Flooded with water deficits

Optimal timing of an environmental flow release, using flow forecasts in the operational management of a reservoir

J. Chen, October 2010

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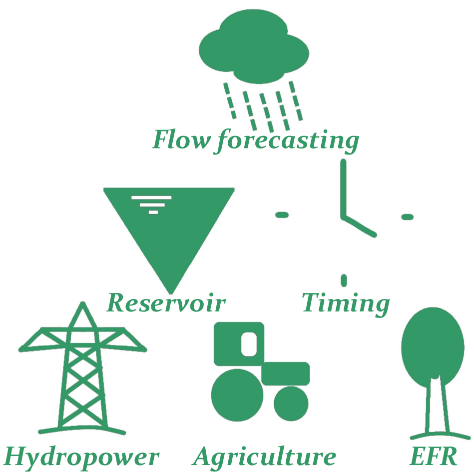

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Abstract

Humankind has modified the natural flow regime of rivers to improve human well-being. Since ecosystems are a result of the flow regime, these flow regulations have impacted ecosystems. Particularly in river branches located downstream of a reservoir, the ecosystems are highly influenced by the altered flow regime. This raised the discussion on the need for a more natural flow regime to sustain the original river ecosystem and its benefits. A flow regime required to maintain certain ecosystem conditions is represented by the environmental flow requirement (EFR). Releases for the EFR are not common, since they may cause water deficits amongst the reservoir's functions.

The EFR includes a low- and a high flow requirement. This research focuses on the high flow requirement, of which the allocation usually has a degree of freedom within the moment that it can be released. Since reservoir inflows and water demands vary over time, the timing of the environmental release has an influence on the water deficits. Therefore, flow- and demand forecasts can help in optimizing the timing of environmental flow releases, to minimize the accompanying water deficits.

This research analyses the extent of the deficit reductions, achieved by an optimization in the timing of environmental flow release by the inclusion of flow forecasting in the operational management of a reservoir. For this, an optimization model is developed with Delft-FEWS software, with hydrological (Ribasim) and numerical (MATLAB) software embedded. The model is applied to the Kafue River (Zambia) with the Itezhi Tezhi dam and Kafue Flats wetlands. Aspects that influence the optimization are identified and analysed for the case study.

For the case study it is concluded that years with reservoir inflows above the long term average, have no additional deficits if the environmental flow is released. During years with lower inflows, the optimization is able to reduce 7% of the deficits caused by the environmental flow release compared to the situation with a fixed moment of environmental flow release.

Optimization is more useful if the EFR is of shorter duration with larger discharges, if the reservoir level is restored in a short time period and during years that the annual mean runoff is below long term average flow. It is considered unnecessary to further quantify these relationships, because many necessary assumptions are case-dependent, making it difficult to develop detailed quantifications. A set of conditions is developed to which a case should suffice before utilizing the optimization model for quantification of the potential deficit reductions. If the optimization is used, customized input and a case specific hydrological model are necessary.

It is recommended to depend the environmental flow on flow forecasts not only in timing, but also in magnitude. If the environmental flow magnitude is lowered in case of a prospected drought, significant deficit is prevented. In this way, deficits due to drought are shared between environment and water usages, and environmental flow release is matched with the reservoir's functions.

Preface

Currently you're reading the thesis with which I will finish my study Civil Engineering and Management. The thesis comprehends my graduation project done for Deltares. This graduation project turned out to be a very personal, since I identified myself with the subject, with the method and with the report.

The subject is fully within my interest, by combining water processes, sustainability and engineering into one project. After all, the research aims for a durable solution on the significant problem of water shortage. The development of a model and the application in a case study made the research practical and interesting.

I also enjoyed the method applied in the research, since I could do some philosophising for the system analysis, puzzle myself to the limit with abstract models, and I experienced the eccentric practice of assembling data in an African country.

In the end, I also identified myself in the reporting of my research. The writing has often been the direct depiction of the brainstorm in my mind, making it utterly difficult to discover a proper introduction, centre and conclusion in my texts. Just like in my well-known command of speech. I have had much sympathy for my tutors who repeatedly had to read it, understand it and commend on it.

Subsequently, I want to thank Karen, Denie, Micha and Eelco for making this research possible and for their infinite patience and valuable comments. My gratitude goes to all people who made my expedition to Zambia a success: Mark Mulder, Rudo Sanyanga, Chris Mwasile, Marcus Wishart, Collins Nzovu, Chiwoyu Sinyangwe and Elen Mwelwa. I want to thank Bram and Jasper for their courage to tackle parts of my report and their valuable comments. Finally, I am grateful for my marvellous parents and my beloved sister, who have always given me unconditional love and support.

Jorik Chen,

The Hague, 22nd of October, 2010.

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Chapter 1 Research set up

1.1 Problem analysis

1.1.1 Definition Environmental Flow Requirement

The environmental flow requirement (EFR) is the amount of water needed within a river, wetland or coastal zone to maintain ecosystems as well as their benefits for society (Dyson et al., 2003). The condition of an ecosystem is to a large extent the result of the prevailing flow regime. Each component of a flow regime such as low and high flows, but also smaller seasonal peaks, can be expected to have their own function for the river ecosystem. For example, low flows are required as a minimum discharge for fish and other aquatic species for water throughout the year, while high flows are important for river channel maintenance, wetland flooding and riparian vegetation.

In short, an environmental flow regime should mimic the natural flow regime to the extent possible. Flow regimes can be described using various flow components: magnitude, frequency, duration, timing and rate of change of hydrologic conditions (Poff, 1997). Each ecosystem is unique, hence in each case the EFR is to be defined by a local environmental flow assessment.

1.1.2 Significance & impediments for environmental flow release

Humankind has modified the natural flow regime of rivers to improve human well-being. Water is abstracted for agricultural and domestic purposes, and water is stored in reservoirs to reduce the dependency on natural variations in availability. Since ecosystems are a result of the flow regime, these flow regulations have impacted ecosystems downstream. Particularly in river branches located downstream a reservoir, the ecosystems are highly influenced by the altered flow regime and an urge exist to sustain the original river ecosystem and its benefits. Then implementation of environmental flow releases are necessary. However, although the importance of the environmental flow release in those situations has been recognized, its implementation can conflict with the reservoir functions and is yet uncommon (Jacimovic et al., 2009).

Various impediments are identified for the lack of implementation (Brown and King, 2003; Hughes and Mallory, 2009), two are of great importance in the light of this research. First, the continual trade-off with other functions and users causes a competition between functions of the dam such as flood protection and availability of water for agriculture, industry and public use. If not enough water is available for all functions, allocation for one function causes less allocation for another function. Within this competition, environmental releases can only be realised if they are given priority above other uses. This is related to the second impediment, which is the unwillingness to include the EFR in operation rules of dam structures. This impediment often originates from the perception that the implementation could be expensive. It is assumed that these expenses are the opportunity costs expressed in water deficits and accompanied damages for water users in case of allocation for the EFR.

Consequently, the impediments for the implementation of environmental flow release could be reduced if its accompanying water deficits for other water users are decreased. Water deficits occur when demand exceeds the supply that is available at the particular moment. Both water availability and water demand show peaks and troughs over the year. So if this fluctuation is synchronized, deficits could be minimized and impediments for implementation of EFR are reduced.

1.1.3 Research opportunity

The EFR includes low- and high flow requirements. Low flow requirement indicates the minimum requirements of fish and other aquatic species for water throughout the year. High flow requirement is important for river channel maintenance, wetland flooding and riparian vegetation. This research focuses on the high flow requirement.

The opportunity to decrease water deficit is based on a characteristic degree of freedom for allocation of the high flow requirements, referred to in this research as the EFR. This degree of freedom is explained as following. Typically, the high flow components of an EFR consist of 'events' that are to take place within a certain time window (a month, a season or even a period of multiple years). The main assumption on which this research is based, is that particularly for peak events, the duration of the events is shorter than the period during which the allocation should take place. So the timing of an environmental flow release has a certain degree of freedom (Wilson, 2003). For example, if an EFR downstream of a reservoir is quantified as 100 m^3/s during one week within the months January and February, the reservoir operator can choose the actual moment of allocation. If the reservoir operator would know by means of flow forecasts that lots of water would become available in the second month, he can prevent water deficits by postponing the environmental flow release to February, given that the demand does not increase. This example is subject to a lot of assumptions and conditions, but it shows the opportunity to decrease the extra water deficit. A visualisation of the effect of two different moments of environmental flow release is given in Figure 1.

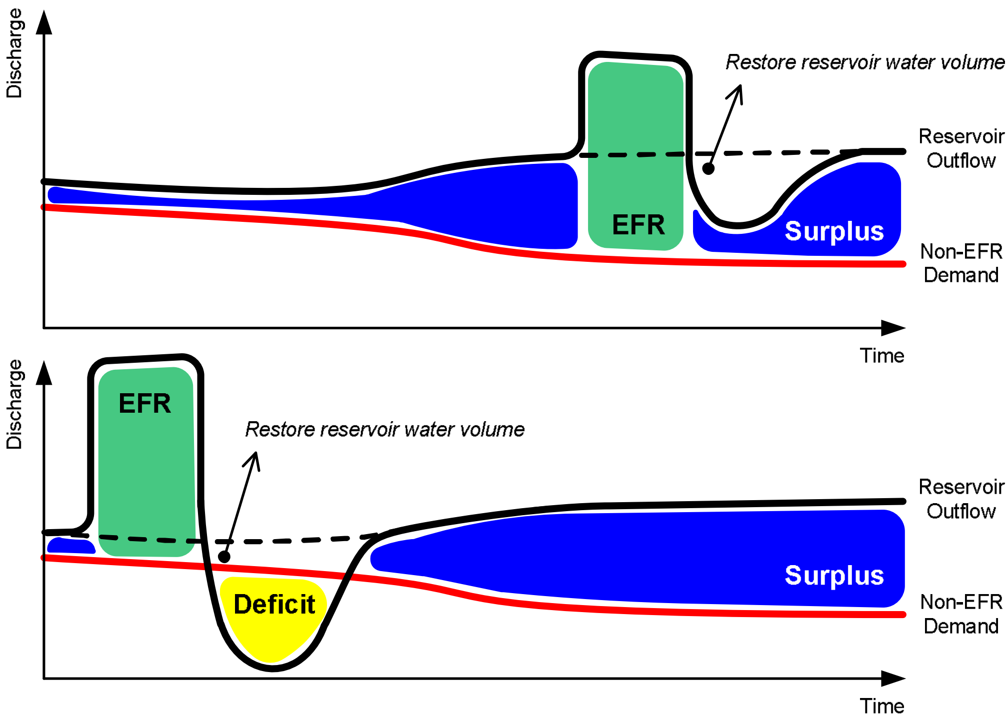

Figure 1. Example of two moments for implementation of a certain EFR. The original reservoir outflow (dotted black line) is increased by the EFR and represents the downstream water supply. The operational management determining the outflow is based on the reservoir level, so that less outflow is allocated after an environmental flow release to restore the water level. In the second situation, the environmental flow release leads to a deficit. The extent of deficits is dependent on several factors, including the method of operational management.

The degree of freedom offers an opportunity to optimize the timing of the environmental flow release to make use of fluctuations in water supply and demand. If peak flows for the EFR are released at moments that supply is not used by the water users, advantage can be taken from this surplus. If no surplus is available during the whole period that EFR can be allocated, the necessary releases for the EFR can be allocated at moments that damages due to deficit are lowest to the users involved.

So the deficit can decrease if the EFR is allocated at moments that supply and demand are in the best possible proportion within the period that EFR can be allocated. This moment can only be determined if information about both supply and demand is available. Fluctuation of water demand is assumed to be rather predictable, since it can for instance be determined based on historical records (United Nations Development Program, 1968), on water rations laid upon users by governmental instances (Malhotra et al., 1984), or by gathering information on expected use for the upcoming season (Suen & Eheart, 2006). On the other hand, fluctuation of water supply can be predicted based on forecasts of the inflow of the reservoir and the resulting reservoir volume, here referred to as flow forecasts. Flow forecasts are already used in the operational management of some reservoirs (Hamlet et al., 2002; Shiau, 2009), but they are not yet used for optimization of environmental flow release.

So the inclusion of flow forecasts in the operational management of a reservoir in combination with knowledge about upcoming water demands, should make it possible to optimize the timing of environmental flow release. Through this optimization, less shortage of water (deficit) is expected to occur than when environmental flow release is implemented without taking into account the predicted water supply and demand. The decrease of water deficit can lead to a different outcome of the trade-off and is expected to improve the perception of reservoir managers about the EFR. Therefore, it can encourage the implementation of environmental flow release.

1.2 Research outline

1.2.1 Research objective & questions

The objective of this research is to analyse the benefits of inclusion of flow forecasting in the operational management of a reservoir for optimizing the moment of environmental flow release. The central research question is quoted as:

> *"To what extent can optimization in timing of environmental flow release by the inclusion of flow forecasting in the operational management of a reservoir reduce water deficits that accompany environmental flow release?"*

This central question is divided into four steps that structure the research:

I. *What aspects influence the deficit reduction of the optimization as in the main question?*
II. *How are the water deficit and the optimization modelled?*
III. *What is the deficit reduction in the Kafue River?*
IV. *How much do the selected aspects influence the deficit reductions of the optimization?*

The first step explores the qualitative relationships within the research to see what aspects are interesting to model. The second step considers how the aspects can be modelled for the optimization of the timing of Environmental flow release. The third step determines the quantitative benefits in a case study by means of the model. The fourth step concludes with a sensitivity analysis of the influences that selected aspects have on the deficit reductions of the optimization.

1.2.2 Research scope

The problem and research topic is the deficit that occurs for water users when a peak flow for the EFR is released. To simulate the impediments of reservoir managers at best, this problem definition is based on the assumption that an environmental flow is required and it directly competes with other water demands. This would be the case if agriculture abstracts water at a location upstream from the river section with an EFR. Assumptions are therefore that EFR has priority above other water users in case of allocation, and that no re-use of water is possible (see Figure 2).

The inflow is determined as the net flow that affects the reservoir water level, including water losses such as evaporation and seepage. This is a simplification of the situation, but it offers overview within the system. The reservoir is operated by rule curves that link the reservoir outflow to the reservoir level and the demands for the EFR and the other water users. The EFR and the other demands are determined as the net demands after subtraction of the supply such as groundwater and local precipitation. This implicates that the demands represent the necessary flows abstracted from the reservoir.

The research focuses on the optimization of timing of environmental flow release, by implementation of demand and flow forecasts. Therefore, a situation is required where an EFR is determined, with a possible period for environmental flow release longer than the duration of the EFR, with an available flow forecast and known water demands. These aspects are modelled with data of a case study.

The case study is the Itezhi Tezhi dam in the Kafue River, Zambia. This choice is based on the interest that Deltares has within the Zambezi River Basin due to a project for the Southern African Development Community. Within the Zambezi River Basin, the Itezhi Tezhi dam complies with the situation as described above.

Three extra assumptions are determined to define the research. First, water deficits are only represented in water volumes. The economic damages are not taken into account since in most cases there are no data available about the exact value of water. Thereby, the unit of water volume is less subjective than economical damages. Second, input data for the case study are assumed if not available. Third, the presence of a reservoir and downstream water demands cannot be altered. Obviously the best solution for the environmental situation would be the removal of the reservoir, but it is assumed that this is not desirable.

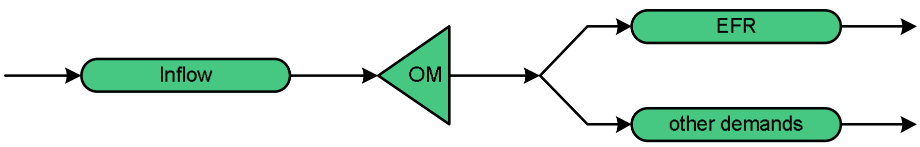

Figure 2. Flow model in the problem definition. Water supply from the reservoir (determined by the operational management, OM) is divided over EFR and the other demands, with priority for the EFR.

1.2.3 Report outline

The outline of the document is displayed in Figure 3. It shows the actions and results per chapter, with the step that is considered in the particular chapter.

Chapter 2 describes the case study. Data for the Itezhi Tezhi dam in the Kafue River in Zambia are described. The use of a case study provides an actual view on the extent of the reduction of water deficits, and a realistic base to determine the extent of the influences that affect the optimization.

In Chapter 3 the aspects are identified that are expected to have a significant influence on the optimization. For this the variables are determined that influence the deficit. The setting of these variables is analysed on their relation to the optimization: The flow forecast, the reservoir, the demand and the EFR. Aspects of these components are used as input in the optimization model and analysed in further chapters.

The model structure used in this research is described in Chapter 4. The model simulates the hydrologic situation of a reservoir, to determine downstream water deficits with several input variables. It optimizes the moment for environmental flow release with use of a hydrological model, that uses the latest flow forecasts, demands and applied operational management.

In Chapter 5, the case study is modelled and the deficit reductions are quantified. Also the application of a flow forecast is analysed, in comparison to the use of a hindcast. Chapter 6 models the key aspects to see how and how much they influence the deficit reductions due to the model. Finally in Chapter 7, conclusions are drawn considering the main research question, and some recommendations are provided.

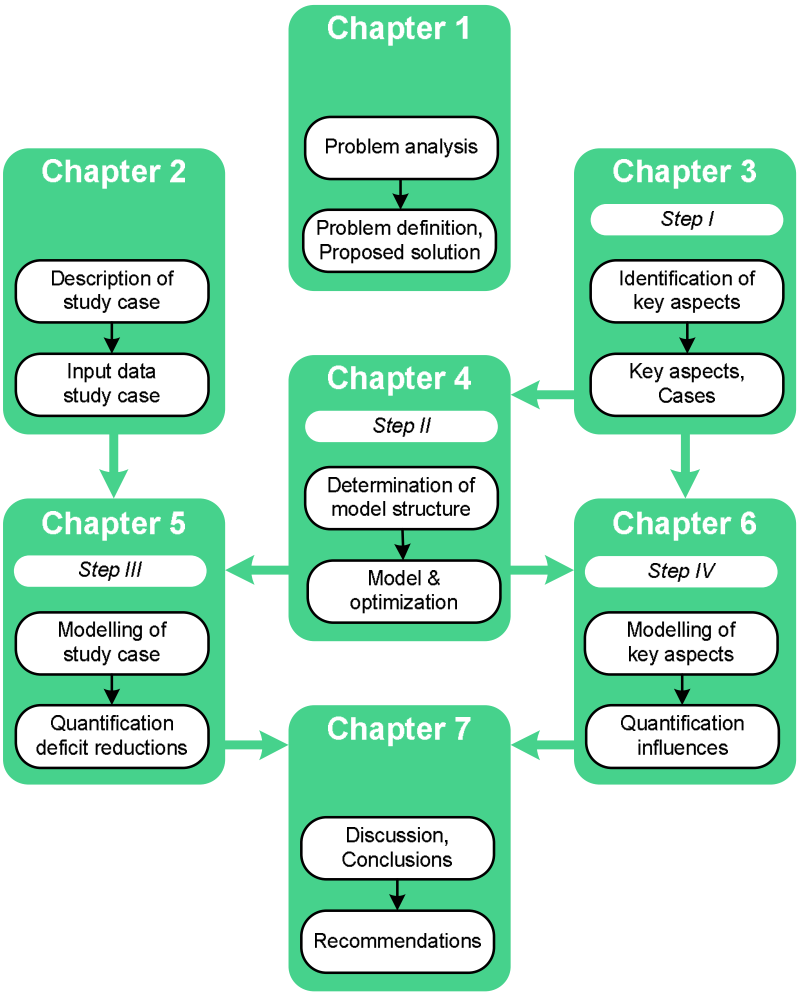

Figure 3. Outline of the document.

Chapter 2 Case study: the Itezhi Tezhi dam

2.1 Introduction

The Itezhi Tezhi dam in the Kafue River in Zambia is chosen as the case study of this research. The dam is operated for seasonal storage to provide a continuous water supply for downstream water users. Since the operational management affects the environment in the Kafue Flats, an EFR was developed, that at the moment is not always allocated for. At the moment a flow forecasting system is developed in the upper Kafue River, so that an optimization as subject in this research is a realistic possibility to implement. Detailed information about the case study is collected in interviews in Lusaka, as found in Appendix A. A geographic overview is displayed in Figure 4.

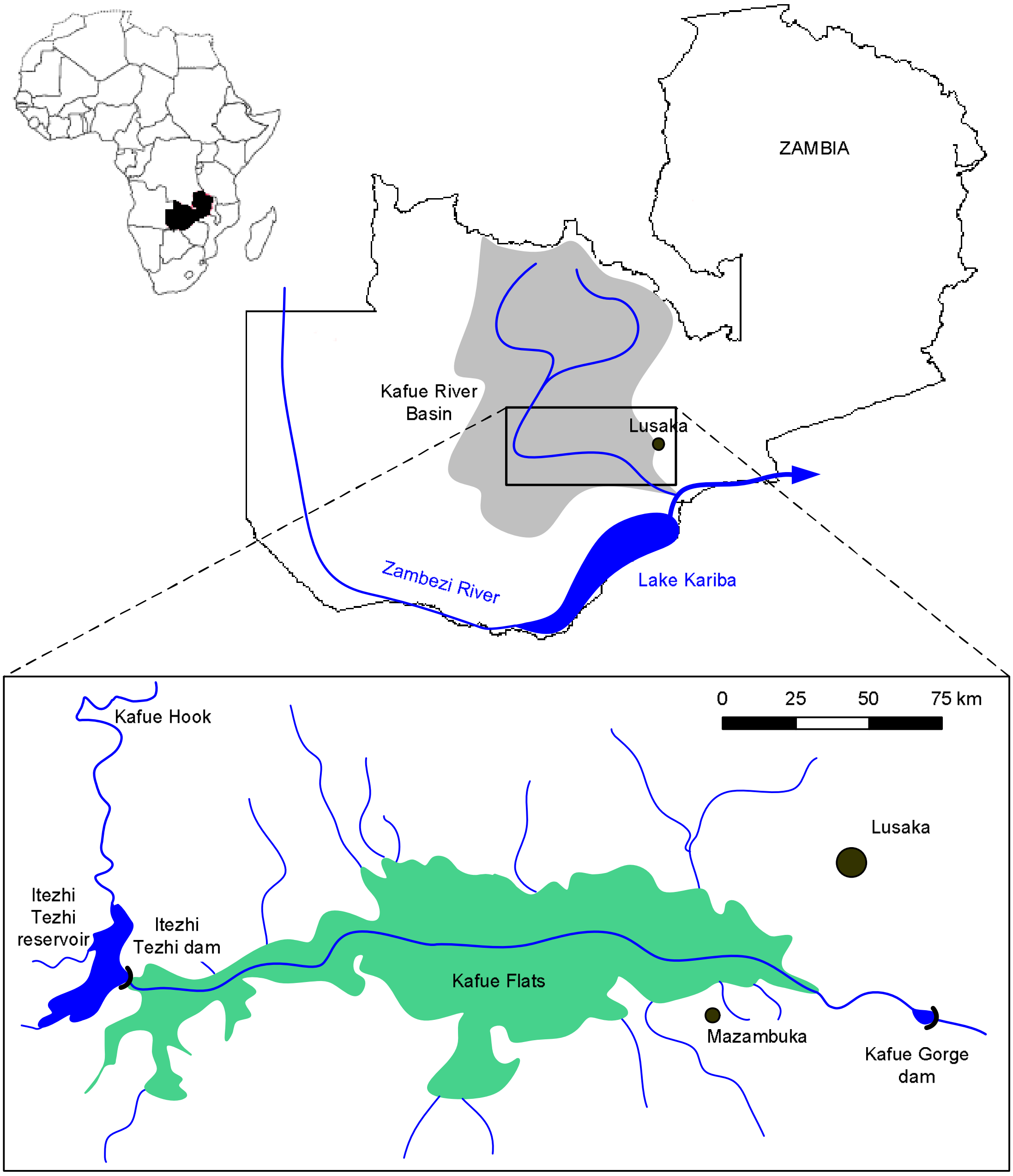

Figure 4. Geographic location of the Kafue River basin in Zambia, and an overview of the Kafue Flats with upstream the Itezhi Tezhi dam and downstream the Kafue Gorge dam.

2.2 Kafue River

The Kafue River flows southwards from the Zambian border with The Democratic Republic Congo, to the Zambezi River. The main river is about 1580 km long and has a catchment of about 155,000 km^2 and is located completely in the tropics. At the Itezhi Tezhi dam, at about 40% of the length of the river, an average flow was registered of 368 m^3/s with peaks commonly at 930 m^3/s. Data are measured from 1961, but since the construction of the Itezhi Tezhi dam in 1977 the data do not resemble the pristine flow anymore. Hence this research only uses the data between 1961 and 1977, which are provided in Appendix B. The average flows are also displayed in Figure 5, where they are divided into averages of the 33% wettest and driest years of this period. This shows that the 33% driest years have peak flows of about 600 m^3/s, and that near the Itezhi Tezhi dam the pristine peak flow usually starts half December and ends around the end of May.

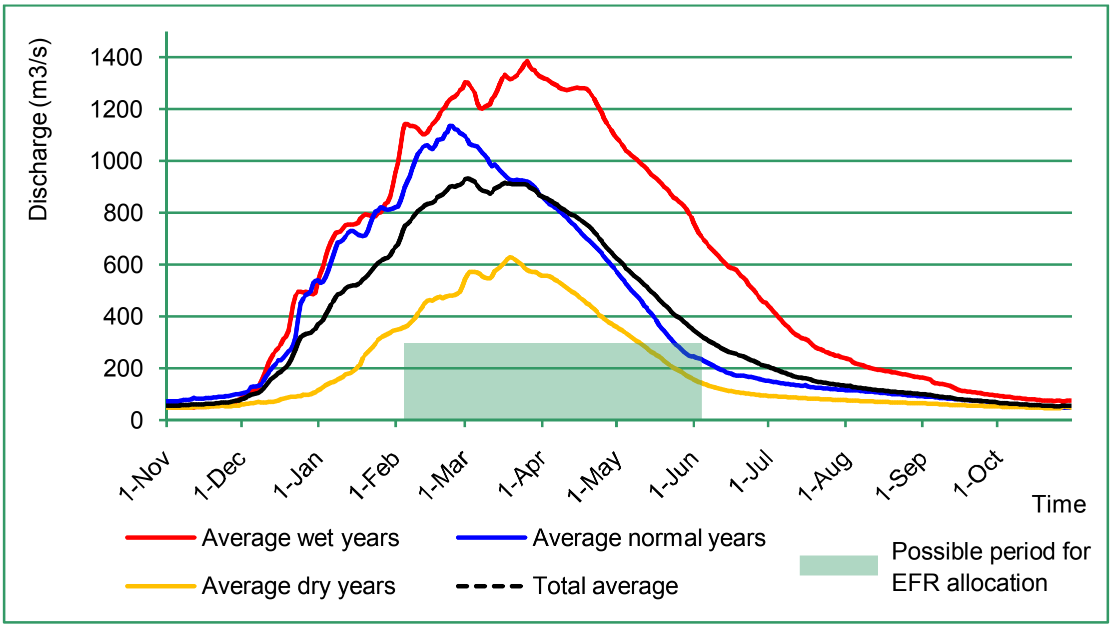

Figure 5. Historical flow data 1961 – 1976 of the Kafue River at Kafue Hook. Dry, wet and normal years are selected as the years with respectively the lowest 33%, highest 33% AMR and the years in between. The 366th day of leap years are excluded. The period that environmental flow release is possible is highlighted.

The Kafue River is essential for the economy and the environment of Zambia: most of the countries' mining, industrial and agricultural activities are located in the catchment of the Kafue River (Crowmarsh Gifford, 1994). The river feeds the Kafue National Park which is the largest national park of the country. Downstream of the Itezhi Tezhi dam, the river inundates the ecologically valuable Kafue Flats seasonally. Since the seventies, the river also provides about 55% of the total Zambian hydropower by means of the water reservoir at the Itezhi Tezhi dam and the hydropower generators in the Kafue Gorge dam, which is located downstream the Kafue Flats.

