning and Managing Water Systems, Sept 28–Oct 1, Venice.
- Central Statistical Office (2011). 2010 Census of Population and Housing. Preliminary Population Figures. February 2011.
- Central Statistical Office (2005). 2005 Labor Force Survey. Government of Zambia.
- CSMA Consultants Ltd. & ACA Howe International Ltd., 2000. Competent person's report – The assessment of First Quantum Minerals Limited in Zambia and Zimbabwe. Ref: 61-0185.
- Dehghanisanij, H., Nakhjavani, M. M., Tahiri, A. Z., and Anyoji, H. (2008). Assessment of wheat and maize water productivities and production function for cropping system decisions in arid and semiarid regions. *Irrigation and Drainage*, 58 (1): 105-115.
- Dinar, A., Rosegrant, M., and Meinzen-Dick, R. (1997). Water allocation mechanisms—principles and examples. *World Bank Policy Research Working Paper*, 1779, 48.
- Dinar, A. & Letey, J. (1996). *Modeling economic management and policy issues of water in irrigated agriculture*. Praeger (Westport, Conn.). Pages 239.
- Doorenbos, J. & Kassam, A.H. (1979). *Yield response to water*. FAO Irrigation and Drainage Paper No. 33, FAO, Rome, Italy, 193 pp.
- ECZ (2007a). Environmental Compliance Audit of Mopani Copper Mines Plc. (Nkana Mine Site).
- ECZ (2007b). Environmental Compliance Audit of Mopani Copper Mines Plc (Mufulira Mine Site).
- FAO (2011). AquaCrop version 3.1 – The FAO crop model to simulate yield response to water.
- FAO (1998). Wetland characterisation and classification for sustainable agricultural development. Harare, 1998. Available on-line: <http://www.fao.org/docrep/003/x6611e/x6611e00.htm#TopOfPage>
- FAO (2005). Irrigation in Africa in figures – AQUASTAT Survey 2005. Zambia Profile. Available on-line: [http://www.fao.org/nr/water/aquastat/countries\\_regions/zambia/zambia\\_cp.pdf](http://www.fao.org/nr/water/aquastat/countries_regions/zambia/zambia_cp.pdf)
- Global Water Partnership (2000a). *Towards Water Security: A Framework for Action*. Stockholm: GWP.

Global Water Partnership (2000b). *Integrated water resource management*. TAC Background papers, Number 4, Stockholm, Sweden.

Gomes, F. & Carr, M.K.V. (2003). Effects of water availability and vine harvesting frequency on the productivity of sweet potato in southern Mozambique. III. Crop yield/water-use response functions. *Expl. Agric.*, 39: 409-421.

GoZ & FAO (2012). National Investment Brief – Zambia. Report of investment in water for agriculture and energy in Zambia.

GoZ (2011a). Sixth National Development Plan (2011-2015) – Sustained economic growth and poverty reduction. January 2011.

GoZ (2011b). Water Resources Management Act. No. 21 of 2011.

GoZ (2011c). 2010 Census of Population and Housing – Preliminary Population Figures. February 2011.

GoZ (2010). National Water Policy. Ministry of Energy and Water Development

GoZ (2009). Zambia-National Water Resources Report for WWDR3 (Theme- Water in a changing world). Prepared by Nyambe, I. and Feilberg, M. Available on line: [http://webworld.unesco.org/water/wwap/wwdr/wwdr3/case\\_studies/pdf/Zambia\\_National\\_Water\\_Resources\\_Report.pdf](http://webworld.unesco.org/water/wwap/wwdr/wwdr3/case_studies/pdf/Zambia_National_Water_Resources_Report.pdf)

GoZ (2004a). National Agricultural Policy. Ministry of Agriculture and Cooperatives. Lusaka: Government Printers.

GoZ (2004b). Irrigation Policy and Strategy. Ministry of Agriculture and Cooperatives. Lusaka: Government Printers.

Hofwegem, P. & Jaspers, F. (1999). *Analytical framework for integrated water resources management*. IHE Monograph 2, Delft, The Netherlands

Igabadun, H.E., Tarimo, A.K.P.R., Salim, B.A., and Mahoo, H.F. (2007). Evaluation of selected crop water production functions for an irrigated maize crop. *Agricultural water management*, 94 (1): 1-10.

Lange, G.M. & Kassam, R. (2006). *The economics of water management in Southern Africa: an environmental accounting approach*. MPG Books Ltd, Bodmin, Cornwall.

Lecler, N. L., & Jumman, A. (2009). *Irrigated sugarcane production functions*. Proceeding of the South African Sugar Technologists' Association, 82: 604 – 607.

Marttunen, M., and Suomalainen, M. (2005). Participatory and Multiobjective Development of Water Course Regulation- Creation of Regulation Alternatives from Stakeholders' Preferences. *Journal of multi-criteria decision analysis*, 13: 29-49.

McCartney, M. P. & Houghton-Carr H. A. (1998). A Modelling Approach to Assess Inter- Sectoral Competition for Water Resources in the Kafue Flats, Zambia. *J. CIWEM*, 12.

Miettinen, K. (1999). *Nonlinear Multiobjective Optimization*. Kluwer Academic Publishers, Boston, 1999.



- Nielsen, D.C. (2001). Production Functions for Chickpea, Field Pea, and Lentil in the Central Great Plain. *Agronomic Journal*, 93: 563-569.
- Russo, D. & Bakker, D. (1987). Crop-water Production Functions for Sweet Corn and Cotton Irrigated with Saline Waters. *Soil Sci Soc American Journal*, 51:1554-1562.
- Schelle, P. & Pittock, J. (2005). Restoring the Kafue Flats – A partnership approach to environmental flows in Zambia. Brisbane River Symposium, September 2005. Available online: <http://wwf.panda.org/?23434/Restoring-the-Kafue-Flats-A->
- Scott Wilson Piésold (2003). *Integrated Kafue River basin Environmental Impact Study: Main Report*. Scott Wilson Piésold, Ashford.
- Simatele, D. M. (2007). Kwacha ngwee: a snapshot at Zambia's contemporary migration patterns. Paper presented at the African Migrations workshop, Accra, Ghana. 18th-21st September 2007.
- Soncini-Sessa, R. (2007a). *Integrated and participatory water Resources Management. Part I: Theory*. Oxford: Elsevier, 2007
- Soncini-Sessa, R. (2007b). *Integrated and participatory water Resources Management. Part II: Practice*. Oxford: Elsevier, 2007
- Uhlendahl, T., Salian, P., Casarotto, C., and Doetsch, J. (2011). Good Water Governance and IRWM in Zambia - Challenges and Chances. *Water Policy*, 13, 845–862.
- Van Cauwenbergh, N., Pinte, D., Tilmant, A., Frances, I., Pulido-Bosch, A., and Vanclooster, M. (2008). Multi-objective, multiple participant decision support system for water management in the Andarax catchment, Almeria. *Environmental Geology*, 54, 478-489.
- de Vente, C. P. (1993). Water occurrences and dewatering practice at Nkana Division ZCCM. International Water Association Symposium Zambia, 1993.
- World Bank (2008). Rapid resource assessment of irrigation and land cover for the Kafue River basin. World Bank – Country Water Resources Assistance Strategy 2008. November 2008, prepared by Imagen Consulting
- World Bank (2009). *Zambia – Managing water for sustainable growth and poverty reduction. A country water resources assistance strategy for Zambia*. The World Bank: Washington DC.
- World Bank (2011). World Development Indicators and Global Development Finance. Website accessed on 24/08/2011 <http://databank.worldbank.org/ddp/home.do>
- Writghts, J. A., Loosemore, H. A., and Farmani, R. (2002). Optimization of building thermal design and control by multi-criterion genetic algorithm. *Energy and Buildings*, 34(9): 959-972.
- WWF (2005) Summary of study findings on Kafue Flats communities livelihoods options and the effect of a changed flooding regime.
- YEC – Yachiyo Engineering Co. Ltd. (1995). *The Study on the National Water Resources Master Plan in the Republic of Zambia*. Final Report – Main Report, Oct. 1995; Lusaka, Zambia.

ZESCO (2006). Site selection report for the Kafue Gorge Lower Hydroelectric Project. August 2006.

## APPENDIX 5.1: Planned agricultural development in the Kafue River Basin

Project Characteristics					Agricultural Development		Project Financing				
Project Name	Brief Description	Region	Beginning	End	Total Hectares	New Irrigation (ha)	Project Cost (US\$ mln)	Financing partners	Public (US\$ mln)	Private (US\$ mln)	Donors (US\$ mln)
Small Scale Irrigation Project	Construction of an earth dam in Kanakantapa and six irrigation schemes at Buleya-Malima, Nega-Nega, Simupande, Nzenga, Sinazongwe and Kanakantapa; and provision of extension and micro financing services.	Southern	2002	2016	3,218	1,380	20.8	GoZ, AfDB, FINIDA	2	1	17.8
Irrigation Development and Support project ( phases I,II,III)	Promotion of a profitable irrigation sub-sector that attracts public and private investments through the construction of bulk water supply and irrigation schemes, marketing facilities and infrastructures.	Copperbelt, Southern	2008	2022	315,750	na	145.3	GoZ, FAO, IFAD, World Bank	14.5	0	130.8
Agricultural Development Support project	Development of cotton seed farm project under the Cotton Development Trust.	Southern	2007	2012	80	80	29.5	WB	3	0	26.5
Chuanshi (Chanyanya) irrigation project	Support the development of large small holder irrigation schemes and strengthening existing WUA.	Lusaka	2008	2012	960	960	2.5	PPP	0	2.5	0.0

Sugar Development	Expansion of sugar estates through outgrower schemes.	Copperbelt, Southern	2009	2013	20,000	15,000	249.4	GoZ, EU	0	243	6.4
Sugar Development Programme	Expand sugar estates to other suitable areas in the North of the Country, to avoid escalation of land and water conflicts in Kafue flats.	Mazabuka	2011	2013	20,000	20,000	50.0	GoZ, EU	50	0	0
Small Scale Irrigation Project- Kanakantapa Phase III	The SIP project will provide farmers in the Kanakantapa Settlement with an earth dam, two irrigation stations and main canals to irrigate 620 ha.	Lusaka	2013	2016	1,380	620	20.3	GoZ,JICA	20.3	0	0
Nansanga Farm Block Development project Phase II	Contribute to commercialisation of agricultural land to attract investment into the development of new farmlands.	Southern	2011	2015	155,000	77,750	57.0	GoZ	51	0	6
Machiya Farm Block Development Project	Contribute to commercialisation of new agricultural land for investment in Copperbelt Province.	Copperbelt	2011	2020	100,000	100,000	50.0	GoZ	5	10	35
Mungu Farm Block Development Project	Contribute to commercialisation of new agricultural land for investment in Kafue, Lusaka Province.	Lusaka	2011	2020	100,000	100,000	50.0	GoZ	40	0	10
Lufwanyama Farm Block Development Project	Contribute to commercialisation of new agricultural land for investment Lufwanyama, Copperbelt Province.	Copperbelt	2011	2020	100,000	100,000	50.0	GoZ	15	0	35
Katanino Farm Block Project	Contribute to commercialisation of new agricultural land for investment in Kapiri-Mposhi,	Central	2011	2020	100,000	100,000	50.0	GoZ	50	0	0

	Central Province.										
Kopa Palm Plantation Development Project	Contribute to commercialisation of agricultural land for palm oil investment in Central Province.	Central	2011	2020	100,000	100,000	50.0	GoZ	40	0	10
Lumwana, Msandile & Mkushi Irrigation Development projects	Promote a well regulated irrigation sub sector through construction of access roads, water resources development and electrification of the farm block.	Central	2011	2020	na	na	51.4	GoZ, WB	5	8	38
Banana Development Project	Expand area for banana plantation, water resources development for commercial irrigation.	Southern	2011	2020	5,000	5,000	40.0	GoZ	1.5	5	33.5
Peri-urban Irrigation project	The project will involve construction of roads, irrigation and electrification of the peri-urban farming zones to facilitate agriculture and create jobs.	Copperbelt, Central, Lusaka and Southern	2015	2020	2,400	2,400	50.0	GoZ	na	na	na
Small Scale Gravity Fed Irrigation Development Project	Development of new farmlands and adoption of better farming methods.	Only Lusaka	2011	2020	1,000	1,000	5.0	GoZ	na	na	na
Integrated Micro-irrigation Programme	Promote small scale irrigation and subsistence farming.	National	2014	2018	na	na	15.0	GoZ	na	na	na

*Source: authors' elaboration from GoZ and FAO (2012)*



## Chapter 6

# Economic valuation of benefits and costs associated with the coordinated development and management of the Zambezi River basin

This chapter is based on Tilmant, A., Kinzelbach, W., Juizo, D., Beevers, L., Senn, D. and Casarotto, C., 2011. Economic valuation of benefits and costs associated with the coordinated development and management of the Zambezi River basin. *Water Policy*, 14, 490–508. The first person plural is used throughout the chapter.

