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Blue water footprint caps for the Orange River basin

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Cover page image
Central-pivot agricultural fields along the Orange River in South Africa (ESA, 2017)

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Preface

This report is the result of my master thesis project about 'Blue water footprint caps for the Orange River basin', which is the final project of the Master at the University of Twente. The master thesis is executed at the University of the Free State in South Africa and at the University of Twente.

During this thesis Arjen Hoekstra passed away very unexpectedly. This came as a big shock and I would like to thank him for making this all possible. Thanks to his international connections I got to have the great experience of living in South Africa. I would like to thank Ashok Chapagain for guiding my stay in South Africa and giving me a warm welcome at the University of the Free State. I would like to thank Maarten Krol for guiding me through the whole process and always taking the time to give feedback. Lastly I would like to thank Rick Hogeboom for filling in for Arjen Hoekstra and helping to bring this thesis to a conclusion.

The Department of Agricultural Economics at the University of the Free State supported me by allowing the usage of their facilities and by including me as a research associate in their team. For that I would like to thank everybody of the department and in particular Henry Jordaan, Frikkie Mare, Adetoso Adetoro and Bennie Grove.

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Summary

The continuous increase in demand for limited freshwater resources leads to overexploitation and violation of environmental flow requirements around the world. This in turn can lead to economic downfall and decreasing health of riverine ecosystems. The Orange River basin is chosen as a case study as the current consumption of water was estimated to violate the environmental flow requirements in many regions for some months of the year.

A policy measure to prevent violation of the environmental flow requirements is to limit humanities water consumption. In this thesis this is done by exploring the setting of blue water footprint caps for the Orange River basin, these caps have been set per months and per sub-catchment to account for spatial and temporal variability in blue water availability. This was done by using a water balance model which is able to include reservoirs, water transfers and water consumption. In combination with the WRSM/Pitman rainfall runoff model it can model the actual runoff in the river. Detailed environmental flow requirements have been used at the river mouth and have been distributed over the upstream sub-catchments. This showed that to preserve the environment an average of 31% of the natural occurring runoff had to be preserved for the environment. Uncertainties in future runoff predictions brought forward the trade-off between violation of the environmental flow requirements and utilizing available flow. This trade-off is quantified on the level of sub-catchments in the Orange River basin by allowing certain levels of violation.

The development of methodology on how water between competing users can be allocated raised two questions, how can water be allocated in an equitable manner and how can an allocation strategy maximize the social and economic welfare. Equity was determined difficult to define and maximisation of the social and economic welfare could be reached by usage of an optimization model with an objective function which determines the social and economic welfare.

A simple allocation strategy was executed and showed that reservoirs can make the trade-off between violation of the environmental flow requirements and utilizing available water less pronounced by reducing inter annual variability in runoff. Despite losses due to evaporation their ability to be able to store the peak flows can make them raise the cap while lowering the violation of the environmental flow requirements.

Content

1. Introduction

Freshwater is a vital resource for humanity, it is used for our primary needs as drinking and food consumption. It is also vital for the economy, recreation and ecology. Water availability is one of the biggest problems of modern time. The increasing world population, improving living standards, changing consumption patterns and expansion of irrigated agriculture are the main drivers for the global rising water demand (Ercin & Hoekstra, 2014; Vörösmarty et al., 2000). The increasing demand for water to fulfil the needs of society has led to a growing scarcity of freshwater in many parts of the world. More rivers are running dry before reaching the sea for substantial periods of the year (Postel, 2000). Groundwater is being pumped in many areas that exceed replenishment rates, thus depleting aquifers and the base flows of rivers (Postel, 2000).

Water as a resource is generally distinguished between blue and green water (Hoekstra et al., 2011), where blue water is the fresh surface and groundwater and green water is the rainfall and moisture in the soil before it reaches the groundwater or becomes runoff (Hoekstra et al., 2011). Blue water scarcity, often referred to as water scarcity, is the ratio between the blue water footprint in an area and the blue water availability (Hoekstra et al., 2011). The blue water footprint measures water consumption from a renewable blue water resource minus the volume of water returned (Hoekstra et al., 2011) and blue water availability is the sustainably available portion of freshwater, respecting environmental flow requirements. Estimated is that 1.8 to 2.9 billion people worldwide live in areas that experience severe water scarcity for at least 4 to 6 months per year, and 0.5 billion people live in places that have severe water scarcity all year round (Mekonnen & Hoekstra, 2016).

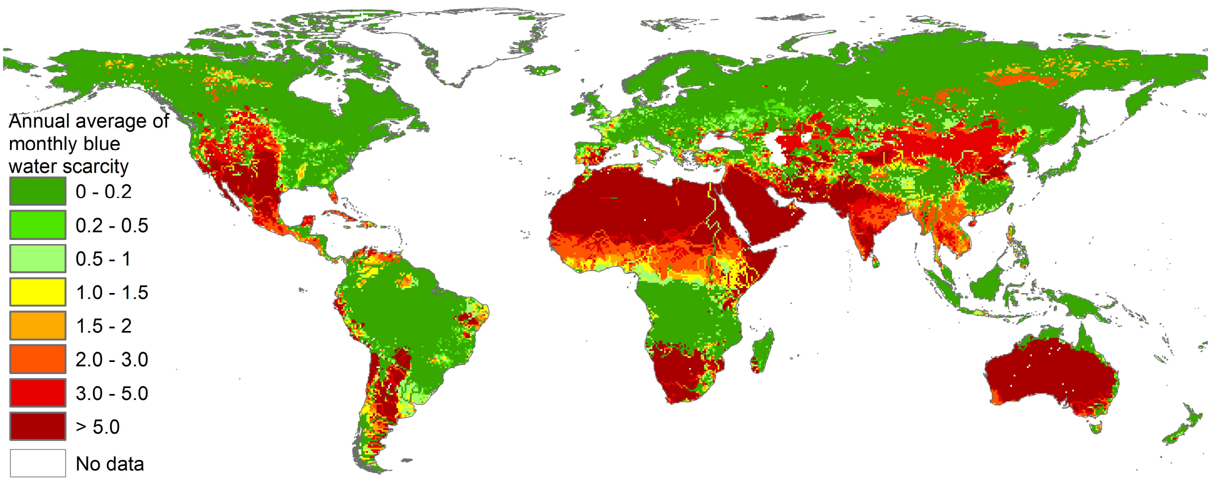

Figure 1: Water scarcity around the world (Mekonnen & Hoekstra, 2016)

If the water scarcity indicator is above 1, we speak of water scarcity and above 2 of severe water scarcity. Figure 1 shows that large areas of the world are facing severe water scarcity. Unsustainable groundwater depletion can threaten the ecology and economy. E.g. an international river basin in the US and Mexico, the Rio Grande (or Rio Bravo) Basin suffers severe water scarcity seven months of the year. This scarcity in combination with pollutants (grey water footprint) resulted in the displacement of 32 native fish species (Contreras-B & Lozano-V, 1994). The water shortages resulted in regional losses of irrigated agriculture, the damage is estimated at $135 million per year including more than 4000 jobs annually (Contreras-B & Lozano-V, 1994).

1.1. Research gap

To counter overexploitation of blue water resources, Hoekstra (2014, 2020) suggests setting a certain sustainable upper limit to the water consumption on which river basins authorities should agree. A blue water footprint cap (BWC) which describes the maximum volume of water that is allowed to be consumed. Water shortage in one basin cannot be crossed against water abundance in another basin, and water shortage in one specific month cannot be crossed against the abundance of water in another month. For this reason, water footprint caps need to be specified spatially, by river basin but also by sub-catchment, and temporally for example by month. This cap can variate between years, dependent on the future predictions and accompanying uncertainties. This blue water footprint cap should drive communities to decide wisely on the allocation of the available water to consumptive uses over sectors, space and time (Hoekstra, 2014, 2020).

Ideally, BWCs are formed dynamically, they should be stricter in dry months and less strict in wet months. Communities will most likely want to know the water cap with a lead time of a season or a year, e.g. farmers need to know in advance the amount of water they can use to make decisions on which crops to plant. However long-term predictions of runoff are surrounded by significant uncertainties. Therefore, when choosing how to set blue water caps, one will inevitably have to strike a balance between some frequency of violation of environmental flow requirements and some frequency of utilizing available water. In river basins with high inter-annual variability, this balance is particularly pronounced (Hogeboom et al., 2020).

Hogeboom et al. (2020) have quantified BWCs for all basins of the world. This is the first global assessment, which does take into account inter- and intra-annual variability of water availability. The detail level is however limited as they do not consider water transfers or the current blue water footprint. The redistributing effect of reservoirs is taken into account, but is not made part of the allocation strategy. The BWCs are also quantified for entire river basins, while many large basins consist of multiple tributaries, and a shortage of water in one tributary cannot be crossed against an abundance of water in another tributary. For this reason the blue water cap is ideally specified per sub-catchment. Zhuo et al. (2019) have analysed the effect of reservoirs when setting a certain blue water cap, but did this based on historical runoff and did not incorporate the large uncertainties of long-term predictions in runoff (inter annual variability). They show that reservoirs can redistribute the available water to better match the demand throughout the year. Zhuo et al. (2019) differentiate the Yellow river basin into three sections but these sections are in linear order. If individual tributaries are resembled by sub-catchment the spatial problem of different upstream tributaries not having access to each other's water becomes clear. Water travels downstream along the river, thus if upstream regions consume a relatively low amount of water, downstream regions can consume relatively more water and vice versa. This is where water allocation methods (or distribution algorithms) start to play a role. Numerous of different allocation strategies exist (Farriansyah et al., 2018; Seyam et al., 2000; Van der Zaag et al., 2002), but none are combined with the concept of blue water footprint caps. In Australia's Murray-Darling basin an attempt has been made to formalize a water cap, which led to some success but showed difficulties with temporal variability in water availability due to the variability in the climate (Grafton et al., 2014).

1.2. Objective

The objective of this thesis is to provide a methodology for formulating blue water caps on the spatial scale of sub-catchments taking inter and intra annual variability into account, which incorporates reservoirs, water transfers, the current blue water footprint while respecting the environmental flow requirements.