Zambia's energy consumption increases due to population growth and a developing industrial sector, so plans exist for the installation of hydropower generators in the Itezhi Tezhi dam. There are also plans for expansion of the agricultural area in the Kafue Flats. Both developments will increase the dependency on the Kafue River and the competition for its resources, and research is done to use the resources of the river as efficient as possible (The Post Newspaper, Zambia, 4th of May 2010). An environmental flow assessment is executed through the agency of the Zambian Ministry of Energy and Water Development. The Zambian

Waterboard together with the WWF are developing a new flow forecasting model based on hydrologic gauges in the upstream catchment.

The presence of (increasing) water demands apart from an EFR, including the potential for a flow forecasting system make the Itezhi Tezhi dam an interesting and relevant case study for investigating the optimization of the timing of environmental flow release.

2.3 Itezhi Tezhi Dam

In 1971, the Kafue Gorge dam was constructed incorporating hydropower generators with an installed capacity of 600 MW. The Kafue Gorge dam is 25 km downstream of the Kafue Flats and has a small reservoir with a capacity of 785 MCM. A larger reservoir is impossible, since the Kafue Flats have a slope of just 0,02 ‰. To guarantee a continual water provision for the Kafue Gorge, the Itezhi Tezhi dam was built 450 km upstream the Kafue River, just at the beginning of the Kafue Flats. This dam does not have hydropower generators itself, although plans do exist to build these in the near future (see Appendix A, Interview Worldbank).

Figure 6. The Itezhi Tezhi dam in the Kafue River. On the left hand side is the controllable spillway.

The Itezhi Tezhi dam is a rockfill construction of 28 m high, up to 1035 meter above sea level and 1800 meter long, an impression is provided in Figure 6. It has two outlet tunnels with a discharge capacity of 1500 m^3/s each, a spillway that can discharge up to 4450 m^3/s, and an emergency spillway with a capacity of 750 m^3/s. The maximum reservoir volume is 6000 MCM.

The dam is operated by the national power company ZESCO, which is also in charge of the Kafue Gorge dam. ZESCO is appointed to allocate for the water rights that are distributed to water users by the Water Department of the Zambian government. The water rights are distributed to ZESCO, several councils for public water supply and agricultural users. The amount of water that ZESCO is accounted for is 215 m^3/s, the rights for public water supply and agriculture are 28 m^3/s. Next to these water rights, ZESCO is now obliged to allocate a minimum flow for environmental purposes of 25 m^3/s, on top of the 28 m^3/s for agricultural and public water supply. At higher flows, the hydropower company is free in its allocation of water. Since ZESCO's first priority is to maximise the energy production at the Kafue Gorge dam, this may lead to the neglecting of water needs that are not protected by water rights, such as the EFR for the Kafue Flats. (Crowmarsh Gifford, 1994; Appendix A, Interview ZESCO)

For the operational management of the dam, ZESCO uses the target storage level as depicted in Figure 7. The boundaries resemble the physical minimum and maximum storage levels of the reservoir, the rule curve provides the target water level in the reservoir throughout the year. This rule curve has been developed in order to maximise the hydropower generation at the Kafue Gorge. The water levels rise during the rainy season and they drop during the dry months, to store water during the wet periods and release them in dry periods. The firm storage level resembles the minimum reservoir volume necessary for the desired production of hydropower. A firm storage level for the Itezhi Tezhi dam was not provided, it is unknown what this level would be and what the hedging rules are below this level. In this research, a firm storage level is assumed at 5 meters below the ZESCO rule curve, to resemble the operational management of a regular reservoir.

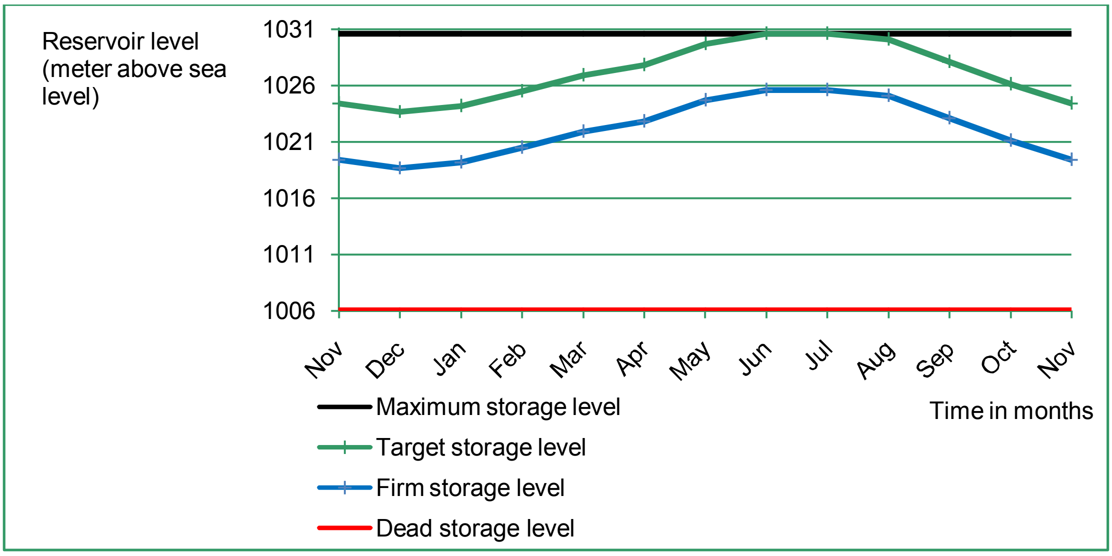

Figure 7. Rule curves operated by ZESCO for the Itezhi Tezhi dam in the Kafue River.

With these rule curves, the operational management works as following: If the reservoir level is above the firm storage level, all water users are granted their full demands. If the reservoir level is above the target storage level, extra water is released to lower the water levels to the target storage level. If the reservoir level is below the firm storage level, the supply for the water users is cut by a certain percentage of their demands. In this research, a percentage of 25 is assumed since no information about the hedging rules was available. To analyse the impact of this assumption, the influence of the hedging rules is considered in section 3.7 and quantified in section 6.2.

2.4 Water demands

The stakeholders in the demand for water between the Itezhi Tezhi dam and the Kafue Gorge dam can be roughly divided into the hydropower company, local councils for public water supply, the sugar cane companies and the environment of the Kafue Flats.

The installed capacity for hydropower at the Kafue Gorge dam is 600 MW, which requires a discharge of 170 m^3/s (ZESCO, 2010). The flow supplied by the Itezhi Tezhi dam arriving at the Kafue Gorge reservoir should be a continual flow of 170 m^3/s, to guarantee a full hydropower generation. Hence the hydropower firm demand is regarded as a minimal continual demand. The abstraction for public water supply does also not fluctuate much, and is approximately around 2,5 m^3/s (Appendix A, Interview ZESCO).

The total sugar cane area covers about 27000 ha, which is irrigated with water from the Kafue River. Abstraction fluctuates within the year between 2 and 17 m^3/s, which is about two times as much as 25 years ago (calculation in Appendix C). As one can see in Figure 8, the water abstraction for the sugar cane area is in opposite phase with the natural water discharge in the Kafue River as depicted in Figure 5. This is due to the precipitation in the rainy season, making abstraction from the river redundant. Plans exist for a large expansion of the sugar cane area, but these depend on the question whether water availability can be guaranteed (Appendix A, Interview The Post). The actual demand for the sugar cane area can deviate from the historical abstraction, since the abstraction does not necessarily meet the actual demand.

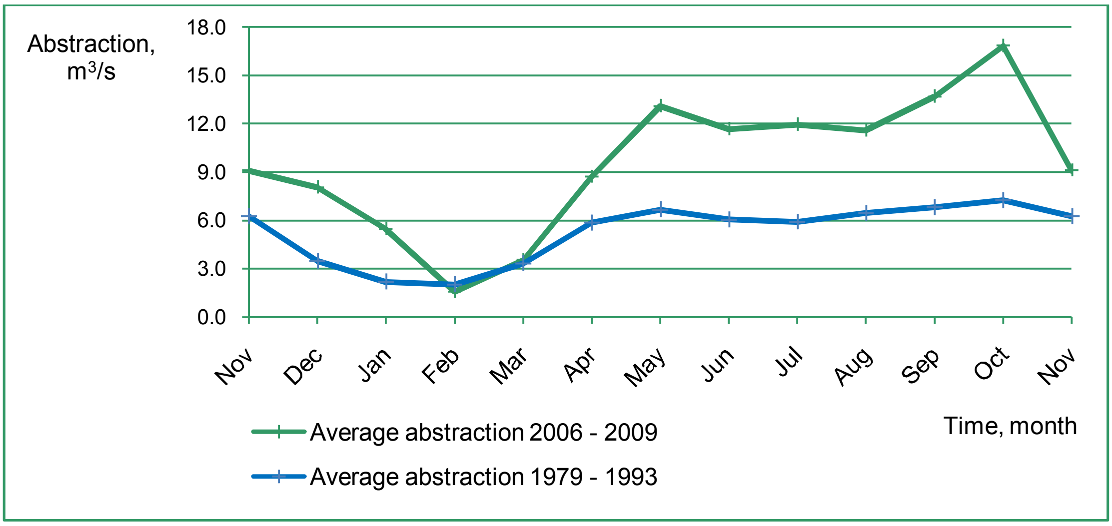

Figure 8. Monthly average abstraction of water from the Kafue River between the Itezhi Tezhi dam and the Kafue Gorge, for the total sugar cane area. Abstractions include losses by seepage and evaporation in the irrigation channels and are based on abstractions for the Nakambala Sugar Estate, which include 52% of the total sugar cane area. (Crowmarsh Gifford, 1994; ZamSugar Company, 2006 – 2010)

2.5 Environmental flow requirement in the Kafue Flats

The Kafue Flats (see Figure 9) are the largest wetlands of Zambia and important for ecological and hydrological functions as well as for its socio-economic values. The Kafue River meanders for about 400 km through the area and floods at discharges from 270 m^3/s. Another resource for the wetlands are fifteen local streams, that feed the flats only during the rainy season. The low slope and the width of the Kafue Flats (240 km long and up to 50 km wide) make 5000 km^2 of the wetlands, which inundate regularly. Regular flooding is essential for the biodiversity, life stock, food and fish production (Nalumino and Chileshe, 2002). Conditions for the local people in the Kafue Flats have deteriorated over time through reduced fishing, reduced grazing land and the disruption of the farming systems that previously provided adequate household food security. This is caused by the building of the two dams in the area, provoking a non-natural flooding and reduced flood peaks (Wilson, 2003; WWF, 2004).

Figure 9. The Kafue River in the Kafue Flats. Its slope is 0,02‰ for about 400 km.

In order to conserve the values of the Kafue Flats, a flow regime that approaches the natural flow regime with an environmental peak flow is required. A first environmental flow assessment defined an EFR of 300 m^3/s in the month of March (known as the March Freshet), while a recent study suggests several cases that can benefit the wetland conservation, which are all based on a flow in between 300 to 600 m^3/s for a duration of 1 to 4 months in the period February to May. These months are highlighted in Figure 5. (Wilson, 2003; Attachment A, Interview WWF)

In the past, the March Freshet was allocated for the EFR, but since this flow caused loss of hydropower generation in the dry year of 1991, ZESCO applies an operational management that only serves the purpose of the hydropower generation and is in accordance with the water rights. Currently, no special allocation for the EFR is taken into account within the operational management; the Kafue Flats are only flooded in case that the reservoir level is high and the inflows force the reservoir to spill above 270 m^3/s.

2.6 Flow forecasting

If a flow forecasting system would be available to ZESCO, peak flows meeting the EFR are more likely to be allocated. In that case, ZESCO is more certain about the water that is left to use for hydropower generation in the next time period. A flow forecasting model for the Kafue River has been developed within a project of the government, the WWF and ZESCO, named KAFRIBA. This model is not in use since ZESCO questioned the accuracy. Nowadays, the WWF together with the Water Board are developing a new flow forecasting model. It will be based on hydrologic gauges and will have a lead time of one month, based on the maximum runoff time in the upper catchment. (Attachment A, Interview WWF)

Chapter 3 Identification of key aspects influencing the optimization

3.1 Introduction

In this chapter, the first step "*What aspects influence the deficit reduction of the optimization as in the main question?*" is central. The optimization as in the main question reduces water deficits by timing the environmental flow release with flow forecasting in the operational management of a reservoir. So this chapter analyses how deficits due to environmental flow release emerge and how an optimization can reduce them. For this, the variables that influence the deficit directly are analysed.

The system diagram as in Figure 10 shows all variables that influence the deficits. Plusses represent a positive relation and minuses represent a negative relation. The setting that determines these variables is shaded in the background of the figure. The setting is divided into the components inflow, its forecast, the demands, the reservoir, its operational management and the EFR. Those are all components that are combined in this research. Each component is analysed on its influence on the optimization. Per component, aspects are selected that have interesting influence on the possibility to reduce deficits by means of the optimization. In the chapter 5 and 6 these aspects will be modelled to quantify their influence on the deficit reduction of the optimization.

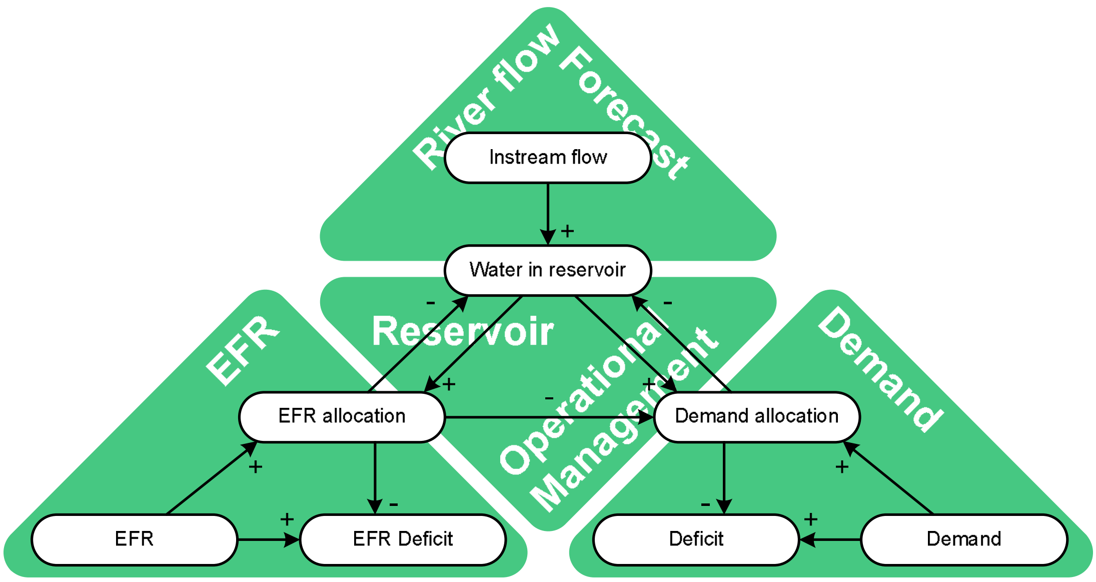

Figure 10. System diagram of variables that determine the deficit. The settings of the variables are shaded in the background, they have influence on the optimization that reduces the deficit.

3.2 Environmental Flow Requirement

As mentioned in the definition of the EFR in section 1.1.1, the EFR differs per river and therefore should be determined through a local environmental flow assessment. An environmental flow assessment is in fact the determination of the flow, necessary to realise an environmental target. Several methods exist to determine the target and the accompanying flow.

The various existing methods for the quantification of environmental flows can be classified in prescriptive and interactive approaches (Brown and King, 2003). Prescriptive methods usually address a specific objective in terms of river condition and result in a recommendation for a flow regime to achieve it. Interactive approaches focus on the relationships between changes in river flow and one or more aspects of the river ecosystem. They result in various cases that can be used in multi criteria analyses. Interactive approaches are open for the stakes of the water users, while prescriptive approaches simply prescribe a certain flow regime. The approaches are further categorised in Appendix D. If the quantifications of their sub categories are summarized, it seems that most of the environmental flow assessments result in flow regimes with both high and low flows.

An EFR can be characterised by five ecologically meaningful and manageable components: magnitude, duration, frequency, timing and rate of change (Richter et al. 1997, Poff et al. 1997).

3.2.1 Magnitude

The magnitude of an environmental flow is expressed in water discharge. Maximum and minimum magnitudes vary with climate and watershed size both within and among river systems (Poff et al. 1997). An example of an EFR magnitude is a discharge that is equal to 200 percent of the annual mean runoff as determined by the Tennant Method, a prescriptive approach for environmental assessments (Brown and King, 2003).

The magnitude of an environmental flow is related to various aspects. First, it is directly related to the size of the catchment and the amount of rainfall, in case that the EFR is in direct relation with the natural flow. Further, other hydrological aspects such as the average roughness of the bottom and the rate of saturation also influence the magnitude of an environmental flow. But also the minimal flow for sediment transport, minimal groundwater level for the vegetation or water quality can determine the EFR magnitude.

3.2.2 Duration

The duration of an environmental flow is expressed as the period of time that a certain flow is required (Poff et al. 1997). For instance, an environmental flow can be characterized by a short duration between 48 and 96 hours to a lengthy flow lasting up to 2 months (International Water Management Institute, 2010; Wilson, 2003).

3.2.3 Frequency

The frequency of an environmental flow refers to how often a flow over a specified time interval recurs. Within a catchment the frequency is inversely related to the magnitude of an environmental flow: the larger a flow, the lower its frequency (Poff et al. 1997).

When simulating the natural flow, the frequency of environmental flow is related to the local seasonal precipitation patterns. A catchment with multiple rainy seasons per year will require a higher frequency of environmental flow events than a catchment with only one annual rainy season. Other environmental flow assessments may determine the frequency by for example the recurrence of a fish migration. Low frequencies can be determined to as low as one allocation per 20 years, defining an interannual EFR (Arthington et al., 2003; Love et al., 2006).

Frequency is not taken further into account, since it does not influence the optimization itself. It only limits the maximum period of the window of opportunity, but this is regarded a minor influence.

3.2.4 Timing

An annual peak flow may occur with low and high seasonal persistence in timing (Poff et al. 1997). If the persistence in timing is high, the ecological system is expected to depend highly on the regularity of the natural flow, and the timing of the environmental flow release should be rather exact.

An exact timing of environmental flow release can be accomplished by a low temporary degree of freedom of the environmental flow release. The degree of freedom, thus the timing of an environmental flow release, is in the optimization defined by the window of opportunity: the period that a certain environmental flow event is required to be allocated. This length of the window of opportunity is reversely related to the persistence in timing, since it becomes smaller as exact timing is more significant. A large window of opportunity could be beneficial for the optimization, since more options for environmental flow release are possible and the chance increases that a better allocation is covered.

3.2.5 Rate of change

The rate of change describes how quickly the flow changes (Poff et al. 1997). A flash flow has a high rate of change in comparison with a slowly developing peak flow.

The rate of change is influenced by hydrological characteristics such as the slope, soil structure, saturation of the soils and so on. Using other approaches of the environmental flow assessment, the rate of change might be influenced by limits on the discharge fluctuations by for example erosion prevention. In this case the rate of change may represent a limitation on reservoir releases.

The variation within the rate of change is not considered in this research. This variation is namely expected to be of minor influence on the effects of optimization of the timing of the environmental flow release: a high or a low rate of change may have influence on the deficit, but not on deficit reduction due to a changed moment of allocation.

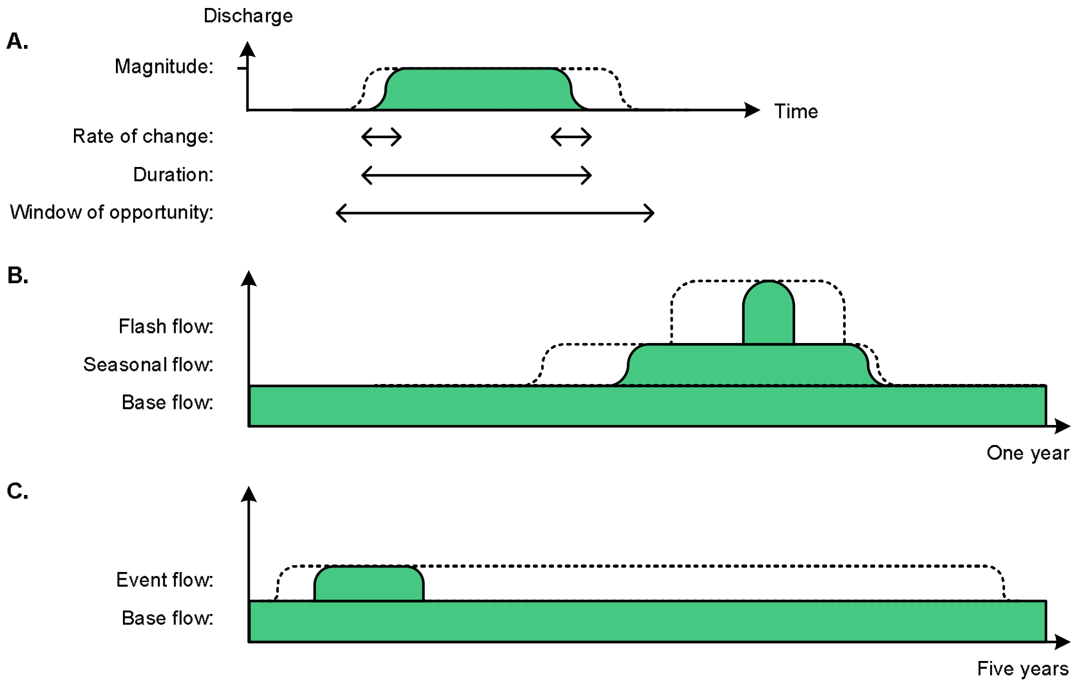

Figure 11. Visualisation of environmental flow components of several natural flow regimes. Flow components (A.) construct flow regimes within one year by increasing margin in the window of opportunity for base, seasonal and flash flow regimes (B.). The window of opportunity includes more years if an EFR is interannual (C.).

3.2.6 Selection of key aspects

The magnitude, duration, window of opportunity and rate of change define a flow regime, and the combination of several flow components can construct many differentiations of a river flow, as seen in Figure 11. However, only a few aspects are taken into account within this research. The window of opportunity is an important factor within the optimization, and it describes a condition necessary for the reduction of deficits. Further only the magnitude and the duration within the environmental flow components are analysed for the optimization of the timing of environmental flow release.

The EFR as aimed at in the problem analysis can be allocated variable in time. Therefore, flow regimes with a window of opportunity equal to its duration are not interesting. So base flows having little degree of freedom in time, are not taken into analysis. Instead, they are treated as a regular demand function. Events such as flash flows, seasonal peak flows or interannual events as depicted in Figure 11 have much more variation in its allocation possibilities. Since a detailed optimization model is not necessary for an interannual environmental flow release (see section 3.4.3), only a seasonal peak flow is taken into account as case.

Magnitude and duration of an EFR are expected to have influence on the optimization of the timing of environmental flow release. Magnitude mostly influences the intensity of the deficit and therefore the extent of the benefit that the optimization can accomplish. Thus to be able to see significant benefits, an EFR with a rather large magnitude and duration is used. To analyse the influence of magnitude and duration on the extent of the benefits, the effect of both environmental components is quantified. The duration is varied in its period of time, the magnitude is varied as the discharge for environmental flow release.

3.3 River flow

The flow regime is unique in each river. Nevertheless here it is generalized, to analyse its influences on the optimization. Two important aspects of the river flow considering water deficits, are the water availability and its fluctuation. The water availability can influence the chance that deficits develop. The fluctuation of the river flow may influence the significance of an optimization in timing of environmental flow release in the prevention of the deficits.

3.3.1 Annual mean runoff

The water availability can be characterised by the annual mean runoff (AMR). The AMR is the average natural flow, which is here assumed to be the net inflow of the reservoir. The AMR of a river differs each year, so the average river flow is better generalized by the long term average. With this average, the water availability can be compared for different rivers. The relation between the AMR and the long term flow average represents the extent of its normality: The deviation of the AMR in comparison with the long term average characterizes the intensity of a dry or a wet year.

A low AMR will initially lower the reservoir levels, and this increases the chance that supply flows for water users are hedged, creating deficits. These deficits may be very large if the AMR is extremely low, and they may appear occasionally if the AMR is only a little below long term average. If deficits appear, optimization of the timing of environmental flow release becomes interesting. Therefore the relation between the deficits due to environmental flow release and the AMR is an important aspect.

3.3.2 River fluctuation

The fluctuation of a river flow is here characterized by its minima, maxima and the regularity of their recurrence interval. Large flow fluctuations exist in an area with, for instance, steep slopes or little vegetation, that have a fast runoff. Peak flows are higher and shorter, while water availability thus the AMR is unchanged. A reasonable difference between the minima and maxima in either the inflow or in the demands is a condition to reduce the deficit volume by an altered environmental flow release. After all, if both aspects would be constant, no variety in deficit exists and optimization would have no effect.

The persistence of the recurrence interval depends on the patterns of upstream precipitation and other hydrological aspects. Rivers in areas with annual rainy seasons have large annual peak flows somewhere within this season. Deficits may appear if the regularity is disrupted, and forecasts of such a disruption my reduce the deficits if environmental flow release is adjusted. On the other hand, if the inflow is the same each year and the conventional EFR is allocated at this same moment, optimization would have minor effects. A variety in the timing of the peak flows is therefore also a condition for an effective optimization.

3.3.3 Selection of key aspects

The aspects of a river flow that are interesting for the optimization subject in this research are the relation between AMR and deficit, and the fluctuation of the river flow. The relation AMR-deficit is considered separately in Chapter 6, while the fluctuation is taken into account along with the analysis of the water demands.

3.4 Flow forecasting

A flow forecast is always subject to uncertainties, due to the many natural processes that cannot be modelled perfectly. In this research however, a hindcast is used in order to study the potential effect of the optimization. A hindcast is equal to the river flow that will actually happen. The data are known within this model because a historical dataset is used as input. Next to the potential benefits of the optimization, the hindcast is also used for analysis of the influence of the uncertainties of a flow forecast. As said, no forecast is without uncertainty, and optimization may determine sub optimal moments of environmental flow release. Subsequently, it is essential to analyse available forecast models and their inevitable uncertainties.

3.4.1 Flow forecasting models

Flow forecasting can be developed with three different procedures: (1) recorded rainfall in the basin in combination with upstream water level observations; (2) recorded rainfall used with a rainfall-runoff model; or (3) rainfall prediction by a weather model, together with a rainfall-runoff model (Carlos et al., 2006 citing Anderson et al., 2002; Koussis et al., 2003; Collischonn et al., 2005). The first two procedures have been used during the last 50 years, based on simple conceptual or stochastic modelling of hydrological variables. The third procedure may extend the lead time of a flow forecast longer than the response time to rainfall within a catchment.

Other models to predict a river flow do exist, but they are more based on available historic data than on the simulation of the natural processes. Examples are artificial neural networks or autoregressive methods, that base their flow forecast on large amounts of data for the specific case. The correct use of these data can provide predictions of upcoming flow. If extra historical information or information about actual water levels or rainfall is added, the accuracy is increased.

Within all these procedures, different models exist all with their own approaches, recommended applications, prevailing uncertainties and so on. However, all models correspond in the presence of uncertainty, which is dependent on the forecasts' lead time. Regarding to the optimization, the uncertainty influences the extent of the deficit reduction. A number of example forecast models is listed in Table 1.