## Abstract

The Zambezi River basin is of utmost importance to its riparian countries in terms of energy, food production and natural resources. Even though there is no legal agreement on the sharing of Zambezi waters, an assessment of basin-wide economically efficient allocation policies will provide valuable information at a time where water managers and policy makers in the region are negotiating the establishment of a unified river basin institution, called the Zambezi Watercourse Commission (ZAMCOM). That institution would be responsible for, amongst other things, the design of allocation rules. In this study, basin-wide allocation policies are derived from a hydroeconomic model that considers the largest existing and planned hydraulic infrastructure and irrigation schemes in the basin. Our results illustrate that the economic value of water varies spatially, driven primarily by large changes in elevation and on the locations of existing or proposed dams. This observation may have implications for future decisions about the siting of expansions in irrigated agriculture. For example, some of the planned irrigation schemes in upstream countries are not economically sound if the power stations that are in an advanced planning phase are implemented. This study also reveals that the economic value of the three largest storage infrastructure (Kariba, Itzhi-tezhi, Cahora Bassa) is around US\$443 million/year.

## 6.1 Introduction

In 2050, assuming a medium population growth rate (United Nations, 2010), the Zambezi River basin will support more than 70 million people. This population growth will increase water demands for food and energy, which may compete with ecological flow requirements for environmentally sensitive areas (Beilfuss & Brown, 2006). Since the construction of the Kariba dam along the main stem of the Zambezi in the late 1950s, the river basin has experienced other infrastructure developments for energy generation, flood control, recreation, fishing and irrigation (see Table 6.1). The Zambezi River basin now hosts two large artificial reservoirs, Kariba and Cahora Bassa, which store more than  $200 \times 10^9 \text{ m}^3$  together, which is about six times the average annual flow at Victoria Falls and two times the average annual discharge flowing to the sea. Two other reservoirs can be found in the Kafue tributary: the Itzhi-tezhi and Kafue Gorge.

According to the Food and Agriculture Organization (FAO), the irrigation potential in the Zambezi River basin is more than 3 million ha, of which only 5% is already developed. If there is considerable scope for irrigation development to boost agricultural production, this may also compete with the production of hydroelectricity as less water will be available for the generators of the hydropower plants. With an installed capacity of more than 4,500 MW, hydropower generation is one of the major commercial uses of water, providing energy to Zimbabwe, Zambia, Mozambique and South Africa. Evaporation from these reservoirs sums to about 16% of available runoff in the basin and currently ranks as the primary anthropogenic consumptive water use in the basin (Euroconsult, 2008). The production of hydroelectricity also conflicts with the need to maintain ecological functions as it alters the hydrological regime downstream. Since the construction of the Cahora Bassa reservoir, the productivity of fisheries, shrimp industry and floodplains in the Zambezi delta has declined due to constant flows and the absence of flooding (Gammelsrod, 1996). The Kariba and Cahora Bassa reservoirs also trap most of the sediment load of the upper and middle Zambezi, releasing essentially clear



water downstream. This lack of sediments and the reduction in nutrients have resulted in major disruptions of the Zambezi's riverine, wetland, deltaic and coastal ecosystems, which could already be observed 10 years after the commissioning of Cahora Bassa. Several studies have shown that restoring a flow regime through the re-operation of the existing reservoirs would not significantly affect the production of hydroelectricity if the operating policies were coordinated (Gandolfi et al., 1997; Tilmant et al., 2010). According to Shela (2000), this coordination issue should fall under the umbrella of the Zambezi Watercourse Commission (ZAMCOM).

Table 6. 1 Major dams and hydropower stations in the Zambezi.

Name	ID	Country	Capacity (MW)	Life storage (km <sup>3</sup> )	Average discharge (m <sup>3</sup> /s)	Existing (E), Planned (P) or Extension Planned (EP)	Productivity (US\$/1000 m <sup>3</sup> )
Nkula + Tedzani + Kapichira	NTK	Malawi	279	ROR	470	E	17.88
Boroma	BO	Mozambique	160	ROR	2,578	P	0.79
Mependa Uncua	MU	Mozambique	1.5	2.32	2,578	P	6.54
Cahora Bassa	CB	Mozambique	2.925	51	2,482	E + EP	11.36
Kariba	KA	Zambia/ Zimbabwe	1.98	65	1,386	E + EP	10
Itezhi-tezhi	IT	Zambia	120	5.3	80	P	4.27
Kafue Gorge	KG	Zambia	1.5	ROR	112	E + EP	58.56
Batoka Gorge	BG	Zambia/ Zimbabwe	1.6	0.58	1,082	P	15.95
Victoria Falls	VF	Zambia	108	ROR	1,082	E	4

ROR: run-of-river

Most of the major irrigation and hydropower projects at the inception stage in the various riparian countries are being developed independently. In a hydropower-dominated river basin like the Zambezi, the opportunity cost associated with upstream withdrawals for irrigation purposes may be significant. Neoclassical economic theory advises allocating water to its most productive uses, thereby maximizing the productivity of water. In a system involving consumptive (irrigation) and non-consumptive (hydropower) users, a trade-off must be found at each stage between diverting, releasing and keeping the water in storage for future uses. The 'temporal' trade-off, i.e. the balance between immediate and future uses, is achieved when the future and immediate marginal water values are equal. The release and withdrawal decisions give rise to a 'spatial' trade-off; at a particular reservoir, the equilibrium between withdrawal and release is reached when the lateral productivity is identical to the sum of downstream productivities. What would therefore be the economically efficient balance between irrigated agriculture and hydropower generation in the Zambezi? Where could water be withdrawn for irrigation and what would be the optimal irrigated areas in the different countries, taking into account the agro-meteorological heterogeneity of a large basin like the Zambezi, the stochasticity of supply (hydrology), the existing and planned hydropower projects, and the productivity of wetlands? What is the economic value of the three largest existing man-made hydroelectric reservoirs (Kariba, Cahora Bassa, Itezhi-tezhi)? While the development of water resources infrastructure in the Zambezi River Basin (ZRB) will not always strictly follow the economical-

ly most efficient path, information about optimally efficient allocation can nonetheless serve as useful guideposts for quantification of the trade-offs that are being made.

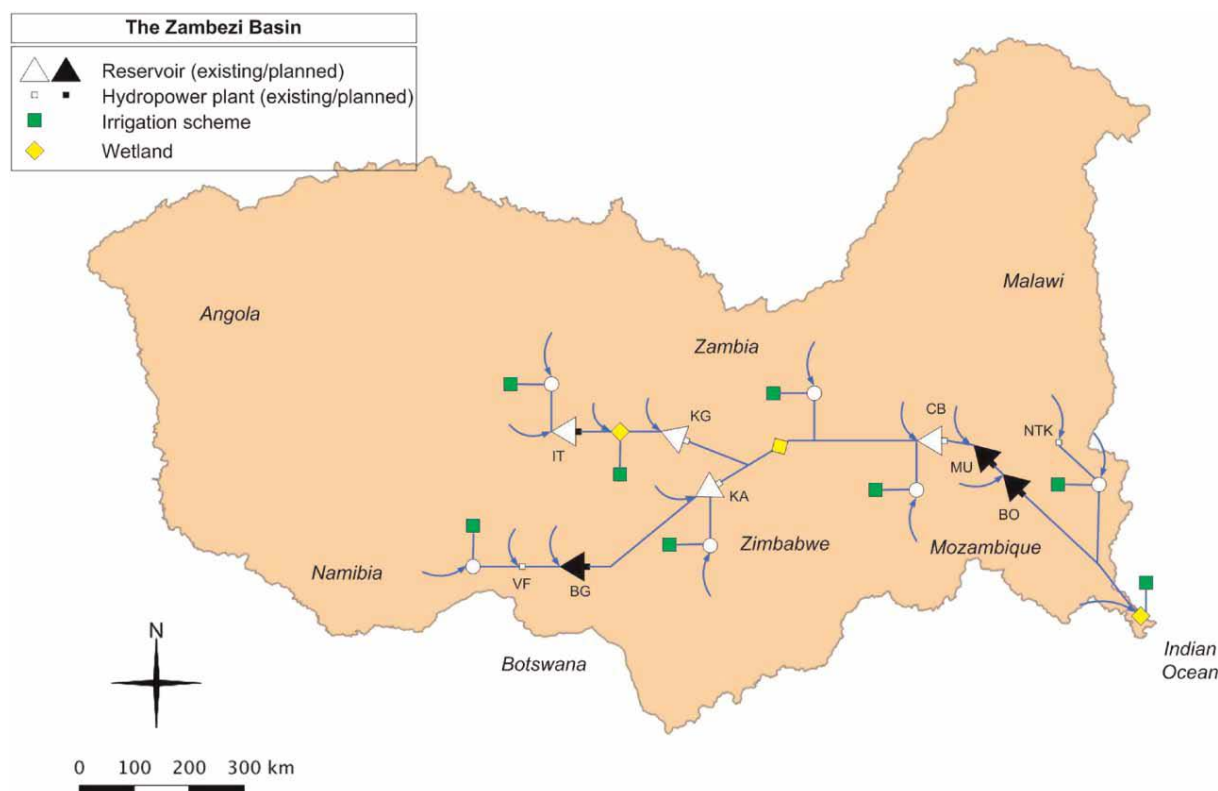
We attempt to answer these questions by formulating the allocation problem as a stochastic hydroeconomic optimization problem, which is solved by an algorithm that belongs to the so-called approximate dynamic programming field (Powell, 2007). The model, called stochastic dual dynamic programming (SDDP), seeks to maximize the sum of net benefits over a given planning period taking into account physical, economic and institutional constraints. It provides statistical distributions of allocation decisions (withdrawals, reservoir releases, spills, storage volumes) and various economic data such as marginal water values, which can be used to analyze the system.

## 6.2 The Zambezi basin

The focus area for the study is the Zambezi basin which has a catchment area of 1.39 million km<sup>2</sup> and is located in south east Africa (Figure 6.1). The river rises in the Kalene hills in north-west Zambia and flows through nine riparian countries along its 2,750 km length, before outfall into the Indian Ocean in Mozambique. It has many tributaries and, in Mozambique, the delta is distinguished by a wide, flat, marshy area with extensive floodplains. The river has three distinct stretches: the Upper Zambezi from its source to Victoria Falls, the Middle Zambezi from Victoria Falls to Cahora Bassa (which includes the major tributary, the Kafue River), and the Lower Zambezi from Cahora Bassa to the delta.

Four main dams exist on the Zambezi: the Kariba dam (1959) and the Cahora Bassa (filled in 1974) are both located on the main stem with installed capacities of 1,350 and 2,075 MW, respectively; the other two dams are located on the Kafue River, only one of which currently has hydroelectric capacity.

Figure 6. 1 The Zambezi River basin



The Kafue dam has an installed capacity of 900 MW while the Iteshi-teshi acts as a storage dam, collecting water for the Kafue dam. Both the Kariba and Kafue dams are currently being upgraded and significant work is underway towards planning new infrastructures in the basin. Table 6.1 lists the main characteristics of existing and planned dams including their average productivity, which corresponds to the net benefit per unit of water used (US\$/1,000 m<sup>3</sup>) when the average energy value is US\$40/MWh (see below). Kafue Gorge, a high head power plant in Zambia, is by far the most productive of all the stations in the basin: 1 m<sup>3</sup> of water flow through the turbines of Kafue Gorge is almost four times more valuable than 1 m<sup>3</sup> at Batoka Gorge, the next more productive station.

Table 6.2 lists the existing and potentially new irrigated areas per country in the Zambezi basin (Euroconsult, 2008). By 2030 the area under irrigation could increase by a factor of four, which would correspond to an addition of 20,000 ha per year over a period of 25 years. According to The World Bank (2008), the production of cereals is expected to be the main driver for this growth. The main ecologically sensitive areas are the Kafue flats in Zambia, the Mana Pools (a World Heritage Site) in Zambia and Zimbabwe, the Barotse Plain in Zambia and, finally, the Zambezi delta in Mozambique. During pre-impoundment times, and therefore also pre-regulation, these wetlands were healthy ecosystems, shrinking and growing according to the natural flow regime. Today, the large reservoirs and hydropower stations have altered the hydrological regime, degrading these fragile ecosystems (Gammelsrod, 1996). This has triggered a series of studies to better understand the value of these wetlands (Turpie et al., 1999; Timberlake, 2000; Beilfuss, 2001).