1.3. Orange river basin case

The Orange River basin is chosen as a case study, because of its high inter and intra-annual variability in runoff (Orasecom, 2007), which makes the balance between utilizable water and violation of environmental flow requirements particularly pronounced (Hogeboom et al., 2020). According to

Pahlow et al. (2015), the Orange river basin suffers from water scarcity for 6 months of the year, without even including the blue water footprint of reservoirs and water transfers. This shows the need for BWCs if the policymakers wish to preserve the environment. The National Water Act (NWA, No. 36 of 1998) (RSA, 1998) describes the ultimate aim of water resource management is achieving sustainable use of water for the benefit of all users and made aquatic ecosystems along with basic human needs the only two sectors with a legitimate right to their water, making this portion an untouchable reserve.

1.4. Research questions

From the objective, the main research question is derived.

> *How can monthly blue water footprint caps for the Orange river basin be formulated and how can reservoir management influence these caps?*

This research question will be answered by answering the following sub research questions which indicate the process steps.

1. What is the historical monthly runoff in the Orange River and has it changed over time?
2. What are the environmental flow requirements in the Orange river?
3. What is the blue water footprint within the Orange River and to which extent does it violate the environmental flow requirements?
4. How can monthly blue water caps be formulated?
    a. How can monthly BWCs be set per sub-catchment?
    b. What is the effect of reservoirs on a BWC?

1.5. Scope

In this paragraph, the scope of the thesis will be discussed. First of all, within the water footprint framework, the focus will lie on blue water and not on grey and green water. The water footprint caps are set on a monthly time step rather than on an annual basis. In this way, the often great intra annual variability of water supply and use throughout the year is incorporated.

1.5.1. Geographical boundaries

The Orange River is named by Colonel Robert J. Gordon, in honour of the Dutch Prince of Orange. It rises at 3200 m AMSL in the Drakensberg Mountains and high plateau of Lesotho, where it is called the Senqu, and flows west with an average gradient of 1.4 m/km about 2300km to the Atlantic Ocean at Alexander Bay. It passes from cool-temperate and moist alpine regions to progressively more arid terrain of the west Atlantic coast. The Orange is the largest river system in Africa south of the Zambezi, with a catchment of 650 000 km^2 (Cambray et al., 1986).

The Orange River (Figure 2) is transboundary, it covers Lesotho, South Africa, Namibia and Botswana.

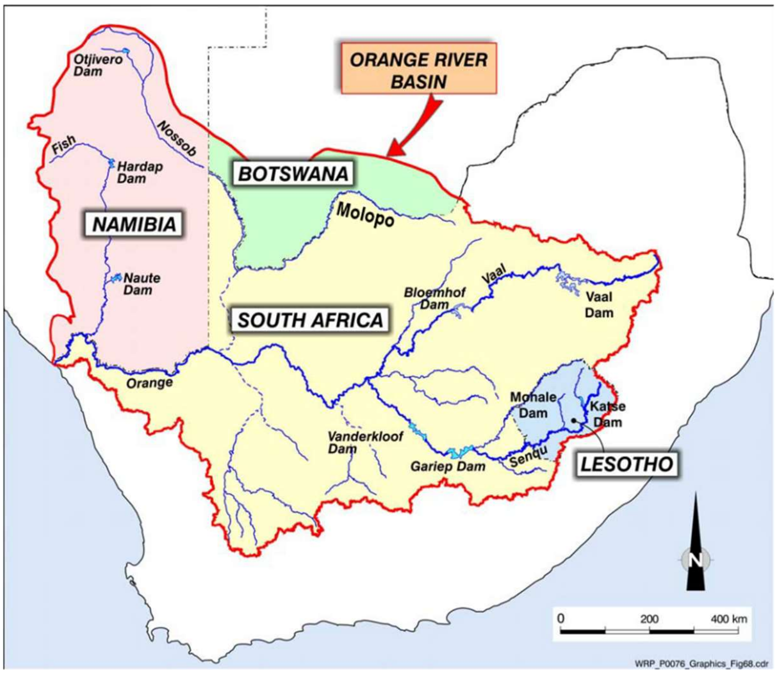

Figure 2: Orange river basin (Orasecom, 2007)

There is some debate whether the Molopo and the Nossob river belong to the Orange River basin. The Molopo river is suspected to historically have contributed runoff to the Orange river (Matthews, 2015). Currently, it is blocked by dunes from the Kalahari desert downstream the confluence of the Nossob river, meaning that surface runoff is unable to reach the Orange River (Heyns, 2003). Water from these rivers might still reach the Orange river through groundwater flows (Heyns, 2003) and the fact that this landscape is dynamic means that these dunes might have moved since 2003. This thesis will follow the current literature (Lange et al., 2007; Orasecom, 2007; Orasecom, 2010) and include the Molopo and Nossob river as part of the Orange River basin.

The most recent water resource study of South Africa, Water Resources of South Africa (2012), did not include Botswana and Namibia. A different study about the Orange River basin by Orasecom (2010) did include Botswana and Namibia but did not openly share their data. Therefore the study area has been to Figure 3. This means that runoff from Botswana and Namibia which contribute <1% and 2% of the total runoff respectively are not taken into account (Lange et al., 2007). The majority of Namibia's runoff flows though the Fish river (Lange et al., 2007). This river enters the Orange River very close to the ocean, meaning South Africa can hardly use this water. Together with the fact that the environmental flow requirements were determined just upstream of the Fish river confluence (Orasecom, 2010), means that these two rivers can be analysed independently.

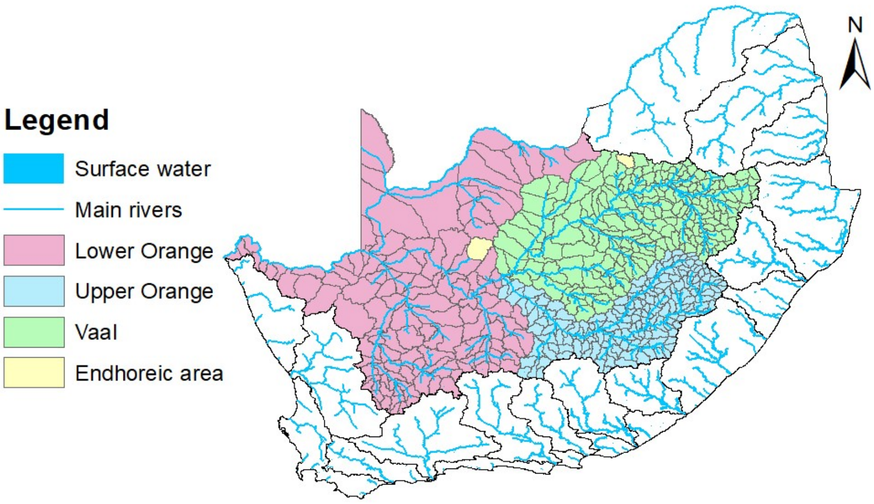

Figure 3: Study area of the Orange River which lies within South Africa and Lesotho

Endorheic areas fall outside the study area as they are not considered part of the Orange River basin and both runoff and EFR data were not available (Orasecom, 2010; Water resources of South Africa, 2012). This does not mean that people living in endorheic areas cannot consume any water. Specific environmental studies have to be performed for these areas, which could result in a certain lake or groundwater level being required for the environment.

1.5.2. Terminology

In this paragraph the used terms and abbreviations during this research are defined, this terminology is in line with the terminology used in the water footprint assessment manual (Hoekstra et al., 2011).

Definition	Abbreviation	Description	Unit
Blue water	BW	Fresh groundwater and surface water	Million m^3 per month
Blue water footprint	BWF	A measure of humanity's appropriation of blue water	Million m^3 per month
Blue water availability	BWA	This is the maximum sustainable amount of water which can be consumed.	Million m^3 per month
Blue water footprint cap	BWC	A set amount of water that is allowed to be consumed in a water allocation policy.	Million m^3 per month
Environmental flow requirements	EFR	Runoff required for the preservation of the environment	Million m^3 per month
Local runoff		Runoff locally generated within a catchment	Million m^3 per month
Present-day runoff		Modelled runoff with land-use set to the situation of 2010	Million m^3 per month
Historical runoff		Modelled runoff with historical land-use estimation	Million m^3 per month
Natural runoff		Modelled runoff under natural conditions, no human influences are taken into account	Million m^3 per month

Actual runoff		Estimated actual river flow, Historical runoff with human influences included.	Million m^3 per month

In Figure 4 a flow chart is given which shows how the research questions are related to each other.

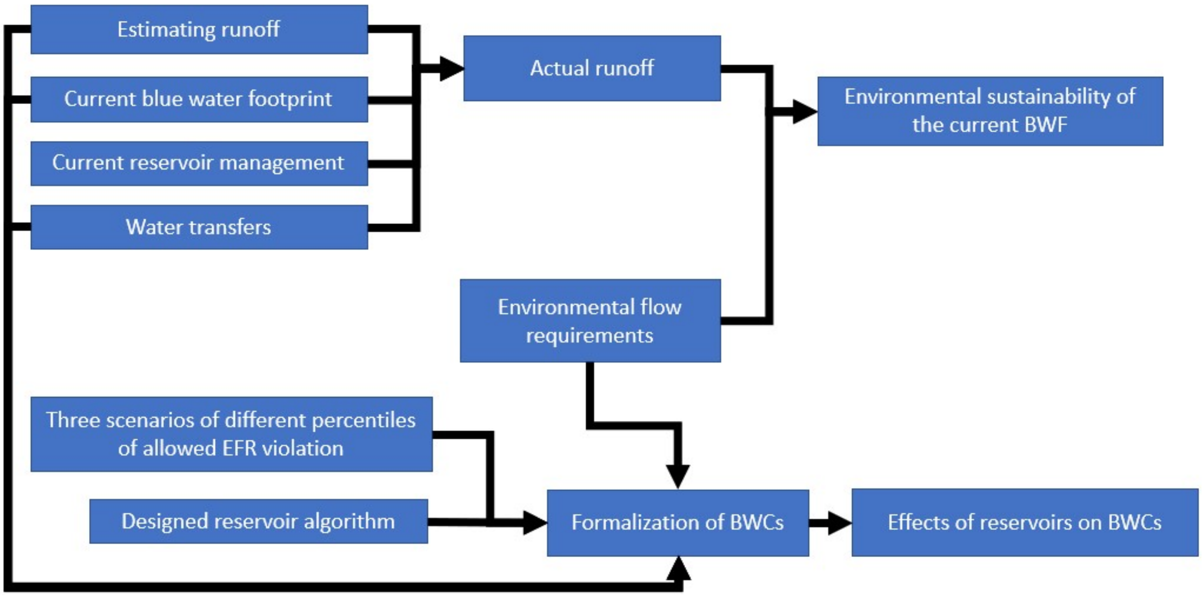

Figure 4: flow chart of how the different steps leading towards answering of the research questions

2. Theoretical framework

In this chapter, the theories and existing models regarding the research questions are discussed.