3.4.2 Uncertainty

The uncertainty of a flow forecast can be classified in model uncertainties, informational uncertainties and numerical errors (Loucks and Van Beek, 2005). The model uncertainty is the inability of a model to simulate the actual processes perfectly, often as a result of assumptions, estimations or lack of understanding of the processes. Informational uncertainties are related to the model's dependency on measured data, so they have a high contribution to uncertainties in flow forecasts if the basin has a large grid for data measurements or if the data are of low reliability. At last, numerical errors are faults within the models, hence they add up to the forecast ambiguity as well.

Uncertainties in a flow forecast may result in a difference between the flow forecast and the hindcast. The flow forecast can over- and underestimate the river flow, and may predict a peak flow or drought too early, too late or not at all. These miscasts can lead to a wrong perception of the optimal moment of environmental flow release.

The lead time is the period that is covered by a flow forecast. Lead time classifies flow forecasts in nowcasting for 0-3 hours, short-term forecasting for 6-24 hours and long-term forecasting up to 24 months of lead time (Collier and Krzysztofowicz, 2000). Lead times above 12 months would make the forecast interannual, as described in section 3.4.3.

Lead time relates the period (time) and area (space) to the forecast. A forecast with a long lead time is dependent on both increased probability and larger amount of precipitation. Since informational and model uncertainties are relative to the total precipitation amount, uncertainty increases with lead time (Krzysztofowicz, 2001; Verbunt et al. 2006). A lead time exceeding the runoff period of the catchment, requires rainfall prediction. The uncertainties of models for such prediction also add up to the total uncertainty of a flow forecast.

An optimization of the timing of environmental flow release requires a flow forecast with a lead time of the period that environmental flow release influences the flows and reservoir level. The longer this period, the larger the forecasts uncertainties become and the less effective the optimization may be.

Model	Source	Location	Lead time	Accuracy
Artificial Neural Network model using rainfall runoff data	Dawson and Wilby, 1999	Mole River	6 hours	Very accurate
Hydrodynamic model with rainfall runoff models	Sprokkereef et al., 2001	Rhine River	3 days	Reliable accuracy
Rain forecast model with hydrological model	Pappenberger et al., 2005	Meuse River	10 days	Accurate
Neural network based on historical flows and actual flows	Amir and Samir, 1999	Nile River	1 month	Fairly accurate
Autoregressive method or artificial neural networks	Jain et al., 1999	Indravati River	1 month	Reasonably accurate
Climate models with hydrological models	Tucci et al., 2002	Uruguay River	1 – 3 months	Reasonably accurate
Climate forecast with hydrologic model	Hamlet and Lettenmaier, 1999	Colombia River	6 months	Rough accuracy
Climate model	Wood et al., 2001	Potomac River	6 months	Low accuracy

Table 1. Several examples of flow forecasting models with their lead time and accuracy. The accuracy is a mutual comparison on a very subjective scale.

3.4.3 Interannual forecasting

Forecasts longer than 12 months are usually based on global circulation models in combination with average historical flows. In line with the decreasing accuracy with extending lead time, the uncertainty of an interannual flow forecast is high. At a certain point the uncertainty level will reach a maximum, since historical data, seasonality and boundary conditions limit the uncertainty. However, at such a level of accuracy it is only possible to speak of the difference between a wet or a dry year.

These interannual flow forecasts are necessary if the EFR has very large window of opportunity, resembling a low frequency and a low persistence in timing. In such a case, accuracy is low and the use of a hydrological model is not expected to be necessary since the forecast itself is already enough to point out the optimal moment of environmental flow release.

3.4.4 Selection of key aspects

The uncertainty of a flow forecast can result in decisions, based on incorrect information. Hence, the influence of uncertainty is selected as key aspect and analysed within the case study in Chapter 5. This is done by the usage of a simple flow forecasting model that is subject to uncertainty. The forecast method used is described here, the input data and the details about its uncertainty is provided with the input data in section 4.4.6.

3.4.5 Flow forecast method used

It is chosen to use an autoregressive model to create a flow forecast with the flow at the current timestep and the historical average flow. Advantage above the other methods of flow forecasting, is that an infinite lead time is obtained. With an infinite lead time, no limitations for the length of the hydrologic simulations exist. Disadvantage is that after a certain time, the flow forecast is only based on historical input, so that flows in a dry year are per definition overestimated and in a wet year underestimated. This might result in an environmental flow release that is stubbornly postponed in dry years and apprehensively put forward in wet years.

The autoregressive model used is a process often applied to predict various types of natural and social phenomena. A common application is the addition of random noise to an observed flow, to simulate the uncertainty of a flow forecast. In reality however, the observed flow is not yet available and such a forecast is purely theoretical. In this research there is chosen to create a flow forecast that is possible to develop in reality, so the model is used to decrease the difference between the actual flow and the historical average flow within a certain amount of time. In the literature, this method is comparable to the linear perturbation model, described by Goswami et al. (2002).

The autoregressive model uses a number (p, also referred as orders) of terms (X) from past timesteps and one parameter per term (φ) determining its influence on the next term. Together with a constant (c), some random noise (ε) and the orders, a new term is generated (see Equation (1)). In this case the constant is the average flow and the terms are the observed flow before the current timestep. The generated term is subsequently used for development of other terms further in the future.

Equation (1) $$X_t = c + \sum_{i=1}^{p} \varphi_i X_{t-i} + \varepsilon_t$$

3.5 Water demands

In the problem analysis, the EFR is described as a function that competes directly with the other demands that are related to a reservoir. To analyse this competition, the demands are characterized and their influences on the optimization are determined.

3.5.1 Functions of a reservoir

A reservoir has multiple functions that are competing for its water. These functions are water supply for municipal, industrial and agricultural needs, and they are focused on practical needs such as hydropower, flood control, navigation and recreation (Verhaeghe, 1997). To be able to analyse all different kind of functions, the fluctuation within their demand is selected as an aspect. The fluctuation is expected to have influence on the deficit reduction by the optimization in case deficits emerge due to environmental flow release. All functions can be expressed in fluctuation, for which only the two most extreme functions are further explained. These are the water needs for agriculture and for hydropower.

The water need for agriculture has commonly a high seasonal variation. Other supply functions such as municipal and industrial water needs are expected to vary less. For the practical needs, hydropower is selected as most common function that competes with the EFR. That is to say, since the accompanying firm storage volume in the reservoir or firm discharge form the reservoir flattens the pattern of the natural river flow.

Fluctuation of the other functions is similar or in between. Navigation and recreation may require constant water level in the river, equal to a demand with little fluctuation. Maximum discharges for these functions can compete with the EFR, but this kind of problem lays outside the research scope. Flood control is also a common function for reservoirs, which prevents downstream flooding. This function requires a minimal storage volume to be available during high floods. Assuming that the magnitude of an EFR never exceeds the maximum discharge that the flood control is designed for, flood control is no impediment for the implementation of an EFR. Reservoirs with flood control as a single purpose are therefore not taken into account in this research. Flood control does affect the operational management if combined with functions that require hedging. Then it influences the outflow and the deficits. Influence of flood control is therefore taken along in the operational management, which is considered in the characteristics of a reservoir (see section 3.7).

Concluding, the agricultural and hydropower demand are representative competitors of the EFR concerning water usage. The characteristics for these types of water demands are here further illuminated.

3.5.2 Characteristics agricultural demand

The agricultural demand consists of the water abstraction that is necessary to fulfil the water requirement of crops. This requirement is not only determined by the water uptake and transpiration by the crops, but it also involves the losses such as evaporation. The evaporation is a large component since irrigation spreads water over a large surface so water temperature rises easily. Depending on the irrigation system and the kind of crops, a portion of the water may flow back into the river and can contribute to the environmental flow. On the other hand, if this water is polluted by for example fertilizers or a high temperature, extra water from the river is needed to dilute the pollution.

All together, a large part of the agricultural demand does not return to the river. This part is always directly competing with the environmental flow. For the part of the agricultural demand that does get back to the river, it depends on the location of the return flow whether it competes with the environmental flow. If the EFR is determined for an area upstream the return flow location, the full agricultural water abstraction competes with the environmental flow.

Agricultural fluctuation

The agricultural demand tends to fluctuate over the year. Most crops are grown in only one season, possibly multiple crops can be grown over the different seasons. Also during the growing of crops, the water demand fluctuates. The agricultural water demand therefore has usually one or more peaks per year.

These demand peaks can have high fluctuation if a crop is grown which only needs irrigation during a limited period, while a more flat demand pattern exist for crops that require irrigation during the whole year. A rough division can be made between crops that are replanted every season for high fluctuations (rice, wheat, corn) and perennial crops that don't need replanting for low fluctuation (fruits, coffee). The fluctuation of the demand peak is determined by the type of crop, the magnitude of the average demand is established by the surface and density of the cultivation. The recurrence interval of the demand peaks depends on the frequency that crops are grown within one year (see Figure 12).

Influence of fluctuation

Under the assumption that EFR gains priority over other water usages, the deficit due to environmental flow release is directly influenced by the magnitude of the demand. So surface and density of the cultivated area determine the possible amount of deficit and the potential deficit reduction by the optimization. Fluctuation on the other hand, may increase the chance that deficit reduction is possible, since an adjusted environmental flow release has more effect on the deficits. So for agricultural demands, whether or not the optimization is useful may be determined by the type of crop.

In some cases demand is low but deficits due to environmental flow release do occur. If the AMR is less than the average yearly demand (excluding the water for the EFR), structural deficits will occur. Even the best possible timing of the EFR cannot prevent deficit. This aspect is partly represented by the relationship between AMR and the deficits. This is already selected as an aspect to be researched, so variation in average water demands is already considered.

All together, the agricultural demands are an important competitor for the environmental flow as long as the abstraction is upstream the environmental area and the possible backflow is located downstream. As defined in the problem definition, abstraction for the demand is assumed to compete fully with the flow for the EFR. The aspect selected of the agricultural demand is the fluctuation of the demand, representing the type of crops.

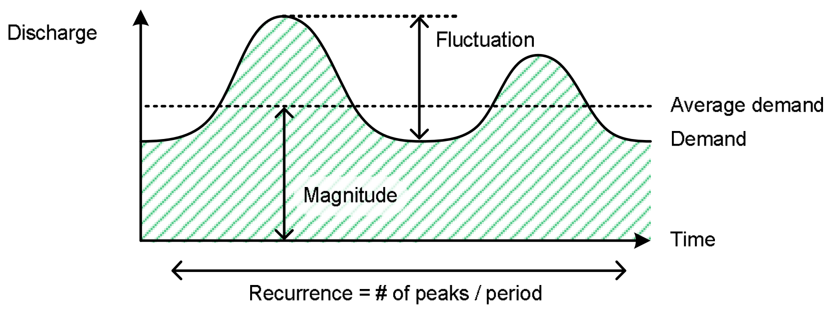

Figure 12. Sketch of an agricultural demand peak, defining its magnitude, fluctuation and recurrence interval.

3.5.3 Characteristics hydropower demand

The water demand for hydropower is based on the need to have a continual and assured potential of production of hydropower. When the power generator is located in the dam itself, a firm storage in the reservoir is necessary to provide a certain amount of pressure that can generate the power. A sufficient water volume is also essential to be able to discharge the reservoir without undermining the firm storage. If the generator is further downstream, discharge is determined to supply a continual and constant flow at the lower dam.

(Lack of) fluctuation

Peaks of power usage do exist and are related to peaks of hydropower demand, since demand is tuned with the price of energy. The recurrence of these peaks can for example be on day time, on week days or during winter months. Changes in the demand for power have various scales. If environmental flow release causes deficit in a situation with small scale fluctuation on an hourly or daily base, this fluctuation does not give any opportunity to optimize the timing of the environmental flow release. After all, the duration of the EFR is usually of a much larger scale so that the fluctuation has no effects on the optimization. If hydropower demand has large scale fluctuations, it influences the optimization subject in the research similar as with the agricultural demand. To research the typical difference between the agricultural and hydropower demand, the latter is characterized by a negligible fluctuation with a constant demand over the whole year.

Influence on deficits and optimization

In contrast with the agricultural demand, hydropower generation does not consume water, and it does not compete directly with the EFR for water volumes. The hydropower demand does compete with the EFR though, based on the different desires concerning the river flow regime. Hydropower generation changes the flow regime: it reduces peak and increases low flows. A more natural flow regime would therefore result in periods during which the turbines cannot be fully used and periods with large releases that may exceed the turbine capacity.

The more continual supply flow decreases the chances to reduce the deficit by changing the timing of the environmental flow release. While the fluctuation in the agricultural demand offers opportunity to allocate for the EFR during moments of low demands, the hydropower deficits can only be reduced if environmental flow release it is timed together with a large inflow.

3.5.4 Selection of key aspects

In this research, all functions above are summarized as a single water consumer, of which the EFR is excluded. Consequence is that the water need for hydropower is also expressed in volumes, which is possible in the case study since the hydropower generation is located downstream the river. There is chosen for the modelling of only a single water consumer, to be able to draw conclusions for the demand in general, and to limit the scope of the research.

To be able to research the different kind of functions, the demand fluctuation is selected as an aspect to analyse in Chapter 6. The fluctuation is characterized by two extremes: agricultural and hydropower demand. Agricultural water demand has a direct competition for the amount of water with the EFR, and the continual hydropower demand competes with the fluctuation necessary for the EFR. To compare the two demands, one quantification is done of a situation with only fluctuating demand and one situation with a continuous demand.

3.6 Physical characteristics of a reservoir

Reservoirs are characterized by their function in the system of a river basin, by the way they are operated and by their physical configuration (Verhaeghe, 1997). The last two aspects are usually designed to serve the first aspect; the reservoir's function. The possible functions have already been described in section 3.5.1. In this section, the relation between the physical configuration and the optimization method is analysed. The operational management is described in the next section.

3.6.1 Effective storage capacity

A reservoir can control the water level and discharge by the use of a controllable gate. As a result, it can store or release water volumes at different rates than the reservoir's inflow, on the presumption that the necessary water or storage volume is available in the reservoir. Physically, the reservoir is therefore reliant on its capacity to store and manage water volumes. The reservoir's capacity is determined by the dam height, valve height and depth-volume ratio. The effective storage capacity excludes the dead storage, which fills the reservoir until the valve height.

Reservoirs that serve a supply function such as agriculture, have a maximum effective storage capacity that is designed for the total demand volume minus the guaranteed inflow during a design drought period. In that sense, the volume of a reservoir is dependent on the magnitude of the design demand downstream. For example, a reservoir built for a small cultivated area with a low demand will have a small storage capacity. If the reservoir serves a large cultivated area along a river with a large probability of droughts, a high storage capacity is necessary to serve the supply function.

Reservoirs that serve a practical need such as hydropower, may be as big as the surrounding area allows. After all, a higher head results in a bigger power generation and a larger water volume gives a better guarantee for the power generation be sustained.

An undersized reservoir in comparison to the river flow, would mean that the reservoir is quickly filled up to the maximum capacity. This causes spilling during high flows making the flow closer to a natural flow (as the hashed line in Figure 13). Both a hydropower functions and agricultural needs would experience more deficits: Potential energy is spilled and the reservoir is not able to store enough water for the dry periods. However, the necessity of an enforced environmental flow will be smaller, and optimization is therefore of less use.

The opposite of an undersized reservoir is a reservoir that can store all water needed for a whole season. If such a reservoir is filled up, it practically controls its yearly outflow. Then it is easy to calculate the moment of environmental flow release that causes the least amount of deficits, as long as the demands are available. A flow forecast is not necessary, since it is replaced by the large size of the reservoir. So it is only necessary to make use of flow forecasting if the time period that the reservoir's inflows can be stored is smaller than the time period for which optimal allocations should be calculated.

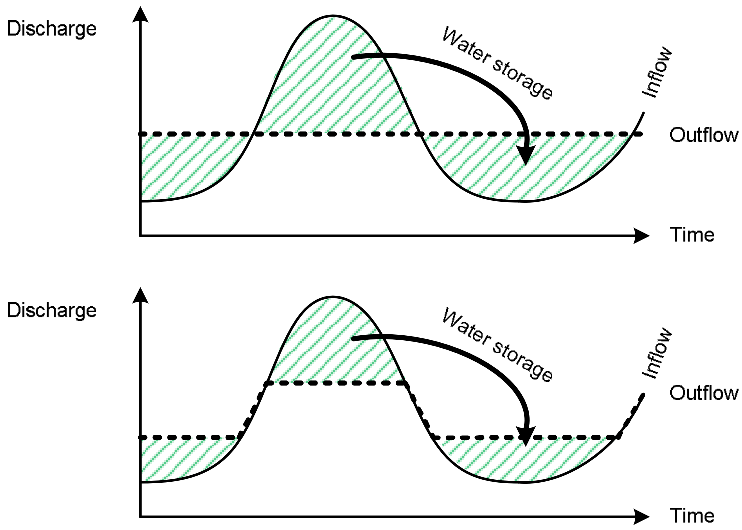

Figure 13. Inflow and outflow of a reservoir with a visualisation of the possibility to store volumes of water for a large reservoir (upper) and for a small reservoir (lower). The outflows of the small reservoir are more dependent on the natural flow than in the large reservoir.

3.6.2 Selection of key aspects

Concluding, the size of a reservoir is the most important aspect of the physical reservoir. Its storage capacity may reduce the need for a flow forecast to reallocate the EFR. On the other hand, if the reservoir gets smaller deficits may increase and optimization with flow forecasting may be more effective. Therefore the storage capacity of the reservoir is decreased in the quantification of Chapter 6.

3.7 Operational management of a reservoir

The operational management determines the outflow of a reservoir, and is always adjusted to the local circumstances. To generalize the operational management though, the base of operational management is subject: Rule curves and hedging rules.

3.7.1 Rule curves and hedging rules

Competing functions of a reservoir as described in section 3.5.1, require operational management to satisfy all assigned functions at best. Therefore the operational management is usually designed with desired conditions (rule curves or rule zones) and guidelines for operations if those conditions cannot be maintained (hedging rules). These conditions include the ideal storage levels or releases per function, which vary throughout the year (Verhaeghe, 1997). During periods of drought, the inflows are low and the reservoir level is under the firm storage target. Then hedging rules are used which restrain the outflows, to balance the current with future shortage in supply.

Hedging rules can have high or low supply restraining percentages. Rules with high percentages would cause large deficit for supply functions but also a fast restoration of the water level, and that reduces the loss of hydropower generation. Rules with low percentages can cause smaller direct deficits for water users but its long restoration time may affect them for a longer time. Hence, different interests for hedging rules exist and negotiated rules are made during the design phase of the operational management.

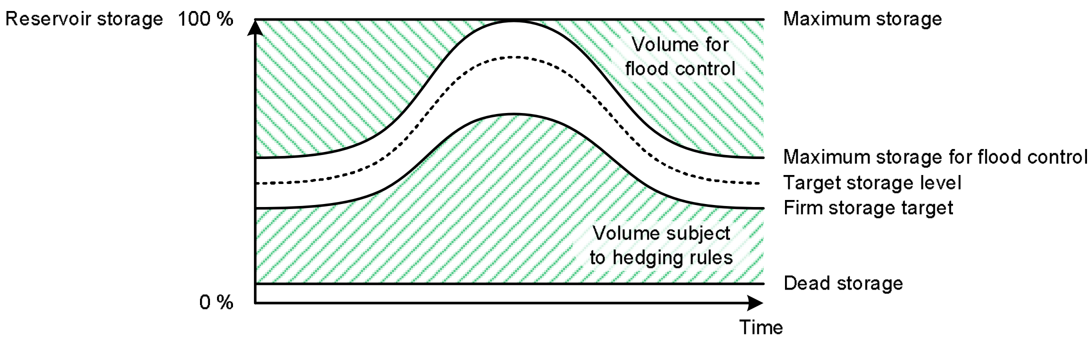

Figure 14. Sketch of example operational management of a reservoir with functions of flood control and firm storage. (Loucks and Van Beek, 2005)

3.7.2 Operational management determined by reservoir functions

Functions may have conflicting ideal storage levels and releases, resulting in strict hedging rules or a narrow target storage zone (the zone between the firm storage level and the maximum storage level in Figure 14). Common functions with mutual conflicts are water supply, hydropower generation and flood control.

Flood control requires a storage volume in the reservoir that can fill up in case of large inflows that can flood the downstream area. The function is represented in the operational management by the maximum storage level. This level can tighten the target storage zone and is (inversely) related to the maximum capacity of the river bed behind the dam and the expected maximal inflows.

Conditions of supply functions and firm storage influence the fluctuation of the firm storage target and the hedging rules. First, the fluctuation of the firm storage target itself is a compromise between required water supply during dry periods and required continual storage for hydropower generation. Second, hedging rules are also a compromise: Firm storage would require the reservoir level to fall above the firm storage target in all cases, so hedging rules that fill up the reservoir as fast as possible are desired. On the other hand, supply functions would require the reservoir outflow to be at least equal to its downstream water demands in all cases, so that no supply is restrained even in the case that the reservoir level is below the firm storage target.

3.7.3 Influence of operational management on the optimization

Competing functions imply little possibility to deviate from the target storage level. This may influence the effects for the deficits. For example, if no margin of storage capacity exists and EFR is allocated, the flow for the other users is directly subject to hedging rules and deficits appear, while some extra allocation might have been allowed if the firm storage target was lower. Concluding, conflicting functions result in larger chances for deficits, and they enlarge the potential of the optimization.

Hedging rules that restrain the water supply much, may cause large deficits for water users, while little restraints in the water supply may cause large problems for the hydropower generation. So if the reservoir level falls below the firm storage target, deficits will appear either way. However, hedging rules can influence the optimization since the restraining percentage is related to the length of the restoration period after reservoir level falling below firm storage level. This length may affect the benefits that the optimization has for the deficits: Deficits spread over a long duration are likely to be less sensitive for a changed timing than deficits spread over a short duration. Therefore optimization may have more benefits for hedging rules with high restraining percentages, which restore the reservoir level in a short period.

3.7.4 Selection of key aspects

Operational management for reservoirs with many competing functions is resembled here by rule curves with a small target storage zone. The consideration between full supply or firm storage is represented by the hedging rules. Only the hedging rules are selected as an aspect to analyse in Chapter 6.

The hedging rule is expressed in the percentage of water supply that is restrained in case that reservoir level is low. The restraining percentage influences determine the restoration time of the reservoir level. Therefore, the restraining percentage is expected to have significant influence on the deficits and their reductions by the optimization.

3.8 Summary of selected key aspects

Here the key aspects that are selected for quantification in the model are summarized.

For the analysis of the influences of the EFR on water deficits and its reductions, the environmental flow components *duration* and *magnitude* modelled and analysed. For the river flow, the reductions by the optimization are compared between several *magnitude of the inflow*. The analysis of the influences of the flow forecast is represented by the *uncertainties* that come with a forecast. The most important differences between water demands are represented by their *fluctuation*. Physical properties of a reservoir are represented by its storage opportunities, so that the *reservoir size* is analysed. Finally, for the operational management the *restraining percentages* of hedging rules are varied to see what their exact effects are on the optimization.

Chapter 4 The optimization model

4.1 Introduction

This chapter is focused on the step *"How are the water deficit and the optimization modelled?"* It is important to clarify the definition of the objective function and the model used in this research, since all results of this research depend on these base-line data. In this chapter, the modelling definitions and the model structure used are determined, the input data to resemble the Itezhi Tezhi dam in the Kafue River are determined and the hydrological model is validated.

4.2 Modelling definitions

The objective of optimizing the timing of the environmental flow release is a reduction of deficit. Therefore a clear definition of deficit is necessary, expressed in variables that can be modelled. The water balance of a reservoir and its outflows are addressed and assumptions made are considered.

4.2.1 Water balance

In the water balance as in Equation (2), water going into the reservoir (Q_{ResIn}) and out of the reservoir (Q_{ResOut}) determine the volume change within the reservoir (ΔV_{Res}) over a certain period (Δt). Here, Q is expressed in m^3/s and is always positive. According to the problem definition of this research, the reservoir inflow is the net inflow discharge including hydrologic processes as precipitation, evaporation, seepage etc. The reservoir outflow is assumed to be equal to the water supply for allocations downstream.

Equation (2) $$\Delta V_{Res} = \int_0^{\Delta t} \big(Q_{ResIn}(t) - Q_{ResOut}(t)\big)\, dt$$

This water balance represents the situation in the reservoir only. Its outflow is dependent on the operational management and the deficit is determined by the allocations downstream, as sketched in Figure 15. These subjects and relationships are explained in the following sections.

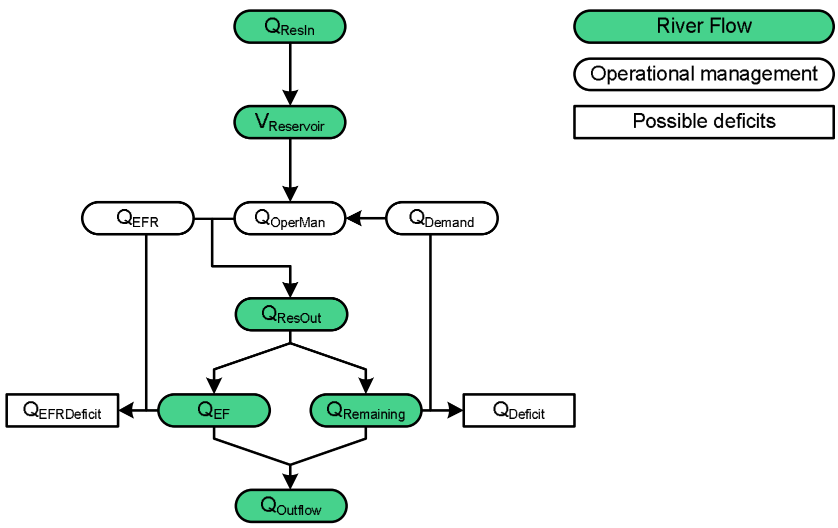

Figure 15. River runoff model, including the operational management and the possible deficits.

4.2.2 Operational management

Reservoirs with dams that can control the outflow, have an operational management based on rules that indicate the desired or required reservoir release or storage volume at any particular time of year (Loucks and Van Beek, 2005). These rules are based on conditions considering water level, flow and users, creating an upstream link between the flow demands and the reservoir outflow. An operational management with these rules determines the outflow of the reservoir ($Q_{OperMan}$). A reservoir with simply this outflow is used in the situation that no EFR is allocated.

To compare the effects of environmental flow release and to create the opportunity to change the moment of environmental flow release in a transparent way, the flow for the EFR (Q_{EFR}) is added on top of the original outflow $Q_{OperMan}$ as in Equation (3). Together they determine the reservoir outflow (Q_{ResOut}).

Equation (3) $$Q_{ResOut} = Q_{OperMan} + Q_{EFR}$$

A reservoir often has multiple functions that require different flow and reservoir conditions. Within this research, all flows required by the downstream functions are simulated as one single demand function (Q_{Demand}), with exception of the EFR (Q_{EFR}). As assumed in the problem definition, in this research the two demand functions cannot re-use each others water. Hence, the more water that is directed to the EFR (Q_{EF}), the smaller the flow that is left for the other water users ($Q_{Remaining}$), as determined in Equation (4).

The second important assumption made in the problem definition, is that the EFR has priority above the other water users in case of water shortage. So water from the reservoir outflow is first used to fulfil the needs of the EFR, and only allocated to the other water users if water is left. Therefore, the allocation for other users is dependent on the allocation for EFR.

Equation (4) $$Q_{Remaining} = Q_{ResOut} - Q_{EF}$$

4.2.3 Deficit

If no water is discharged from the reservoir, or if the water allocated for the EFR reduces the remaining outflow below the demand of the other users, a deficit for these users exist ($Q_{Deficit}$), as in Equation (5). There is a surplus of water if the flow remaining after allocation for the EFR, is larger than the other users' demand. The surplus forms no problem within this research, but the deficit does. The aim of the optimization is to minimize the deficit that emerges due to environmental flow release.