Table 6. 2 Irrigated areas

Country	Existing Area (ha)	Potential new area (ha)
Angola	1,989	20,000
Botswana	4	40,000
Malawi	43,987	163,000
Mozambique	11,211	49,000
Namibia	139	15,000
Tanzania	9,070	15,000
Zambia	34,016	117,600
Zimbabwe	70,850	45,360
<b>Total</b>	<b>171,266</b>	<b>464,960</b>

### 6.3 Stochastic hydro-economic model for the Zambezi basin

The allocation problem in the Zambezi was solved by SDDP, an optimization technique well suited to sequential decision-making problems. SDDP is an extension of traditional discrete stochastic dynamic programming (SDP) that can handle a large state space, i.e. a large number of reservoirs. SDP solves the multistage decision-making problem by solving a set of recursive, one-stage, optimization problems in which the decision variables are chosen so as to maximize the sum of expected immediate and future benefits. SDDP belongs to the so-called Approximate Dynamic Programming field, where the main idea to remove the computational burden associated with discrete dynamic programming consists of constructing an approximation of the benefit-to-go function (Powell, 2007). In SDDP, the approximation relies on piece-wise linear functions (hyperplanes) which are constructed from the primal and dual information of the one-stage optimization problems.

This section only provides an overview of the algorithm; readers should refer to Tilmant et al. (2008) for a recent and complete description of the SDDP algorithm. Let  $Y_t$  and  $X_t$  be the state and the decision vectors respectively at stage  $t$ . The state vector typically includes the vector of storage volumes, the vector of reservoir inflows and the vector of volumes of water diverted to irrigation demand sites. The decision vector, on the other hand, includes the vector of turbined outflows, the vector of irrigation withdrawals, and the vectors of spillage and evaporation losses.

Assuming that the immediate benefit function  $f_t(\cdot)$  is linear, and using  $L$  hyperplanes to approximate the benefit-to-go function  $F_{t+1}$ , the one-stage SDDP optimization problem can be written as:

$$F_t(Y_t) = \max\{f_t(Y_t, X_t, X_{t+1}) + F_{t+1}\}$$

subject to:

$$\underline{Y}_t \leq Y_t \leq \bar{Y}_t$$

$$\underline{X}_t \leq X_t \leq \bar{X}_t$$

$$Y_{t+1} = g(Y_t, X_t)$$

where  $g$  is a transition function.

The following  $L$  constraints are the hyperplanes providing an outer approximation of  $F_{t+1}$ :

$$\begin{cases} F_{t+1} - (\alpha_{t+1}^1)^T Y_{t+1} \leq \beta_{t+1}^1 \\ \vdots \\ F_{t+1} - (\alpha_{t+1}^L)^T Y_{t+1} \leq \beta_{t+1}^L \end{cases}$$

where  $\alpha_{t+1}^L$  and  $\beta_{t+1}^L$  are the parameters of the expected  $L^{\text{th}}$  hyperplane, which are derived from the primal and dual information available after the solution of the SDDP one-stage optimization problem at stage  $t+1$  (while the model is progressing backward in time). Details on the derivation of hyperplane parameters can be found in Goor et al. (2011).

The immediate benefit function  $f_t(\cdot)$  can include up to three terms: (1) the net benefits from energy generation; (2) the net benefits from irrigated agriculture (only observed at the end of the irrigation season, which is specific for each crop); and (3) penalties for not meeting operational, physical, institutional and/or legal constraints such as minimum flows, minimum storage volumes, minimum water withdrawals, etc. Note that capital costs are ignored and considered as sunk costs, which is a reasonable assumption for mid-term water allocation among sectors, i.e. when the capacity of the hydraulic infrastructures remains the same (Young, 2005).

The SDDP model for the Zambezi basin includes 17 nodes, as depicted in Figure 6.1. Due to the low level of development in the upper Zambezi, a single node is used to represent irrigation and other consumptive uses in the upstream countries (Angola, Botswana, Namibia). The planning period was defined as 120 months, while the number of SDDP simulation sequences is set at 50: in other words, the optimal reservoir operating policies calculated during the optimization phase of SDDP are simulated 50 times over a period of 10 years. These 50 hydrologic sequences are generated by a built-in periodic autoregressive model with cross-correlated residuals whose parameters were estimated from time series of historical natural discharges, provided by Dr R. Beilfuss or derived from the Global Runoff Data Center (GRDC, World Meteorological Organization). Beilfuss & Dos Santos (2001) carried out an extensive hydrological study of the Zambezi to reconstruct the historical time series at key locations in the basin using statistical analysis techniques. Historical monthly inflows over 30 years could have been used in simulation but it was decided to increase the number of sequences in order to get finer empirical statistical distributions of the results. The number of sequences is a trade-off between the representativeness of the stochastic process that generates the inflows and computation time.

The economic valuation of water for hydropower requires that a value be assigned to the energy (MWh) produced by the hydropower plants. In this study, we assume that the increase in energy load will be matched by cheap domestic (South African) coal-fired power plants and by hydroelectric power plants. Consequently, a value of US\$40/MWh is attached to the energy generated by the system. Note that the Master Plan for the Mozambican Power Sector released in 2009 also assumes energy values between US\$20/MWh and US\$60/MWh.

For the irrigation demand sites, we assume horizontal demand curves with an at-site water value of US\$50/1,000 m<sup>3</sup>, which is consistent with international experiences (Whittington et al., 2005; Young,

2005). This value is somewhat lower than those found in Hoekstra et al. (2001) (US\$110–US\$160/1,000 m<sup>3</sup>) because our study focuses on marginal uses and thus marginal crops, which are the least valuable in the crop mix. Moreover, since this study deals with mid-term (seasonal) allocation problems, only short-run estimates of marginal water values are needed, and they tend to be lower than long-run ones. Table 3 lists the typical annual crop water requirements (CWR) for various regions in the Zambezi basin (Denconsult, 1998).

Finally, two-block demand curves are also attached to the three largest wetlands considered in this study to maintain the hydrological dynamics in the river, including high and low flows. The at-source water value in the first block is equal to US\$10/1,000 m<sup>3</sup>, a medium value as explained in Tilmant et al. (2010). Note that the value in the second block is always set to zero to reflect that excess water is valueless. Beyond a certain flow, that value could even become negative to reflect the damages caused by large floods. However, because reservoir operators have strong incentives for storing water during the high flow season, a third block with a negative value would not change the reservoir operating policies as it would barely be visited. The target flows, which define the size of the first block, are 6,000 m<sup>3</sup>/s in the Delta, 2,500 m<sup>3</sup>/s in the Mana Pools and 300 m<sup>3</sup>/s in the Kafue Flats. These demand curves are imposed on the system in February and March in order to force the reservoir to release more water during the high flow season.

## 6.4 Management and development scenarios

To study the intersectoral allocation of water in the Zambezi, several management and development scenarios were analyzed. All the scenarios share the following features: they all include the power stations listed in Table 1, and the potential irrigated areas and the crop water requirements given in Tables 6.2 and 6.3, respectively.

However, the scenarios differ in: (i) the allocation policy for irrigation water; (ii) the value attached to environmental flows; and (iii) the type of hydroelectric power station (storage versus run-of-river). When it comes to allocating water to the various irrigation demand sites, two different policies are investigated: a static and a dynamic one. As its name indicates, a static policy considers irrigation water as a static asset: farmers are receiving fixed amounts of water regardless of their economic productivity and the hydrologic status of the system. In other words, this policy reflects a ‘food security’ concern and would be translated by giving priority to the irrigation sector within each riparian country. If water were considered as a dynamic asset, it would be allocated so as to maximize its productivity; this would also correspond to an economically efficient allocation mechanism. Although economic efficiency is not the single criterion to be considered when designing allocation mechanisms (Dinar et al., 1997), economic efficiency does provide a yardstick against which the other policies can be compared. Moreover, we consider here that a cooperative development of the Zambezi basin would ultimately lead to the implementation and management of infrastructure that maximize basin-wide benefits.

Table 6. 3 Crop water requirements (CWR)

Country/region	CWR (m <sup>3</sup> /ha)
Mozambique (Delta)	7,690
Mozambique (Tete)/Zimbabwe (Tete)	4,910
Malawi/Tanzania (Shire)	7,430
Zambia (Luangwa)	4,700
Zimbabwe (Kariba)	8,060
Zambia (Kafue)	8,050
Upper Zambezi	4,660

As mentioned in the previous section, different values for the environmental flows are considered. In scenario 1, the value of environmental flows is negligible and the ecological services are simply ignored. In this scenario, water is allocated to maximize the benefits from the other two sectors: irrigation and energy. In the second and third scenarios, environmental flows do have a value in February and March in order to force the reservoirs to release more water during the high flow season and to mimic the natural hydrological regime. The extent to which the hydrological regime can be restored will depend on the value attached to those environmental flows. Based on preliminary runs (Tilmant et al., 2010), a value of US\$10/1,000 m<sup>3</sup> is given to environmental flows.

Finally, scenario D focuses on environmental integrity by preserving the natural hydrological regime. This is done by replacing all the storage power plants in the system by run-of-river ones. In this imaginary scenario, the absence of storage capacity implies that river discharges are not altered by the power stations and that the impact of the energy sector on the wetlands is minimal. This scenario is of course not realistic (the huge reservoirs do exist), but the comparison with other scenarios will help us assess the economic value of storage in the Zambezi. Table 6.4 describes the different scenarios. Analysis of scenario A will reveal the number of hectares that can be irrigated in each country and that are still basin-wide optimal. In fact, the irrigation areas can be derived from the statistical distribution of the annual volumes of water diverted to the irrigation demand sites and a given reliability level: the volumes of water diverted to the irrigation demand sites belong to the set of decision variables and are thus available at the optimal solution; the reliability level, on the other hand, indicates the frequency by which the irrigation demand sites will be supplied without rationing. For example, a 66% reliability means that farmers will get their annual entitlements two years out of three.

Comparing scenario B to A provides an estimate of the benefits forgone by the hydropower sector should priority be given to the irrigation sector. In a dynamic allocation scheme, farmers directly compete with downstream power stations and, since they are mostly non-rival water users, their water demands can be summed vertically, meaning that the water value for power generation can become quite high compared to that of irrigated agriculture. In other words, downstream power stations can form a coalition in order to attract water downstream. If priority is given to agriculture, then this mechanism no longer works and farmers receive their annual entitlements independently of their productivity. With less water available for the power stations, the reduction in net benefits is the opportunity cost associated with the complete development of all irrigation demand sites listed in Table 6.3.



The comparison between scenarios A and C will help us understand the impacts of environmental flows on the production of hydroelectricity and on the number of irrigated hectares that could be developed in the basin. Implementing environmental flows in a hydropower-dominated basin will obviously reduce the power producers' flexibility, i.e. their ability to adjust power generation, and may also affect the amount of energy that can be generated by altering the draw-down refill cycle. The impact on the agricultural sector should however be limited since the environmental flows are needed during the high flow season when crop water requirements are low. Thus, the opportunity cost associated with these environmental flows is likely to be borne by the power sector.

Table 6. 4 Scenarios

Scenario	Allocation to irrigation	E-flows	Storage	Interpretation
A	Dynamic	No	Yes	Focus on hydropower generation→Energy security
B	Static	Yes	Yes	Focus on irrigated agriculture→Food security
C	Dynamic	Yes	Yes	Water–agriculture–energy–environment nexus
D	Dynamic	No	No	Focus on environmental flows→Environmental integrity

The comparison between scenarios B and C will allow us to assess the impacts of a full development of the irrigation sector. Here again the impacts are likely to be felt primarily by the power sector since irrigation withdrawals will reduce the volume of water that can be released through the turbines of the downstream power stations at a time when the electrical load, and therefore energy prices, are high (June–October). Together with the comparison between A and C, we should also be able to assess the relative contribution of policies focusing on food security or driven by ecological considerations on power production.

Finally, scenario D, which represents a situation in which there is no storage capacity (where there is no dam or where the reservoirs are operated at constant pool elevation) is used as a benchmark to assess the economic value of seasonal storage capacity in the Zambezi. As can be seen in Table 6.4, there is no value attached to environmental flows; water is no longer a scarce resource during the high flow season as it is no longer stored upstream in the reservoirs.

## 6.5 Analysis of simulation results

After convergence, the SDDP model provides statistical distributions of primal and dual results obtained from the last simulation (forward optimization) phase. The most interesting results here are the turbined outflows, spillage losses, storage volumes, evaporation losses, irrigation withdrawals and irrigation return flows. Since the simulation is carried out over 50 synthetic streamflow sequences, each result consists of a population of 50 members whose empirical cumulative distribution function provides a complete description of the uncertainty. Remember that the cumulative distribution function  $G(X)$  of a random variable  $X$  gives the non-exceedance probability of  $X$  for a given value  $x$ :

$$G(X) = P(X \leq x).$$



### 6.5.1 Basin-wide benefits

The subsequent analysis focuses on the two dominant sectors: energy generation and irrigated agriculture. On average, the maximum total benefits that can be reaped from the Zambezi system is around US\$2.60 X 10<sup>9</sup>/year, with hydropower having the lion's share (95%). As shown in Table 6.5, these hydropower and irrigation benefits are not evenly distributed amongst the riparian countries: Mozambique would provide much of the energy whereas Tanzania/Malawi would be the main food producers.