2.1. Monthly runoff in the Orange river

Because of the large intra annual variability, the choice is made to set the BWCs on a monthly time scale as water shortage in one month cannot be crossed against the abundance of water in another month (Hoekstra, 2013). This gives the first requirement: The runoff should be determined on at least a monthly time scale. The second requirement has to do with the spatial resolution. Hogeboom et al. (2020) have set monthly BWCs for the entire Orange River basin, but ideally they are set on the level of sub-catchments (Hoekstra, 2013), as water shortage in one tributary cannot be crossed against water abundance in another tributary. This means the runoff should be determined on the grid level or small sub-basins. The last requirement has to do with the influence of humans. To determine EFRs, natural runoff needs to be known. This means runoff has to be estimated which excludes human influences.

The amount of runoff can be either observed or modelled. Since BWCs will be set per sub-catchment and runoff has only been measured at a few locations, the runoff will have to be modelled. Runoff can be modelled in many different ways. Rainfall-runoff models are classified based on model input and parameters and the extent of physical principles applied in the model (Devia et al., 2015). The structure of a model determines how it calculates runoff. Hydrological models are generally sorted into three categories: Empirical, conceptual and physical models. Physical models require much more data than there is available and conceptual models are regarded as more detailed than empirical models (Devia et al., 2015). The Pitman (1973) conceptual rainfall-runoff model is chosen because it is specifically designed for South Africa and has over the past 46 years become one of the most widely used hydrological models in southern Africa (Hughes, 2013). It is chosen instead of global hydrological models because calibrated conceptual models based per sub-catchment are considered as more detailed than global hydrological models (Zhang et al., 2016).

2.2. Environmental flow requirements in the Orange river

Freshwater ecosystems provide a range of goods and services for humans, including fisheries, flood protection, wildlife, etc. (Acreman, 2001; Revenga et al., 2000). Water needs to be allocated to these ecosystems to maintain them. Balancing the requirements of the aquatic environment and other uses is becoming critical in many of the world's river basins as population and associated water demands increase (Vörösmarty et al., 2000). Meanwhile, the assessment of the EFRs is also a major challenge due to the complexity of physical processes and interactions (Smakhtin et al., 2004). Environmental flows are defined in the Brisbane declaration (2018): "*Environmental flows describe the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being.*" There are multiple methods to determine the environmental flow requirements (EFRs) of a river. These methods are categorised in four categories: Hydrological methods, hydraulic methods, habitat simulation methods and holistic methods (Tharme, 2003).

Holistic methods are methods which combine hydrological, hydraulic and ecological data in combination with experts to estimate site-specific EFRs. These methods are generally assumed to best estimate the ecological needs of a river (Pastor et al., 2014; Tharme, 2003). Holistic methods are mainly developed in South Africa and Australia (Hughes & Louw, 2010), unfortunately the results of many holistic EFRs studies are not available. Only one study for the Orange river basin could be found. In 2010 the following study was performed: Support to Phase II ORASECOM basin-wide integrated water resources management plan (Orasecom, 2010). One of the main objectives of the study was to assess

EFRs at key areas of the Orange River Basin. They selected six hotspots on which detailed EFR assessments have been carried out. The process of setting EFRs in South Africa centres on the concept that aquatic ecosystems may be maintained at different levels of condition (health). These different classes can be seen in Table 1.

Table 1: Management classes for the environmental flow of South Africa (King et al., 2008)

Class	*Description*
A	Negligible modification from natural conditions. Negligible risk to sensitive species.
B	Slight modification from natural conditions. Slight risk to intolerant biota.
C	Moderate modification from natural conditions. Especially intolerant biota may be reduced in number and extent.
D	High degree of modification from natural conditions. Intolerant biota unlikely to be present.

The study selected different management classes for different parts of the Orange River. The assigned management classes are set one class higher than the current state. E.g. if a river section has currently management class D the EFRs have been determined for class C. Combining these different EFR sites would result in river sections with negative EFRs and situations where the EFRs are impossibly met due to lower management classes assigned upstream and a lack of locally generated runoff. Next to this, the vision of setting BWCs is that the environment is respected, it would be strange to set a BWC based on EFRs which still results in a high degree of modification from the natural condition.

For these reasons, the decision has been made to only use the EFR from one site. The strictest site in the main orange river is chosen, which is EFR O3: Augrabies with management class A. This site is located just upstream of the Fish River, the river from Namibia of which no runoff data is available. Thus only South Africa and Lesotho are responsible for the runoff which reaches this EFR site, which means that the Fish river can be neglected.

2.3. Blue water footprint accounting

The water footprint is a measure of human's appropriation of freshwater resources (Hoekstra et al., 2011). For this study, the focus will lie on the blue water footprint which refers to the consumption of blue water resources (surface and groundwater). The blue water footprint of production within the Orange river basin is the sum of all water-using processes in the area (Hoekstra et al., 2011).

It is not feasible to get data on all the individual processes taking place, therefore the choice is made to account the major processes. Hoekstra and Mekonnen (2012) have estimated the national BWF of production in South Africa which resulted in a total blue water footprint of national production of 7123 million m^3. The main contributors are crop production (90.0 %), domestic water supply (5.5 %), industrial activities (0.5 %) and animal water supply (4.0 %). In addition to these sectors, the BWF of reservoirs and inter-basin transfers have also been taken into account as the literature indicates that these are major water consumers (Lange et al., 2007; Orasecom, 2007). Inter-basin water transfers do not consume water themselves, but water is taken out of the Orange river basin and is not returned. Hoekstra et al. (2011) state: 'The export of real water out of an area, as in the case of an inter-basin transfer, will be counted as a process water footprint in the area from which the water is exported'. No spatial data was available of the location of farm animals within the orange river, thus this BWF has been left out. Which leaves the following sectors as blue water consumers:

- Production of crops
- Domestic water supply
- Industrial water supply
- Reservoir evaporation
- Inter-basin water transfer

2.4. Environmental sustainability of the blue water footprint

To assess the environmental sustainability of the current BWF, environmental sustainability has to be defined. Hoekstra et al. (2011) state *'When, in a certain month, the blue water footprint within a catchment exceeds the blue water availability, the blue water footprint is environmentally unsustainable, because the environmental flow requirements are violated.'* Therefore to assess the environmental sustainability the number of times in which the EFRs are violated per sub-catchment is analysed.

Hoekstra et al. (2011) identified a second criterion to analyse the effect the BWF has on groundwater and lake levels in a catchment. the blue water scarcity is defined by Hoekstra et al. (2011) as follows:

$$WS_{blue}[x,t] = \frac{\sum BWF[x,t]}{BWA[x,t]} \quad (1)$$

There are some flaws to this criterion identified by Pellicer-Martínez and Martínez-Paz (2016), which make it unable to be used as interpretation of the results becomes meaningless. First, it is unable to cope with zero and negative values of BWA. This becomes especially problematic when analysing the criteria spatially. To give an example for a downstream sub-catchment with no local runoff and upstream users who used the maximum sustainable amount of water. The inflow is 100 units of water, the BWF is 1 unit of water and the EFRs are 100 units of water. This would result in a water scarcity value of infinite. Does this mean that this catchment is infinitely depleting the groundwater stocks and lake volumes? No, because the actual EFRs are only violated for a mere 1 %. Second, it is unknown how reservoir management should be taken into account. A reservoir increasing its storage can be seen as either as a water consumer or a reducer of the BWA, which result in different WS_{blue} values.

Wada et al. (2011) use a different definition of water scarcity, they neglect EFRs and use average monthly values for runoff and demand. Neglecting EFRs and inter annual variability means that also this criterion cannot be used for the assessment of environmental sustainability.

Pellicer-Martínez and Martínez-Paz (2016) propose a new indicator, called the environmental blue water scarcity. This indicator is obtained by comparing the environmental flow required $Q_{eco}[j,t]$ with the actual runoff $WA_{Blue\_Eco}[j,t]$ in time interval t.

$$WS_{Blue\_Eco}[j] = Max[j]\left[\frac{Q_{eco}[j,t]}{WA_{Blue\_Eco}[j,t]}\right] \quad (2)$$

If the $WS_{Blue\_Eco}[j]$ is above one than the environmental flow requirements in sub-catchment J are not met and is regarded as unsustainable. This is a somewhat crude way of making the water scarcity indicator set by Hoekstra et al. (2011) spatially applicable. Taking the maximum value means the results will only reflect the worst moment in a time series, which makes it dependent on the length of the analysed period. Modelled runoff combined with historical BWF and reservoir storage data will result in some bad model discrepancies, where the modelled actual runoff is very or low or high compared to observed runoff. Hence this indicator will probably bring forward the data inconsistencies. Pellicer-Martínez and Martínez-Paz (2016) also differentiate between environmental demand and environmental flow, but it is unclear how they define these terms.

The choice is made to regard the added value of these different water scarcity indicators as neglectable, therefore sticking to the original definition by Hoekstra et al. (2011) of sustainability and analysing the frequency of an unsustainable situation. Besides a new indicator is proposed which can analyse the severity of EFR violation.

2.5. Formulating potential BWCs per sub-catchment

The idea of setting BWCs has only been explored by two studies so far (Hogeboom et al., 2020; Zhuo et al., 2019). Zhuo et al. (2019) divide the Yellow River basin into three sections, which is similar to dividing into sub-catchments but does not take into account the temporal variability in runoff. Hogeboom et al. (2020) do take temporal variability into account by setting BWCs on different percentiles of BWA for entire river basins, allowing for some accepted violation of the EFRs to utilize potential sustainable water consumption.