Equation (5) $$Q_{Deficit} = Q_{Demand} - Q_{Remaining} \quad \text{For:} \quad Q_{Demand} > Q_{Remaining}$$
Equation (6) $$Q_{Deficit} = 0 \quad\quad Q_{Demand} \leq Q_{Remaining}$$

A deficit for the EFR exists if the flow for the environment does not meet the EFR, as in Equation (7). Taking the assumed priority for the environmental flow into account, a deficit for the EFR would imply that no water is allocated for the other users at all. This situation would entail significant water shortage and deficits would be as large as the users' demands. It is questionable if a flow for the EFR should be allocated in such a case at all.

Equation (7) $$Q_{EFRDeficit} = Q_{EFR} - Q_{EF}$$

4.3 Model structure

The model structure used in this research is described in this section. It is developed specially for this research, to be able to adjust the selected aspects and to determine the water deficits.

The model is set up in Delft-FEWS software, which can provide clear overview of the datasets and can initiate the processes in Ribasim and MATLAB software. Ribasim is used for the hydrological simulations and MATLAB for the decision processes. Other hydrological and numerical computing programs may also be used. Here is chosen for Ribasim since it is software developed and applied at Deltares.

In Figure 16, a schematic view of the model is given. It divides the process in three parts: preparation, optimization and application. In the preparation, data are imported into the FEWS environment to create a forecast and to determine the moments that the EFR can be allocated. During the optimization part, the best possible moment of allocation for the EFR is selected by means of hydrological modelling in Ribasim and set criteria in MATLAB. Finally the chosen allocations are applied with the hydrologic model and the flows, reservoir level and deficits are abstracted. These three parts are processed each timestep. The model can be run for multiple successive timesteps to calculate the deficit for a full test period.

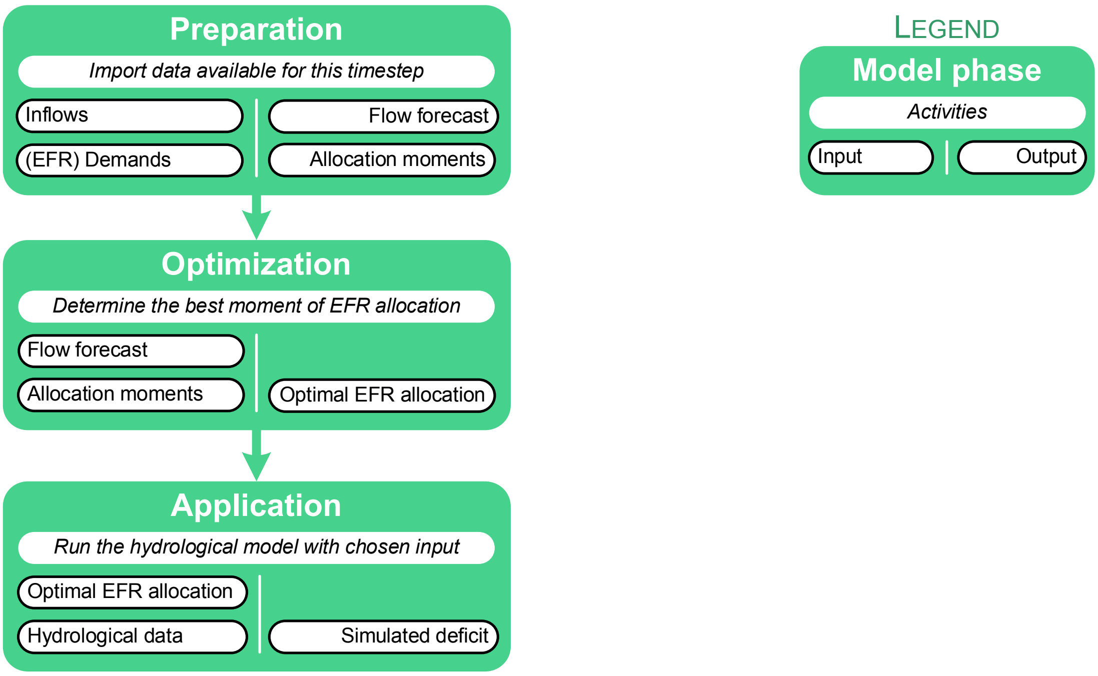

Figure 16. Summary of model procedure during one timestep in Delft-FEWS.

A timestep of one week is applied for adjustment of reservoir operation. The most direct implication of this timestep is that calculation of the best moment for environmental flow release is done once a week, and that the allocation can only start at the beginning of a week. It is possible to make the timestep smaller, but this would enlarge the allocation moments and therefore the calculation time. Now, calculation time is about 20 seconds per timestep. Since input data for the hydrologic model (inflows, historic flow averages and water demands) are on daily base, detail of the flows is maintained by the application of a daily timestep in the hydrologic model. So simulation in the hydrologic model is on daily base, while optimization of the environmental flow release is reviewed on weekly base.

4.3.1 Preparation

The preparation procedure imports data and prepares the necessary data sets for the simulation and optimization procedures. The actions taken are summarized in Figure 17.

Import data

At the start of the timestep, necessary data are imported into the Delft-FEWS workspace. The observed flow and the average historical flow are imported to be able to simulate the actual flows and to create a flow forecast. The components of the EFR such as the window of opportunity, the magnitude and the duration are imported to determine its possible allocation. The demand for the other users is also collected, for calculation of the deficits in the optimization and simulation procedure.

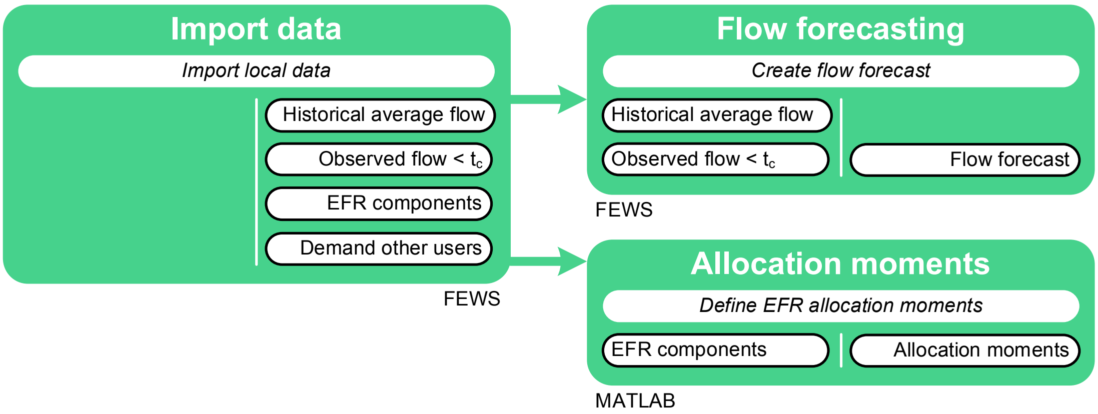

Figure 17. Preparation.

Flow Forecasting

After importing data, a flow forecast is created. The flow forecast can either be imported from another model or created within the Delft-FEWS software. In this research, a straightforward flow forecast is developed using the historic flow average and the actual inflow at the current timestep (t_c). The difference between the two flows is decreased over a certain time period using an autoregressive error correction. A module for this method is available as an autoregressive moving average (ARMA) error correction in FEWS, making it easy for application.

In section 3.4.5 the flow forecast method used has been described, in section 4.4.6 the input data used for this autoregressive model is discussed, along with a figure representing the flow forecast (Figure 23).

This research also makes use of a hindcast. Then observed inflow data are used instead of the flow forecast described. With help of a hindcast, the influence of the uncertainty of flow forecasting is determined. If other variable as selected in Chapter 3 are tested, the maximum possible benefits of the optimization can be determined. This provides a more objective view on the influences of the variables analysed.

Allocation moments

In order to determine the moments that the EFR can be allocated, MATLAB is used. Based on the window of opportunity and the duration of the EFR, all possible moments for environmental flow release are returned by the MATLAB script, and imported into FEWS as an ensemble. For example a weekly timestep, an EFR duration of 4 weeks and a window of opportunity of 7 weeks provide 4 allocation possibilities, starting in the first four weeks (see Figure 18).

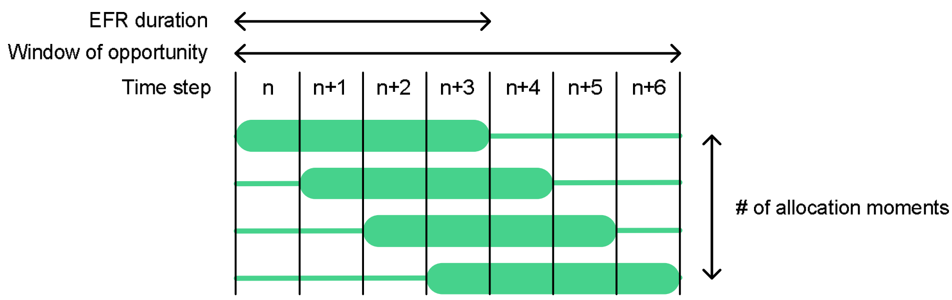

Figure 18. Determination of possible moments for environmental flow release (environmental flow release ensemble). The number of moments depends on the sizes of the window of opportunity, the EFR duration and the timestep.

4.3.2 Optimization

The optimization executed in this research comprises a straightforward calculation of all possibilities and selecting the one that complies best to the optimization variable (having the smallest deficit). Therefore, the hydrological model is run with the ensemble of allocation moments, and for each ensemble member the resulting deficit is calculated. The allocation moment resulting in the least amount of deficit is selected as optimal allocation (see Figure 19).

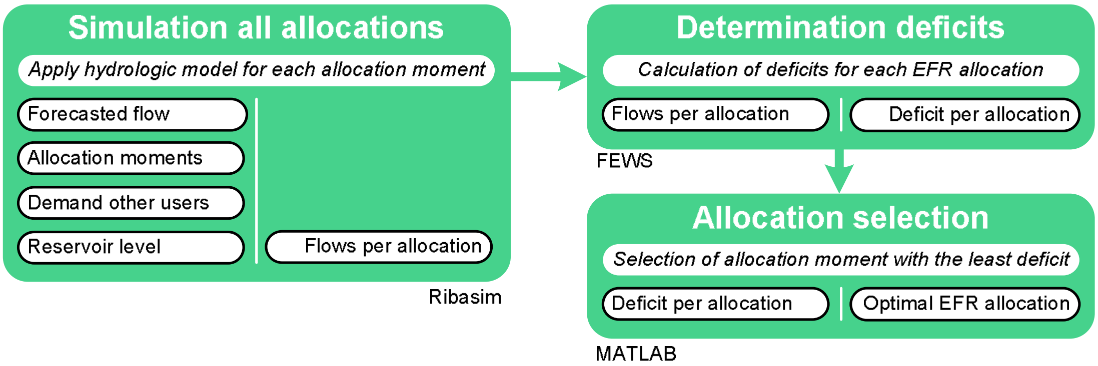

Figure 19. Optimization.

Simulation all allocations

The hydrological effects are simulated for each member of the allocation ensemble in the hydrological model. The simulation is run for the expected period that members of the allocation ensemble have impact on the hydrologic situation (period T). This period is constricted by the window of opportunity of the environmental flow release, plus the time that this allocation affect the reservoir level and the downstream flows. In this research, a period of 50 weeks is used.

The hydrological software Ribasim is used for its possibility to model reservoirs and its available link to Delft-FEWS. The set up of the hydrological model is provided in Appendix E. Important of this set up is the configuration of the operational management and the way that EFR is imposed.

The original outflow of the reservoir ($Q_{OperMan}$) is dependent on the rule curves as in Figure 7. The actual outflow is also dependent on the allocation for EFR (Q_{EFR}). According to the problem definition, this last flow is allocated without hedging, even if the reservoir level is below firm storage level. In Ribasim, the EFR and the other users are simulated by two different demand nodes. The node for EFR is based on a variable dataset, making it possible to submit the EFR from the FEWS environment to the Ribasim environment. Since the reservoir's outflow depends on the demand nodes, it is possible to alter the moment of allocation for the EFR from the FEWS environment.

A Ribasim state file is used that remembers the reservoir level after a run is done. It is updated only after the simulation in the application procedure, so each Ribasim run continues with the reservoir level that is determined in the end of the last timestep.

Determination deficits

If all flows are known for each ensemble member, the accompanying deficits are calculated with the use of the demands. The flows as produced by Ribasim are compared to the water demands for the corresponding period. Using definitions of Equation (5) and Equation (7), deficit is calculated. Because discharges vary per timestep, deficit is a function of time and comparison of deficit is done based on the accumulated deficit for the full simulated period of 50 weeks. The accumulation of the deficit (V_{Def}) over the simulated time period (T) as defined in Equation (8), is compared between the different members of the allocation ensemble (m).

Equation (8) $V_{Def\,m} = \left(\int_{t_c}^{T} Q_{Deficit}\, dt\right)_m$

Selection optimal allocation

After the calculation of deficit for all ensemble members, the member with the smallest deficit is selected with help of a MATLAB script and the accompanying optimal moment for environmental flow release is returned to FEWS. This optimal moment of allocation is used in the definite simulation.

4.3.3 Application

Finally, the definite simulation is run in the same hydrological model as used during the optimization. This simulation however, has the observed flow as input instead of the forecasted flow and the model only runs for one optimization timestep (one week). After running the model, the definite deficit is calculated and feedback data are created for the next timestep (see Figure 20).

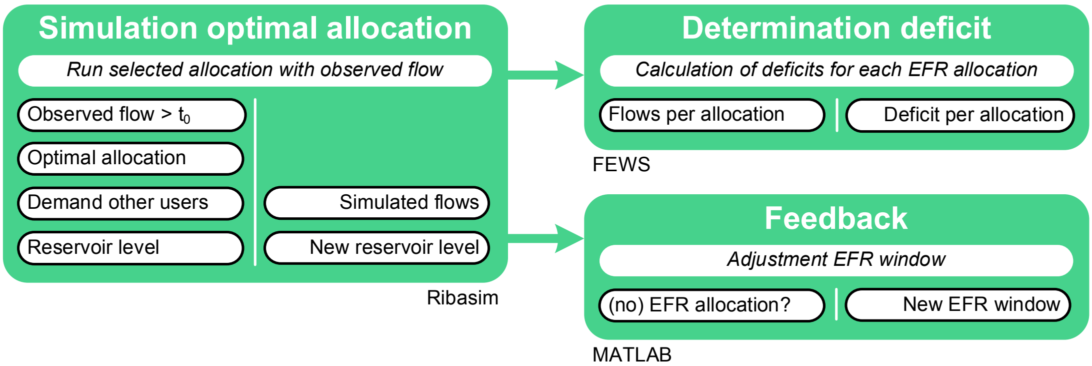

Figure 20. Application.

Simulation optimal allocation

If the optimal moment for environmental flow release is determined to start at the current timestep, environmental flow release is applied within the simulation for this timestep. Else, the simulation for this timestep is done without allocation for the EFR. This decision, together with the observed flow for this timestep, is used for the definite simulation in the hydrological model. This simulation is executed in Ribasim with the same hydrologic situation as in the optimization part. Simulated flows are exported back to FEWS and the reservoir level is updated in the Ribasim state file.

Determination deficit

With the output allocations of the hydrological model and the earlier imported water demands, the deficit is calculated in a transformation module in Delft-FEWS as during the optimization. The only difference with the optimization is that the deficits accumulation only covers one timestep.

Feedback

The optimal allocation according to an optimization with flow forecasts can change through time, since the flow forecasts evolve. Hence, each timestep the optimization algorithm is run again. At the start of the next run, information is taken along that is written at the end of the last run. This information is included within the size of the window of opportunity. Adjustment of this size is necessary since the window shortens if time passes by, and since the window should be limited to the EFR duration if environmental flow release has taken place in a former timestep. The latter adjustment provokes a continued environmental flow release once it has been started.

4.4 Model input for case study

The case study is designed to simulate the situation at the Itezhi Tezhi dam in the Kafue River, within the possibilities of the Ribasim hydrological model. This section determines the input for the model as described above, based on the situation of the Kafue River as in Chapter 2. The situation is determine by both input data and the hydrological model. An overview of the exact input variables is shown in Table 2, the set up of the hydrological model as used in Ribasim is provided in Appendix D.

4.4.1 Model run

The period that the model is run is dependent on the availability of natural river flow data. Data is available from 1961 up to present day, but it resembles the natural flow only until the construction of the Itezhi Tezhi dam in 1978 (SWRSD Zambezi Basin Joint Venture, 2010). For this, the model is run for 18 years, starting at the first day of November 1961. This day is chosen so that the it has the least possible influence on the result of 1962, since at this point the flow just starts to build up and the opportunity window is not yet begun. The model ends 16 years later at the 31st of October in the year 1977 and calculates for each year the accumulated deficit for the past 12 months.

Three hydrologic years are left out of the calculation of deficit due to a technical problem of the model structure. The synchronisation of the timesteps of FEWS and Ribasim provides an error at the end of three years: 1964, 1970 and 1976. Result of this error is that at those moments the reservoir level is set back to the initial level and that the optimization model does not work correctly during these years. The initial level is set to the reservoir level that is common at this point, so the hydrological situation is not affected much. Hence, the particular three years are not taken into account in the results since optimization is impossible, while the other 13 years provide results which are possible to analyse. The origin of this error is known at Deltares but it has not been possible to find a solution.

4.4.2 River flow

The observed inflow obtained from the ZAMWIS database (SWRSD Zambezi Basin Joint Venture, 2010) is used as reservoir inflow. The inflow is on average 368 m^3/s and has annual peaks up to a maximum of 1715 m^3/s, which occur from the months January until May (see Appendix B). This variation in both discharge and timing of the annual peak flows are important, since these are conditions of the reservoir inflow for a beneficial optimization.

The initial reservoir level is set to 33.5 meters, equal to 1023 meters above sea level. This level approaches the reservoir level at the three moments that the reservoir level is set back.

4.4.3 Demand

The demand other than the EFR, is in the case study simulation based on the demands for agricultural usage and for hydropower generation. Other usages are left out of consideration. The demands of agriculture are based on data from the ZamSugar Company (Attachment A, Interview ZamSugar, Figure 8). The demands for hydropower generation are based on the firm discharge of 170 m^3/s necessary for the power production of 600 MW at the Kafue Gorge dam. Both demands are simulated within one demand node in Ribasim, so they are added up. This results in a flow demand fluctuating between 171.6 and 186.8 m^3/s (see Figure 21). Now the demand has a minor fluctuation, which reflects the fact that the Itezhi Tezhi dam's main purpose is the continuous discharge for hydropower.

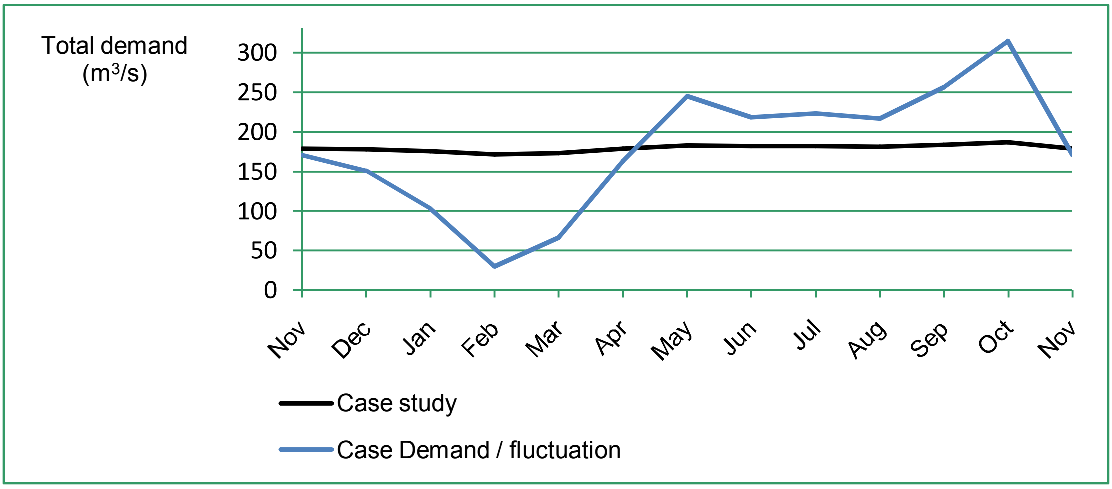

Figure 21. Total water demand of agriculture (ZamSugar Company) plus hydropower (ZESCO), as input for the demand function in Ribasim. The case study demand is applied in all cases in chapters 5 and 6, except for case "Demand/fluctuation", which shows more fluctuation than the case study.

4.4.4 Reservoir size and operational management

The total volume of the Itezhi Tezhi reservoir is 6616 million m^3. The gate level is situated at 17 meters above the lowest point, causing a dead storage of 721 million m^3. This results in an effective storage volume of 5895 million m^3. The exact surface area and storage volume as entered into Ribasim is found in Appendix D.

For the modelling of the operational management, Ribasim has two options: based on reservoir level and based on demand. In this research it is necessary to model the operational management based on demands. This method can enforce an allocation for EFR at predefined moments. To approach the operational management of ZESCO, the maximum storage level, target storage level and the firm storage level as displayed in Figure 7, are set in Ribasim as respectively the flood control, target level and firm storage level. The reservoir in Ribasim allocates for two demand nodes: a *low flow node* which represents the EFR and a *public water supply node* for the other water demands. If the reservoir level gets below the firm storage level, only the supply for the *public water supply node* is hedged. In the case study 25 percent of the demand is restrained. In the next chapter, this percentage is increased and decreased to see its influence.

4.4.5 EFR

The EFR of the case study is based on a compromise between two environmental flow assessments of the Kafue Flats: the March Freshet (Attachment A, Interview WWF) and the environmental scenarios of Wilson (2003). This results in a flow of 300 m^3/s for a duration of two months, with an opportunity window between February to May, as used in the case study with an optimized EFR (c). In the case study with a fixed environmental flow release (b), the flow is each year allocated from the first week of February. In the case study without any environmental flow release (a), obviously no window of opportunity exists, as seen in Figure 22.

In this research it is chosen to allocate for the EFR at the start of the opportunity window, from the first week of February. This moment comprises the month March in which the March Freshet used to be allocated in practice. However, this chosen moment influences the deficit reduction attributed to the optimization: if the optimal moment of environmental flow release is constantly in the end of the opportunity window, the optimization would reduce a lot more deficits than if the optimal moment is at the start of the opportunity window. So the optimal moment for a fixed environmental flow release has a large influence on the extend of deficit reduction of the optimization. For this, the fixed moment of environmental flow release is analysed in section 6.6, after the input and results of the various cases from Chapter 6 are described.

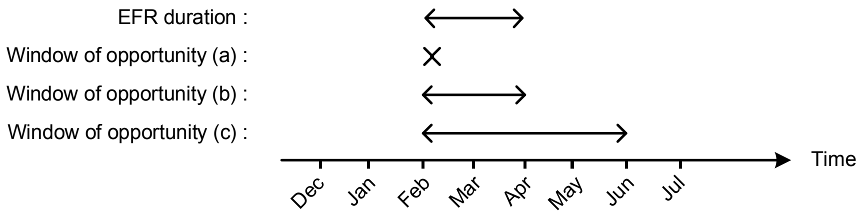

Figure 22. Duration and window of opportunity of modelled EFR in the case study, for a situation (a) without EFR, (b) a fixed EFR and (c) an optimized EFR.

4.4.6 Input data flow forecast

In order to determine the best possible deficit reduction in the case study that can be obtained by the optimization, a hindcast is used in the case study with optimized environmental flow release (c). Hence, there the flow forecast is equal to the observed flow and the uncertainties are not considered.

To determine what the more realistic deficit reductions of the optimization are, a straight forward flow forecast with uncertainties is applied. The applied flow forecast is an autoregressive method that corrects the difference between the inflow at the current timestep and the historical average of the inflow of the Itezhi Tezhi reservoir. This method is described in the model description (section 4.3.1).

In this research, two orders are used in the autoregressive method, with parameters of 1.5 and -0.55. These parameters are chosen so that the difference between the flow at the current timestep and the average historical flow is decreased with 90 percent in about three weeks. In Figure 23 a detail of the result for the flow forecasts at the first of February 1965 is shown.

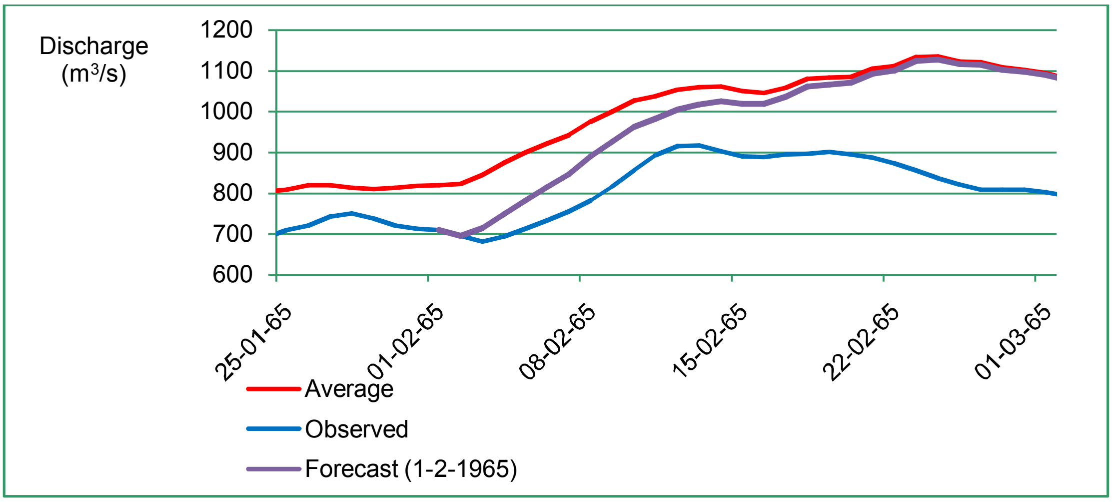

Figure 23. Detail of a forecasts for 1-2-1965. Forecasts are developed by an autoregressive method decreasing the difference between the available observed flow and the average flow from 1961 until 1977.

The correlation between the flow forecast and the observed flow is variable, since the difference between the observed flow and the average flow changes over time. The forecast is determined for each timestep separately so that each timestep another correlation exists. The correlation of the example forecast as in Figure 23 is 0.94. This is measured for 16 weeks; the length of the opportunity window.

It is unknown what the uncertainty or correlation with observed data would be of the flow forecast that is under development by the WWF and the Water Board (Attachment A, Interview WWF), but more reliability is expected than the autoregressive method has. To use this flow forecasting system in real time, an average flow from the past is to be taken since future flows are not available. However, the uncertainties of this method are high and therefore not recommended to use in practice. It is only applied in this research due to the lack of more reliable flow forecasting methods.

4.4.7 Input data overview

The data used in the case study are provided in Table 2. In run *b*, all aspects are changed regarding run *a*. Run *c* only has the length of the window of opportunity changed with respect to run *b*, while run *d* is similar to run *c* except for the use of uncertainty in the flow forecast.

Case title					1 a - Case study	1 b - Case study	1 c - Case study	1 d – Case study
Model run	start			November	1961	1961	1961	1961
	duration			years	16	16	16	16
River flow	initial level			m above sea level	1023	1023	1023	1023
	fluctuation	average		m3/s	382	382	382	382
		min		m3/s	15	15	15	15
		max		m3/s	1715	1715	1715	1715
Demand	fluctuation	average		m3/s	180	180	180	180
		min		m3/s	172	172	172	172
		max		m3/s	187	187	187	187
Reservoir	reservoir size			MCM	5895	5895	5895	5895
	operational management			hedging %	25	25	25	25
EFR	magnitude			m3/s	0	300	300	300
	duration			weeks	0	8	8	8
	window	start		first week	-	Feb	Feb	Feb
		length		weeks	-	8	16	16
Forecast				uncertainty	0	0	0	AR

Table 2. Input parameters for the case study, divided over (a) no EFR, (b) fixed EFR, (c) optimized EFR, and (d) optimized EFR with an autoregressive flow forecast (AR). Unique specifications are encircled.