The storage capacity of the three largest hydroelectric reservoirs contributes to 17% of these benefits: the average economic value of flow regulation in the Zambezi is US\$443 million/year, with a minimum and a maximum of US\$136 million/year and US\$744 million/year, respectively. Remember that the difference between scenarios A and D reveals the economic value of the three largest reservoirs, i.e. the ability to move water in time. It is this value that should ultimately be traded-off against the environmental and social costs due to the disturbed flow regimes that follow the damming of freeflowing rivers.

Compared to the current situation, the increase in net benefits is substantial. The current situation includes the existing power stations in Table 6.1 and the existing irrigation areas listed in Table 6.2.

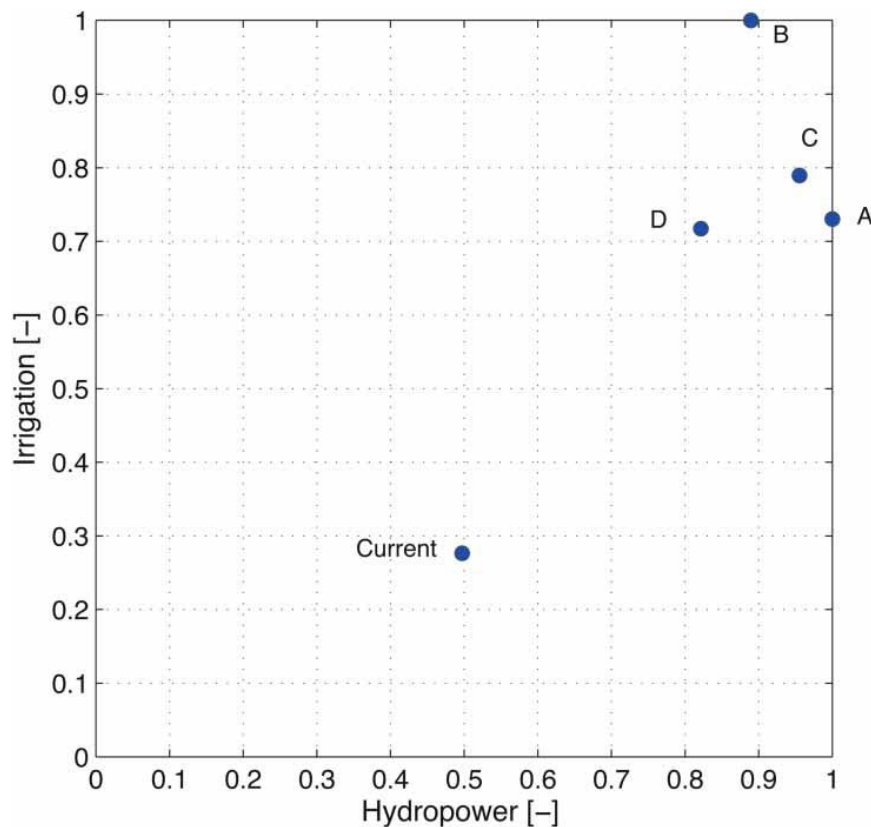
Table 6. 5 Average annual benefits

Sector/distribution	Scenario A	Scenario B	Scenario C	Scenario D
<i>Hydropower (US\$ million/year)</i>	<i>2,480</i>	<i>2,206</i>	<i>2,369</i>	<i>2,037</i>
Malawi (%)	2	2	2	2
Mozambique (%)	55	59	54	52
Zimbabwe (%)	10	6	10	8
Zambia (%)	33	33	34	38
<i>Irrigation (US\$ million/year)</i>	<i>111</i>	<i>152</i>	<i>120</i>	<i>109</i>
Kafue Flats (%)	1	6	1	7
Upper Kafue (%)	1	16	2	13
Lower Kafue (%)	0.1	0.1	0.1	0.1
Upper Zambezi (%)	10	10	12	10
Mozambique/Zimbabwe (Tete) (%)	8	8	9	8
Malawi/Tanzania (Shire) (%)	51	37	47	38
Mozambique (Delta) (%)	13	10	12	10
Zambia (Luangwa) (%)	3	2	3	2
Zimbabwe (Kariba) (%)	12	11	14	12

Figure 6.2 displays the net benefits normalized on a unit interval. It shows the relative increase in net benefits in the two main sectors (hydropower and irrigation) when moving from the current situation to the possible future situations represented by the different scenarios. The current net benefits from hydropower generation and irrigation correspond to 50 and 30% of their respective maximum potential, respectively. As indicated earlier, the maximum potential for hydropower generation would be achieved in scenario A only if the riparian countries agree to forgo 28% of the maximum

potential net benefits from irrigated agriculture (point A). At the other extreme lies point B, where the maximum irrigation potential is achieved for a loss of about 10% of the hydropower potential. Scenario C is located in between B and A by attempting to restore a flow regime in the largest wetlands. Since this objective is difficult to commensurate, it is not shown here, but the best results are obtained with the imaginary scenario D where the storage power plants are replaced by run-of-the-river ones. In that case, the Zambezi could produce roughly 80 and 70% of the maximum potential benefits in both sectors.

Figure 6. 2 Normalized net benefits from the hydropower and irrigation sectors



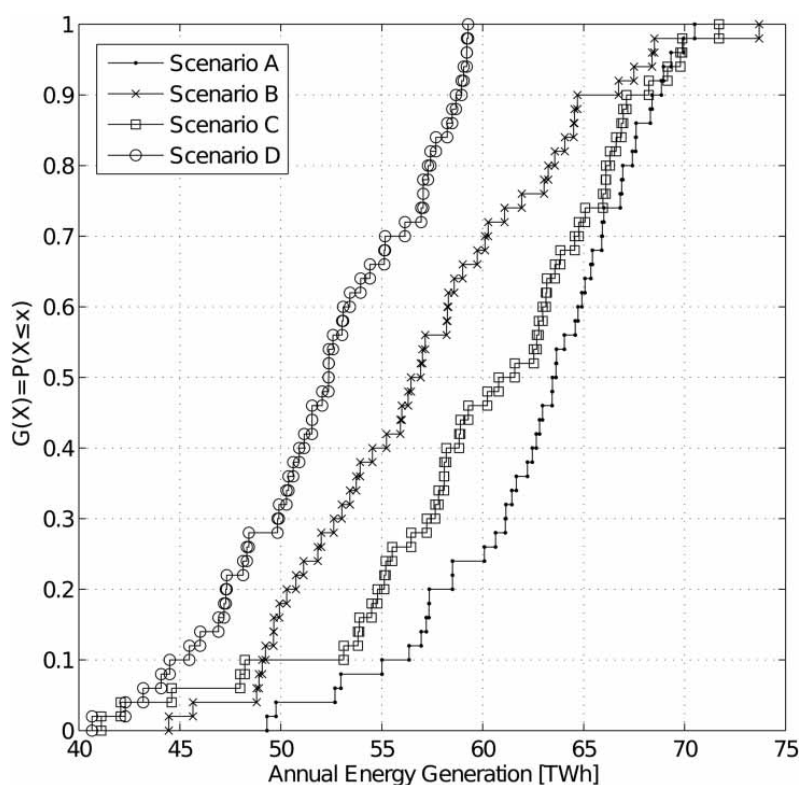
The examination of Figure 6.2 also reveals that the role played by the large hydroelectric reservoirs (Kariba, Itzhi-tezhi, Cahora Bassa) will remain the same in the future; they are mostly single-purpose infrastructures for energy generation. The comparison between points A and D shows that downstream irrigation (e.g. in Mozambique) does not benefit from the regulation capacity of this infrastructure. In both cases, about 73% of the potential maximum irrigation benefits can be achieved, indicating that the irrigation sector is independent of the three largest man-made reservoirs in the basin.

### 6.5.2 Hydropower generation

Figure 6.3 displays the cumulative distribution functions of the annual energy that can be generated by the system for the four different scenarios. As expected from the definition of the scenarios, the largest production of energy is achieved under scenario A with a median value of 63 TWh ( $63 \times 10^9$  kWh), while only 52.5 TWh can be produced if the power stations do not have storage capacity (sce-

nario D). In other words, the presence of reservoirs increases the average annual production of hydroelectricity by 24%. This is also reflected in the load factor, which is the percentage of time that a power station is running at full capacity; it increases from 59% in scenario D to 73% in scenario A. Looking at firm energy (defined here as the energy that can be generated 90% of the time) the differences between scenarios A and D is fairly similar with a loss of 12 TWh. We can also see that the contrast between dry and wet years is significant. For scenario A, for instance, the production under wet hydrological conditions can be as high as 70 TWh, but only 49 TWh during the driest year.

Figure 6. 3 Annual energy generation: statistical distributions



If the priority were given to irrigated agriculture (scenario B), the average reduction in annual hydropower generation would be 5.86 TWh. With an average energy price at US\$40/MWh, the benefit forgone for the power sector would be around US\$234 million/year. This cost corresponds to 9% of the average annual benefits (US\$2.59 X 10<sup>9</sup>/year) and involves 1.25 km<sup>3</sup>/year of water transfers, i.e. 39.6 m<sup>3</sup>/s, which is less than 20% of the average evaporation losses from the reservoirs (7.8 km<sup>3</sup>/year), and only 1% of the average Zambezi discharge into the ocean (4.155 m<sup>3</sup>/s). Similarly, if the multi-reservoir system were operated taking the value of wetlands into account (scenario C), the average reduction in hydropower generation would be 2.61 TWh (US\$104 million/year).

Table 6.6 lists, for each scenario, the expected SDDP-derived annual production of each power station. As expected from the installed capacity, the largest contribution comes from Cahora Bassa followed by Mependa Uncua, both in Mozambique. They both account, on average, for more than half of the energy generated in the basin. The comparison between scenarios A and B reveals that under normal hydrologic conditions, the energy output from Kariba and Batoka Gorge, both on the Zambezi main stem at the border between Zambia and Zimbabwe, would be affected by increased irrigation

withdrawals in the upper Zambezi. The same pattern is observed in the Kafue basin where increased consumptive uses in the upper reaches would reduce the output of Itezhi-tezhi and Kafue Gorge power plants. The impact on Cahora Bassa and Mependa Uncua in Mozambique is less evident due to the large incremental flows from the confluence of the Zambezi and Kafue to the Cahora Bassa reservoir. However, the production at Cahora Bassa would be reduced by 23% if there were no upstream reservoir (scenario D). Note that the even larger reduction (-36%) observed at Kafue Gorge stresses the important role played by the Itezhi-tezhi reservoir in regulating the inflows into Kafue Gorge (at the cost of degraded wetlands in the Kafue flats located in between these two infrastructures).

Table 6. 6 Average annual energy generation (TWh/year)

Name	Scenario A	Scenario B	Scenario C	Scenario D
ROR plants (Shire)	1.1	1.1	1.1	1.1
Boroma	1.33	1.24	1.25	0.97
Mependa Uncua	12.4	11.26	11.57	8.68
Cahora Bassa	20.83	20.25	19.71	16.1
Kariba	6.74	5.58	6.36	6.81
Batoka Gorge	7.9	7.85	7.86	7.97
Victoria Falls	0.88	0.87	0.87	0.88
Kafue Gorge	10.66	8.01	10.5	9.11
Itezhi-tezhi	0.82	0.64	0.82	0.49
Total	62.66	56.8	60.05	52.13

### 6.5.3 Irrigated agriculture

If water were allocated to its most productive uses, such as in scenario A, the upstream irrigation areas would be in a difficult position: the upstream farmers would face a coalition of downstream consumptive and non-consumptive users, and would therefore be likely to see their entitlements curtailed, especially during dry years when marginal water values increase throughout the basin. The comparison of the maximum potential irrigated areas and the average number of hectares that can be effectively irrigated with the economically efficient allocation decisions is shown in Figure 6.4. The size of the horizontal bars is proportional to the potential number of hectares that can be irrigated in the region. Each bar is then subdivided into two parts: light grey gives the proportion of hectares that can effectively be irrigated, and dark grey gives the unserved irrigation areas. We can see that the unserved irrigation areas are mainly located upstream. As explained earlier, this is due to the fact that the hydropower stations are mostly non-rival water users; their water demands can therefore be summed vertically, meaning that the at-source water values will increase stepwise with the distance from the ocean. Consequently, everything else being equal, an upstream farmer must be highly productive in order to compete with the cascade of power stations.