2.6. BWC allocation

If BWCs were to be set solely based on the locally generated runoff, then water is distributed based on the source. This would imply that downstream areas which depend completely on river flow from upstream would be without water. For this reason, an allocation method has to be implemented to distribute water in a fair and equal way. The Global Water Partnership defined Integrated Water Resource Management as a *"process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems"* (Global Water Partnership, 2000). Previously the sustainability part has been assessed. The allocation of water to maximize the resultant economic and social welfare in an equitable manner will be discussed by first looking at the concept of 'equity' in water allocation and next to the maximization of the economic and social welfare.

2.6.1. Equity

Rasinski (1987) defines two factors which describe equity of distribution of a resource in the context of social welfare, 'proportionality' and 'egalitarianism'. Proportionality implies that resources should be distributed according to people's effort or 'deservedness'. Egalitarianism suggests that everyone should be treated equally (Rasinski, 1987). When looking at equity in the context of water resource management, Gleick (1998) defines equity as: *'a measure of the fairness of both the distribution of positive and negative outcomes as well as the process used to arrive at particular social decisions*.' Cremers et al. (2005) even distinguish five levels of equity for water management at the local level: *'equitable water distribution and allocation among different water users and uses; equitable distribution of the services involved in irrigation development; equitable distribution of the added agricultural production and other benefits under irrigation; equitable distribution of the burdens and obligations related to functions and positions; and equitable distribution of the rights to participate in the decision-making process.'* All these explanations of equity make it seem like a positive goal, but it is still unclear how it can be implemented in an actual allocation strategy.

Van der Zaag et al. (2002) and Seyam et al. (2000) attempt to define measurable criteria based on which water resources can be equitably allocated to the riparian countries. They try to calculate each countries equal share or 'right' by applying different allocation strategies. The allocation strategies are based on population size, surface area and locally generated blue and green water. The strong points of these algorithms are that they are very simplistic and simple to understand. Weak points are that they fail to grasp spatial and temporal variability (Seyam et al., 2000; Van der Zaag et al., 2002).

The algorithms of Seyam et al. (2000) and Van der Zaag et al. (2002), do not allow for any storage or release of water as the algorithm only considers a single time step. If these algorithms were to be used to set monthly caps, the 12 months of a year have to be seen independent from one another, which is not the case when reservoirs are included. Reservoirs are vital in the distribution of water and have to be part of an allocation strategy. This is the most important argument against the use of these algorithms. A second argument against the appliance of these algorithms on the level of sub-catchments is that the criteria which seem to resemble equity between competing countries do not resemble equity on the level of sub-catchments. E.g. allocation based on the surface area does not seem equitable for a small sub-catchment with a large city, on the other hand, allocation based on population size can limit the sub-catchments which are very dependent on their agricultural sector.

For the basin level, Wolf (1999) argues that equity is *'a vague and relative term in any event. Criteria for equity are particularly difficult to determine in water conflicts, where the international water law is ambiguous and often contradictory'*. Hence instead of defining equity, Wolf shows different approaches currently utilized on the international level, but it is debatable whether these approaches are in fact 'equitable' or just convenient for two or more parties sharing the basin. Wegerich (2007) concludes on his research on equity in the Amu Darya basin that: *'Even though a quest for equity is popular at the current time in the water policy debate, the discussion on equity has shown that equity is an ambiguous concept. For example a policy intention to establish equity on one matter might imply inequity on a different matter (equity of inputs could lead to inequity of outputs)*'. Young (1995) even argues: *'The arguments against existence (of equity) take three different forms. The first is that equity is merely a word that hypocritical people use to cloak self-interest – it has no intrinsic meaning so therefore fails to exist. The second – is that even if equity does exist in some national sense, it is so hopelessly subjective that it cannot be analysed scientifically – it fails to exist in an objective sense. The third argument that there is no sensible theory about it – thus it fails to exist in an academic sense.'* The literature above (Seyam et al., 2000; Van der Zaag et al., 2002; Wegerich, 2007; Wolf, 1999) already shows that equity can be analysed scientifically and therefore exists in an academic sense proving Young (1995) wrong.

Farriansyah et al. (2018) do asses equity for a water allocation problem on a river basin represented by network nodes including reservoirs similar to the one in this thesis. Farriansyah et al. (2018) assess equity by setting the percentage of which the current demand is met at each node equal. This percentage is evaluated at the most downstream node and lowered if not enough water is available here. This gives some level equity in their example because the total demand cannot be met by the available water and the EFRs are set on 5% of actual runoff and thus always met. Applying this method together with the EFRs set in this thesis would result in some level of equity, but it would reduce the size of the BWC further than necessary for the EFRs. Not using available blue water just for the sake of treating everybody equally is similar to telling a country not to use its natural resources, because its neighbour doesn't have any resources either. Also, Farriansyah et al. (2018) do not differentiate between different sectors. A similar water availability model WRAP (Wurbs, 2005) mentions nothing about equity in water allocation, the CWAM allocation model (Wang et al., 2008), does allow for equity and non-equity constrains but fails to mention how these could look like.

Although some attempts have been made to specify 'equity' in water allocation management (Farriansyah et al., 2018; Syme et al., 1999; Van der Zaag et al., 2002), none provide a way to define equity and show how an allocation strategy can be designed which promotes efficiency, equity and sustainability. As Wegerich (2007) concluded that 'equity' is always an ambiguous concept, therefore difficult to analyse scientifically. To give a typical example for South Africa, assumed that the agricultural BWF has to be reduced to meet the environmental regulations. One could argue that the least water-efficient farmers should reduce their water consumption as they proportionally bring the least economic welfare in euro per unit water. On the other hand, these are often the poor black farmers who do not have the money to buy modern equipment, taking away their water is not regarded as equitable.

For this thesis, the concept of 'equity' is left for the actual policymakers as it will always be an ambiguous concept. Wolf (1999) also argues that other policy instruments can be used to achieve equity besides the allocation strategy, such as taxes on water consumption and compensations. For now, the focus will lie on the maximisation of the resultant economy and social welfare without compromising the sustainability of vital ecosystems.

2.6.2. Maximisation of the resultant economy and social welfare

Maximisation of the resultant economy and social welfare is more straightforward. Many articles do this by assigning an economic value to every aspect of the allocation strategy (Rosegrant et al., 2000). They then sum the economic value of every aspect (e.g. consumption of sectors, hydropower benefits of reservoirs or lake levels for recreational purposes.) resulting in a price of what a certain allocation strategy is worth.

Maximisation of the economic value requires an optimization technique (Zhu & Van Ierland, 2012). Optimization is difficult due to the spatial variability of BWA. Downstream consumption means that upstream consumption has to be limited, but it is difficult to determine which upstream sub-catchments should limit their consumption. In literature, this is solved by applying numerical optimisation techniques (Divakar et al., 2011; Farriansyah et al., 2018; Ringler, 2001). Applying an optimisation algorithm consists of four components:

- Objective function
- Set of parameters to be optimized which determine the objective
- Boundary conditions
- Selection of an optimisation algorithm

How this will be implemented will be further discussed in paragraph 3.4.

3. Methodology

In this chapter, the methods used to answer the research questions are described and discussed.

3.1. Estimating historical runoff

The latest water resource study by Royal HaskoningDHV has provided calibrated parameters for the WRSM/Pitman model for 1944 sub-catchments of South Africa of which 479 are located within the Orange river basin (Water Resources of South Africa, 2012). This model in combination with monthly rainfall data results in monthly runoff data per sub-catchment from 1920 through 2010. The model can be simulated with different settings for the paved area, alien vegetation and afforestation, which results in the following three types of runoff.

- Natural runoff would occur without the man-made influences such as dams, irrigation schemes, abstractions for mines, industry and towns, return flows from treatment works, etc. This natural runoff has been simulated by disabling: paved areas, afforestation and alien vegetation.
- Present-day runoff would occur with the most recent land use. The model has thus been simulated with paved area, afforestation and alien vegetation set to the situation of 2010 (which is the most recent land-use setting) with historical rainfall.
- Historical runoff would historically have occurred without abstractions and has been modelled with historical estimated paved area, afforestation and alien vegetation.

Data on the runoff direction from the sub-catchments, which sub-catchment flows into which other sub-catchment, has been retrieved with SPATSIM (Spatial and Time Series Modelling) from the National V2 databank of South Africa (SPATSIM, 2019). This data has been transformed into a river network tree Figure 5. Each node represents a sub-catchment, this representation is used to properly account the flow accumulation from upstream to downstream.

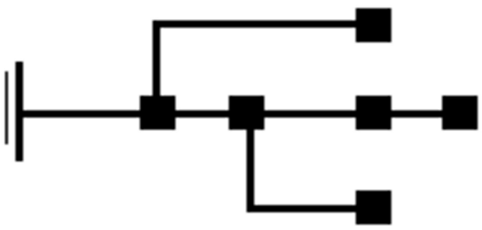

Figure 5: Tree structure of a river with each node being a sub-catchment and with the flow direction from right to left

At each node the following mass balance equation is used:

$$Q_{in} - Q_{out} = \Delta S \tag{1}$$

Where Q_{in} is the inflow, which is the locally generated runoff plus inflow from an upstream sub-catchment. Q_{out} is the outflow which is water consumed in the sub-catchment plus outflow to a downstream sub-catchment. ΔS is the change in storage in the sub-catchment. $\Delta S = 0$ at all the catchments without a reservoir (Figure 6).

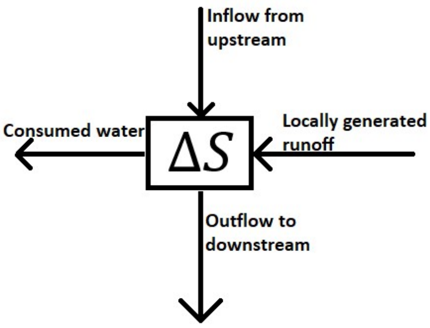

Figure 6: input-output balance at a network node (sub-catchment)

There are 3 water transfer entering the Orange River, 2 leaving the Orange River and 1 intra-basin transfer. Water transfers change the network structure of the river, a normal sub-catchment has only one downstream sub-catchment while a sub-catchment with an intra-basin transfer has two downstream sub-catchments and the sub-catchment of which receives water can no longer be considered most upstream. An inter-basin transfer entering the Orange river basin is seen as inflow from upstream. The inter-basin transfers out of the Orange river are regarded as consumers. Data on water transfers is retrieved from Water Resources of South Africa (2012).