4.5 Model validation

The model as described above is validated to ascertain the representation of the actual situation in the case study. The validation is done by means of a comparison between the observed and the modelled outflows at the Itezhi Tezhi dam. The modelled flow has no implementation of environmental flow release, for the observed flow this is unsure.

A problem for this validation is that both datasets are not available for the same time period. Flows of the Kafue River just downstream of the Itezhi Tezhi dam are available for the period before and after the construction of the dam. The data before construction are used in this research as inflow data of the reservoir, the data after construction can represent the data of the actual situation for validation. Validation is therefore only possible at a very subjective scale, by the qualitative comparison of the characteristics of these datasets.

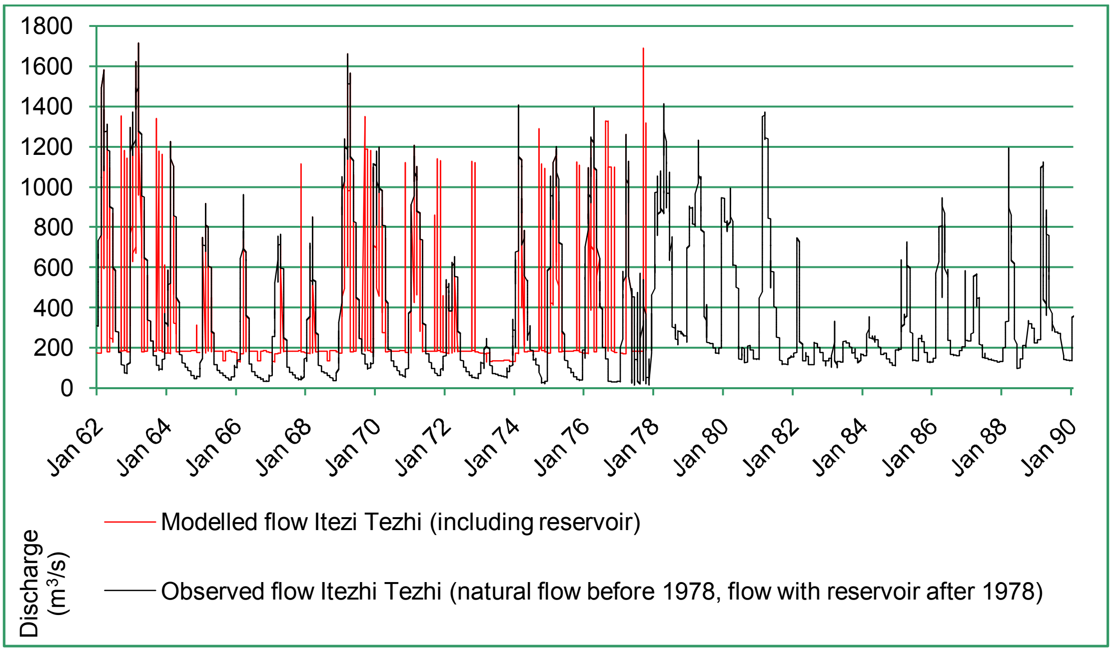

Figure 24. Observed and modelled flows in the Kafue River at the Itezhi Tezhi dam. The dam is constructed in the year 1978. The observed flow before this year is the natural river flow, the observed flow afterwards is the outflow at the Itezhi Tezhi dam.

In Figure 24 the observed and the modelled flows are displayed. The modelled flow is only available up to the construction of the Itezhi Tezhi dam in 1978, because afterwards no natural flow is available, which is necessary for the model as reservoir inflow. If the hydrological situation is modelled accurately, the modelled flow before 1978 should have similar characteristics to the actual reservoir outflow after 1978. A few similar characteristics are recognized. First, the modelled outflow has larger minima than the natural flow, this is obviously the effect of the operational management of the modelled reservoir. The enlarged minima are also recognized in the observed outflow, where the minima correspond higher discharges. The minimum discharges are in the modelled situation about 180 m^3/s with some exceptions to 140 m^3/s during droughts. In the actual situation the minimum discharges are between about 130 m^3/s and 170 m^3/s.

The lower discharges in reality may be caused by the neglecting of the reservoir evaporation. If evaporation would have been taken into account, lower outflows would be seen, especially during droughts.

Further on, it is easily seen that the modelled outflow often has lower maximum peaks than the reservoir inflow during the same period. It is interesting to see if the maximum flows for the actual situation are also decreased. Although the actual outflow cannot be compared to its actual reservoir inflow, it seems to have some lower maxima than during the years before. For example, during the drought between 1982 up to 1985, the maxima are much lower than during the drought of 1965 up to 1968. Of course, this may be caused by a natural difference between both droughts, but it may give an indication of the similarities between the modelled flow and the observed flow.

More cannot be said about the two datasets for validation. However, the similarity of increased minimum flows and the indication of comparable decreased maxima, imply similar effects of the presence of the reservoir in the model as in the reality. Therefore, enough confidence of the hydrological model is available for the goals of this research.

Chapter 5 Application of the optimization to the Kafue River

5.1 Introduction

This chapter considers the third step *"What is the deficit reduction in the Kafue River?"*. So the deficit reduction is analysed, which is acquired by an optimization of the moment of environmental flow release for the Itezhi Tezhi dam in the Kafue River, with help of flow forecasting. For this, the model and model input from Chapter 4 is used.

Attention is given to the difference between optimization with a hindcast and a more realistic flow forecast. This gives insight in the difference between possible deficit reductions and realistic deficit reductions.

5.1.1 Method

The quantification for the case study and for the following cases in the next chapter, is done by means of three runs. They include the situation (a) without any environmental flow release, (b) with a conventional fixed environmental flow release and (c) with an optimized timing of environmental flow release. The difference between the first two situations determine the deficits due to environmental flow release, the difference between the last two situations determine the reduction of deficit that an optimization could accomplish.

The moment that the EFR is allocated for run b is taken as a reference situation to determine the benefits of the optimization, so this moment is therefore of direct influence on the results of this research. In section 6.7 it is checked if the chosen moment is actually the best moment of allocation if no flow forecast is applied.

An extra run (d) is done as in run c, but with the autoregressive flow forecast instead of a hindcast. The difference between the results of run c and d, determine the influence that the uncertainties of the flow forecast have on the deficit reductions by the optimization.

It is noticed that in Kafue River no standard procedure for environmental flow release is available, so the fixed environmental flow release does not represent the actual situation. It only offers a reference situation for EFR implementation with the use of flow forecasting, to see the effects of the optimization.

5.2 Results case study

The results of the case study are provided in the order of the runs. First, the deficits due to the environmental flow release is subject, then the deficit reduction due to the optimization, and at last the influence of the flow forecast is considered.

The yearly accumulated deficits for all runs of all cases are provided in Appendix G, the most important results are summarized in the end of this section (Table 3).

5.2.1 Deficits due to environmental flow release (1a & 1b)

The results of the cases 1a and 1b provide the deficits that occur due to environmental flow release. In Figure 25 the total deficits are compared between the situations with (y-axis) and without (x-axis) an environmental flow release. The volume of the deficit above the '*y = x' line* represents the deficit due to the environmental flow release. If on this line, no extra deficits appear.

Various conclusions can be drawn from this graph. First, it appears that even without an environmental flow release already deficits exist. This is due to the fact that during some years, the inflow is not able to satisfy the demand even without an environmental flow release. The five years that are subject to initial deficits have all low average flows: all years have an AMR less then 30% under the long term average, except for the year 1974. This year has an AMR equal to the long term average, but is affected by the prolonged deficits of the extreme dry year of 1973.

It is not surprising that the years with an initial deficit are vulnerable for extra deficit due to environmental flow release: Five of the six years have extra deficit and only the deficit of the year 1965 is undisturbed. This is possible since in 1965 the environmental flow release is simultaneous to the peak flow.

Furthermore, it is also notable that most of the years with deficit due to environmental flow release are sequential. This is caused by the inflow series in which the dry years seem to follow each other. This may point at wet/dry climate cycles.

The quantified results are shown in Table 3. In total there are 5 years that have their deficit increased with more than 1% of a yearly demand. The total extra deficit over all years is 1.30 km^3. The year 1968 has the highest deficit due to environmental flow release, with 0.36 km^3 which is five times as much as its initial deficit. A water volume of 0.36 km^3 is the equivalent of a constant flow of 11.3 m^3/s during a whole year.

An interesting result for the implementation of environmental flow release is that the 8 remaining years do not have any extra deficit if EFR is allocated. This is represented by the dots close to the origin of the graph in Figure 25. This fact is an important result which proves that environmental flow release for the Kafue Flats in many cases does not lead to any deficit. The relation between the AMR and the deficit due to environmental flow release is further analysed in section 6.6.

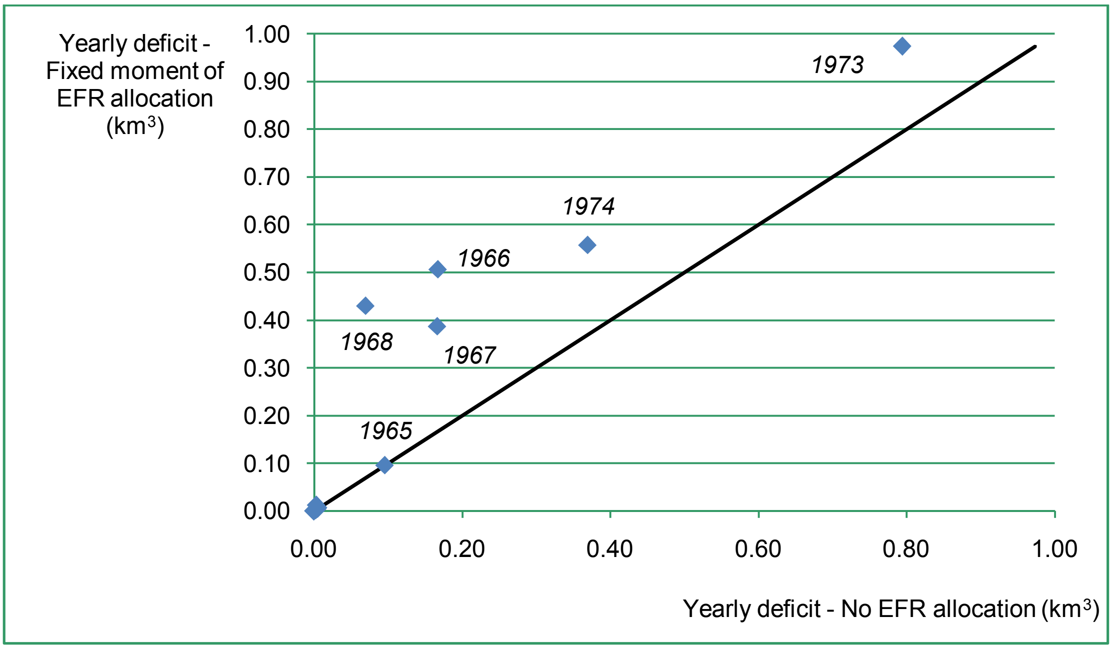

Figure 25. Total yearly deficits as result from case 1. The positive difference between the results and the *x = y -line* is the deficit that is directly caused by the allocation for the fixed EFR. Most years have no deficit, and are clustered in the origin.

5.2.2 Benefits due to optimization (1b & 1c)

The results of the optimization for the case study with a hindcast are displayed in Figure 26. The volume that the total yearly deficit is below the '*y = x' –line* is the decrease in volume of the deficit, caused by the optimization.

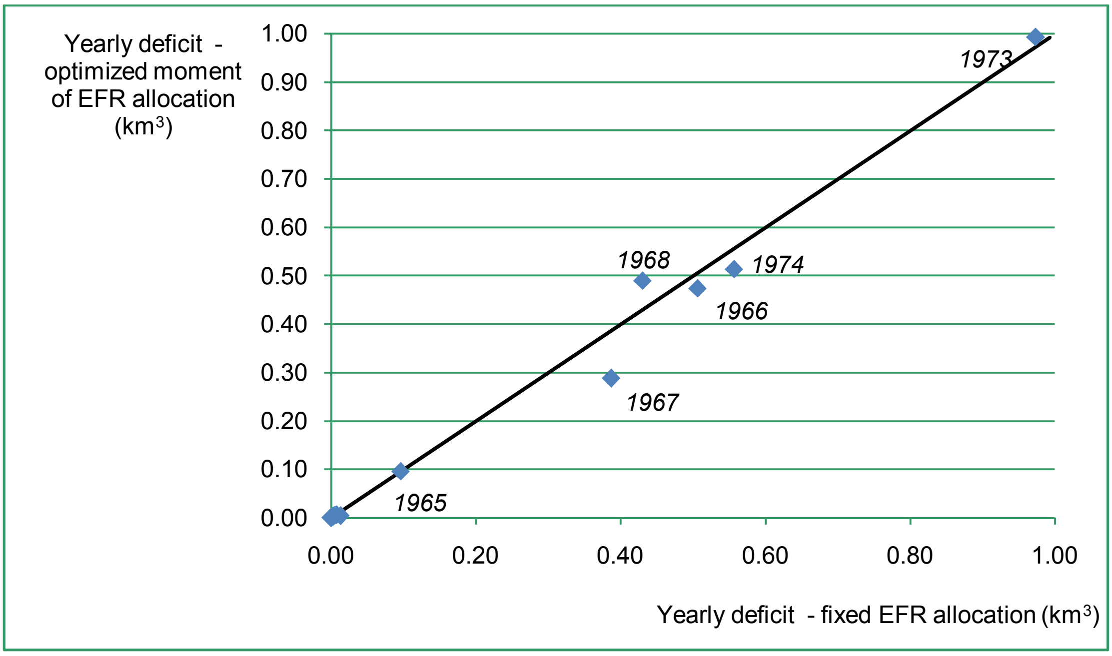

Figure 26. Difference between total yearly deficits of the situations with fixed environmental flow release and optimized allocation. The negative difference between the results and the *y = x -line* is the benefit that is directly caused by the optimization compared to the fixed environmental flow release.

Negative result

The increases of the deficit for the years 1968 and 1973 are remarkable. Both years are a result of the shortcomings of the model structure. In the first case, a suboptimal allocation is done by the limited period of simulation, in the second case an optimal allocation is done but it results in deficits after the moment of measuring the yearly deficit.

The deficit of 1968 is a result of a change in the moment of environmental flow release in the preceding year. This is possible since the period that the allocations and deficits are calculated for the optimization (period T in Equation (8)) is limited to 50 weeks. Resulting deficits in the next year are therefore not taken into account in the consideration of the optimal moment of environmental flow release. They would be taken into account if the period T was extended. However this is not possible because the period T would get longer than the recurrence period of the EFR and the model is not suitable to determine one optimal environmental flow release if the other environmental flow release is not yet determined.

The increased deficit of 1973 has also to do with period T, but now because it actually reaches further than the moment that the total deficit for the hydrological year is calculated. In detail: The period T in the optimization of 1973 reaches as far as January 1974, while the total deficit for the year 1973 is calculated half way October 1973. Some deficits due to the environmental flow release in 1973 are therefore attributed to the total deficit of year 1974.

To obtain a full projection of the benefits of the optimization, the negative optimization should be taken into account in the benefits of the other years. Therefore in the results in next sections, the increased deficit of 1968 is added up to the year 1967, and the deficit reduction of the year 1974 includes the extra deficit of 1973.

Benefits of optimization

Benefits of the optimization are represented in the years 1966, 1967 and 1974. With the subtraction of the deficit increase of 1968 and 1973, these years have a deficit reduction of respectively 0.03 km^3, 0.06 km^3 and 0.02 km^3. These decreases are 10%, 18% and 13% of the deficits due to fixed environmental flow releases in the same years. This makes a total decrease of 0.10 km^3 (see Table 3), which is 7% of the total deficits due to environmental flow release.

Optimization analysis

The inflows, environmental flow release, demands and deficits along with the reservoir levels of the year 1966 are displayed in Figure 27. This figure shows how the deficits are decreased by postponing the environmental flow release. At the moment of the fixed environmental flow release (the first of February) the reservoir level is just at the firm storage level and it falls further below due to environmental flow release. According to the operational management, then the supply flow for the demands is restrained with 25 percent and deficits appear. In the optimized situation however, the environmental flow release takes place at the 2nd of March when the inflow has already restored the reservoir level enough to keep the reservoir level above the firm storage level, hence deficits are prevented.

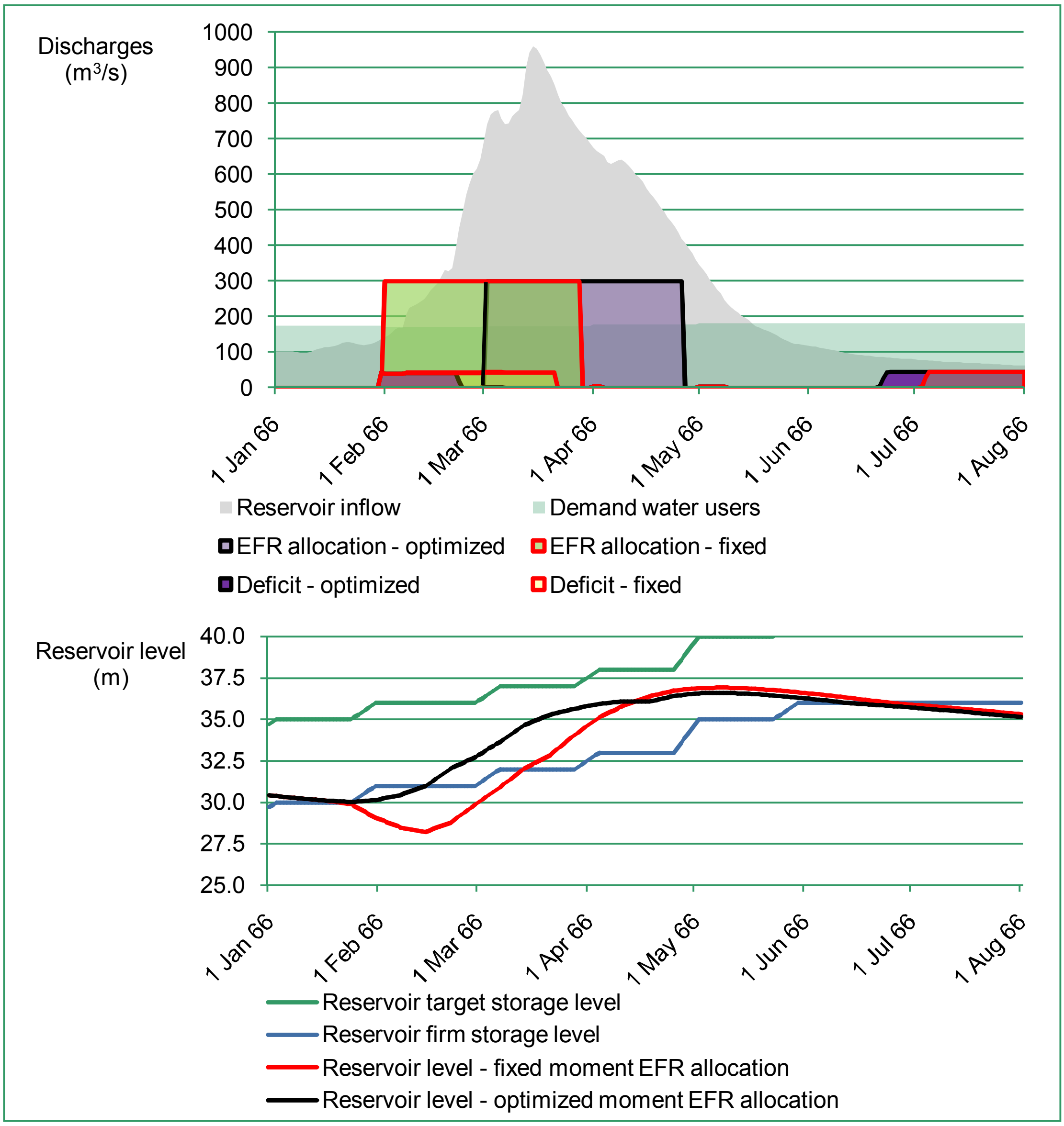

Figure 27. Discharges (above) and reservoir levels (below) for the environmental flow release in the case study with the fixed situation (red lines) and the optimized situation (black lines). Deficits appear for 25% of the demands if reservoir level falls below firm storage level. The optimized environmental flow release is postponed one month, so that reservoir level is restored above the firm storage level at the moment of environmental flow release and deficits are reduced.

However, despite the reduction of deficits, the optimization is only successful if it does not increase the deficits at a later stage. After all, the reservoir volume is decreased at the end of the period in Figure 27 in reference to the situation with a fixed environmental flow release. This is a potential deficit, because a decreased reservoir level has a larger chance to fall down the firm storage level at a later stage, causing deficits in the future.

The decreased reservoir volume is recognized by the difference in reservoir levels between the situations with a fixed and an optimized environmental flow release. In Figure 27, the decrease is about 20 cm at the end of the period. On a reservoir level of 35 m, this is the equivalent of 0.05 km^3. This is explained with help of the water balance: in comparison to the situation with a fixed environmental flow release, the optimized situation has an equal inflow but its accumulated outflows are increased (because of the smaller deficits). A smaller reservoir volume with a lower reservoir level must be the result.

Optimization without postponing the deficits

As recognized in the results above, optimization can lead to postponing of deficits which diminishes the overall benefits of the optimization. However, an optimization in the moment of environmental flow release does not always result in the postponing of deficits. First, it is possible that after a reduction of the reservoir volume, the level is restored to the target level before new deficits appear. Second, the reduction of the reservoir volume is prevented if the optimization of the moment of environmental flow release makes use of flows that were unused by the water demands in the initial situation. After all, if in the initial situation extra outflow is generated because the reservoir level is above the target storage level, this outflow is not used by the water demands. This surplus is a potential for the optimization, which can decrease the deficits without a reduction of the reservoir volume.

5.2.3 Effectiveness of optimization in case of realistic forecasting (1c & 1d)

The results of the optimization for the case study with a hindcast and an autoregressive flow forecast method are not that much different. Table 3 shows the different allocation moments and resulting deficit reductions for the years that have deficits. For the years 1967, 1968 and 1973 a different optimal moment of environmental flow release is determined due to overestimation of the future inflows. However, in these cases the total deficit reduction is not affected. Only the years 1973 and 1974 show a different partition in the deficit reductions, but their total is equal to the situation with a hindcast.

		1965	1966	1967	1968	1973	1974	Total
Average inflow	m^3/s	254	202	227	199	92	371	
Relation to 16 year inflow dataset	standard normal value	0.25	0.16	0.19	0.15	0.05	0.51	
Initial deficit	km^3	0.10	0.17	0.17	0.07	0.79	0.37	
Deficit due to EFR	km^3	0.00	0.34	0.22	0.36	0.18	0.19	1,29
Fixed environmental flow release (1 b)	start	1 Feb	1 Feb	1 Feb	1 Feb	1 Feb	1 Feb	
New environmental flow release (1 c)	start	27 Jan	2 Mar	8 Mar	7 Feb	24 Jan	6 Mar	
Deficit reduction (1 c)	km^3	0	0.03	0.10	-0.06	-0.02	0.04	0.095
New environmental flow release (1 d)	start	27 Jan	2 Mar	1 Mar	21 Feb	7 Feb	6 Mar	
Deficit reduction (1 d)	km^3	0	0.03	0.10	-0.06	0.02	0.00	0.092

Table 3. Characteristics and results of the 6 years that have initial and increased deficits. The results of the years 1967 & 1968, and the years 1973 & 1974 should be accumulated for a balanced comparison.

The uncertainty of a flow forecast does not affect the benefit of the optimization much. This is a positive result for the practical application of a flow forecast in the optimization of the moment of environmental flow release. However, it does not prove the reliability of a flow forecast yet. After all, according to the limited window of opportunity, the chance that a random algorithm would guess the right timing may be rather large. Hence a lot more test runs in various cases are necessary to be sure about the actual influences of the uncertainties of a flow forecast.

Chapter 6 Analysis of the influences of the selected aspects

6.1 Introduction

In this chapter, the last step *"How much do the selected aspects influence the effectiveness of the optimization?"* is subject. The influences of the selected aspects in Chapter 3 are analysed with the optimization model of Chapter 4. First, the optimization model is run with specific input for the components operational management, EFR and demand. For each case, the model is run three times: without environmental flow release, with a fixed and with an optimized moment of environmental flow release. For each case the deficit reductions are determined relative to the deficits due to the environmental flow release, so that the cases can be compared to the case study and to each other. The comparison provides insight in the influence on the optimization for each aspect separately. Afterwards, the results of all cases are used to determine the influence of the inflows, and the fixed moment of environmental flow release in the case reference is analysed for its compatibility.

The yearly accumulated deficits for all runs of all cases are provided in Appendix G. An overview of the analysed aspects is given in Table 4.

Analysed component/aspect	Description	Compared to case	Described in section
Operational management/ Hedging-10	The hedging rule of the operational management is adjusted to a restraining percentage of 10.	Case study & Operational management/Hedging-40	6.2
Operational management/ Hedging-40	The hedging rule of the operational management is adjusted to a restraining percentage of 40.	Case study & Operational management/Hedging-10	6.2
EFR/magnitude	The magnitude of the EFR is increased to 600 m^3/s.	Case study	6.3
EFR/duration	The duration of the EFR is extended to 12 weeks, with an increased EFR magnitude.	EFR/magnitude	6.3
Demand/ fluctuation	The minima and maxima of the inflow are more extreme, with an increased EFR magnitude.	EFR/magnitude	6.4
Reservoir/size	The reservoir volume is decreased with 25%, with an increased EFR magnitude.	EFR/magnitude	6.5
Forecast/ uncertainty	The flow forecast has uncertainties, due to the use of an example flow forecasting system.	Case study	5.2.3
Inflow/AMR	All optimal moments of the cases above are stacked to the accompanying AMR.	Not applicable	6.6

Table 4. Overview of aspects selected in Chapter 3. The first seven aspects are analysed with help of customized cases. The inflow/AMR is analysed with help of all these cases. The influence of the aspect 'uncertainty' is already determined with the case study in Chapter 5.

6.2 Hedging rules of the operational management

The hedging rules of the operational management are adjusted in accordance with the case study to see their influences on the optimization. All other aspects are unchanged so that the difference in output is fully attributed to the hedging rules.

6.2.1 Input

In the case study, the outflows are restrained for 25% if the reservoir level falls below the firm storage level. In this section, two cases are developed. The first case 'Operational management/hedging-10' has a hedging rule that cuts 10% of the reservoir outflow within the hydrological model, in the second case 'Operational management/hedging-40' the hedging rule cuts 40%. To consider the optimization of both cases, the same method is used as in the case study. Hence three situations are simulated: (a) without environmental flow release, (b) the a fixed moment of environmental flow release and (c) with an optimized environmental flow release. For all three cases, the effect of the optimization (c minus b) is compared to the deficits due to the environmental flow release (b minus a). This comparison provides the influence of a lower or a higher restraining percentage.

6.2.2 Result

First, the effects of the different styles of operational management on the total yearly deficits is analysed. Then, the actual deficit reduction due to the optimization is considered.

The deficits due to the environmental flow release in the optimized situation are plotted against the deficits in the fixed situation in Figure 28. The regression of the yearly deficits is presented by arrows. The arrows cluster the deficits per year, and show the relation from high to low restraining percentages. Almost all arrows point towards the origin, meaning that for both the fixed situation and the optimized situation, the deficit is smaller if restraining percentage is lower. So the less supply is restrained, the smaller the deficits.