Figure 6. 4 Average number of irrigated hectares (scenario A)

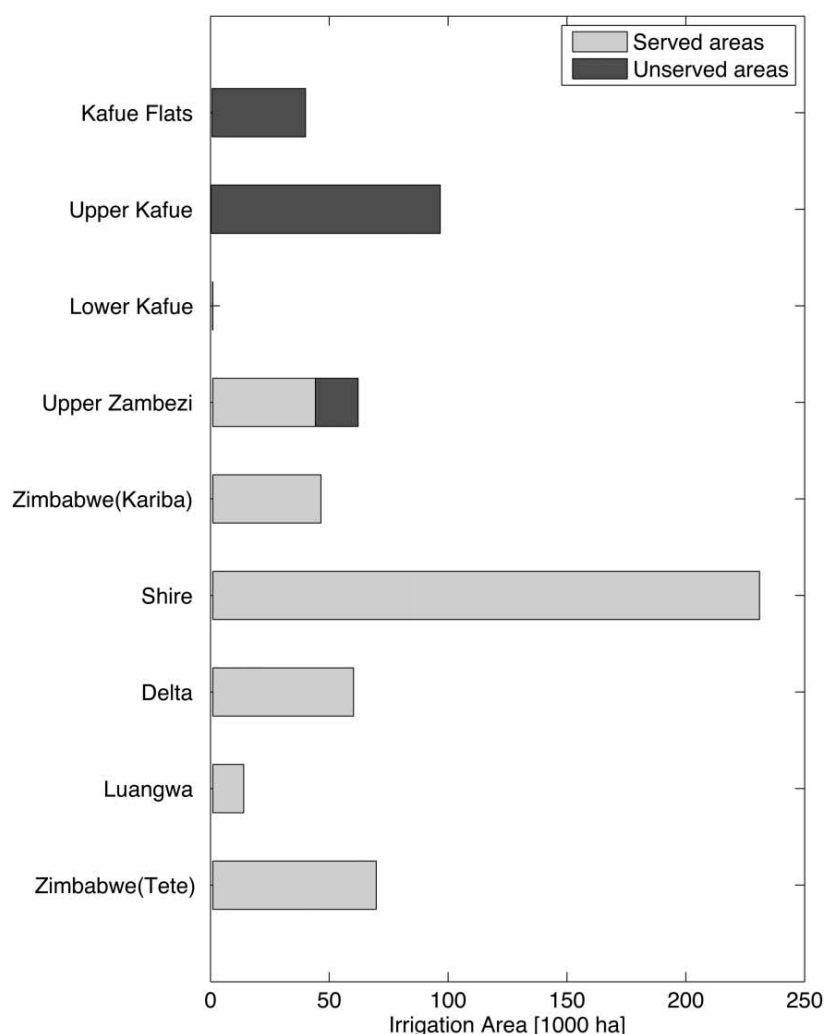
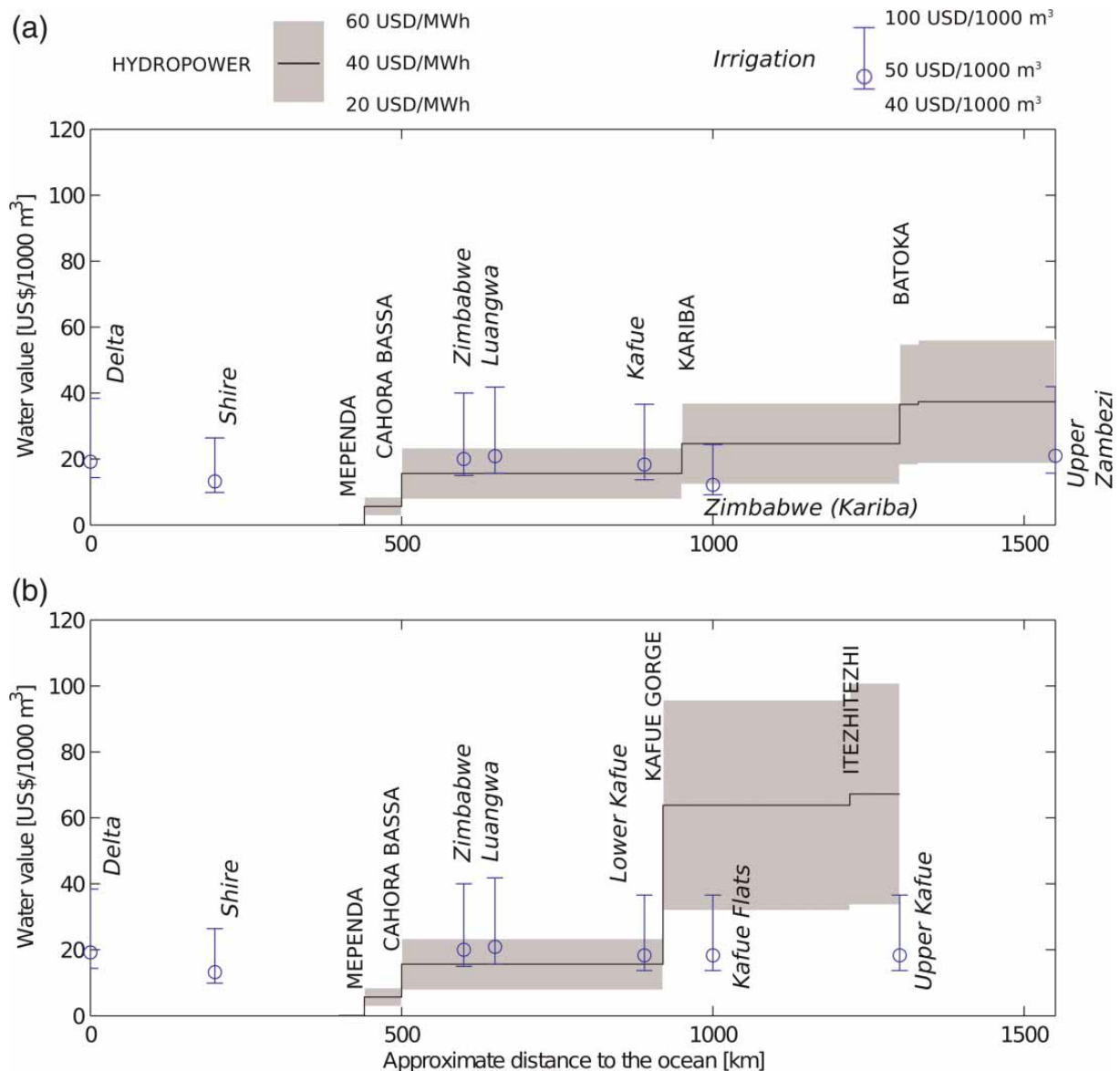


Figure 6.5 shows the longitudinal profiles of the water value for electricity generation. The first profile corresponds to the Zambezi main stem whereas the second one shows the Lower Zambezi–Kafue system. Water value for hydropower generation increases up to about US\$40/1,000 m<sup>3</sup> at Victoria Falls on the Zambezi main stem. In the Kafue, a sudden increase is observed at the Kafue Gorge power station, which is a high head, efficient, power plant. Upstream of Kafue Gorge, the water value is above US\$60/1,000 m<sup>3</sup>. Hence, from an economically efficient point-of-view, a farmer in the Upper Kafue who wants to fully irrigate the area under command should be almost twice as productive as a farmer in the Upper Zambezi. Although this proposition is not realistic, it is useful to provide the information in order to understand the economic consequences, especially the opportunity costs, of unilateral developments.

During wet years, when the marginal at-source water values tend to decrease, it may become economically sound to irrigate areas that were previously not cultivated because the withdrawal decisions were not economically efficient. Although farmers can adjust the number of irrigated hectares according to the supply conditions, water is usually allocated by a system of annual rights to use a fixed volume of water, which is typically less than what farmers would expect. Risk-prone farmers might take advantage of the upsides associated with the uncertainty of supply. Risk-averse farmers,

however, prefer to receive constant supply and, for them, the annual entitlements are also expected to remain fairly constant. Remember that scenario B gives priority to the irrigation sector; in that case, all the irrigation demand sites are fully supplied and no rationing occurs.

Figure 6. 5 Water values: longitudinal profile



#### 6.5.4 Marginal water values

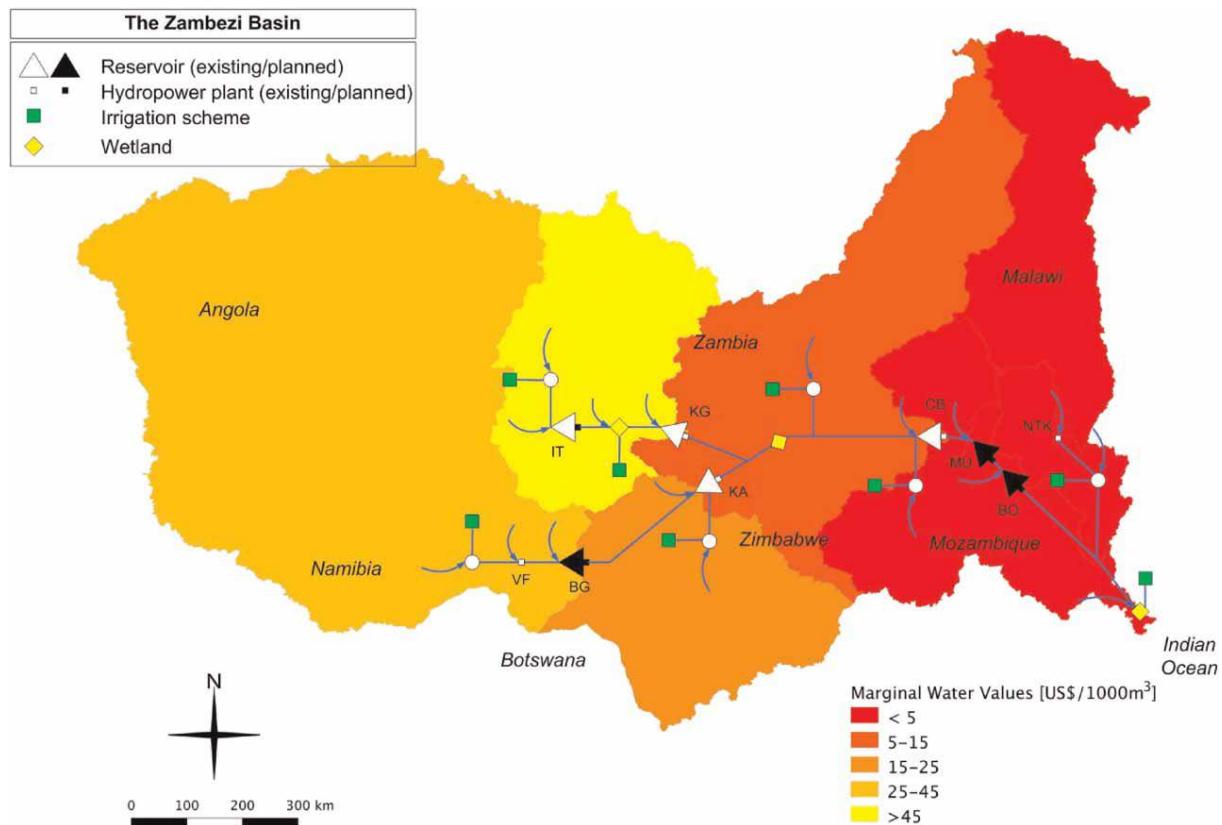
When analyzing water resources allocation problems, it is often interesting to examine the marginal water values. The marginal value of water gives the contribution of an additional unit of water to whatever public or private objective is under consideration. Marginal water values can be used in river basin management to signal water scarcity, to prioritize zones where soil and water conservation measures must be implemented, or to increase the productivity of water by (re)allocating it to more productive uses. Since markets are usually absent or ineffective, allocation decisions can seldom rely on market prices. Instead, accounting or shadow prices reflecting the value of water must be assessed. Here, the marginal water values correspond to the Lagrange multipliers associated with

the mass balance equations at each node of the network depicted in Figure 6.1. These multipliers, also called shadow prices, would correspond to market prices if water were being traded on a market.

Generally speaking, the type of water value to be assessed depends on the policy problem at hand. In this study we analyze mid-term allocation policies that can capture the stochasticity of the hydrologic input and, therefore, provide hedging strategies against the hydrological risk. Since a monthly time step is fairly common in mid-term (strategic) studies of hydropower systems (Labadie, 2004), the SDDP model identifies monthly release and irrigation withdrawal policies that maximize the net benefits associated with the operation of the system. Consequently, the model calculates short-run marginal water values; the fixed costs (e.g. dams, canals, hydropower plants) having zero opportunity costs are thus ignored. In addition, the model provides estimates of the marginal value of product and the benefits from return flows; existence values and the benefits from indirect uses are ignored. Finally, the Lagrange multipliers associated with the mass balance equations correspond to at-source water values, i.e. the value observed at a location where bulk water is diverted, whereas the at-site value corresponds to the value of water delivered to the off-stream user (at the end of the conveyance and distribution system). At-site water values are usually larger than at-source ones since they include losses in the conveyance/distribution system as well as conveyance and treatment costs.