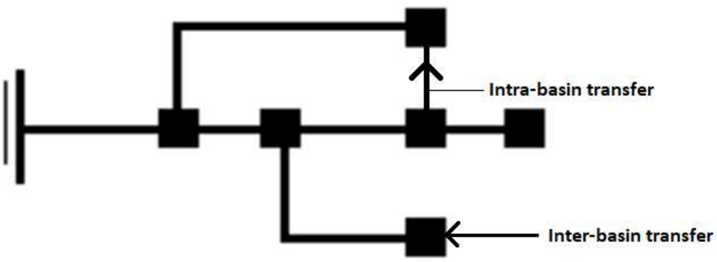

Figure 7: The effects of water transfers on the river network schematic

3.1.1. Climate change analysis

The influences of climate change on the historical runoff are analysed to determine the required length of the historical runoff used for the forecast of future runoff. If the climate has changed a lot then runoff from 1920-1930 will probably not resemble future runoff. On the other hand, the used historical period should be as long as possible as an increased sample size means more inter annual variability is included. Natural runoff is used because human influences (except their influences on the climate) have to be excluded.

Meng et al. (2016) distinguish three factors to determine the effects of climate change on historical runoff. The total amount of runoff, the shape of the flow peak and the timing of the flow peak. Change in the total amount of runoff is analysed by analysing the yearly runoff and the decade mean runoff for the entire Orange River basin to limit the inter-annual variability (Meng et al., 2016). The shape of the flow peak is analysed by looking at the intra-annual variability of the runoff. If the intra-annual variability is low then the flow peak is smooth, if the intra-annual variability is high then the flow peak is steep (Meng et al., 2016). The intra-annual variability has been determined by taking the standard deviation of the runoff. Lastly, the timing of the flow peak has been determined by analysing the month in which the maximum monthly runoff occurred and drawing a trendline through these months to see if the timing has changed (Burn, 1994; Meng et al., 2016).

3.2. Environmental flow requirements

Data on EFRs has been retrieved from Orasecom (2010) and were provided in the format of a flow duration curve table together with a natural flow duration curve table, an exemplary month is plotted in Figure 8. The environmental flow study uses several older natural runoff model outputs for several sections of the Orange river (Orasecom, 2010). Different hydrological models will give different results, for this reason, a check is performed whether the natural runoffs used are comparable. This check is performed in Appendix A by transforming the natural runoff from paragraph 3.1 to monthly flow duration curves.

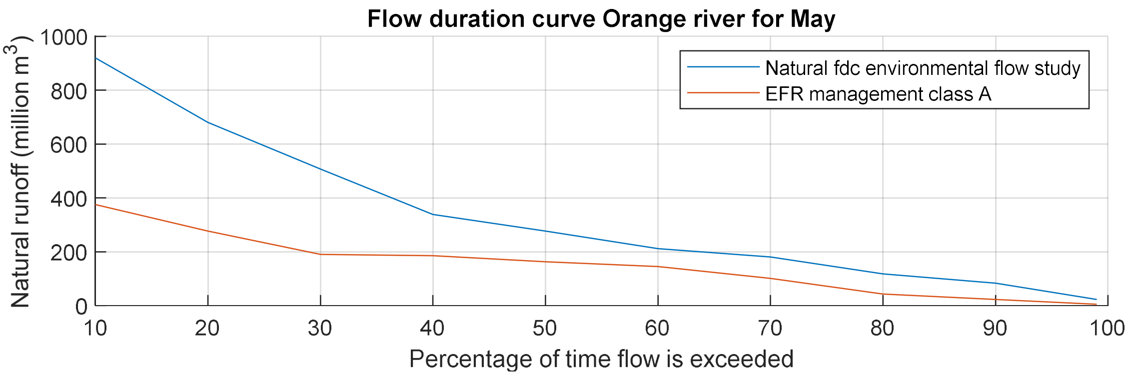

Figure 8: The provided environmental flow requirements for the Orange River basin upstream of the Fish river for May in the format of a flow duration curve (fdc), management class A stands for negligible modification from natural conditions.

The flow duration curves from the natural runoff of paragraph 3.1 and the natural runoff used by the consultancy for their environmental flow study are similar (Appendix A). The next step is to implement the EFRs. The EFRs are linearly interpolated to estimate the EFRs between the table values given. The environmental flow requirements are based on natural river flow. To transform this data to environmental flow requirements per sub-catchment the following procedure is used for the full duration of the data series.

- The total natural runoff for the Orange river is calculated by summing the natural runoff from all the sub-catchments.
- For the total monthly natural runoff, the EFRs are selected which belong to the amount of runoff, e.g. in Figure 8, the EFRs for runoff of 600 million m^3 in May are 231 million m^3.
- This environmental flow is evenly spread out over the sub-catchments based on the amount of natural runoff which each sub-catchment contributes to the total natural river flow (equation 3).

$$EFR_{local}[x,t] = EFR_{total}[t] \frac{Runoff_{local}[x,t]}{Runoff_{total}[t]} \qquad (3)$$

Where EFR_{total} is the EFRs retrieved from Orasecom (2010), $Runoff_{local}$ the locally generated natural runoff and $Runoff_{total}$ the natural runoff at the river mouth. A downside of this procedure is that no difference is made between regions with a different hydrological regime or different ecology, also the table does not provide EFRs data for flow peaks which occur less than 10% of the time. For this reason, the EFRs have been compared with the variable monthly flow method (Pastor et al., 2014) for a dry downstream sub-catchment and a wet upstream sub-catchment to see if the results are comparable.

3.2.1. Variable monthly flow method

Pastor et al. (2014), developed a parametric method: The variable monthly flow (VMF) method. This method follows the natural variability of river discharge by defining EFRs on a monthly basis. The VMF method adjusts EFRs according to the flow season. The VMF method is developed to increase the protection of freshwater ecosystems during the low-flow season with a reserve of 60% of the monthly mean flow and a minimum flow of 30% during the high-flow season.

Table 2: Environmental flow requirements computed with the variable monthly flow method (Pastor et al., 2014).

Requirements	Description
High flow	Runoff > 0.8 * $Runoff_{year, avg}$
High flow requirement	EFR = 0.3 * Runoff
Intermediate flow	Runoff < 0.8 * $Runoff_{year, avg}$ Runoff > 0.4 * $Runoff_{year, avg}$
Intermediate flow requirement	EFR = 0.45 * Runoff
Low flow	Runoff < 0.4 * $Runoff_{year, avg}$
Low flow requirement	EFR = 0.6 * Runoff

3.3. Environmental sustainability of the historical blue water footprint

The environmental sustainability for the period of 1990-2010 will be analysed. This is done by accounting the BWF, furthermore the historical reservoir management has to be included to determine the actual runoff. Lastly, this actual runoff has been compared with the EFRs to determine the environmental sustainability of the BWF.

3.3.1. Blue water footprint accounting

The total BWF in the Orange River basin can be described with the equation below:

$$BWF_{total} = BWF_{crops} + BWF_{indusrial} + BWF_{domestic} + BWF_{reservoir} + BWF_{inter\ basin\ transfer} \quad (4)$$

The BWF of crop production was obtained from Hogeboom, et al (in review), who estimated the monthly global water footprint for crops on a 5 by 5 arc minute spatial resolution. This data is summed over the area of the sub-catchments giving the BWF of crops per month per sub-catchment. Summing the grid values over the sub-catchment is done with the ArcGIS zonal statistics tool. This results in monthly BWF of crops in million m^3 per sub-catchment.

The water footprints related to industrial production and domestic water supply were estimated by using water withdrawal data from the AQUASTAT database (FAO, 2016). Assumed is that of water withdrawn for industrial purposes 5% is actual consumption and that the remaining fraction is return flow (Mekonnen & Hoekstra, 2011). For the domestic water withdrawn, 10% is assumed as actual consumption (Mekonnen & Hoekstra, 2011). The water footprints related to industrial production and domestic water supply were mapped using population maps. A spatial distribution map of the population in 2010 for South Africa and Lesotho were used (Worldpop, 2018).

Underlying assumptions in this methodology are:

- The industrial BWF is spread based on population, this choice is made as the industry tends to be located around towns and cities (Kemper & Schmenner, 1974).
- No distinction in BWF between poor and rich people (even when South Africa is one of the world's most unequal countries), but this choice is made as the impact of the domestic BWF is estimated to be minor.

The domestic BWF varies throughout the year (LAO, 2017) for this reason the domestic yearly BWF has been multiplied by an urban monthly water consumption trend. The trend used is the inverse of a trend of California (LAO, 2017), the inverse because South Africa and Lesotho lie in the southern hemisphere. The industrial BWF is assumed to be constant throughout the year. In the tables below are the withdrawal data retrieved from AQUASTAT (FAO, 2016).

Table 3: South Africa's water withdrawal (FAO, 2016)

	1990	1995	2000	2017
Industrial water withdrawal (10^9 m^3/year)	1.448	1.102	1.052	4.100
Municipal water withdrawal (10^9 m^3/year)	2.281	3.092	3.904	3.890

Table 4: Lesotho's water withdrawal (FAO, 2016)

	1987	2000
Industrial water withdrawal (10^9 m^3/year)	0.011	0.020

Municipal water withdrawal (10^9 m^3/year)	0.011	0.020

The above water withdrawal data is linearly interpolated for the years 1990 to 2017 for South Africa and for the years 1987 to 2000 for Lesotho. For Lesotho, it is assumed that the water withdrawal increases with the same ratio as the population increases for the period of 2000-2010 (Worldpop, 2018), to provide monthly BWF data from 1990 through 2010.