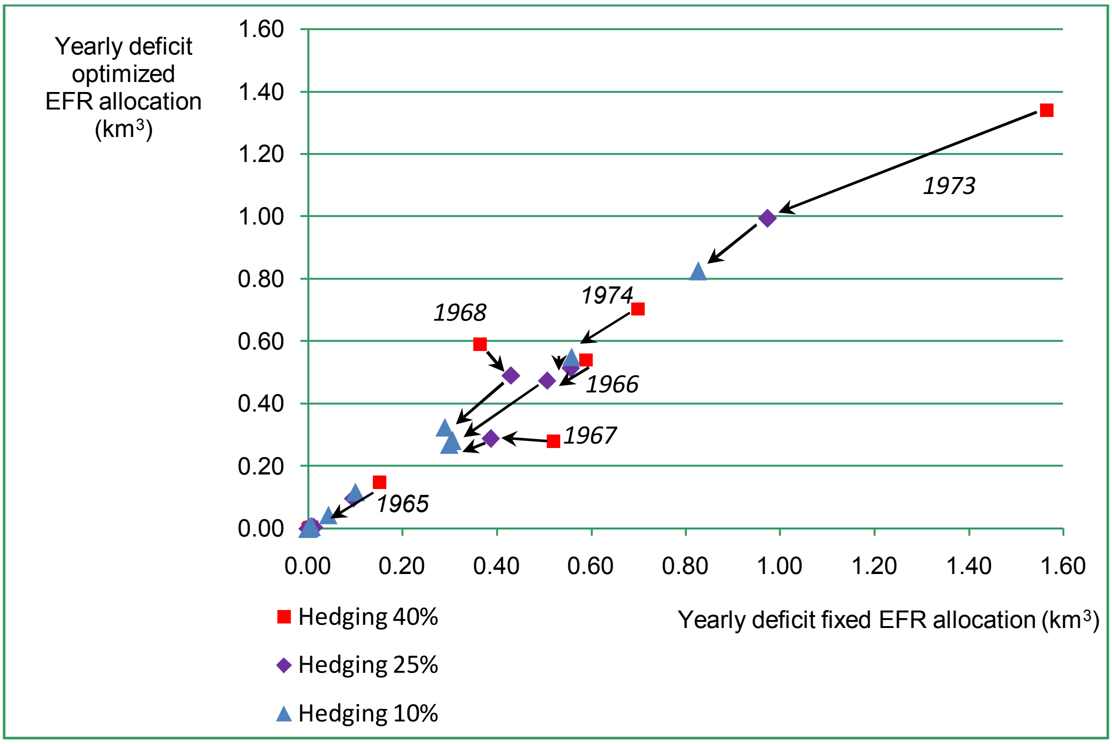

Figure 28. Regression of deficits in relation to lower restraining percentages. Deficits due to environmental flow release are plotted for the optimization situation (y-axis) to the situation with fixed moments of environmental flow release (x-axis). The arrows connect the deficits for the same year that apply for the three different hedging rules.

Since the deficits decline with a lower restraining percentage, the case study would be best off with restraining percentages of 10%, or even with no restraining at all. This is a result of the definition for the deficit within this research: the duration and volume that the reservoir level is below the firm storage level is not taken into account. If deficit would include the unaccomplished firm storage level, hedging with low percentages had larger deficits, and optimization might have more effect.

Figure 29 shows the actual deficit reduction of the optimization, compared to the total deficits due to environmental flow release. The dotted '*x = y'-line* resembles the deficit due to environmental flow release, hence the maximum reduction possible. Resulting deficits above the x-axis are the reductions, the results below the x-axis are deficit increases after the application of the optimization model. These increases are caused by deficit reductions the year before, as described for the case study.

The figure shows the deficit reduction for the three hedging rules of 10%, 25% and 40%. The case with 25% is equal to the case study. Both other cases have about the same average considering the deficits for a fixed environmental flow release. However, the effects of the optimization are more extreme in the case 'Operational management/hedging-40' and less extreme in the case 'Operational management/hedging-10'. This is seen in the figure by the deficit clouds, which are closer to the x-axis if restraining percentage is less.

The optimization has relatively more effect in cases with higher restraining percentages. Although the case with a high restraining percentage has larger deficits due to the environmental flow release, the optimization does reduce the deficits even more. The three cases (10%, 25% and 40%) have total deficits over the full dataset of respectively 0.77 km^3, 1.69 km^3 and 2.31 km^3. These deficits are reduced by the optimization with respectively 0.02 km^3, 0.10 km^3 and 0.28 km^3 (including the deficit increases). The relation between the reduction and the total deficit due to environmental flow release is considered to be the optimization effectiveness. The optimization effectiveness of these three cases is 1%, 7% and 17%. Conclusion is that the optimization has more effect if high restraining percentages are applied.

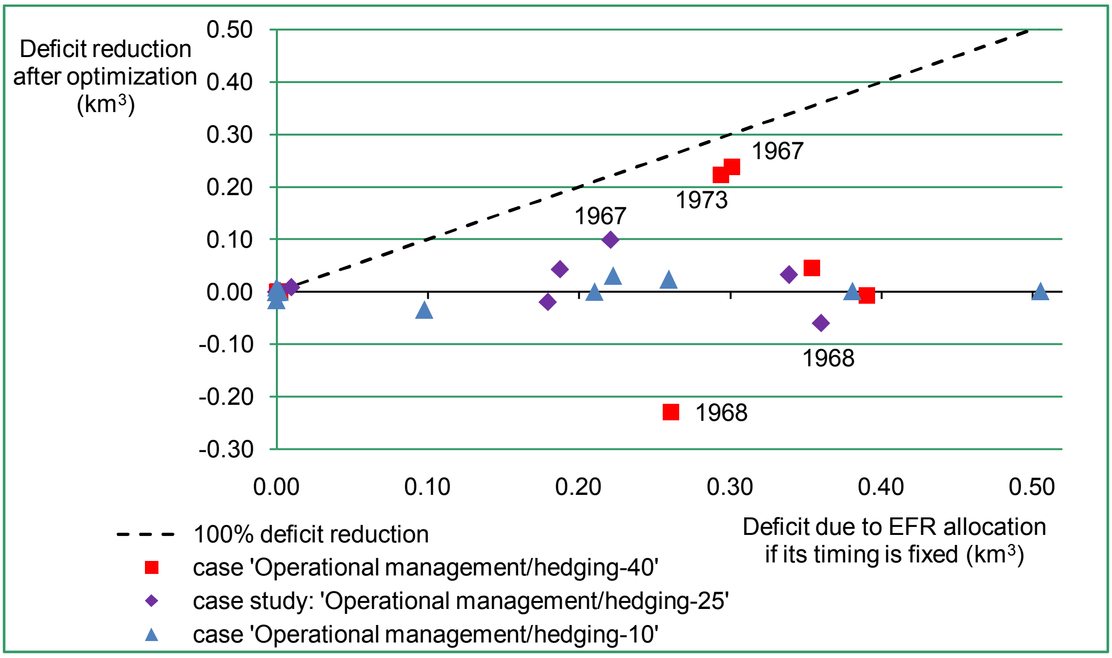

Figure 29. Deficit reduction due to optimization, for 10%, 25% and 40% hedging rules. Deficit increases of 1968 are caused by environmental flow release in 1967.

6.3 EFR duration & magnitude

To see the influence of the environmental flow components on the optimization, two cases are run in the model. In this first case, the magnitude of the duration is enlarged and in the second case the duration is lengthened. All other aspects are unchanged with respect to the case study, so that the difference in output is fully attributed to the change in EFR. Again, each case is run three times: without environmental flow release, with a fixed and with an optimized moment of environmental flow release.

6.3.1 Input

In the case 'EFR/magnitude', the EFR magnitude is doubled compared to the case study to 600 m^3/s. This is in line with some of the proposed scenarios in the environmental flow assessment for the Kafue Flats (Wilson, 2003). All other aspects are unchanged with respect to the reference situation.

In the case 'EFR/duration', the EFR duration is extended from 8 weeks in the case study to 12 weeks. This is as long as the longest environmental scenario in the environmental flow assessment (Wilson, 2003). The EFR magnitude within the case 'EFR/duration' is set to 400 m^3/s, to equal the total volume of the EFR in the case 'EFR/magnitude'. This makes both cases comparable to each other.

In both cases the model is run three times: without environmental flow release, with a fixed and with an optimized environmental flow release. This provides the possibility to compare the deficit reductions to the deficits due to EFR, which differ from the case study if aspects are changed.

6.3.2 Result

A larger EFR magnitude than in the case study results in higher deficits, but they are more easily reduced by the optimization. If EFR duration is longer, about the same amount of deficit emerges but this is more difficult to reduce.

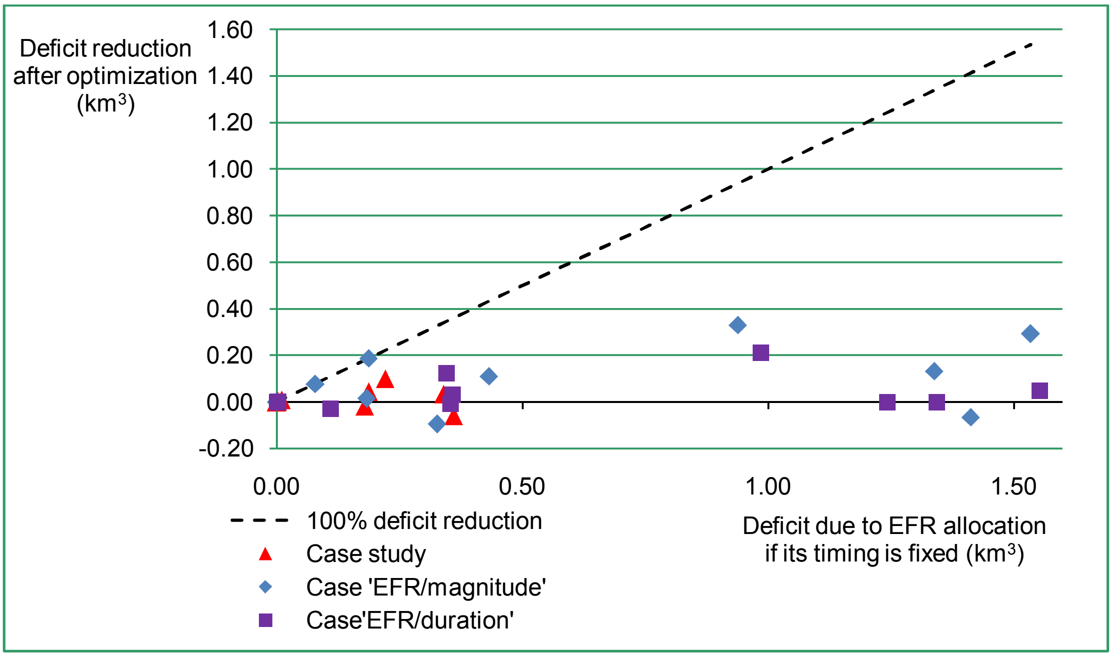

Figure 30. Deficit reduction due to optimization, for cases with variation in the EFR. The magnitude is compared with the case study, the duration is compared with the magnitude.

If an increased magnitude is applied in the case study, more years have initial deficits and their volumes are larger. After environmental flow release, 9 years develop extra deficit. Some of them become larger after optimization by the same processes as in the case study, but for 7 years the deficit is reduced with on average 42%. In Figure 30 it is seen that some smaller deficits are reduced fully by the optimization, while larger deficits are relatively less reduced. Over the whole dataset, environmental flow release on a fixed moment results in a deficit of

6.43 km³. Optimization in timing reduces this with 0.98 km³, providing an optimization effectiveness of 15%.

Main reason for the increased reductions is the reservoir level, which falls more often just below the firm storage level. If reservoir level falls down the firm storage level only a little, a different timing of environmental flow release has larger chance to reduce the deficits.

The extended duration results in slightly lower initial deficits than the normal duration: 8 years develop a deficit and its total volume is 6.29 km³. However, the benefits of the optimization are relatively smaller than in the reference case: Just 4 years have benefits of the optimization, with an average reduction of 18%. Taking into account the deficit increase within the dataset, the deficit of the total dataset is just reduced with 0.38 km³. This provides an optimization effectiveness of 6%, so relatively less deficit reduction is acquired if the duration of the EFR is longer.

The reduced effectiveness is explained by the spread of the environmental flow release. There is a larger overlap between the different environmental flow releases than if duration is short. The effects of the allocations on the reservoir level are then more similar to each other, and an optimization induces less variation in the deficit.

6.4 Fluctuation of the demand

The type of water demand is characterized by its fluctuation. The fluctuation is here enhanced to see its influence within the optimization.

6.4.1 Input

To determine the influence of the fluctuation on the optimization, the model is run with an adjusted demand. Fluctuation is added to the demand, based on the water abstraction for sugar cane production (Attachment A, Interview ZamSugar, Figure 8). The abstraction of ZamSugar Company is multiplied by a factor of 18.7, such that its average is equal to the average demand of the reference case (181 m³/s). The advantage of an unchanged average is that the total demand is equal and the cases are comparable. Differences in the result can be assigned fully to the extra fluctuation within the demand.

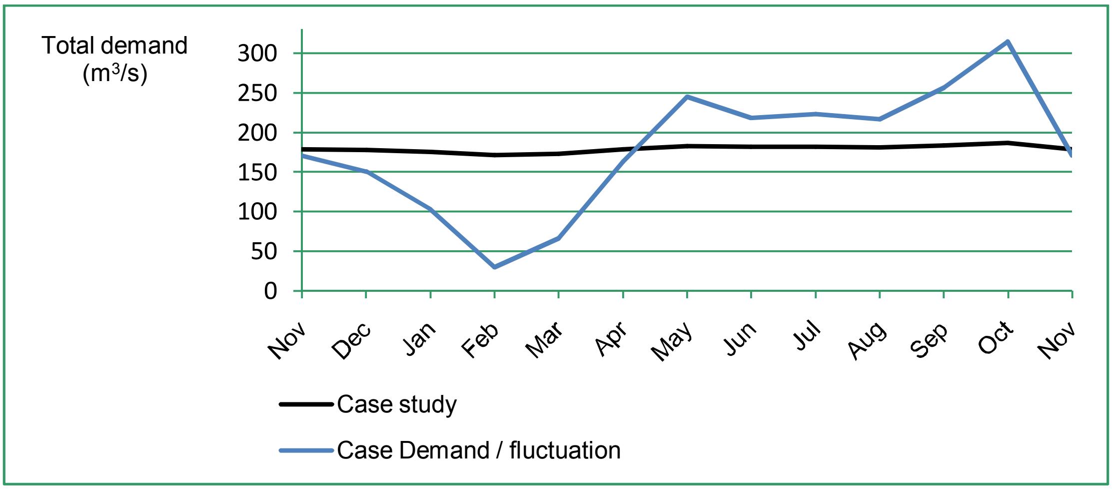

Figure 31. Demand: flows required for the water users. The fluctuation is enhanced in the case 'Demand/fluctuation'.

The input demand for the case 'Demand/fluctuation' is depicted in Figure 31. This input is imported in the model structure by the FEWS environment, but it is also applied within the *demand node* in the Ribasim hydrological model.

Reference is the case 'EFR/magnitude', which means that all input is equal to the case study except the magnitude of the EFR (600 m^3/s, as in case 'EFR/magnitude'). This reference has been chosen for its large number of years with an initial deficit. The large number is expected to provide a better insight in the effects of the adjusted demand.

6.4.2 Result

An increased fluctuation of the demand leads to slightly smaller initial deficits which are caused by environmental flow release. In Figure 32, this is depicted by the similar horizontal spread of the deficits for the case 'Demand/fluctuation' and its case reference. Also the vertical spread is not much different, hence the optimization does not have much more effect if demand shows more fluctuation. The total effectiveness of the optimization with more demand fluctuation is even lower than its reference: 13% of the deficit due to environmental flow release in the whole dataset is reduced, compared to 15% in the situation with less fluctuation.

This result is remarkable, since it was expected that more fluctuation would give opportunity for optimization. After analysis, it seems that the lack of extra reductions has to do with the fixed moment of environmental flow release and the uniform demand fluctuation. After all, the fixed timing of environmental flow release is exactly at the same moment that the water users require a very low amount of water. This means that in many years, the EFR is already allocated at the optimal moment, so an optimization has no use.

Concluding, the optimal moment for environmental flow release is dependent on the moments that de demand is low. If demand fluctuation rises, at a certain point the optimal moment is fully determined by the water demand and not by the reservoir inflow. If the moment that water users require less water is indifferent over the years, optimization of the timing of environmental flow release is not effective.

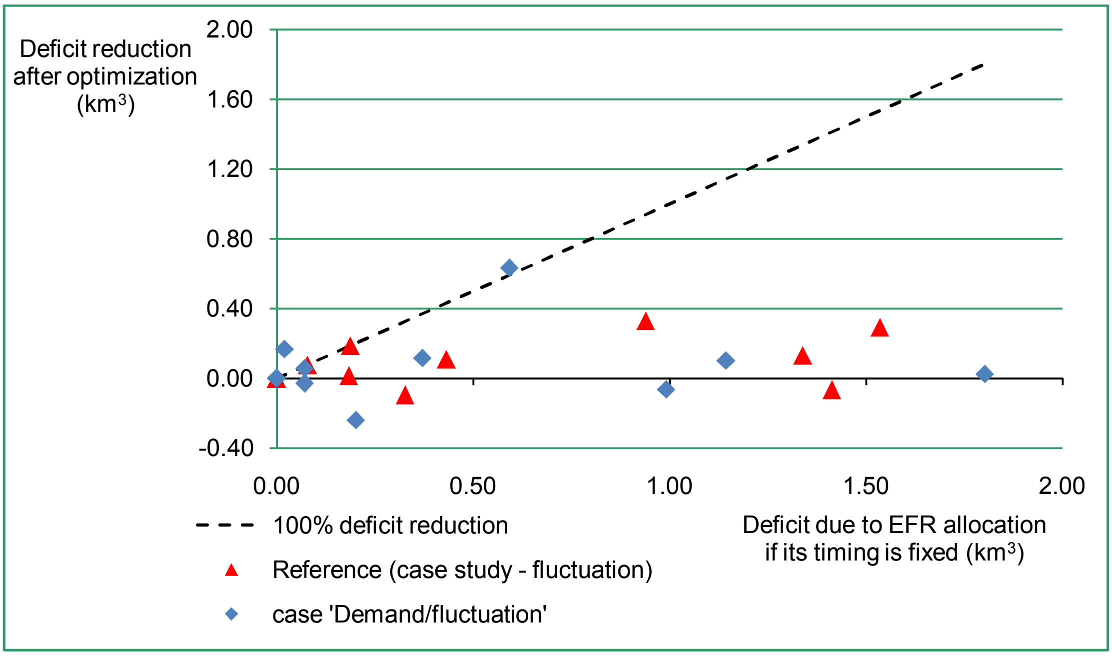

Figure 32. Deficit reduction due to optimization, for case 'Demand/fluctuation'. This case has more fluctuation than the reference case 'EFR/magnitude'.

6.5 Reservoir size

Except for the operational management, also the physical configuration of a reservoir can have influence on the optimization for the moment of environmental flow release. In this section, the storage volume is adjusted in a new case.

6.5.1 Input

In the case 'Reservoir/size', the storage volume of the reservoir is modelled a quarter smaller than in the case study. All volumes over the full height of the reservoir are adjusted, so that a relatively narrow reservoir is the result. Instead of a full reservoir storage volume of 6616 m^3, the size is now 4962 m^3, with a dead storage of 541 m^3.

The case 'EFR/magnitude' is again reference, hence the magnitude of the EFR is set to 600 m^3/s. This case is chosen as a reference for its large number of years with a deficit due to environmental flow release, to gain a better insight in the effects of the adjusted demand.

6.5.2 Result

According to the results in Figure 33, the smaller reservoir size does not benefit extra from the optimization. While the deficits due to environmental flow release are rather similar, their reductions are much smaller. Only 0.12 km^3 of the deficits is reduced, which is just 2% of the deficit volume in the total dataset, in comparison to the 15% effectiveness in the reference case.

The small deficit reduction is especially due to the drought within the years 1966, 1967 and 1969. In the case reference, a lot of deficit reductions are gained during this period. In the case 'Reservoir/size' this turns out to be impossible: Due to the smaller reservoir, the target storage level and the firm storage level represent a smaller reservoir volume. For this, the reservoir has less water volume available at the beginning of the period 1966 to 1968. Since the demand is equal to the case reference, the inflows are not able to restore the firm storage for three years long. All these years continuously hedging takes place, and optimization has no effect on the deficit.

Concluding, the combination of low water availability during a drought and a small reservoir that can provide limited water, make a situation with more water deficits than if the reservoir would have been larger. These deficits are of such a structural type, that they are not reduced by an optimization in timing of the EFR. For that, the optimization is ineffective if the reservoir storage is low in combination with a small water availability.

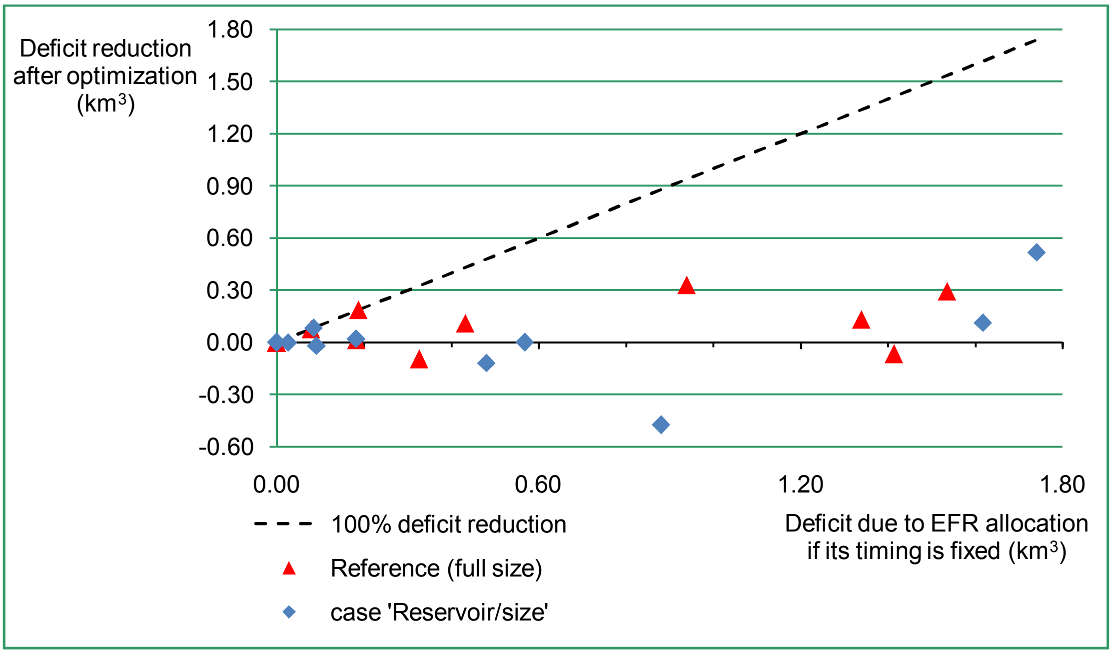

Figure 33. Deficit reduction due to optimization, for case 'Reservoir/size'. The reservoir volume is 75% of the volume in the reference case.

6.6 Magnitude of the inflow

In Figure 34, the resulting yearly deficits of all cases with hindcasting in this research, are shown in relation to the AMR of the accompanying year. The particular cases are the case study, two cases for changes in the operational management, two cases for variation in the EFR, a case with more fluctuation in the demand and a case with a smaller reservoir. The deficits are the difference between the model runs without environmental flow release and the model runs with a fixed moment of environmental flow release. The AMR is dispersed according to its relation to the long term average of the whole dataset between 1961 to 1977 (368 m^3/s).

The figure shows a relation between a low runoff and the chance that deficit appears due to environmental flow release. All years with an AMR below the long term average, develop deficits at some point if the EFR is allocated. Within this dataset, a partition exists between years that have minor deficits and years that have guaranteed and significant deficits. This partition is at about 65% of the long term average, equal to an AMR of 243 m^3/s. Above this boundary, the deficits are not more than about 6 percent of the yearly demand volume (5.67 km^3). This is limited compared to the deficits for years with an AMR below the partition. Then the inflow is not sufficient for the demand in any case of this research and deficits rise up to 40 percent of the volume required by the water users in one year.

Although the clear relation between low inflows and high deficits due to environmental flow release, the partition on 65% is probably very case dependent. This value is therefore just an indication about the large vulnerability for deficits due to environmental flow releases.

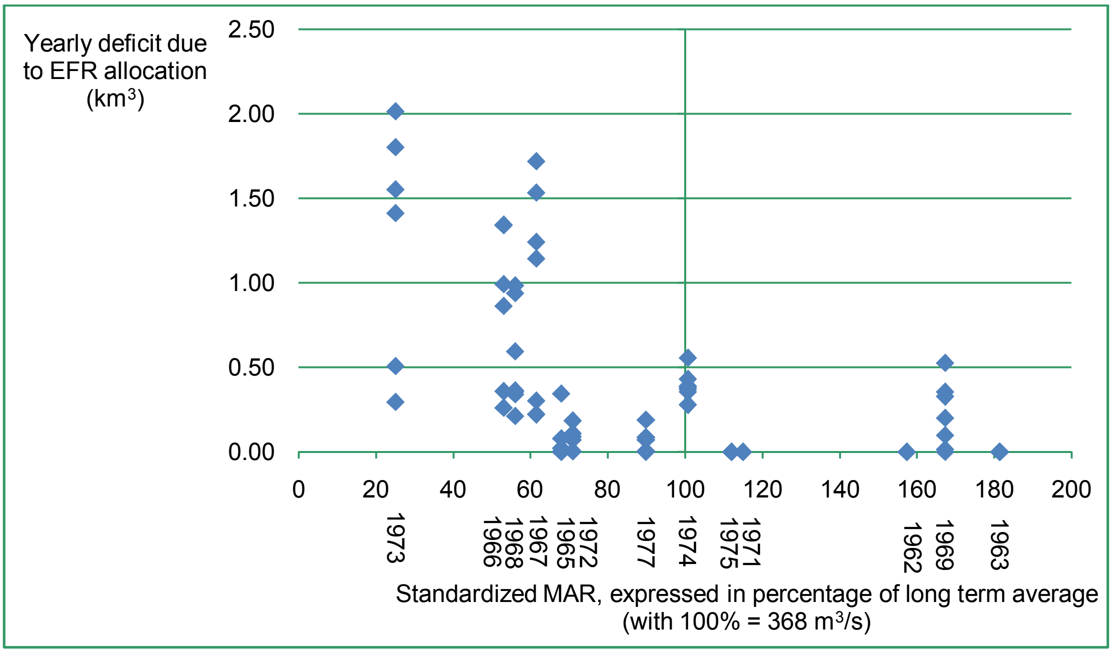

Figure 34. Deficit due to EFR grouped per associated AMR. The deficit of all cases in this research is expressed in the total yearly volumes and grouped per year. The years are distributed over the x-axis in relation to their standardized AMR. The years 1969 and 1974 are influenced by environmental flow releases in respectively the years 1968 and 1973.

Figure 35 shows the yearly deficit reductions acquired by the optimization, for the same cases as in Figure 34. Hence, the difference is shown between the results of the model run with optimized and with a fixed environmental flow release. Below the x-axis, deficits are increased as result of the optimization, which is caused by deficit reductions in the year before. A few deficit increases are added up to the deficit reductions in the year before, to provide an transparent overview of the deficit reductions.

The figure makes the relation clear between the AMR and the reduction of deficits. Of course, the results are direct related to the deficits due to environmental flow release which mostly occur during years with an AMR below the long term average (Figure 34). Deficits can only be reduced if they are present. However, the dispersion of the deficit reductions is a confirmation of the larger effects of optimization in cases that AMR is smaller.

Compared to the deficits due to environmental flow release in Figure 34, the reductions are limited. The deficits due to environmental flow release have a range until 2.0 km^3, while the maximum deficit reduction is about 0.35 km^3. This proportion confirms the effectiveness of the optimization that has been determined in the cases of Chapter 6. An effectiveness up to 17% is determined, which is approximately equal to the proportion between 0.35 and 2.0 km^3.