The marginal water values are expected to vary both in space and time. The spatial dimension corresponds to the drainage area responsible for the incremental flows; any additional cubic meter generated in a given intermediate basin has the same value, as it will end up in the node that drains that basin. Figure 6.6 displays the marginal water values in the Zambezi and how they change in space. We can see that marginal water values in the Lower Zambezi and the Shire are close to zero meaning that there is no scarcity problems in these regions, which is confirmed by the fact that planned irrigated areas can be fully developed and supplied (see Figure 6.3). Moving upstream along the Zambezi main stem, the marginal water values increase according to the pattern illustrated in Figure 6.5 (a), where the lower and upper limits of the shaded area are derived from the minimum and maximum value of energy (i.e. US\$20/MWh and US\$60/MWh). For illustrative purposes, the at-source water values of the different irrigation demand sites (nodes) are also plotted. They are derived from the at-site value of US\$50/1,000 m<sup>3</sup>, the crop water requirements listed in Table 6.3 and the irrigation efficiencies. For comparative purposes, a lower and an upper bound on the at-source water values for irrigation are also calculated for at-sites values of US\$40/1,000 m<sup>3</sup> and US\$100/1,000 m<sup>3</sup>, respectively. Examination of Figure 6.5 confirms that irrigation activities remain competitive until Kariba and Kafue Gorge. Beyond these two points (power stations), especially in the Kafue basin, when striving for strict economic efficiency, irrigation should focus on high-value crops in order to minimize the opportunity cost (even when energy prices are low).

Figure 6. 6 Average water values in March (US\$/1,000 m<sup>3</sup>)

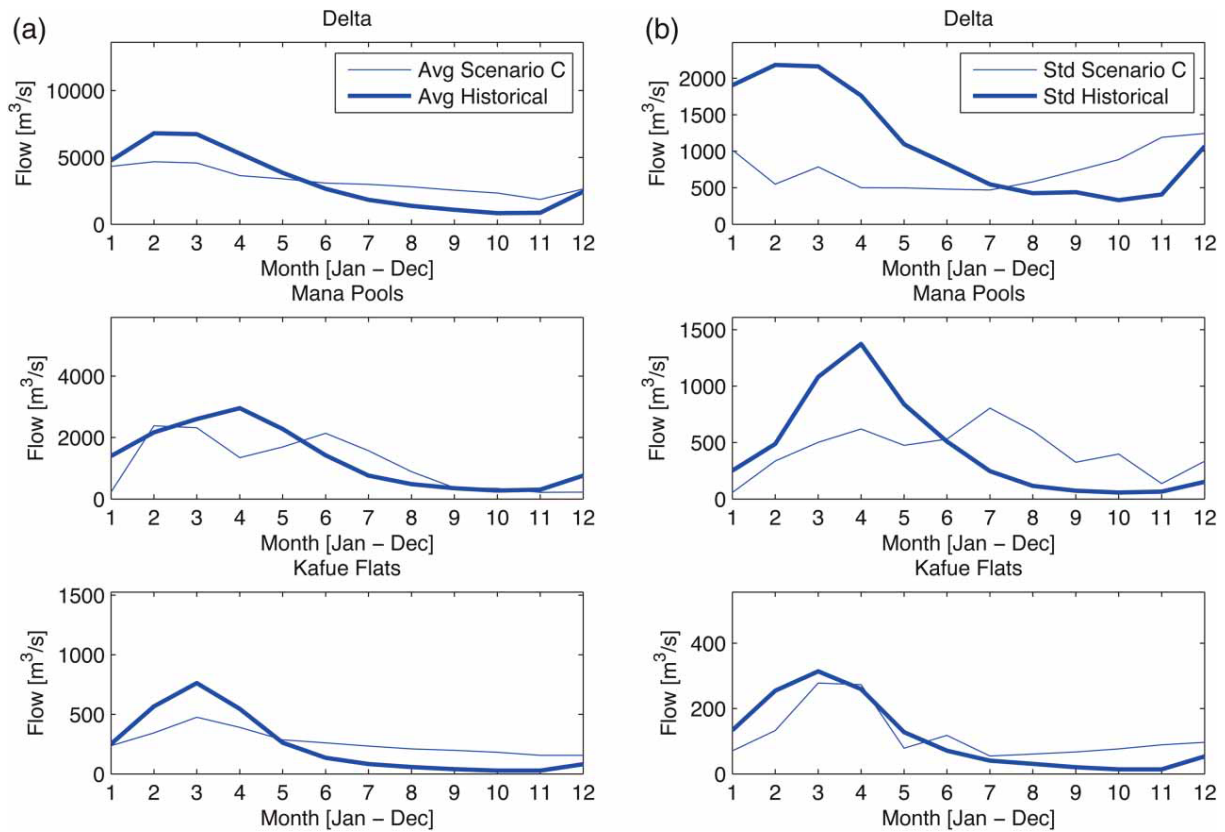


### 6.5.5 Environmental flows

Figure 6.7(a) displays the average monthly discharges in the three largest wetlands affected by dams and upstream water abstractions (scenario C). The thick lines represent the historical, undisturbed, average monthly flows, whereas the thin lines indicate the average discharge after regulation and abstraction. It can be seen that the discharges in the delta remain fairly constant throughout the year despite the fact that flood pulses are valued during the high flow season (at-source water value ¼ US\$10/1,000 m<sup>3</sup>). The difference between the dry and wet season is more evident in the two wetlands upstream, the Mana Pools and the Kafue Flats.



Figure 6. 7 Average (a) and standard deviation (b) of monthly discharges in the wetlands



The impact of the reservoir operating policies on the variability of the monthly discharges, which is represented by the monthly standard deviations in Figure 6.7(b), is also significant: as expected, the standard deviations are more or less constant throughout the year, whereas under natural conditions, the variability would increase during the high flow season. It is clear from Figure 6.7(b) that the year-to-year variability is dramatically reduced in the delta, and to a less extent in the Mana Pools and Kafue Flats. Restoring a flow regime in the delta will require a larger value being attached to the environmental flows.

## 6.6 Conclusions

The Zambezi basin is a largely untapped resource. Although sub-optimal in economic terms, expanding the irrigated areas in the upstream countries at a rate of 20,000 ha/year over the next 20 years would cost 9% of the total benefits that can be reaped from the basin (provided that the power stations that are in an advanced planning phase are all implemented). These new hydropower plants should not further degrade the major wetlands on which local communities rely as their combined storage capacity is much lower than that already existing. Increased water withdrawals for consumptive uses in the agricultural sector should also have moderate impacts downstream as the volumes of water lost by evapotranspiration remain largely smaller than the evaporation losses from the existing hydroelectric reservoirs.

The economic value of the storage services brought by the three largest existing reservoirs (Kariba, Cahora Bassa, Itzhi-tezhi) corresponds to US\$443 million/year, i.e. 17% of the expected total bene-

fits. The present study focuses on two dominant economic uses (irrigated agriculture and hydropower generation) and on environmental flows. Navigation and fisheries could also be included in the analysis should relevant information be made available.

## Acknowledgements

This study was initiated when A. Tilmant and L. Beevers were both at UNESCO-IHE (Delft, The Netherlands). The authors acknowledge funding by the ADAPT project (Competence Center for Environment and Sustainability, ETHZ, Switzerland) and by the POWER2FLOW project (UNESCO-IHE Partnership Research Fund).

## References

- Beilfuss, R. (2001). Hydrological Degradation, Ecological Dynamics and Restoration Potential: The Story of an African Floodplain. PhD Thesis, University of Wisconsin-Madison, WI, USA.
- Beilfuss, R. & Brown, C. (2006). Assessing Environment flow Requirements for the Marromeu Complex of the Zambezi Delta: Application of the Drift Model (Downstream Response to Imposed flow Transformation). Museum of Natural History, Maputo, Mozambique.
- Beilfuss, R. & dos Santos, D. (2001). Patterns of Hydrological Change in the Zambezi Delta, Mozambique. International Crane Foundation, Maputo, Mozambique.
- Denconsult (1998). Water Consumption and Effluent from Food and Agricultural Sector Including Fisheries and Livestock.
- Southern African Development Community, Water Division/Zambezi River Authority (SADC-WD/ZRA), Lusaka, Zambia.
- Dinar, A., Rosegrant, M. & Meinzen-Dick, R. (1997). Water Allocation Mechanisms: Principles and Examples. World Bank, Washington, DC, USA.
- Euroconsult (2008). Integrated Water Resources Management Strategy and Implementation Plan for the Zambezi River Basin.
- Southern African Development Community, Water Division/Zambezi River Authority (SADC-WD/ZRA), Lusaka, Zambia.
- Gammelsrod, T. (1996). Effect of Zambezi River management on the prawn fishery of the Sofala bank. In: Water Management and Wetlands in Sub-Saharan Africa. Acreman, M. C. & Hollis, G. E. (eds). World Conservation Union (IUCN), Gland, Switzerland.
- Gandolfi, C., Guariso, G. & Togni, D. (1997). Optimal flow allocation in the Zambezi River system. *Water Resources Management* 11, 377–393.
- Goor, Q., Kelman, R. & Tilmant, A. (2011). Optimal multipurpose-multireservoir operation model with variable productivity of hydropower plants. *Journal of Water Resources Planning and Management* 137, 258–267.
- Hoekstra, A., Savenije, H. & Chapagain, A. (2001). An integrated approach towards assessing the value of water: a case study on the Zambezi basin. *Integrated Assessment* 2, 199–208.
- Labadie, J. W. (2004). Optimal operation of multireservoir systems: state-of-the-art review. *Journal of Water Resources Planning and Management* 130, 93–111.
- Powell, W. (2007). Approximate Dynamic Programming: Solving the Curses of Dimensionality. John Wiley, Hoboken, NJ USA.
- Shela, O. (2000). Management of shared river basins: the case of the Zambezi River. *Water Policy* 2, 65–81.

The World Bank (2008). *Zambezi River Basin – Sustainable Agriculture Water Development*. The World Bank, Washington, DC, USA.

Tilmant, A., Pinte, D. & Goor, Q. (2008). Assessing marginal water values in multipurpose multireservoir systems via stochastic programming. *Water Resources Research* 44, W12431.

Tilmant, A., Beevers, L. & Muyumda, B. (2010). Restoring a flow regime through the coordinated operation of a multireservoir system – the case of the Zambezi River basin. *Water Resources Research* 46, WR07533.

Timberlake, J. (2000). *Biodiversity of the Zambezi Wetlands*. IUCN ROSA Biodiversity Foundation for Africa, Bulawayo/The Zambezi Society, Harare, Zimbabwe.

Turpie, J., Smith, B., Emerton, L. & Barnes, J. (1999). *Economic Value of the Zambezi Wetlands*. World Conservation Union (IUCN), Nairobi, Kenya.

United Nations (2010). *World Population Prospects Database, 2010*. UN, New York, NY, USA.

Whittington, D., Wu, X. & Sadoff, C. (2005). Water resources management of the Nile basin: the economic value of cooperation. *Water Policy* 7, 227–252.

Young, R. (2005). *Determining the Economic Value of Water – Concepts and Methods*. Resources for the Future, Washington, DC, USA.

## Chapter 7 Conclusion and Outlook

### 7.1 Zambia's treasure hunt

Zambia is now confronted with the challenge of implementing principles of good governance in the water sector and fostering an efficient, equitable, and socially optimal allocation of its water resources. This challenge is made even more complex by the interactions, development plans, potential for collaboration and tension derived from Zambia's strategic position within the water rich Zambezi River basin. Managing water for a complex set of national priorities in the uncertainty of future climatic and development scenarios and subject to the demands of the downstream Zambezi riparian countries is a multi-objective and stochastic problem by nature. The present work aimed at providing a set of answers to the water allocation question for Zambia at a national and regional scale within the boundaries given by the country's policy and legislative framework.

#### 7.1.1 Summary of results: opportunities and challenges ahead

The revised Water Policy (GoZ, 2010) approved by the Cabinet in February 2010 and the new Water Resources Management Act (GoZ, 2011b) approved by Parliament in 2011 clearly point towards the implementation of good water governance in Zambia. From a highly centralised structure for water governance that left little room to stakeholders' participation Zambia is moving towards a decentralised and participative governance framework in line with the principles of Integrated Water Resources Management. Given the short time since the enactment of the new regulations it is not surprising that the transition is far from being complete and big challenges to the effective implementation of the renovated governance framework exist. Human and financial resources are a main constraint that could hinder or delay the decentralisation process. A massive number of well-trained professionals will be needed to manage such decentralised institutions at national, catchment and sub-catchment level as well as to assist the work of the water users' associations. Without enhancing human and related financial capacity the success of the new water policy is at stake. In addition, there is also a resistance to change the current water governance system as some ministries fear to lose their power and authority with the decentralization process and a number of stakeholders, particularly in the agricultural sector, fear the implementation of additional water charging measures.

Effective participation is also a key issue not to be overlooked when integrated water management decisions are to be taken and participation has been an overall goal of the restructuring of the governance framework. Though the Kafue River basin was chosen as a pilot case for the early implementation of the renovated governance structure, the statistical analysis of data from a formal household survey that we conducted on the Kafue River basin shows worrisome low rates of awareness of and participation in the governance institutions. Only about 5.5 percent of the respondents declare to be aware of the institutions introduced with the recent Water Act, demonstrating that the institutional reforms have not yet been implemented on the ground. In particular, women participate the least and generally do not contribute to decision making with regards to water. This is in contrast to the pivotal role given to women's empowerment and participation in the 2010 Water Policy and 2011 Water Resources Management Act and the key role that they play in water collection and use in the rural areas. In order to implement an effective reform process with a strong decentralization focus that realizes the subsidiarity principle, it is a priority to increase smallholders' and women's awareness and participation in the water sector, and to improve the capacity of women to act politically in the management of water resources at the grass-root level.