Hogeboom et al. (2018) determined that the BWF of a reservoir has both an operational and a supply chain component. The supply chain component will not be determined as this falls under the industrial BWF and double counting should be avoided. The operational component is calculated as follows:

$$BWF_{reservoir} = 10 * A * E \qquad (5)$$

Where BWF of reservoirs is determined in m^3 per month, A is the surface area in ha and E the depth of water that evaporates per month in mm. Monthly surface areas of reservoirs have been provided by the Department of Water and Sanitation (2019). To estimate the evaporation of reservoirs, the same potential evaporation is used as the hydrological model uses, which is determined by pan evaporation measurements multiplied by pan factors (Water Resources of South Africa, 2012). This is the Kohli and Frenken (2015) method.

Data on inter-basin water transfers in the Orange river basin is retrieved from the Water Resources study of South Africa (2012)

3.3.2. The influence of current reservoir management on the BWA

To analyse to which extent the BWF of 1990-2010 violates the EFRs, the historically redistributing effect of reservoirs has to be included. The mass balance from equation 1 becomes:

$$Q_{in} - Q_{out} = \Delta S = S_{t+1} - S_t \qquad (1)$$

Where S_{t+1} is the storage in the next month and S_t the storage in the current month. E.g. ΔS in October is the storage on the 1st of November minus the storage on the 1st of October.

Monthly data of reservoir storage and surface area has been provided by the Department of Water and Sanitation of South Africa (DWS, 2019). Data was provided at a monthly resolution and the start and end dates with the reservoir capacities are listed in appendix B. Data was available for 219 reservoirs of which 40 lie in the Orange river basin. 1 reservoir had missing records, to make the data usable missing records op to the length of four months have been interpolated. The interpolation method used was linearly interpolation, because of the small lengths of the missing records. This left three reservoirs with data series outside the period of 1990-2010, which leaves 37 reservoirs with proper data. These reservoirs have a combined storage capacity of approximately 18.8 billion m^3. FAO (2016) gathered detailed information about the dams of Africa, and summing the dam capacity within the Orange river gave a total capacity of 20.7 billion m^3. For a very large portion (90.3 %) monthly data is thus available.

Table 5: Reservoirs which have insufficient data for a significant portion of the period 1920-2010

Reservoir name	Opening date	Capacity (million m^3)	Data provided by DWS	
			Start date	End date
C2R008 Luciana Barrage	1923	55.44	2018	2019
C3R006 Taung Dam	1995	61.37	2016	2019
C2R002 Johan Neser dam	1922	5.67	1920 2013	1952 2019

In table 5 the reservoirs with insufficient data are shown, they have a combined capacity of 122 million m^3 and are located in the Vaal tributary. This is not much when compared to the 8 billion m^3 of combined storage capacity in the Vaal tributary for which data is available. Small farm dams have been neglected as no surface are nor storage capacities could be found (DWS, 2019; Orasecom, 2010; Water Resources of South Africa, 2012), although literature concludes that these small dams significantly compromise the river flow in the Orange river (Mantel et al., 2017).

3.3.3. Environmental sustainability of the blue water footprint

A sub-catchment is considered environmentally unsustainable when the environmental flow requirements are violated (Hoekstra et al., 2011):

$$Q_{out} < EFR_{sub-catchment} \tag{6}$$

Where Q_{out}, is the outflow from a sub-catchment and $EFR_{sub-catchment}$ the EFRs at the river section where the sub-catchment is located. This is determined by adding the EFRs belonging to the locally generated natural runoff to the EFRs of the upstream sub-catchments.

$$EFR_{sub-catchment} = \sum_{i=1}^{n} EFR_{local,i} \tag{7}$$

With n the number of upstream sub-catchments, EFR_{local} being the EFRs belonging to the locally generated natural runoff determined in equation 3. At the river mouth $EFR_{sub-catchment}$ equals the total EFRs for the Orange River basin retrieved from the EFR study (Orasecom, 2010). The amount of times in which EFR violation occurs is counted and presented as a frequency indicator to show how often the current BWF violates the EFRs to show how often the current BWF violates the EFRs.

A second indicator is proposed which should be used together with the frequency indicator to describe the severity of which the EFRs are violated, the severity of violation indicator S_{EFR}. This indicator is proposed because a slight violation of the EFRs is considered less harmful to the ecosystem as total violation of the EFRs (Hoekstra, 2020). It is only calculated for the months in which the EFRs are violated and is calculated per sub-catchment.

$$S_{EFR} = \frac{R_{actual}}{EFR_{sub-catchment}} \tag{8}$$

Where R_{act} is the actual runoff and $EFR_{sub-catchment}$ are the EFRs at the river section. The closer this value is to zero the severer the violation is. The average of this value is taken in case of multiple months of violation of EFRs.

3.4. Formalization of blue water footprint caps

Historical violation of the EFRs has already taken place, therefore if policymakers wish to preserve the riverine ecosystem the future BWF has to be limited. This is where BWCs come into play. To preserve the EFRs the BWF has to be limited on the amount of BWA. Future BWA is determined by future runoff minus the EFRs. This brings the first two steps of formalizing BWCs, forecasting future locally generated runoff for all sub-catchments and determination of the EFRs.

Next, a model is required which can assess if and to which extend a proposed BWC violates the EFRs. This has to be modelled as violation in the most downstream sub-catchment is dependent on the consumption of all the upstream users together with reservoir releases.

The best way to preserve the environment is by stopping the consumption of water. This is however not desirable as humanity will keep demanding water. Violation in a downstream sub-catchment can be prevented in countless of ways. E.g. reducing the local BWF, reducing the upstream BWF, adopting different upstream reservoir management schemes or a mixture of all these measures. This is where an allocation strategy is needed. The vision of the Global Water Partnership (200) was the maximization of the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems. As sustainability has been addressed by the EFRs the maximization of the resultant economic and social welfare in an equitable manner has yet to be addressed. Previously was determined that this could be achieved by the use of an optimization model consisting of a set of parameters, an objective function, boundary requirements and an optimization technique.

The set of parameters refers to everything which affects the allocation of water, the degrees of freedom. The objective function consists of a combination of assessment criteria which together determine the desired objective. In the boundary requirements, constrains can be set which the allocation strategy at least should fulfil. Here the concept of equity could be implemented by policymakers such as a certain percentage of water should be allocated for basic human needs. An optimization technique should be chosen which can find the best solution occurring to the objective function. This framework is represented in Figure 9 below.

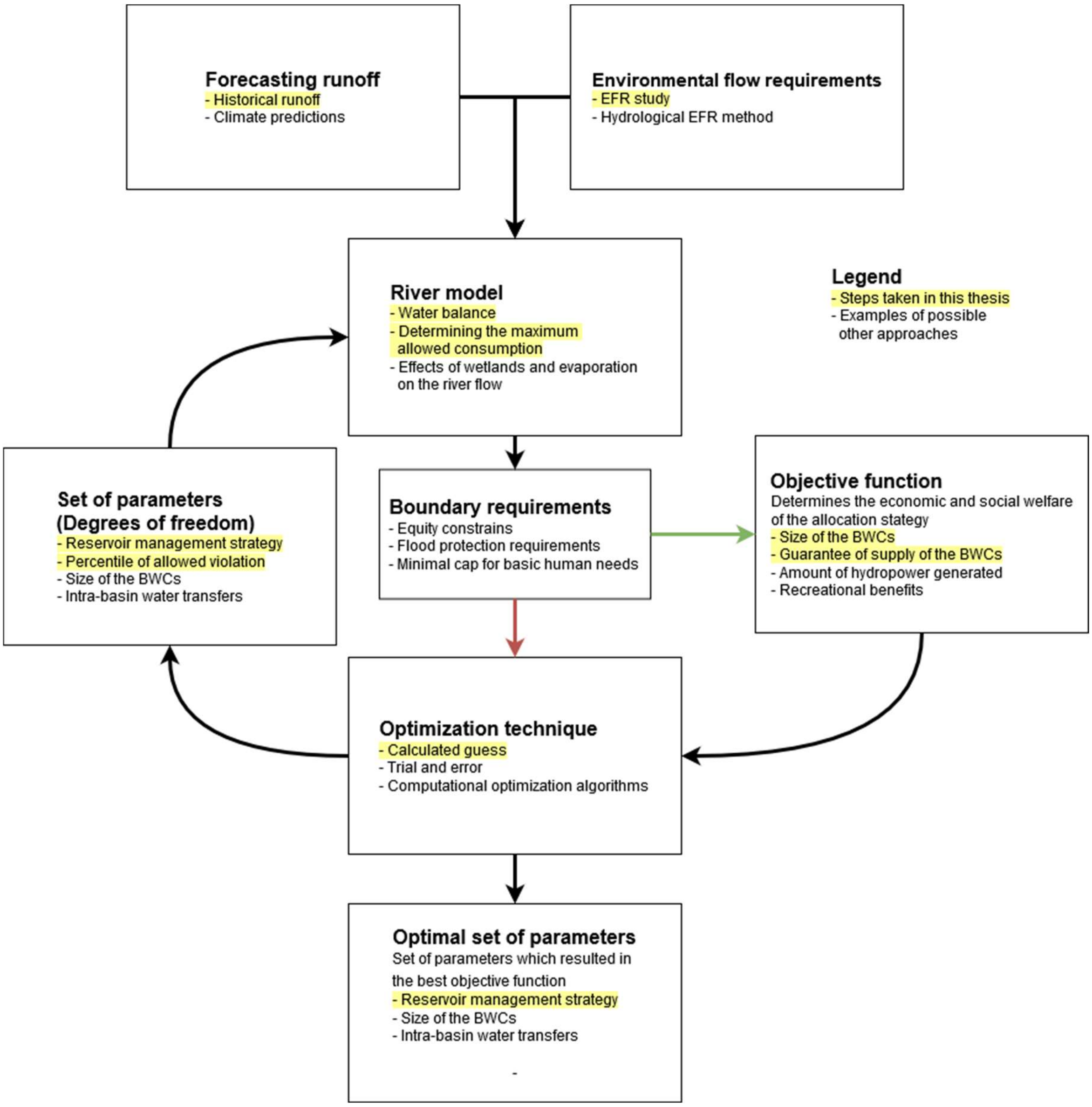

Figure 9: Representation of the framework on how policymakers can determine optimal BWCs per sector per sub-catchment with a corresponding reservoir management strategy.