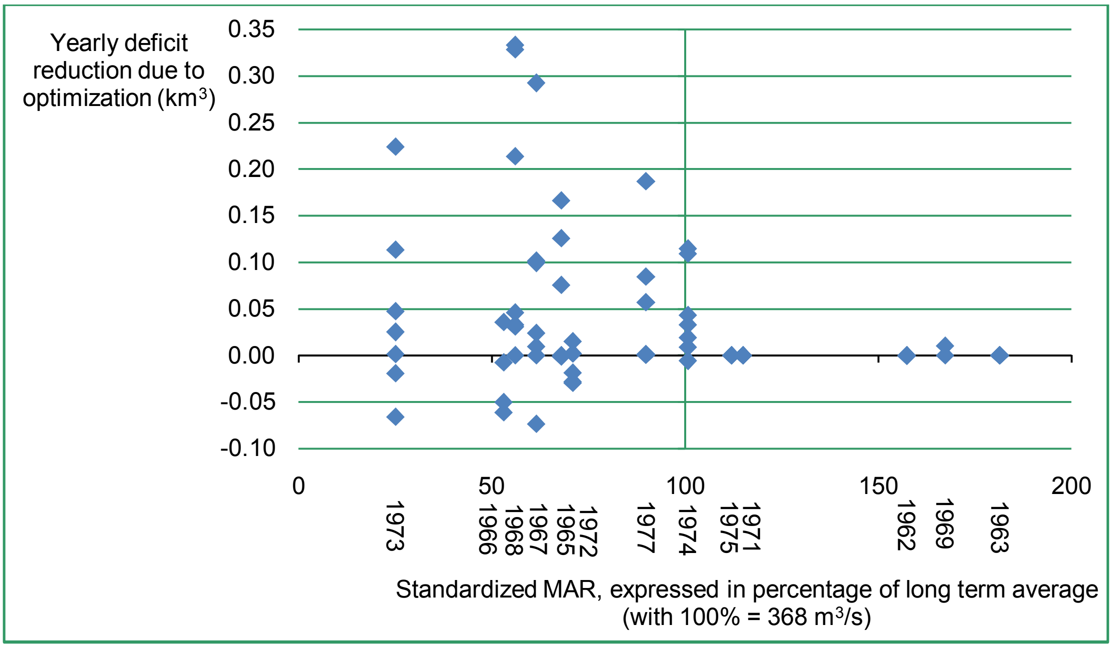

Figure 35. Deficit reduction due to the optimization, grouped per associated AMR. The deficit of all cases in this research is expressed in the total yearly volumes and grouped per year. The years are distributed over the x-axis in relation to their standardized AMR. Large deficit increases are abstracted from the deficit reductions the year before.

6.7 Fixed moment of environmental flow release

The moment that the EFR is allocated in the situation with no optimization in its timing, influences the effectiveness of the optimization. This moment is especially significant if the optimal moment of environmental flow release is each year the same. This happens for example in case 'Demand/fluctuation', where the demand has large influence on the calculation of the deficit while its lowest point is each year at the same moment.

In the histogram of Figure 36, the optimal moments are shown as determined by the optimization. All situations are assessed in which the environmental flow release has a degree of freedom and where a hindcast is used. In total these are 7 cases with each 13 years, so 91 calculated optimal moments of allocation. Within the window of opportunity there are 8 moments that allocation can be started, only for the case 'EFR/duration' just has 4 possibilities for environmental flow release (as seen in Figure 18).

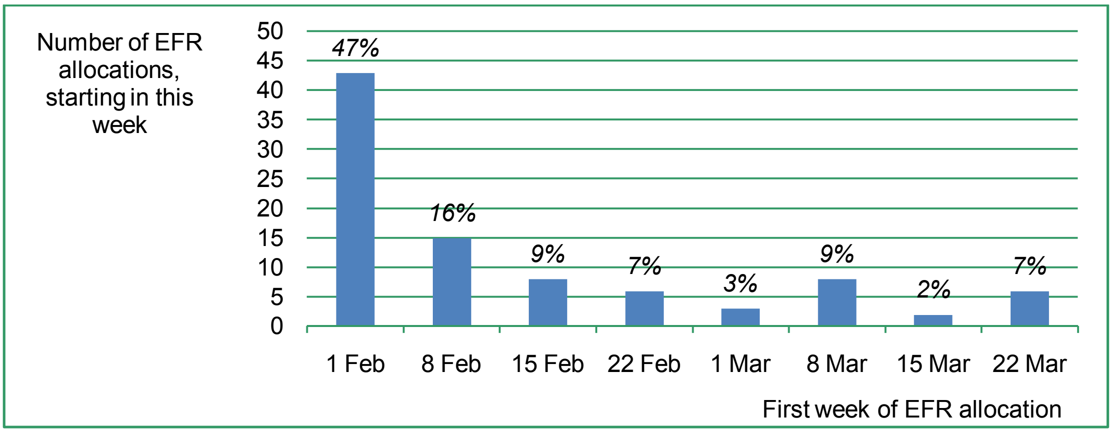

Figure 36. Spread of the determined optimal moments that the environmental flow release should start, for all years in all cases within this research.

The spread in the histogram shows that almost half of the determined moments is within the first week of the opportunity window. This is the same moment as used in the situation with a fixed environmental flow release. Hence the best possible moment for the fixed moment of environmental flow release is chosen, and the reference situation was indeed the best possible situation without optimization. The other half of the determined moments in Figure 36 represent the number of moments that the environmental flow release can be optimized.

Chapter 7 Discussion, conclusions and recommendations

This chapter discusses the methods and results of the research, and summarizes the answer for the research question. This will lead to several recommendations.

7.1 Discussion

A number of choices and assumptions has been made within this research: for the problem situation, for the model structure and for its input. In some cases, these assumptions may have a significant influence on the results and should not be unattended. For this, the most important assumptions and their influences are discussed here.

7.1.1 More focus on optimization than on case study

In this research, the analysis of the optimization of the timing of environmental flow release is central. As stated in the problem definition, it was not the intention to develop a flow forecast, improve the operational management or execute an environmental flow assessment for the local situation of the Kafue river. The case study is only used as a ground for realistic input. Therefore no calibration of the model was performed, and the validation for the hydrologic model (section 4.4) has rather low value. This reduces the significance of the case study results for the Kafue River. Nonetheless, the results are still valuable as an indication of the potential deficit reductions and the attached conditions if flow forecasts are utilized in the operational management of a reservoir for the environmental flow release.

7.1.2 The integrity of the water deficit as objective function

The objective function of the optimization model, has been the reduction of water deficit for users downstream a water reservoir, expressed in volumes. This definition includes all tangible reservoir functions within the case study. However, the definition excludes the costs for the time that firm storage is not made and the maximum power production is not accomplished.

In the case study the applied definition is sufficient because a reservoir level below firm storage level does not affect the power production, which is located downstream. However, the deficit definition as defined in this study will not sustain in reservoirs that do have costs for unaccomplished firm reservoir storages. After all, in this research deficits can only represent costs or losses if expressed in volumes, while losses in power production are not linear related to water volumes. To avoid this problem, the definition of deficits should be expressed in economic values, so a transparent conclusion can be drawn about the optimal moment for allocation. In practice this is a difficult task because of the complicated valuation of exact economical losses due to water shortage, but it certainly is necessary if local hydropower generation is involved.

7.1.3 Prioritizing of environmental flow release at all times?

In the problem analysis, the environmental flow release is assumed to have priority above other water usages, to simulate the deficit for the other water users, which has been found an impediment for reservoir operators. No distinction for the environmental flow release is made for any situation, so also if the reservoir level is very low, EFR is allocated while the other demands are restrained in their supply. Therefore this research has many cases in which EFR is allocated despite the large deficits which are already present.

This may be a somewhat unrealistic situation, because in practice the allocation of the EFR is probably reconsidered if reservoir level and inflow forecasts are both very low. And if unrealistic assumptions are made, the sense of reality in the research is affected and conclusions may not be taken seriously. Therefore, the prioritization of environmental flow release at all times should be reconsidered, if a reservoir manager is to be convinced.

7.1.4 Possibilities for flow forecast ensembles

In the research, an autoregressive method has been used to create a flow forecast out of the historical average inflow and the current inflow. The advantage was the simplicity of the forecast and its infinite lead time. However, in practise flow forecasting systems can also provide ensembles of possible inflows. The developed optimization model is not ready to use such a forecast ensemble directly, but its approach does give the opportunity to adjust the model for forecast ensembles.

The optimal moment of environmental flow release can be found with help of a forecast ensemble if deficits for all possible moments for environmental flow release are determined, for each forecast ensemble member again. Some extra decision criteria are necessary to choose the optimal moment for all different deficits: first, the most probable deficit should be determined per moment of environmental flow release, and afterwards the moment with the smallest deficit should be selected.

7.1.5 Period of simulation run

Results for several cases in this research showed environmental flow releases which affect the reservoir level over multiple years. The period that the simulation in the hydrologic model is run for optimization is limited to a single year. Deficits that were reduced by the optimization in one year, caused extra deficit in the following year. To improve the optimization and to acquire a more transparent view of the effects, the period that the model is run should be extended. However, the model run would then exceed the recurrence period of the window of opportunity of the EFR, and the environmental flow release in the next year should also be taken into account. The developed optimization model is not able to include this extra dimension.

7.2 Conclusions

The research question is "*To what extent can optimization in timing of environmental flow release by the inclusion of flow forecasting in the operational management of a reservoir reduce water deficits that accompany environmental flow release?*" For this, an optimization model is developed and applied to a case study in the Kafue River with the Itezhi Tezhi dam and Kafue Flats. Aspects that influence the optimization are determined and analysed for the case study. In this way, the effects of EFR allocation on the water deficits for the Kafue River are quantified, and insight is acquired about the effectiveness of the optimization under different conditions.

7.2.1 Case study: the Kafue River

The research has determined that the optimization of the moment of the peak flows of environmental flow release in the Kafue River reduces 7% of the water deficits accompanying the allocation, measured over a period of 13 years. This is in total a water volume of 0.10 km^3. These deficit reductions are acquired in a total of five years, in the other eight years no deficits occur due to the environmental flow release.

The optimization reduces the deficits in situations that the reservoir volume is restored directly after a successful deficit reduction. Then deficits are not simply postponed and the optimization is effective. So the condition for deficit reductions by the optimization, is that water availability must be sufficient to restore the reservoir level after an allocation for the EFR, before the next dry period. This situation has relationships to many aspects, which are provided in the next section.

The influence of the forecast uncertainty on the effectiveness of the optimization is determined to be small in the case study (section 5.2.3, Figure 37-A). This research shows that the uncertainty of an autoregressive flow forecasting does not affect the deficit reductions of the optimization much. So despite its uncertainties, any flow forecast is effective for the determination of the optimal moment of environmental flow release. The only condition for the use of flow forecasting in the optimization, is that its lead time covers the period that the environmental flow release influences the reservoir level (3.4.2).

7.2.2 Influences on the optimization

Aspects of the flow forecast, the EFR, the reservoir and the demand are analysed for their influence on the optimization. The effectiveness of the optimization is analysed, i.e. the percentage of deficit reduced compared to the deficits that are caused by the environmental flow release. Various conclusions are drawn from this analysis.

Environmental flow components

Most important environmental flow components that determine the EFR are the magnitude, duration, and the window of opportunity. The window of opportunity provides the necessary degree of freedom, as long as it is determined longer than the EFR duration (3.2.6, Figure 37-B). A larger magnitude of the EFR comes with more deficits but they are relatively more reduced by the optimization (6.3, Figure 37-C). A shorter duration of the EFR increases the effectiveness of the optimization since larger differences exist within the possible environmental flow releases (Figure 37-D).

Operational management and reservoir size

As found from the case study, the optimization reduces more deficits if after allocation for EFR the reservoir level is restored before the next dry period. This is more likely to happen if the reservoir level is restored within a short period. A short restoration period is acquired if the hedging rules in the operational management of a reservoir have high restraints on the supply flows (6.2, Figure 37-E). This type of hedging rules are most found in reservoirs with a hydropower function. Reservoirs with mainly a supply function have operational management have smaller restraints on the supply flows, and these reservoirs may benefit less of the optimization.

Reservoir size has also an influence on the effectiveness of the optimization. It is argued that optimization is only of value if the reservoir has not the storage capacity to store all water needed for a full drought period. On the other hand, a very small reservoir will not affect the natural flow and special allocation for the EFR is not required (3.6, Figure 37-F).

Fluctuation of inflow & demand

If the demand has a high fluctuation, chance is that the optimization is not effective (6.4, Figure 37-G). This relation is caused by the deficit's dependency on the demand, and the assumed high persistence of the demand peaks and troughs. After all, the higher the demand's fluctuation hence the larger the difference between low and high water demands, the more the optimal allocation moment is determined by the timing of a low demand. This timing is persistent, so the optimal moment is always the same and a variation of the allocation for EFR would not reduce any deficits.

The recurrence of reservoir peak inflows has more temporal variation then the fluctuation of the water demand. This variation is necessary for the optimization to be able to reduce the deficits (3.3.2, Figure 37-H). The lower the persistency of the recurrence of the inflow peaks, the higher the potential effects of the optimization.

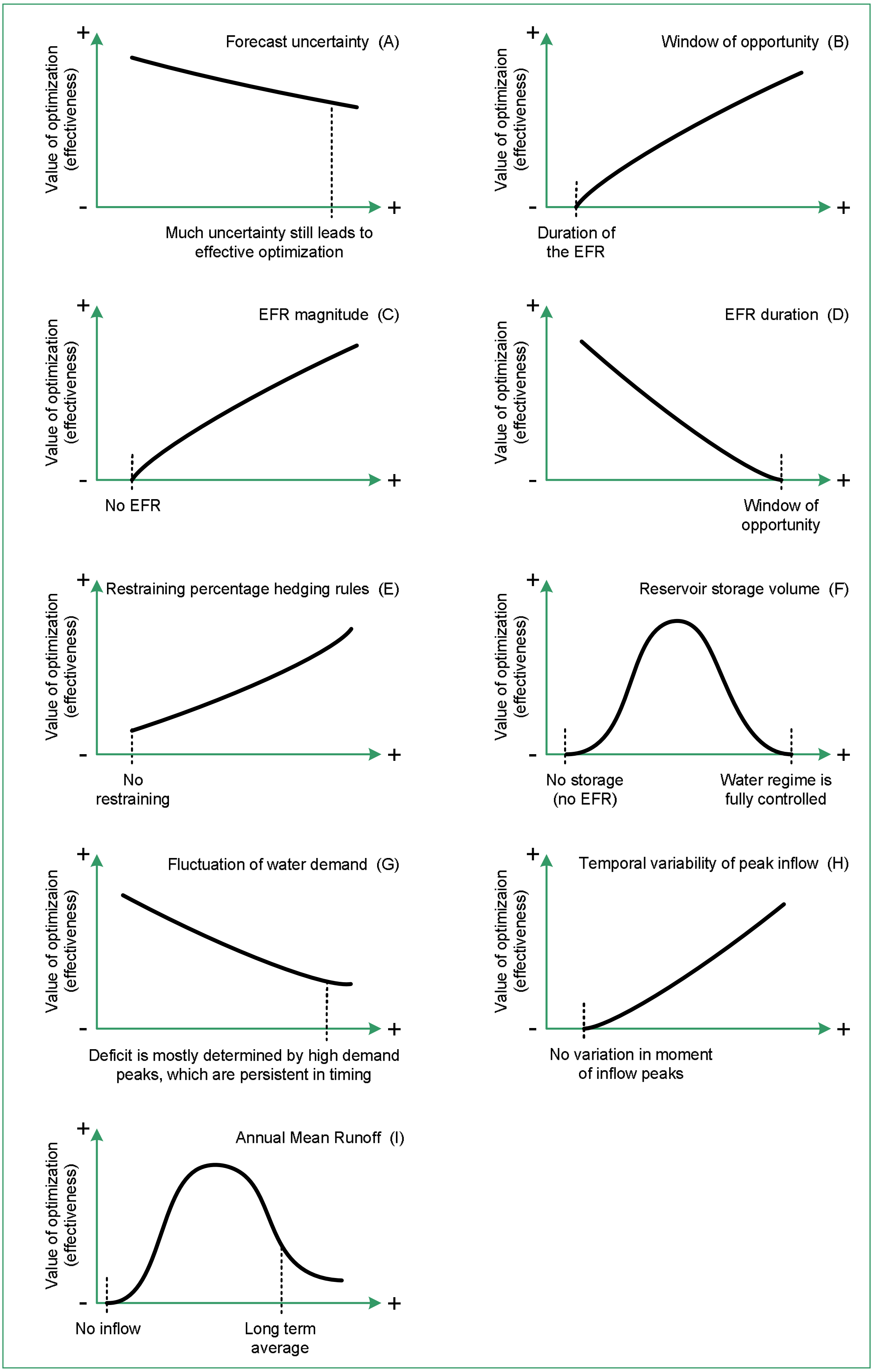

Figure 37. Overview of determined relations between various aspects and the value of optimization of the timing of environmental flow release.

Water availability

Within the modelled case study, large deficits occur in years that the annual mean runoff (AMR) is smaller than 70% of the long term average inflow. Years with an AMR above the long term average have in general no deficits. Optimization is therefore most effective if the AMR is below long term average inflow. However if the AMR is lower than 70% of the long term average, the optimization can only reduce a small percentage of the deficits that accompany the environmental flow release and optimization is less effective (6.6, Figure 37-I).

7.2.3 Checklist

At last, the conclusions are summarized and presented in a checklist as in Figure 38. The checklist provides the conditions and considerations under which optimization of the moment of environmental flow release using flow forecasts, is likely to reduce deficits.

Conditions for the effectiveness of the optimization

- ☐ Window of opportunity exceeds the EFR duration
- ☐ Reservoir provides storage volume such that sufficient water is available for environmental flow release
- ☐ Reservoir inflow or the water demand has variation in its moment of high or low flows/demands
- ☐ Forecast has a lead time as long as the environmental flow release influences the reservoir level

Considerations for when optimization is more effective

- ☐ more effective if EFR is of short duration with larger discharges
- ☐ more effective if hedging rules acquire a short restoration period for the reservoir level
- ☐ more effective in years that AMR is below long term average flow

Figure 38. Checklist with conditions and considerations that apply for the optimization to reduce deficits due to environmental flow release.

7.3 Recommendations

Recommendations are considered for the optimization of the moment of environmental flow release, for further possible research and for river basin management.

7.3.1 Recommendations with respect to the optimization model

If this research is extended, or if the optimization model is applied to another reservoir, a few extra aspects may be interesting to analyse, to improve the understanding of factors that influence the optimization model.

Improve hydrological model of the Kafue Flats

The hydrological model should be improved for more accurate deficit predictions. The model is improved if the water demands are inquired with more detail. The inflows of the Itezhi Tezhi reservoir need to be measured, and the hydrological system of the Kafue Flats should have more measuring points to analyse the extra inflows between the Itezhi Tezhi dam and the agricultural areas. With these data, a proper calibration and validation of the hydrological model can be executed.

Reconsider the assumptions of the scope

The research scope has a large influence on the conditions that are valid for the results of this research. So next to the aspects determined as such in the system analysis, also the aspects confined by the scope are interesting for analyse. So in case of a further analysis, assumptions for the research scope such as the deficit definition and the direct competition between the EFR and water demand, should be reconsidered.

To include the reduced revenue of hydropower generation due to reservoir levels below firm storage volume, the deficit definition should be adjusted. This can be done with by expressing the water deficit in economical costs. An other expression implies that information is necessary about upcoming power prices and economical damage of water shortages for all other users. Also the deficit determination should be done for each demand separately, and all demands need to be modelled apart.

The direct competition between the EFR and water demands represents the exclusion of water re-use between the demands, and is assumed to simulate the impediments of reservoir managers at best. Situations in which water allocation for the reservoir's functions does not directly compete with the EFR, can be compared to cases within this research. After all, these situations may be represented by a smaller EFR or a more continual reservoir outflow. However despite the possible comparison, the actual situation should be modelled as accurate as possible. So if the optimization is applied to a case study, the direct competition should be reconsidered and the hydrological model should be more accurate.

7.3.2 Recommendations with respect to further research

Further research is recommended for a real-time dependency of the full operational management of a reservoir on flow forecasting. Also a more case specific approach is recommended to research possible deficit reductions if utilizing the optimization model.

Research a full dependency of operational management on flow forecasting

Variation within the hedging rules of the operational management of the reservoir has shown a significant influence on the deficit reductions of the optimization. Especially the period needed for the reservoir to recover has effect on the deficit reductions. Because this period is fully determined by the operational management, it is expected that adjustments within the operational management might profit from flow forecasting considering the deficit reduction. Although the operational management is already an elaborated compromise between the various reservoir functions, it may be possible to reduce the deficits due to environmental flow release if the rule curves and hedging rules would be real-time dependent on flow forecasting.

Encourage specific modelling after qualitative analysis

Due to the large network of influences, it is hardly possible to determine a general quantification for the exact relationship between an aspect and the deficit reduction by the optimization. An infinite number of cases and a full understanding of all processes within the system would be necessary. For this, it is not recommended to develop fully quantified rules that select which reservoir have potential benefit of the optimization.

Instead, it is more practical and efficient to just check for a specific reservoir if optimization has potential to reduce deficits. This can be done based on a qualitative analysis with the help of the checklist of Figure 38. Only if a case suffices the conditions, the specific case should be modelled to obtain an indication of the quantified deficit reductions by the optimization. The checklist for general conditions and relations as in Figure 38 is probably not much further expandable, since any more relationships between aspects and deficit reductions are simply too case specific. So further research on general relationships is discouraged, while a more applied approach for specific cases is recommended.

7.3.3 Recommendations with respect to river basin management

Conclusions of this research lead to a few recommendations which may reduce the impediments that reservoir operators have regarding the implementation of the environmental flow release. Recommendations are done for the Kafue River but also for river basin management in general.

Consider demands in timing of the environmental flow release

In this research it is recognized that the moment of environmental flow release determines the water deficits. For this, the fixed moment of environmental flow release should be well considered if no further optimization is done with help of flow forecasts.

Hence, the timing of the environmental flow release should be a part of river basin management. If the approaches for environmental flow assessments in Chapter 3 are recalled, an interactive approach for determining the EFR is expected to overcome the impediments of reservoir operators better than the prescriptive approaches, in case no flow forecast is available. This, because the interactive approach also considers the other water demands within the determination of the preferable EFR, so that deficits for these demands are taken into account.

Consider the optimization possibilities within the interactive approach

The optimization subject in this research can reduce deficits due to environmental flow release. Hence, impediments that exist for environmental flow release can be weakened by adjustments in the operational management. For this, it is recommended to take the potential of a variable operational management into account within the river basin management. If knowledge is available in river basin management about the possibilities to reduce the deficits by adjustments within the operational management, it might be more easy to overcome the contrasting stakes for the environmental flow and the other water demands.

Reconsider the environmental flow release, before optimizing it

A conclusion for the case study in the Kafue River is that environmental flow release does not result in any deficits for all years that have an annual mean runoff above the long term average inflow. Despite this, the environmental flow is generally not released, not even in years with large water availability.

Some reservoir operators have no direct incentive to allocate for EFR because of the possible deficits. The operator might only allocate the EFR if convinced that no deficits are caused. In that case, a forecasting model with a threshold that represents a (statistical) certainty that no deficits occur, may be a valuable asset. In that way, a flow forecast can provide confidence about whether or not deficit will take place in case of environmental flow release.

For this, it is recommended to use a flow forecasting system in the Kafue River that provides a prediction about the seasonal water availability. Such information could determine whether it will be a dry, normal or wet year. The distinction between these classifications provides information whether or not the environmental flow release will cause deficits, and the environmental flow for the Kafue Flats can be released with less hesitation.

It is also recommended in general to use flow forecasting, for both the determination whether or not the environmental flow should be released, and at which timing this would result in the least amount of water deficits. Together, the reconsideration of environmental flow release with the possible optimization of its timing, make a solid approach to prevent deficits. This approach may convince a reservoir operator for environmental flow release in cases he would otherwise refrain from the allocation.

So flow forecasting can play a role within the operational management whether for the question *if* EFR should be allocated or for the question *when*. All in all, flow forecasting is valuable in any way. It provides extra information, so it enhances the knowledge about the system. That makes it possible to steer the situation more to one’s desires.

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SWRSD Zambezi Basin Joint Venture, 2010. *Inception Report, Dam synchronization and flood releases in the Zambezi River basin.* Southern African Development Community, GTZ.

Appendix A. Interviews

A.1 Unesco-IHE

Name: Elen Mwelwa
Profession: PhD student, Environment of Kafue Flats - IHE, Delft
Contact: e.mwelwa@unesco-ihe.org
Interview: 23rd of April 2010, Delft

Abstract: The EFR downstream of the Kariba Dam is naturally developed, since the Mana Pools developed after the construction of the dam. However, if a supplementary environmental flow would be necessary, it is estimated on a flow of 5000 m^3/s once in the 5 years.

More interesting for me may be the Kafue Dam. The EFR has already been defined on about 350 m^3/s once in the rainy season. It was implemented by the March Freshed; four standard weeks in March with allocation. Nowadays it is allocated somewhere within the rainy season. Competing water uses include hydropower, environment and agriculture that is to be expanded. Flow forecasts may be used with a lead time of 2 until 3 months.

Obtained: Contact within ZESCO.

A.2 The Post Newspaper

Name: K. Chiwoyu Sinyangwe
Profession: Journalist Business and Financial Desk - The Post Newspaper Limited, Lusaka
Contact: chiwoyu.sinyangwe@post.co.zm
Interview: 4th of May 2010, Lusaka

Abstract: The Kariba Dam is under the management of the Zambezi River Authority, it consists of ZESCO(Zambia) and ZESA (Zimbabwe). There are two outlets and hydropower stations within the dam, one for both countries. The Zimbabwe hydropower station has much more capacity, Zambia will extend its capacity before the year of 2030. More information about the Mana Pools should be found at the Environmental Council of Zambia.

However, it would be much more easy to collect data from the Kafue River, since this runs fully through Zambia, and it is the single most important river or the country. 50 percent of the Zambian population is dependent of this river, and for example 99 percent of the sugar cane production is located here.

Obtained: Document on sugar cane production within the Kafue Flats: "Strategic Environmental Assessment (SEA) of the Sugar Sector in Zambia" (Palerm et al. 2010).

A.3 ZESCO hydropower

Name: Collins Nzovu
Profession: Hydrologist – ZESCO power company, Lusaka
Contact: cnzovu@zesco.co.zm & rmbila@zesco.co.zm
Interview: 7th of May 2010, Lusaka

Abstract: ZESCO is power company of Zambia and is the operational manager of the Itezhi Tezhi Dam and the Kafue Gorge Dam. They are restricted by the governmental water rights: They always have to allocated a minimal flow of 28 m^3/s for public water supply and agriculture plus a minimal flow of 25 m^3/s for environmental purposes. They are allowed to use until 215 m^3/s for hydropower. An EFR is defined by the WWF, at 300 m^3/s . If water availability tolerates, ZESCO tries to approach this flow.

The water demand for agriculture fluctuates. Within the rainy season (December until March) it falls back until around 30 percent of their water rights, depending on the rainfall. Outside the rainy season the full water rights are used (until 90 percent). The water demand for public water supply fluctuates only a little, around the 10 percent of the water rights.

The agricultural water demand is divided in multiple sugar cane farms, of which ZamSugar is the largest. However, fluctuation of one farm will be typical for the other farms. The main office of ZamSugar is located in Mazabuka (125 km from Lusaka).

Inflow forecasts at Kafue Hook are tried to be forecasted by a flow forecasting model up to 3 weeks. However, this model didn't work and is disposed. Input was the moment of the season with the meteorology data. The hydrological model was the Pitman model: KafRiver. A new hydrological model is KafGin, a Hec3 simulation model.