The changing water governance structure presents invaluable opportunities for the Zambian society. Water in fact plays a critical role in the future economic development of the country and an improved management of water resources, based on a sound and well-structured governance framework, could foster country and region-wide economic growth. The overall water resources potential has not been fully tapped and plans exist to further develop both irrigated agriculture and hydropower production, particularly in the Kafue River basin. We analysed the Kafue's stakeholders' objectives and the potential trade-offs among different development options using a hydro-economic modelling framework. The optimisation model allows to determine a range of optimal solutions of the water allocation problem, among other things dependent on considerations of fairness in the distribution of water resources to different users (as a constraint for allocation of water to the urban centres) and the need to allocate water for environmental purposes (through the binding environmental flow constraint to the dams operation).

Zambia's key policy priorities and development objectives are the increase in irrigated agriculture, both large and small-scale farming, and the further development of the country's hydropower capacity. We analysed several development scenarios and we highlighted the trade-offs arising among different uses of water. Our analysis shows that, if current level of agricultural development is maintained, it would be possible for the Kafue River basin to further develop its hydropower resources. Nonetheless, particularly in a dry hydrological year, not all of the future agricultural developments are economically feasible, and the optimal allocation of water resources depends on the policy priorities of the stakeholders. Clear trade-offs exist between irrigation and hydropower generation due to the different temporal allocation necessary to maximise the net benefits from either agriculture or hydropower generation. Besides the tensions between irrigation and hydropower development, population growth across the Kafue basin alone will put a strain on water resources. This will force the government, among other things, to reduce water delivery system losses and increase efficiency in water use while striving to increase access to safe water and sanitation to urban and rural centres GoZ (2011a). In addition, the Zambian mining sector is also closely connected to the overall water management of the Kafue due to its considerable dewatering operations. Would dewatering cease, overall net benefits would be reduced by, on average, 20 percent with respect to the baseline case (today) indicating that it should be already compelling for the

government of Zambia to adopt forward-looking approaches to manage alternative sources of livelihood in the Copperbelt and ensure adequate supplies of water of sufficient quality for the growing cities.

A central theme that emerges from the studies at hand is the necessity for policy makers to consider the impacts of development scenarios on all water using sectors and the importance to proceed to a holistic assessment of the consequences of different water allocation scenarios and the intrinsic trade-offs between users' objectives. This is even more paramount considering that the Kafue River basin is a pivotal part of the Zambezi River basin. With the reform of the water sector Zambia significantly embraces the principles of Integrated Water Resources management both at national and Zambezi-wide level. In fact in May 2013, following all other Zambezi riparian countries, Zambia signed the Zambezi Commission (ZAMCOM) Agreement, which has been on the drawing board since 1987. If on one side the ZAMCOM provides the necessary framework to manage the Zambezi waters collectively for a shared long-term benefit (both social and economic), on the other side challenges lie ahead. The national and water-users objectives (often conflicting) need to be accounted for and ZAMCOM will have the difficult task to strike a balance. As the Kafue basin, the whole Zambezi basin already faces competition between, mainly, irrigated agriculture and hydropower generation. Although sub-optimal in economic terms, expanding the irrigated areas in the upstream countries at a rate of 20,000 ha/year over the next 20 years would cost 9% of the total benefits that can be reaped from the basin, provided that the power stations that are in an advanced planning phase are all implemented. These new hydropower plants should not further degrade the major wetlands on which local communities rely, as their combined storage capacity is much lower than that already existing.

### 7.1.2 Unearth the potential

Zambia's endowment of water resources is a treasure that still needs to be fully discovered. Several avenues exist to improve the country's management of water resources and the renovated policy and legal framework constitute a good foundation for the government and the stakeholders to enact measures that could foster the optimal management of water resources within the Kafue and the Zambezi River basin.

A priority for the government of Zambia should be the increased efficiency of the water supply network for the urban areas. Today about half of the water abstracted from the sources is lost throughout the conveyance network. The Zambian National Water and Sanitation Council (NWASCO) has already been given the mandate by the government of Zambia to introduce measures aimed at reducing water losses in the supply system and institutional audit teams have been created to implement strategies to address the issue. At the same time, though, water supply, together with sanitation, is a policy priority and the country's policy vision is to ensure access to water and sanitation to all users by 2030 (GoZ, 2011a). Progress on both objectives has remained slow so far: in the period 2012-2013 system losses were reduced by about 2.5 percentage points, still remaining at alarmingly high values around 42%, access to sanitation did not improve and national urban water coverage increased from 81.8 to 83.5 percent (UNDP, 2013). The allocation of additional funds to the water supply sector is to be expected but the government should be encouraged to prioritize projects that lead to the decrease of system losses, including the maintenance and substitution of the pipelines and measures to reduce water thefts. In addition the integration of urban planning and delivery of water supply services, and the increase of the share of metered users and the water supply revenue collection rate (at the moment still below 50% in the Kafue

region) should be the precondition for the future expansion of the water supply network and the sustainable operation of the water supply system.

At the same time our results showed that while efficiency in the water supply system will free considerable water resources that could be allocated to alternative uses, the main trade-offs emerge from the interplay of future agricultural and hydropower development. Significant investments are planned for the future ten to fifteen years in both the agricultural and hydropower sectors but our results show that not all developments can be undertaken at the same time. A careful investment planning is paramount for Zambia to appropriately allocate resources to those sectors that prove to be more strategic for the country. Our results brought to the surface the inherent trade-offs related to each scenario which should be considered when screening development initiatives according to financial, economic, social and environmental criteria. In addition, since development initiatives will generally be chasing scarce financial resources, some means of phasing objectives to match finance availability need to be anticipated. At the national level the generation of nationally owned recurrent and capital expenditure plans need to be much more adept at defining priorities and matching these with the various finance sources. This can be done in an iterative and consultative fashion through the collaboration of all stakeholders. The purpose of prioritization and phasing is to build in some measure of equity, certainly with respect to public expenditure and regional balance, and also to avoid dilution of investment where only periods of concentrated investment – such as building dams during dry seasons – will bring results.

Among the priorities that need to be considered at Zambia and Zambezi level is the environment. The massive developments planned will necessarily have an impact on the Zambezi wetlands, on its vegetation and wildlife, and ultimately on the existence of precious ecosystems. Our results showed that the current management of the dams in order to ensure environmental flows does lead to a bearable reduction of system net benefits. Nonetheless, the current operation rules of the Itzhi-tezhi dam that allow a minimum water release over a pre-defined period of time have been questioned by a number of stakeholders. It is thus the role of the river basin organisations or the Catchment Councils to consider the environment as a proper stakeholder and consider Pareto solution that would improve or at least not decrease the environmental status of key ecosystems. Taking the moves from scientifically based evidences and holistically considering all stakeholders' objectives it will be possible to consolidate a set of improved and agreed-upon operating rules for the reservoirs that could ultimately result in a Pareto-efficient solution.

It is indeed also important to recognise that significant benefits can be gained from the active cooperation of stakeholders and from the coordination of policies and actions. Our models show that it would be possible to co-ordinately manage the Kafue and the Zambezi systems for the joint benefits of the various sectors and countries involved. This is true only if stakeholders and countries agree to jointly set priorities and regulate the system based on the maximization of the marginal value of water. It would be possible then to enact a system of payments or compensations in favour of the sectors or countries that would need to bear losses. The Zambezi Commission at transboundary level would be in a good position to enact such coordinated management, but the organization still needs to be fully legitimized and empowered to effectively manage the Zambezi waters. At national level, instead, coordination could be achieved through a more appropriate use of the existing stakeholders' dialogue platforms. Our governance analysis showed that often the consultation processes are used as validation *fora* rather than occasions to foster a true participation of the stakeholders and stimulate dialogue on the essential issue of



identifying and prioritizing the development objectives for Zambia as a whole. The renovated governance frameworks sets the basis for a participatory approach to water management, but also in this case the governance institutions still need to be fully legitimized and the stakeholders' ownership of the whole reform process needs to be reinforced.

The reform process, in fact, has been guided and shaped in good part by the cooperating partners. When looking only at the snapshot provided by the results of our research, we should recognise that the objectives of the water governance reform are not fully understood and agreed upon by a good number of stakeholders. This has created uncertainties as to whether the implementation and uptake of the proposed reforms will be possible. If Zambia wants to harness its water resources the stakeholders need to share the vision and objective embedded in the new water governance framework and participate in shaping its future and the decisions related to water management. Only with a clear stakeholders' ownership of the governance structure it will be possible to ensure the long term success of the reform process.

## 7.2 Perspectives

A large amount of research studies have focused on the Zambezi and Kafue River basin systems and on the allocation dilemma of their waters. Our study is a unique example of comprehensive analysis of the water governance structure in conjunction with the economic aspects of water resources allocation. The massive amount of data required for our analysis, the integration of hydrological, economic, and governance models and data in a well-structured framework, the in-depth data collection conducted in the field, the need to understand and strike a balance between different societal objectives, and the necessity to constantly liaise with the stakeholders made this study an example of truly interdisciplinary and integrated research. Needless to say that such an ambitious research effort carries a number of limitations that future studies could complement and overcome.

### 7.2.1 Limits and future research

Like many other hydro-economic modelling efforts also for the model presented in this study a key aspect is the need to cut through complexity in order to, on one side allow a sufficiently realistic representation of reality and, on the other side, favour a clear understanding for decision makers of the main trade-offs facing water resources allocation. Assumptions and simplifications have been carried out throughout the study in order to ease the model construction and the interpretation of results.

Hydro-economic models are data-intensive structures. Zambia is rich in economic, social, and hydrological information and, on paper, a centralised authority mandated for data collection, the Central Statistical Office, exists in order to systematize and store a wealth of information, also water-related. Regrettably, though, the unclear structure of the Central Statistical Office, the often inadequate informatics capacities, and the lack of communication between the Central Statistical Office and other organizations in charge of data collection (e.g. other ministries, international organisations, research institutes) make data collection and cleaning a major effort. Some of the main challenges in data collection include: 1) duplications in mandates for data collection among different institutions; 2) incongruence of datasets collected from different sources; 3) incomplete time series and incongruent methodologies used for the same survey over time; 4) lack of a comprehensive Global Information System data depository; 5) granu-

lar but not systematic data on surface water pollution; 6) lack of comprehensive groundwater data (both in terms of quantity and quality).

These shortfalls led to a complex data collection process that involved a wide number of alternative sources, the careful comparison of data points, the quest for primary data, and the need to carry out data collection campaigns in successive rounds, also including the collection of own data. It was not possible, though, to solve all the data-related challenges. In particular, our model is constructed to include a full set of groundwater data, but the lack of data availability did not enable the author to fully exploit this feature of the hydro-economic model. In addition, the projections in terms of future hydrological and agricultural scenarios implemented in the hydro-economic model are examples based on the most accurate intelligence available at the time of the study. The hydro-economic framework is flexible to include additional scenarios and modify the existent ones, provided more accurate data are collected.

The mathematical formulation of the hydro-economic model can be refined and enhanced to take into account additional specificities of the Kafue River basin. Scientific studies are being carried out in the wetlands of the Kafue Basin to assess the relation between water levels, vegetation cover, and density of endemic fauna. Based on the results of such studies it would be possible to estimate appropriate ecological functions that would give a clearer and more accurate insight on the environmental benefits and costs related to different development scenarios. At the same time, the availability of information regarding the relation between water levels and fish catch across the basin could further enrich the correct understanding of the environmental demand for water. Finally, a complete pollution transport model could be accommodated within the existing modelling framework, which would allow accurately assessing the risk of pollution and its environmental and economic impacts. Pollution data quality and availability was not sufficient at the moment of the study, but further research could enhance the data basis and fulfil such objective.

Similarly, the water governance structure in Zambia is a living subject. The study at hand was developed in an extremely vivid and interesting period where we could monitor the evolution to a highly decentralised water governance system from an extremely centralised one. This historical moment created a number of structural complexities such as the need to repeat stakeholder interviews at different stages of the project and accept a certain degree of uncertainty in the stakeholders' responses. The authors could achieve an accurate picture of the changing governance structure, but the analysis of the governance challenges and the uncertainties related to the implementation of the new governance framework are strongly time-dependent and would need to be re-discussed and analysed on a timely basis. In addition, the governance analysis captured the view and priorities of a range of stakeholders and served as a basis for the identification of the hydro-economic model's scenarios. Nonetheless, a final validation of the water allocation priorities in terms of a stakeholders' workshop could not be carried out and the results of our governance and hydro-economic analysis can only be considered as an outlook of possibly optimal solution. The trade-offs and challenges outlined in our research should form the basis for the identification of socially optimal solutions in terms of water allocation, which should take into consideration the changing governance structure and should be validated by the interaction of the stakeholders.