3.4.1 Application of the framework

Predicting the runoff will be done based on historical runoff data. The longer the used historical period gets, the less accurately it resembles the future due to changes in climate. On the other hand, a short historical period is unable to capture the inter-annual variability properly and therefore lead to incorrect predictions. This means that a balance between the relevance of a longer period and the length of the sample size has to be found. From the analysis of the effects of climate change on runoff was seen that no significant effects of climate change could be found (Paragraph 4.1). Therefore the full historical period could be used, however data on the inter-basin transfers entering the Orange River basin is only available from 1990. The used historical period is thus from 1990 – 2010. Due to the large uncertainties in the prediction of runoff three different levels of allowed violation of EFRs have been chosen to allow for some consumption.

Hogeboom et al. (2020) have set the cap on the average, 25th percentile and minimum value of BWA. In this thesis a slightly different approach is taken, the BWC will be set on the 50th percentile (median), the 25th percentile and the 5th percentile of BWA. The 50th percentile has the advantage that it allows the largest amount of water for human appropriation, but the disadvantage is that despite the cap the EFRs can still be violated half of the time. This is what Hogeboom et al. (2020) intended to do with their first alternative. The 5th percentile is the most strict scenario in which the EFRs will rarely be violated, this scenario could be useful for nature reserves. The 5th percentile is chosen instead of the minimum because it describes a percentage which tells us something about the future. E.g. by setting a BWC on the 5th percentile of BWA results in a future situation which will be sustainable for 95% of the time, while setting a cap on the minimum of BWA does not result in a future situation which will be sustainable for 100% of the time, due to the sample size not being the entire population. To achieve a future with 100% sustainability either the BWC has to be set on zero or uncertainties in future runoff have to be eliminated. The 25th percentile lies somewhere in between the other scenarios, it gives more importance to the environment while still allowing some water for human consumption.

Present-day runoff is used, which means that the alien vegetation, paved areas and afforestation are set to the situation in 2010. The BWCs are meant for the future and it thus has no use to use historical land use.

3.4.2. River model: Determining the maximum allowed consumption per sub-catchment

A BWC per sub-catchment based on a percentile of BWA can be set in two different ways: It can be set based solely on locally generated BWA and it can be set based on the total BWA (including BWA inflow from upstream). When setting a BWC based on locally generated BWA the following potential BWC is determined.

$$BWC_{potential}[x,t] = Percentile(BWA_{local}[x,t], P) \quad (9)$$

With BWA_{local} being the locally generated runoff minus the local EFRs and P the percentile of allowed EFR violation. An advantage of this methodology is that a BWC can be set independent of upstream water usage. A water consumer knows that they fulfil their part of preserving the environment. A disadvantage is that it does not take advantage of the fact that interannual variability in runoff tends to decrease from upstream to downstream making downstream river flow more constant than upstream river flow (Singh, 1997). For this reason, a 2nd approach is analysed, setting a BWC while accounting for inflow from upstream. This calculation has to be performed from upstream to downstream. The algorithm starts at an arbitrary sub-catchment located at the end of a tributary upstream and each step is one sub-catchment downstream. At a confluence, the algorithm starts again most upstream of the encountered tributary. At each sub-catchment the following equation is performed:

$$BWC_{potential}[x,t] = Percentile(BWA_{total}\ [x,t], P) \quad (10)$$

$$BWA_{total} = Runoff_{local} + Inflow_{upstream} - EFR_{sub-catchment} \quad (11)$$

Where $Runoff_{local}$ is the locally generated runoff, $Inflow_{upstream}$ is the contribution from an upstream sub-catchment considering the consumption of this upstream catchment and $EFR_{sub-catchmen}$ being the EFR at the river section of the sub-catchment (equation 7). To compare both methodologies the violation of EFRs and the size of the BWC are analysed with the assumption that BWF is equal to the BWC set on the 50th percentile of BWA. This is done because if the cap where to be fully utilized the EFRs should still be respected half of the time.

3.4.3. Choosing the objective function, optimization technique, set of parameters and the boundary conditions.

Assigning an objective function could be done by assigning an economic value for the BWCs assigned per sector. This could be elaborated by including hydropower or combined with temporal variability limitations. E.g. it could be argued that a domestic BWC does not provide social welfare if it is completely unable to meet the demand for certain months of the year.

The set of parameters is determined by the amount of BWCs which have to be determined together with other factors which can be manipulated such as reservoir management and the intra-basin transfer. This set is determined as follows: There are 479 sub-catchment of which the consumption can be manipulated. Within a sub-catchment 1 parameter can be set which determines the total BWC for the sub-catchment which can then be assigned to each sector based on prioritization. There are 40 reservoirs and 1 intra-basin transfer, considering the BWCs are set at a monthly time scale this will result in (479+40+1)*12=6240 total parameters. Considering each parameter needs to be optimized by iterations, assumed that each parameter needs 10 to 100 iterations to find an optimal solution and considering one iteration currently takes 11 seconds, then it would take between 8 to 80 days for a computer to calculate a solution. These calculation times are unrealistic, therefore the problem has to be simplified. To improve computing speed some articles (Haro et al., 2012) ignore spatial variability, while others choose for a yearly cap for one single sector with a relatively small river network (Farriansyah et al., 2018). Up to this date, there is no literature which applies an optimization algorithm for such a comprehensive river network as the Orange River basin (Divakar et al., 2011; Farriansyah et al., 2018; Ringler, 2001).

The choice is made to simplify the problem by shifting the focus from maximisation of the economy to maximisation of the consumption. This means all sectors are considered equal and the first-come-first-served algorithm can be adopted (Jenkins, 2007). This eliminates 5736 parameters. This still leaves the reservoir management and intra-basin water transfer to be optimized.

To select an optimization algorithm the optimization problem has to be classified within the optimization framework. The problem is considered as a Black Box optimisation problem, because the allocation model to optimise does not have an algebraic model that can be solved analytically (MathWorks, 2020). Furthermore, the objective function is considered as non-smooth, because an objective function limited by maxima (reservoir capacity) or minima is classified as non-smooth (MathWorks, 2020). This still leaves plenty of algorithms with different properties to choose from. This choice can have major implications on the results, because optimisation algorithms can get stuck at local maxima instead of global maxima. The choice is therefore made to further simplify the problem by selecting two important reservoirs for which a simple management strategy will be designed. This reservoir management strategy will be determined by making a calculated guess. Regarding 38 reservoirs and the intra-basin water transfer as non-excitant is a large step away from reality, but still leaves room to analyse the effects which reservoir management can have on BWCs.

3.4.4. Model adjustments

The first-come-first-served algorithm means that the first user can consume their demand as long as they remain within the ecological boundary conditions. The BWC for a certain sub-catchment is determined as follows.

If $BWF \leq BWC_{potential}$, more water could be used than needed and the BWC can become the BWF.

$$BWC[x,t] = BWF[x,t] \tag{12}$$

If the $BWF > BWC_{potential}$, less water can be used than needed and the BWC is set to be the maximum potential BWC.

$$BWC[x,t] = BWC_{potential}[x,t] \tag{13}$$

Where $BWC_{potential}$ is the maximum usable amount of water given an accepted level of violation of the EFRs.

A reservoir balance equation is implemented to allow a reservoir management strategy to be tested.

$$S_{t+1} = S_t + Q_{in} - S_{release} - BWF_{reservoir} - S_{spill} - EFR \tag{14}$$

Where S_t is the reservoir storage at the current month and S_{t+1} the storage at the next month. Q_{in} the inflow, $BWF_{reservoir}$ the BWF of the reservoir and S_{spill} spillage. $S_{release}$ is the amount of water which the reservoir releases for consumption downstream. The initial storage is set to be equal to the average reservoir storage $S_0 = \bar{S}$. The boundary conditions of the reservoirs are that the reservoir storage cannot exceed the capacity and cannot become negative ($0 \leq S_{t+1} \leq S_{cap}$). If $S_{t+1} > S_{cap}$ spillage will occur, if $S_{t+1} < 0$ than the amount of water released is reduced. $BWF_{reservoir}$ is determined by taking the average monthly historical evaporation. This makes evaporation independent of the storage but leaves the annual pattern.

3.4.5. Set of parameters and model adjustments

The chosen reservoirs are the reservoirs responsible for the inter-basin transfers out of the Orange river basin, the largest reservoir in the Vaal catchment (Vaal dam), the largest reservoir in the upper orange (Gariep dam). Because of the monthly time scale, this results in a total of 24 releases per year, thus 24 parameters to be optimized. $S_{release}$ in equation 14 is the parameter which needs to be optimized to achieve maximum consumption.

3.4.6. Optimization technique

The calculated guess is made as follows, first the downstream area for which the reservoir is meant to provide water for is determined. Based on Matthews (2015) is determined that the Gariep dam should provide water for the area from the dam till the river mouth and that the Vaal dam should provide water for the area from the dam till the confluence with the Lower Orange. The BWF from this area is summed and the amount of water which the reservoir can provide is determined by trial and error and the previously set boundary requirements. This meant that the Vaal dam was able to deliver 50% of the average demand below and the Gariep dam was able to deliver 100% of the average demand below. This resulted in the following releases Table 6.

Table 6: Monthly reservoir releases in million m³ determined by the calculated guess

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Gariep	159	168	177	176	150	138	122	99	44	101	120	143
Vaal	76	77	78	77	71	72	66	61	46	61	67	74

3.5. Analysing the effect of reservoirs on BWCs

With the previously mentioned methods, 6 different sets of BWCs can be determined, 3 scenarios for allowed violation of the EFRs and these scenarios with and without the reservoir algorithms. The evaluation period is from 1990-2010. The objective of the allocation strategy was set on maximum consumption of water. This goal can be divided into two assessment criteria, the size of the BWC and the rate in which this BWC can be supplied (supply guarantee). The size of the proposed BWCs tells not much about the impact of the measure, therefore it is chosen to analyse this criterion by the required reduction of the existing BWF. Furthermore, the BWCs have been set to increase sustainability in the Orange River basin. To check if this happens the amount of times in which the EFRs are violated is analysed. This is done by analysing the sub-catchment which violates the EFRs the most often, the worst sub-catchment is chosen because even this sub-catchment should not violate the EFRs more than allowed.