Obtained: Rule curves and reservoir volumes of Itezhi Tezhi Dam and Kafue Gorge. Contact within ZamSugar Company.

A.4 The World Bank, Lusaka

Name: Marcus J. Wishart
Profession: Water Resource Specialist - The World Bank, Lusaka
Contact: mwishart@worldbank.org
Interview: 28th of May 2010, Lusaka

Abstract: The World Bank maintains contacts with ZESCO, the government and the WWF. In the past they have done some projects on the Kafue River, considering the hydropower optimization, the evaluation of the agriculture in the Kafue Flats and the environmental flow requirement. They have a lot of reports and data of this area dating back to 1968.

According to Marcus, the allocation of the EFR in the Kafue Flats has indeed a degree of freedom within the season. This is commonly misunderstood by dam operators, and insight in lower deficits than expected for the dam operators is of value. Flow forecasting increases the ability to manage the allocation efficiently over time. Since next generation flow forecasts may be improved, they might be an interesting alternative to the enlargement of reservoir volumes.

The flow forecasting model for the Kafue River has been developed within a project of the government, WWF and ZESCO: KAFRIBA. According to literature, the model should be fine, while ZESCO claims it is not working. ZESCO does not use the model anymore and since then it has disappeared.

Sugar cane production is indeed the main agricultural productivity, which is expanding the last years. The water rights that are granted by the government are however not fully in correspondence with reality. A lot of water is unregistered retrieved from groundwater, which results in a large gap within the water balance between the up and downstream dams.

The agricultural water demands in the Kafue Flats are considered as a minor concern, since they do not experience large deficits. In the future however, shortages may appear since the agricultural surface expands while hydropower generation has a prioritization above the agricultural production. The Itezhi Tezhi dam may be installed with hydropower generators (for now it was just a reservoir dam to serve the hydropower generators at the downstream Kafue Gorge dam) and might have alternative rule curves that prejudice the agricultural water demands.

Marcus remarks that it is important to take along the water demand for hydropower within the modelling, since this is its main purpose. In the future, the hydropower is likely to compete with the environmental flow, since construction of a hydropower generator in the Itezhi Tezhi dam might imply a river flow that has no fluctuation apart from a two daily small peak.

Obtained: Reports on Kafue Flats, Itezhi Tezhi dam and the Kafue Gorge:

- Multipurpose survey of the Kafue River Basin (United Nations Development Program, 1968).
- Hydrological Review on the Kafue River, Zambia (Crowmarsh Gifford, 1994).
- Integrated Water Management Project for the Kafue Flats (Nalumino and Chileshe, 2002).
- Decision making system for Improved Water Resources Management for the Kafue Flats (WWF, 2004).

Contact within WWF.

A.5 WWF

Name: Chris Mwasile
Profession: Specialist on Environmental Flows in the Kafue Flats – WWF, Lusaka
Contact: cmwasile@zamtel.zm
Interview: 8th of June 2010, Lusaka

Abstract: The WWF is the stakeholder concerning the environmental flow requirements in the Kafue Flats. The three main water dependencies in the Kafue Flats are the environment, the sugar cane sector and the hydropower generation. The sugar cane sector uses only a slight part of the available water in comparison with the hydropower generation. However, plans exist to expand the sugar cane crop area.

The inundation of the Kafue Flats is currently fully dependent on ZESCO, who operates the dam. Its operational management was based on a research of SOWECO that included a March Freshet. However, since 1991 (a year with nihil precipitation and therefore no hydropower generation) ZESCO applies an operational management that only serves the purpose of the hydropower generation, complied with the water rights. Since no flow forecast is available, this implies that ZESCO always tries to fill the reservoir as much as possible.

The Kafue Flats are subject to fifteen local streams, fed by their own sources during the rainy season up to 300 m^3/s (see Figure 39). Water from these streams serves the hydropower generation, resulting in hedging of water by the Itezhi Tezhi dam during the rainy season and allocation during the dry season. The closing of the dam during rainy season is harmful for the environment, so that the WWF now tries to develop rule curves that do implement a minimal flow during the whole year. Flow forecasts can be helpful to diminish the necessity of a full closing of the Itezhi Tezhi dam.

Chris explained the history of the development of a inflow forecast for the Itezhi Tezhi lake and told that the WWF is now together with the Water Board busy to develop a new flow forecasting model. It will be based on hydrologic gauges and will have a lead time of one month, based on the maximum runoff time in the catchment.

An environmental flow of 270 m^3/s fills the river up to the banks. According to Chris, such a flow is right now for the WWF of less interest than the minimum flow, since the minimum flow is not guaranteed as well. However, in the report of Scott Wilson (2003) he gave me, is stated that an environmental flow of 300 up to 600 is substantially necessary for the Kafue Flats.

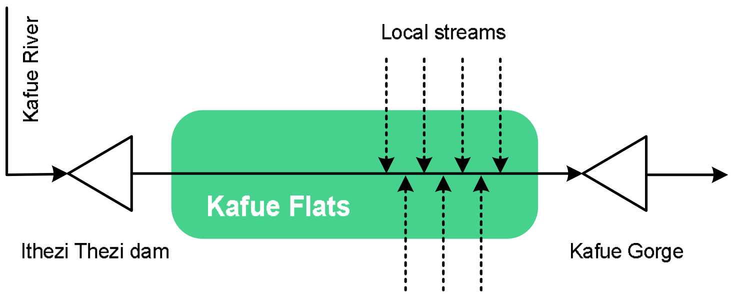


Figure 39. Actual situation in the Kafue Flats. Local streams can contribute to the hydropower generators in the Kafue Gorge. In that case the Itezhi Tezhi dam is closed for hedging.

Obtained: Document of an Environmental Flow Assessment: Wilson, S., 2003. *Strategic Integrated Kafue River Basin Environmental Impact Assessment Study, Strategic Environmental Impact Assessment.* Scott Wilson Piésold. (Wilson, 2003)

A.6 GTZ project – environmental flows

Name: Rudo Sanyanga
Profession: Specialist on Environmental Flows – WRNA.
Leader Ecosystems Team – Zambezi River Basin Dam Synchronization Project
Contact: ras1264@gmail.com
Interview: 16th of June 2010, Lusaka

Abstract *Is it likely that an EFR has a large window of opportunity?*

Environmental flows have indeed a degree of freedom within the moment of allocation. Although they are meant to simulate natural flows and should follow the peaks and troughs, flows vary from year to year and they also shift when they peak and trough. Therefore based on weather forecasts and onset of rains upstream the time and magnitude of e-flows could then be varied.

I think that in general, agricultural demands abstract water from a river so that the downstream environment lacks water. Hydropower however, does not use the water but only flattens the original flow pattern of a river to get a regular flow for its firm power generation. Therefore, agricultural demands directly *compete with the environment about volumes of water, while hydropower competes with the environmental flow only about the timing of large water volumes. Can you agree with this view, or do you have some extra thoughts about this?*

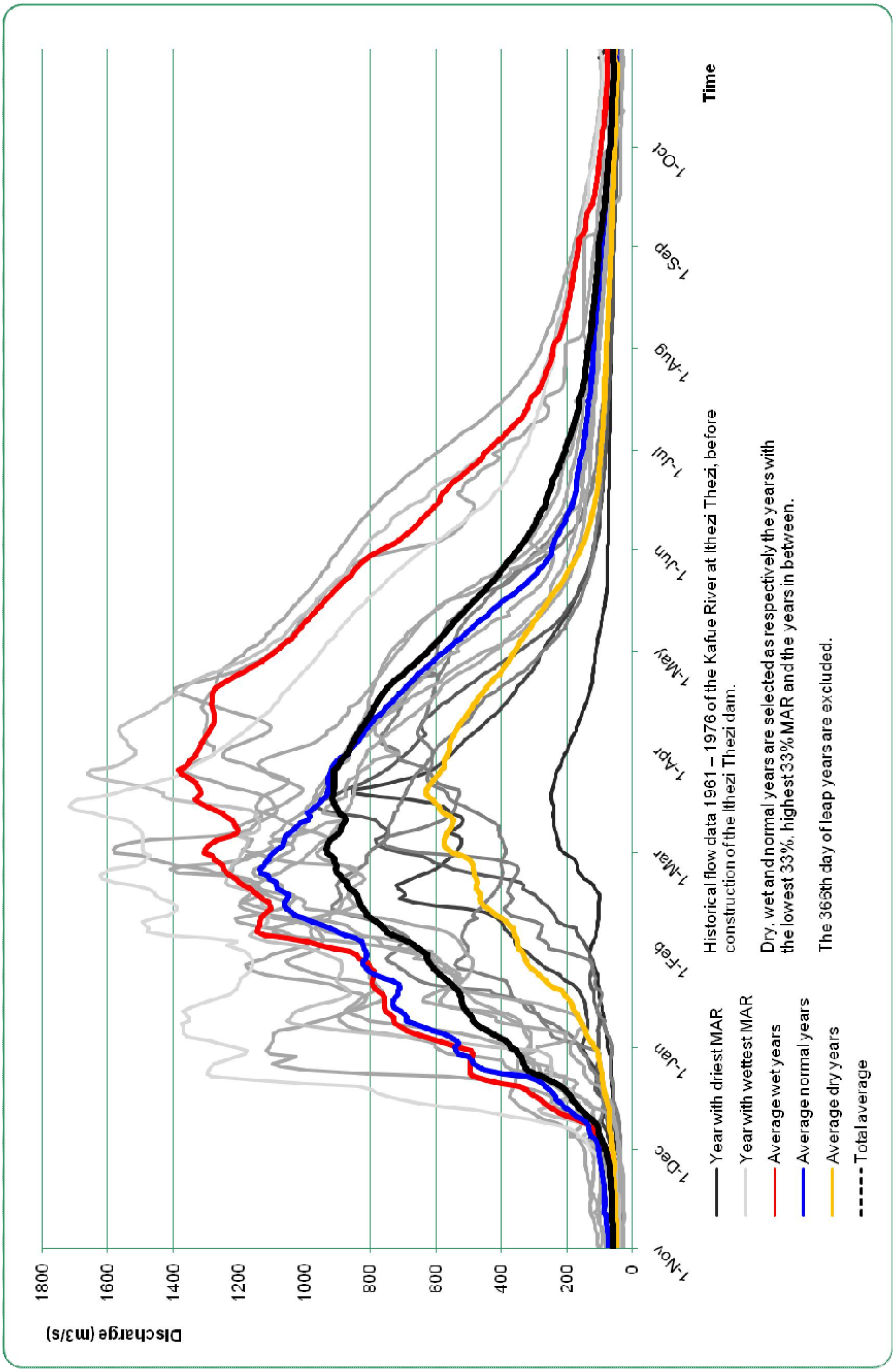
Partially you are correct but for some hydro schemes water storage robs the downstream of water. Examples are Kariba and Cahora Bassa. It is reported that Cahora form some years before its rehabilitation did not release any water yet it was not even generating electricity. The lack of flows in the Zambezi delta are due to huge dam storage (For power generation) and not for agriculture. Kafue system (Itezhi Tezhi and the Kafue gorge dam) may be slightly different since storage capacity is less and the dam at the gorge is narrow. I do not know the balance of water in the systems. For example which sector uses more water and at what times of the year etc? Although it is a fact that more water is used for irrigation during the dry seasons.

What do you think is the best method to persuade the dam management to implement an EFR despite the believed opportunity costs?

Dam management authorities will only release e-flows if that does not compromise their profits. Whatever method one comes up with has to prove that there is no loss of profit to them or that they can make up the loss by maximising generation or water sales at certain times of the year. Unless e-flows are put into legislation compliance will be minimal if it causes hustles for the dam management authorities.

Shared: WWF reports
World Bank reports
All gathered knowledge concerning the Kafue System

Appendix B. Historical discharges at Kafue Hook



Appendix C. Abstraction for the sugar cane area

	Abstraction * 1979 – 1993 (MCM)	Abstraction ** 2006 – 2009 (MCM)	Evaporation & Seepage (MCM)	Abstraction 1979 – 1993 (m^3/s)	Abstraction 2006 – 2009 (m^3/s)
Apr	14.43	21.83	0.79	5.87	8.73
May	16.52	33.14	0.81	6.69	13.10
Jun	14.93	29.46	0.78	6.06	11.67
Jul	14.55	30.16	0.81	5.93	11.95
Aug	15.96	29.28	0.81	6.47	11.61
Sep	16.9	34.70	0.8	6.83	13.70
Oct	17.99	42.82	0.83	7.26	16.84
Nov	15.45	22.84	0.8	6.27	9.12
Dec	8.23	20.09	0.82	3.49	8.07
Jan	4.87	13.40	0.82	2.20	5.49
Feb	4.55	3.41	0.74	2.04	1.60
Mar	7.86	8.39	0.82	3.35	3.55

Table 5. Monthly averages of water abstraction from the Kafue River at the Nakambala Sugar Estate. Discharge includes the evaporation and seepage.

***Source: Crowmarsh Gifford, 1994.**

****Abstraction extrapolated from data of the ZamSugar Company, which represents 52% of the sugar cane area, with thanks to the irrigation manager Mark Mulder.**

Appendix D. Categorisation Environmental Flow Assessments

The approaches for environmental flow assessments are further categorised as such in Table 6. These categories are described in detail in the book of Gordon et al. (2004), and their applications worldwide are found in the paper of Tharme (2003). A large database with examples of methods, including description and references, is provided by the International Water Management Institute (2010).

Approach	Category	Example method	Quantification of the EFR
Prescriptive	Hydrological index methods	Tennant Method (Tennant, 1976)	Percentage of natural flow
	Hydraulic rating methods	Wetted-Perimeter Method (Gippel and Stewardson, 1998)	Minimum flow
	Holistic approaches	Building Block Method (King et al., 2008)	One modified flow regime
Interactive	Habitat simulation	IFIM (Bovee, 1982)	Habitat effects for multiple flow regimes
	Holistic approaches	DRIFT (King et al., 2003)	Full scenario effects for multiple flow regimes

Table 6. Quantification of EFR for each category of environmental flow assessment. (Gordon et al., 2004; Tharme, 2003; Brown and King, 2003; Richter et al., 1997)

Appendix E. Hydrological setup Ribasim Model

Overview

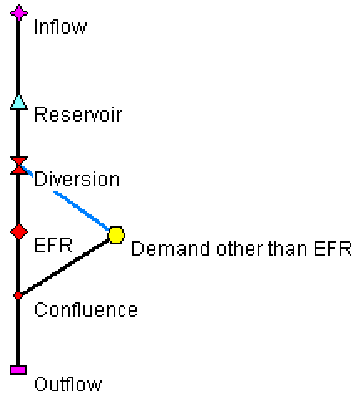


Figure 40. Overview hydrologic setup in Ribasim.

Inflow

Variable inflow node, dependent on discharge time series exported from FEWS.

Reservoir

Surface water reservoir node, with target curve and hedging on priorities. See Table 7 for details.

EFR

Low flow node with a variable flushing time series. Priority fraction is 100% for allocation priority 1. The time series is regulated by the output of FEWS.

Demand

This is modelled by a Public Water Supply node, for its possibility to regulate the demand by a variable time series in discharge (m^3/s). This node however represents in this research all the water demands downstream of a reservoir except for the EFR.

In the case study, the demand node has a priority fraction of 75% and a allocation priority 2. The node has no distribution losses and no return flow, since it considers a net water demand.

Storage characteristics			**Level [m]**	**Surface area [ha]**	**Volume [Mcm]**
			0,00	400	2
			4,00	2200	63
			10,00	4600	231
			15,00	7600	533
			20,00	11300	1003
			25,00	15800	1673
			30,00	21400	2595
			35,00	28400	3827
			40,00	36400	5439
			43,00	42000	6616
	Length	**[m]**	60000		
	Initial level	**[m]**	33,5		
	Full reservoir level	**[m]**	41.5		
Spillway gate	**Net head**	**[m]**	0.00	0.00	
	Discharge	**[m3/s]**	10.00	1000.00	
Main gate characteristics	**Gate level**	**[m]**	17		
			Net head [m]	**Discharge [m3/s]**	
			0.00	0.00	
			26.00	9515.00	

Operation rules		Timestep	Flood control level [m]	Target level [m]	Firm storage level [m]
		Week 1	35.00	35.00	30.00
		Week 2	35.00	35.00	30.00
		Week 3	35.00	35.00	30.00
		Week 4	35.00	35.00	30.00
		Week 5	36.00	36.00	31.00
		Week 6	36.00	36.00	31.00
		Week 7	36.00	36.00	31.00
		Week 8	36.00	36.00	31.00
		Week 9	36.00	36.00	31.00
		Week 10	37.00	37.00	32.00
		Week 11	37.00	37.00	32.00
		Week 12	37.00	37.00	32.00
		Week 13	37.00	37.00	32.00
		Week 14	38.00	38.00	33.00
		Week 15	38.00	38.00	33.00
		Week 16	38.00	38.00	33.00
		Week 17	38.00	38.00	33.00
		Week 18	40.00	40.00	35.00
		Week 19	40.00	40.00	35.00
		Week 20	40.00	40.00	35.00
		Week 21	40.00	40.00	35.00
		Week 22	41.00	41.00	36.00
		Week 23	41.00	41.00	36.00
		Week 24	41.00	41.00	36.00
		Week 25	41.00	41.00	36.00
		Week 26	41.00	41.00	36.00
		Week 27	41.00	41.00	36.00
		Week 28	41.00	41.00	36.00
		Week 29	41.00	41.00	36.00
		Week 30	41.00	41.00	36.00
		Week 31	41.00	41.00	36.00
		Week 32	41.00	41.00	36.00
		Week 33	41.00	41.00	36.00
		Week 34	41.00	41.00	36.00
		Week 35	41.00	41.00	36.00
		Week 36	39.00	39.00	34.00
		Week 37	39.00	39.00	34.00
		Week 38	39.00	39.00	34.00
		Week 39	39.00	39.00	34.00
		Week 40	37.00	37.00	32.00
		Week 41	37.00	37.00	32.00
		Week 42	37.00	37.00	32.00
		Week 43	37.00	37.00	32.00
		Week 44	37.00	37.00	32.00
		Week 45	35.00	35.00	30.00
		Week 46	35.00	35.00	30.00
		Week 47	35.00	35.00	30.00
		Week 48	35.00	35.00	30.00
		Week 49	34.00	34.00	29.00
		Week 50	34.00	34.00	29.00
		Week 51	34.00	34.00	29.00
		Week 52	34.00	34.00	29.00
		Week 53	34.00	34.00	29.00
Operation switches	Apply	hedging	No		
	Apply	special	No		
		Online	Yes		
	Operate	on	No		
Hedging rules based on priorities	Water allocation	priority	1	2	
	Water allocation	[% of target release]	100	75	

Table 7. Input data for hydrological model in Ribasim

Appendix F. Model input

Scenario title				1a - Study Case	1b - Study Case	1c - Study Case	1d - Forecast	2a - Operational Managemen	2b - Operational Managemen	2c - Operational Managemen	3a - Operational Managemen	3b - Operational Managemen	3c - Operational Managemen	4a - EFR / Magnitude
Model run	start		November	1961	1961	1961	1961	1961	1961	1961	1961	1961	1961	1961
	duration		years	16	16	16	16	16	16	16	16	16	16	16
River flow	initial level		m+sealevel	1023	1023	1023	1023	1023	1023	1023	1023	1023	1023	1023
	fluctuation	average	m3/s	381,5	381,5	381,5	382	381,5	381,5	381,5	381,5	381,5	381,5	381,5
		min	m3/s	15	15	15	15	15	15	15	15	15	15	15
		max	m3/s	1715	1715	1715	1715	1715	1715	1715	1715	1715	1715	1715
Demand	fluctuation	average	m3/s	179,7	179,7	179,7	179,7	179,7	179,7	179,7	179,7	179,7	179,7	179,7
		min	m3/s	171,6	171,6	171,6	171,6	171,6	171,6	171,6	171,6	171,6	171,6	171,6
		max	m3/s	186,8	186,8	186,8	186,8	186,8	186,8	186,8	186,8	186,8	186,8	186,8
Reservoir characteristic	Reservoir	size	% of ITT	100	100	100	100	100	100	100	100	100	100	100
	Operational Managem		Hedging %	25	25	25	25	40	40	40	10	10	10	25
EFR	magnitude		m3/s	0	300	300	300	0	300	300	0	300	300	0
	duration		weeks	0	8	8	8	0	8	8	0	8	8	0
	window	start	first week	-	Feb	Feb	Feb	-	Feb	Feb	-	Feb	Feb	-
		length	weeks	-	8	16	16	-	8	16	-	8	16	-
Forecast			uncertainty	0	0	0	AR	0	0	0	0	0	0	0
Run label				201	202	203	204	205	206	207	208	209	210	201

Scenario title				4b - EFR / Magnitude	4c - EFR / Magnitude	5a - EFR / Duration	5b - EFR / Duration	5c - EFR / Duration	6a - Demand / Fluctuation	6b - Demand / Fluctuation	6c - Demand / Fluctuation	7a - Hydrological / Reserv	7b - Hydrologic	7c -
Model run	start		November	1961	1961	1961	1961	1961	1961	1961	1961	1961	1961	1961
	duration		years	16	16	16	16	16	16	16	16	16	16	16
River flow	initial level		m+sealevel	1023	1023	1023	1023	1023	1023	1023	1023	1023	1023	1023
	fluctuation	average	m3/s	381,5	381,5	381,5	381,5	381,5	381,5	381,5	381,5	381,5	381,5	381,5
		min	m3/s	15	15	15	15	15	15	15	15	15	15	15
		max	m3/s	1715	1715	1715	1715	1715	1715	1715	1715	1715	1715	1715
Demand	fluctuation	average	m3/s	179,7	179,7	179,7	179,7	179,7	181	181	181	179,7	179,7	179,7
		min	m3/s	171,6	171,6	171,6	171,6	171,6	30	30	30	171,6	171,6	171,6
		max	m3/s	186,8	186,8	186,8	186,8	186,8	315	315	315	186,8	186,8	186,8
Reservoir characteristic	Reservoir	size	% of ITT	100	100	100	100	100	100	100	100	75	75	75
	Operational Managem		Hedging %	25	25	25	25	25	25	25	25	25	25	25
EFR	magnitude		m3/s	600	600	0	400	400	0	600	600	0	600	600
	duration		weeks	8	8	0	12	12	0	8	8	0	8	8
	window	start	first week	Feb	Feb	-	Feb	Feb	-	Feb	Feb	-	Feb	Feb
		length	weeks	8	16	-	8	16	-	8	16	-	8	16
Forecast			uncertainty	0	0	0	0	0	0	0	0	0	0	0
Run label				211	212	201	213	214	215	216	217	218	219	220

Appendix G. Model output

Results - yearly data

run label		201	202	203	204	205	206	207	208	209	210	201	211	212	201	213	214	215	216	217	218	219	220
year		1a - Study Case	1b - Study Case	1c - Study Case	1d - Forecast	2a - Operational Management / 6	2b - Operational Management / 6	2c - Operational Management / 6	3a - Operational Management / 9	3b - Operational Management / 9	3c - Operational Management / 9	4a - EFR / Magnitude	4b - EFR / Magnitude	4c - EFR / Magnitude	5a - EFR / Duration	5b - EFR / Duration	5c - EFR / Duration	6a - Demand / Agriculture	6b - Demand / Agriculture	6c - Demand / Agriculture	7a - Hydrological / Reservoir	7b - Hydrological / Reservoir	7c - Hydrological
1962	m3	4160160	4139424	4160160,25	4160160,25	4160160,25	4160160,25	4160160,25	4139424	4139424	4160160,25	4160160	4160160,25	4139424	4160160	4160160,25	4139424	49126180	49127036	6774624,5	1823040	1823040	1802304
1963	m3	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	38692512	38692512	38693376	2210112	2210112	2210112
1964	m3																						
1965	m3	95572224	95572224	95572224	95572224	149821920	149821920	149821920	42692832	42692832	42692832	95572224	173877408	98356032	95572224	440031712	314577216	560584832	580264960	414178272	118432800	121004936	122606800
1966	m3	167402592	506357568	473836640	473836640	234300368	587866432	541844672	88408800	298689984	268116480	167402592	1106000384	777657088	167402592	1151862400	938097536	758068480	1350416512	717033664	285237504	647282880	767466112
1967	m3	166261248	387207648	288019584	291653568	218643872	519594080	280204704	83338848	305921664	281949120	166261248	1700637184	1408382208	166261248	1408382208	1408382208	362407360	1505294592	1403808256	188696736	1906669184	1390327296
1968	m3	69884640	429953184	489956256	489069760	103099392	363698272	592422336	30270238	289534176	323628480	69884640	1408382208	1277678848	69884640	1412407680	1412407680	456310368	1446510464	1510943232	89121600	950476864	1425440256
1969	m3	2903040	12480480	3843417	37616832	2903039,75	2945376	2987712,25	2945376	100493568	116754040	2903040	329356800	424743232	2903040	355816832	363376800	161856576	363146112	602287488	43936128	570354048	570354048
1970	m3																						
1971	m3	4815936	4815936	4815936	4815936	4815936	4815936	4815936	4815936	4815936	4815936	4815936	4815936	4815936	4815936	4826304	4815936	85057344	85056480	187857792	4755456	4755456	4755456
1972	m3	5196960	7226496	5559840	7226496	5196960	7226496	5559840	5196960	7226496	5559840	5196960	188116128	173383216	5196960	113908032	142112448	74452608	145642752	175391136	5084640	96204680	115057160
1973	m3	794434176	973663296	993167168	955260032	1270744448	1564543360	1340451968	321173856	826412544	825332544	794434176	2207457792	2273540864	794434176	2346441728	2298984704	929248448	2730232320	2705307648	395367232	2410903040	2297504768
1974	m3	369326272	556795328	513656640	552410496	307602144	697849344	703759104	177427584	558046400	549069440	369326272	800870976	691967232	369326272	725494720	692369024	395731872	766395648	651634816	273319488	551052288	531780768
1975	m3	2689632	2689632	2689632	2689632	2689632	2689632	2689632	2689632	2689632	2689632	2689632	2689632	2700000	2689632	2689632	2717280	36603360	36602496	36602496	2675808	2675808	2675808
1976	m3																						
1977	m3	5967648	6784992	5967648	5967648	5967648	6784992	5967648	5967648	6784992	5967648	5967648	193451328	6676127,5	5967648	7602336	6676127,5	70541280	141673536	84658176	5452704	90601632	5988384
average	m3	130064231	229992822	221805048	224807685	177858923	301093575	279762009	59329816,5	188436010	187150510	130064231	624772032	549712361	130064231	613526479	583913605	306052402	710696571	656551614	108931788	565847228	556766867
max	m3	794434176	973663296	993167168	955260032	1270744448	1564543360	1340451968	321173856	826412544	825332544	794434176	2207457792	2273540864	794434176	2346441728	2298984704	929248448	2730232320	2705307648	395367232	2410903040	2297504768
min	m3	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	2220480	36603360	36602496	6774624,5	1823040	1823040	1802304
average	km3	0,130	0,230	0,222	0,225	0,178	0,301	0,280	0,059	0,188	0,187	0,13	0,62	0,55	0,13	0,61	0,58	0,31	0,71	0,66	0,11	0,57	0,56
max	km3	0,794	0,974	0,993	0,955	1,271	1,565	1,340	0,321	0,826	0,825	0,79	2,21	2,27	0,79	2,35	2,30	0,93	2,73	2,71	0,40	2,41	2,30
min	km3	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,04	0,01	0,00	0,00	0,00
total	km3	1,69	2,99	2,88	2,92	2,31	3,91	3,64	0,77	2,45	2,43	1,69	8,12	7,15	1,69	7,98	7,59	3,98	9,24	8,54	1,42	7,36	7,24
reduction	km3			0,11	0,07			0,28			0,02			0,98			0,38			0,70			0,12
effectiveness	%			8,2	5			17			1			15			6			13			2