### 7.2.2 Dissemination and uptake of research results

The research results outlined in the present study are of immediate relevance to the policymaking process and can inform decision makers on the various economic development options in the Kafue River

basin. An investigative approach aimed at critically studying the status quo to propose evidence-based scientific approaches to improve water management can be the basis for a substantiated policy discussion. The analysis of conflicting demands, the effects of the expansion of the different economic sectors on water availability, and the effect of alternative policy priorities can inform the stakeholders in their decision making process and can provide precious insights to steer the management of water resource. In fact, a clear understanding of the interactions between water supply and demand can drive changes in water policy that improve society's use of limited water resources (Burke, 1994). To this extent, the multi-objective model should be considered as an integrated and transparent tool for supporting decision making.

Nonetheless, the optimisation results are only a first step towards the identification of socially optimal allocation pattern and policy options. A participative and open interaction among all stakeholders is needed to select an acceptable, sustainable, and agreed upon Pareto optimal solution. Similarly, our results provide a non-exhaustive set of efficient solutions and it is up to the decision makers in the basin to further define each user's objectives and the overall system priorities in order to expand the set of optimal solutions. The identification of societal objectives requires an intense interaction between the stakeholders and, particularly, the key decision makers in charge of water management in Zambia, which is of utmost importance to ensure that the research results will flow back to the potential users.

In order for the models and frameworks described in this study to be effectively used by the stakeholders and for research to be translated into policy making, it is necessary to invest into the dissemination of results through stakeholders' workshops and outreach activities. The integrated work conducted within the ADAPT, the massive data gathering effort, the quest to encompass different disciplines in a coherent framework is of great value to the Kafue and the Zambezi stakeholders. The role of a research group such as the ADAPT should not stop with the publication of the results for the scientific public, but should include one further challenge, that of simplifying and restructuring the research findings for the proper consumption of the stakeholders.

The treasury of knowledge, data, and insights collected during years of research can be thus given back to all those stakeholders who contributed to our studies with the promise of tangible and easily applicable results. As part of this effort, it is important to hand over the models developed with the present study not only to the stakeholders but also to an appropriate partner organization. In fact, it is necessary to fully empower one of the research partners in order to ensure a wide implementation and the appropriate follow-up over time. One of the main efforts of the present research has been the interaction with a wide number of stakeholders, including civil society organizations, international organisations and research institutes. It is thus possible to identify a number of partners, such as the Zambian office of the World Bank or the Food and Agriculture Organization, which closely collaborated throughout the research and which showed interest in pursuing follow-up studies, making use of the models developed, and partly implementing the research findings.

Such organizations would be the ideal partner for the further dissemination of our research due to their influential position among the Zambian stakeholders, the longstanding presence on the territory, and the capability to mobilize decision makers and foster policy change. This would ensure the possibility to conduct an effective monitoring of the policy changes and shape, through the continued dialogue among stakeholders, the objectives included in the hydro-economic model in order to accurately mirror

a continuously changing setup. It would also be possible to disseminate the data and information across the Kafue and Zambezi River basins while at the same time pursuing further data collection and systematization. The additional data could feed into the models proposed in this study and fill some of the research gaps outlined in the previous section. At the same time, such organizations could also replicate and adapt to different basins across Africa the models and frameworks developed in here, thus contributing to enhance the coordinated management of water well beyond the scope of our research.

## References

Burke, J. J. (1994). Approaches to integrated water resource development and management: the Kafue Basin, Zambia. *Natural Resources Forum* 18(3), 181–192.

GoZ (2011a). Sixth National Development Plan (2011-2015)) – Sustained economic growth and poverty reduction. January 2011.

GoZ (2011b). Water Resources Management Act. No. 21 of 2011.

GoZ (2010). National Water Policy. Ministry of Energy and Water Development

GoZ (2004). National Agricultural Policy. Ministry of Agriculture and Cooperatives. Lusaka: Government Printers.

UNDP (2013). Millennium Development Goals – Progress Report Zambia 2013. New Horizon Printing Press, Lusaka, Zambia.



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18 March 2013

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# Curriculum Vitae

## PERSONAL DETAILS

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- Date of birth: June 8<sup>th</sup> 1983
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## EDUCATION

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- |                       |  |
|-----------------------|--|
| Feb. 2009 – Mar. 2013 | PhD candidate at the Swiss Federal Institute of Technology (ETHZ), Zurich. Thesis topic: "Water economics and governance in the Kafue River basin, Zambia".                      |
| Sep. 2005 – Jul. 2007 | Master degree in International Economics, Università degli Studi of Pavia, Italy. Dissertation on Water Charging: Efficiency and Equity Considerations. Grade: 110/110 honour.   |
| Sep. 2002 – Jul. 2005 | Bachelor degree in Economic and Social Sciences, University of Milan "Luigi Bocconi". Dissertation on Water Availability and Conservation in Sub-Saharan Africa. Grade: 107/110. |
| Jul. 2002             | High School at "Liceo Ginnasio Giovanni Berchet" specialized in Classical Studies. Certificate grade 100/100.  |

## SKILLS

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- |           |   |
|-----------|---|
| Languages | Italian: Mother tongue.<br>English : Advanced<br>Spanish: Advanced<br>French: Intermediate<br>German: Pre-Intermediate<br>Arabic: Elementary  |
| IT        | Microsoft Office 2010 and Vista. Excellent knowledge of the statistical software SPSS, the mathematical programming software GAMS, and the qualitative analysis software Atlas.ti. Good knowledge of the statistical software Stata and R-Project, the mathematical programming software Matlab, and the data entry software CSPro. |

## EXPERIENCES

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**January 2012 – up to date**

**Risk Manager (Assistant Vice President) at Swiss Re, Sustainability and Political Risk Department, Zurich/Switzerland**

- Overview of sensitive risks regarding projects related to hydropower, water management, forestry, mining, defence, and oil and gas exploration.
- Elaboration of an environmental, social and governance sovereign rating.
- Evaluation of the risk of social unrest in the mining sector through the development of a rating system and GIS data elaboration.
- Collaboration in the “Economics of Climate Adaptation” study.
- Participation in the UN Global Compact and UN Principles for Sustainable Insurance task teams.
- Training of Swiss Re professionals on sustainability and risk management.

**January 2009 – March 2013**

**Doctoral candidate at the Swiss Federal Institute of Technology (ETHZ), Centre for Development and Cooperation, Zurich/Switzerland**

- Research focus: economics and governance in the Kafue River basin in Zambia.
- Analysis of the different water uses in the basin and applied mathematical modeling techniques to examine trade-offs in the use of water resources.
- Governance analysis of the Zambian water sector that lead to concrete policy recommendations.
- Close collaboration with stakeholders (government agencies, international organizations, farmers, interest groups).
- Conceptualization and execution of a rural household survey. Tasks included intensive project management, field work, training and supervision of eight Zambian enumerators, data analysis.
- Supervision of three Master students from developing countries.
- Lecturer of the post-graduate course on “Water management - theory and practical applications” and guest lecturer for “Challenge the Best 2012”, University of St. Gallen.

**August 2012**

**Consultant (part-time) at Food and Agriculture Organization of the United Nations (FAO), Land and Water Division, home based**

- Conceptualization of a Toolbox for Sustainable Water Management in line with the NEPAD-CAADP initiative. The Toolbox integrates context, institutional and policy, and financial tools to facilitate sustainable water management and investment planning.
- Elaboration of financial calculation algorithms to facilitate the prioritization of investments in water for agriculture and energy.
- Presentation of the final output at the World Water Week 2012 in Stockholm in the context of the FAO-AgWA Seminar.

**May 2008 – December 2008**

**Consultant (full-time) at Food and Agriculture Organization of the United Nations (FAO), Land and Water Division, Rome/Italy**

Main tasks included:

- Technical preparation of the Ministerial Conference on “Water for Agriculture and Energy in Africa: the Challenges of Climate Change”.



- Preparation of Investment Briefs for 53 African Countries.
- Collection and systematization of investment projects and investment costs related to water and energy at national and regional level.
- Development of a financial model to facilitate the prioritization of water-related projects at national level.
- Coordination with national counterparts and with representatives of international organizations and donors (African Development Bank, African Union, Economic Commission for Africa, etc.).
- Participation in the national and regional consultation processes.

Other tasks included:

- Collaboration in the investment chapter of “The State of the World's Land and Water Resources (SOLAW)”;
- Formulation of the Technical Cooperation Project “Water and energy resources in the Near East and North Africa in the context of climate change”. The work also entailed: (1) the revision of the projects’ portfolios provided by the national consultants, (2) the application of the financial model to derive investment needs, (3) the preparation of the economic analysis section of the national investment profiles;
- Formulation of the Technical Cooperation Projects: 1) “Support Cooperation on Water Resource Management in the Lower Mesopotamia Region” project, funding: Italian Cooperation; 2) “Support to Agricultural Water Management (AWM) in the Horn of Africa”, funding United States Department of State.

#### **October 2007 – May 2008**

**Intern at ICARDA (International Centre for Agricultural Research in the Dry Areas), Integrated Land and Water Management Division, Aleppo/Syria**

- Research focus: irrigation water rationing and allocation across space and time for enhanced profit and water productivity.
- Formulation of a theoretical non-linear economic optimization model making use of the MS Excel Solver.
- Participation in stakeholders’ surveys.

#### **January – April 2007**

**Volunteer at Food and Agriculture Organization of the United Nations (FAO), Land and Water Division, Rome/Italy**

- Analysis of water pricing methods and models in agriculture, considering also efficiency and equity implications.
- Statistical analysis of investment costs in irrigation.

#### **July – September 2005**

**Intern at HanseNet Telekommunikation GmbH, Marketing– Business Analysis Department, Hamburg/Germany**

- Statistical analysis of drivers in current access area in order to prepare selection of further MDFs for German Expansion and to calculate the number of potential customers;
- Churn rate analysis and market Analysis.
- Support to the Business Analysis Team: budgeting, competitors research, reporting, etc.

#### **VOLUNTARY SERVICE**

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From September 2004 until August 2007 I was a volunteer with Amref, a NGO whose mission is to provide international aid to Developing Countries. My tasks focused on the water and sanitation projects in rural and peri-urban context. I also helped organizing a series of fund raising events.

Since July 2012 I provide technical advice to The Water Network, a non-profit institution based in Zurich whose aim is to provide a free web-based platform for the exchange of knowledge and information among water sector professionals.

## **PERSONAL INTERESTS**

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I am particularly interested in economic development and in topics concerning the Least Developed Countries: I took part in several seminars and courses on development and poverty or natural resources management held by ISPI (Istituto per gli Studi di Politica Internazionale) and ETHZ and I am an active member of the International Water Association.

I enjoy travelling and I am animated by a sincere curiosity towards different cultures and environments. In my spare time I enjoy hiking, swimming, horse riding, and reading a varied range of literature. I am also improving my knowledge of the German language.

## **PUBLICATIONS**

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Casarotto, C., and Kappel, R., 2013. A half empty bucket: women's role in the governance of water resources in Zambia. *Journal of Gender and Water*, 3 (2013).

Casarotto, C., Salman, M., and Sassi, M., 2012. Diagnostic financial and institutional tool for investment in water for agriculture. Presented at the World Water Week, Stockholm, 26<sup>th</sup> August 2012.

Simfukwe, T., Casarotto, C., Kalinda, T., Tembo, G., 2012. Rural household water use in the Kafue River basin in Zambia. Presented at the World Congress on Water, Climate and Energy, Dublin, May 2012.

Tilmant, A., Kinzelbach, W., Juizo, D., Beevers, L., Senn, D. and Casarotto, C., 2012. Economic valuation of benefits and costs associated with the coordinated development and management of the Zambezi River basin. *Water Policy*, 14 (2012) 490–508.

Koohafkhan, P., Salman, M. and Casarotto, C., 2011. Investments in land and water - SOLAW Background Thematic Report – TR17. In “The state of the world's land and water resources for food and agriculture (SOLAW) - Managing systems at risk”. Food and Agriculture Organization of the United Nations, Rome and Earthscan, London.

Uhlendahl, T., Salian, P., Casarotto, C. and J. Doetsch, 2011. Good Water Governance and IRWM in Zambia - Challenges and Chances. *Water Policy* 13 (2011) 845–862.

Casarotto, C., Kappel, R., Bernauer, T., Simfukwe, T., Kalinda, T., G. Tembo. Water Economics and Governance in the Kafue River (ADAPT). CCES Latsis Symposium 2010. Zurich, Switzerland, 15-17 November 2010.

Casarotto C, P Salian, R Kappel, 2009. Water Governance in Zambia – The Case of the Kafue River basin. Presented at Tropentag 2009, 6-8 October 2009, University of Hamburg, Germany.