4. Results

In this chapter, the results are discussed.

4.1. Analysing runoff

In Figure 10 the mean locally generated annual runoff for the Orange River basin can be seen. Most of the runoff comes from the east, this is caused by the Drakensbergen mountain range which lies mainly in Lesotho. The entire western region receives almost no locally generated runoff.

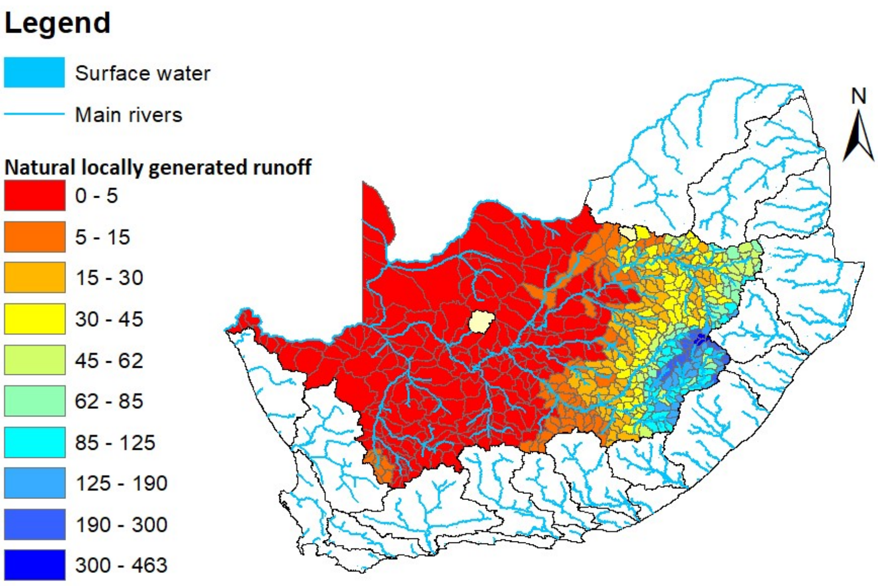

Figure 10: Mean annual natural runoff (mm)

In Figure 11 the flow accumulation in the orange river can be seen, the main contributors for the flow in the Lower Orange River are the Upper Orange River and the Vaal. The average annual natural runoff in the Orange river basin is 10649 million m^3.

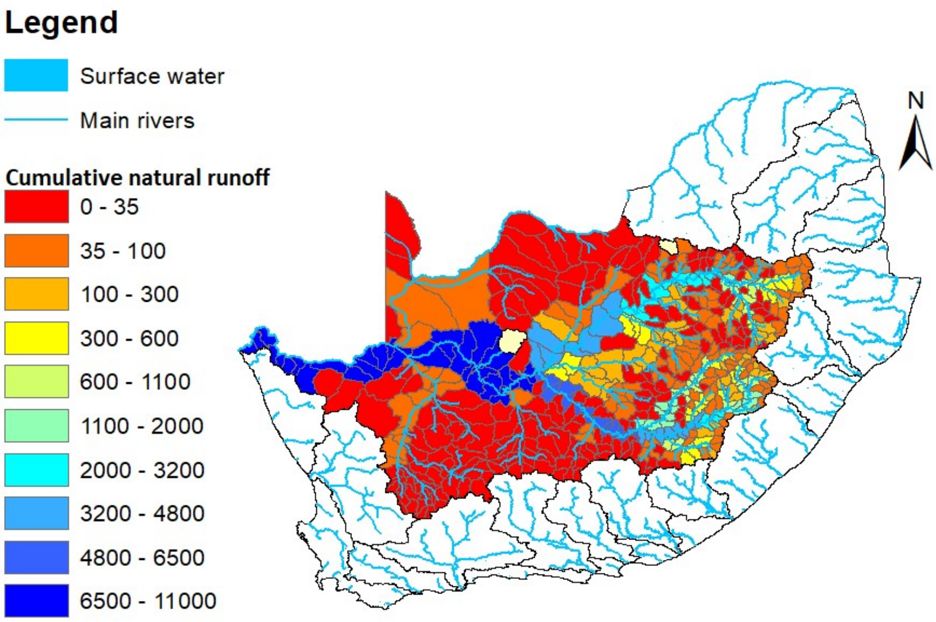

Figure 11: mean annual natural flow accumulation/cumulative runoff (million m^3)

4.1.1. Effects of climate change on the historical runoff

In this section change in runoff pattern throughout the years is analysed. This analysis is performed with the use of natural runoff because human influences in the flow regime have to be excluded.

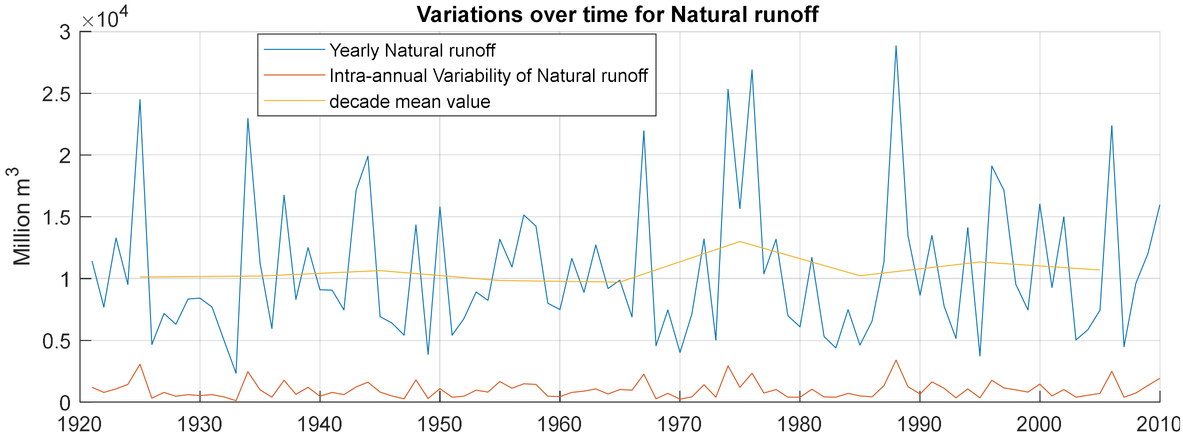

Figure 12: Yearly natural runoff in the Orange River basin with intra annual variability and the decade mean value. Intra annual variability has been determined by the standard deviation.

From Figure 12 can visually be seen that there is not any significant change in runoff over the years, also the intra annual variability stays constant over time indicating that the shape of the flow peak has not changed. The decade mean value is shown to indicate the total amount of runoff with limited effects of inter-annual variability. From this decade mean value can be seen that the total amount of runoff also stays similar over time. The last factor to be analysed is the timing of the flow peak.

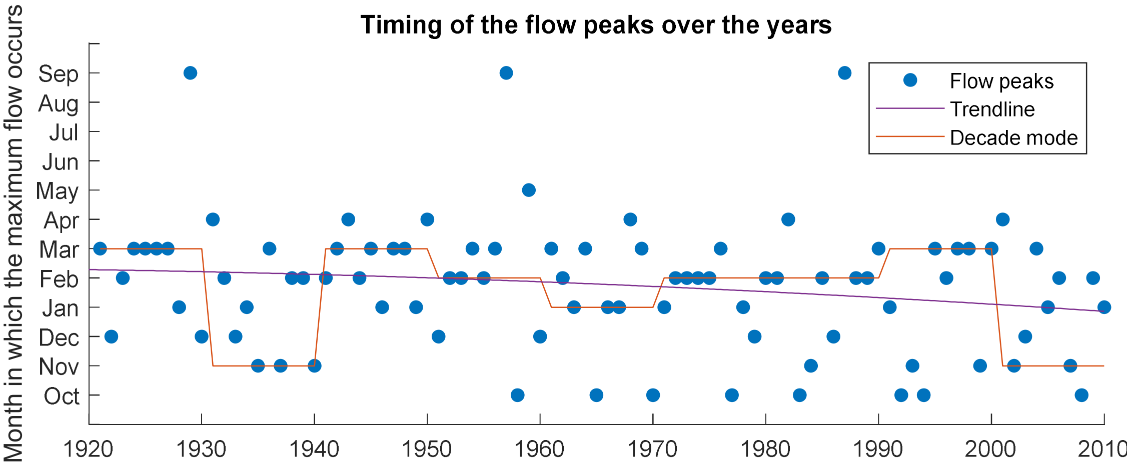

Figure 13: Yearly timing of the maximum monthly runoff occurring within a year.

In Figure 13 the timing of flow peak is shown, it can be seen that there is large interannual variability in the timing of the flow peaks. The choice is made to show a quadratic trendline instead of a linear trendline because it is expected that the amount of change in climate has increased over the past century (Burn, 1994; Meng et al., 2016). The trendline shows that there a small negative effect over time meaning that the flow peak is occurring earlier in the year. The trendline assumes eleven months difference between October and September, which is a flaw in this methodology for river basins with very high temporal variability in the timing of the flow peaks. For this reason, the decade mode has been plotted which is the month in which the flow peaks most frequently occurs in a decade. From the decade mode value, no significant difference is visually seen throughout the years. From figure 12 & 13 is thus concluded that no significant impact from climate change can be detected in the historical runoff. Orasecom (2010) also concludes that up to 2007 there were no clear signals of climate change in the Orange River basin, and reasoned that 'Conclusive evidence is hard to obtain due to the high variability of the local climate where natural variability tends to mask the more subtle influences of Climate Change'.

4.2. Environmental flow requirements

In Figure 14 & 15 are the environmental flow requirements shown. As expected the EFRs of management class B are lower than those from management class A. The pattern of all EFRs methods is very similar, but according to the EFR study significantly less water is needed for the environment than the variable monthly flow method predicts. The difference between EFR methods is largest during high flows. On average the management class A requires 31% of the natural runoff for the environment, class B 20% and the VMF method 52%. This shows the large uncertainty related to EFRs.

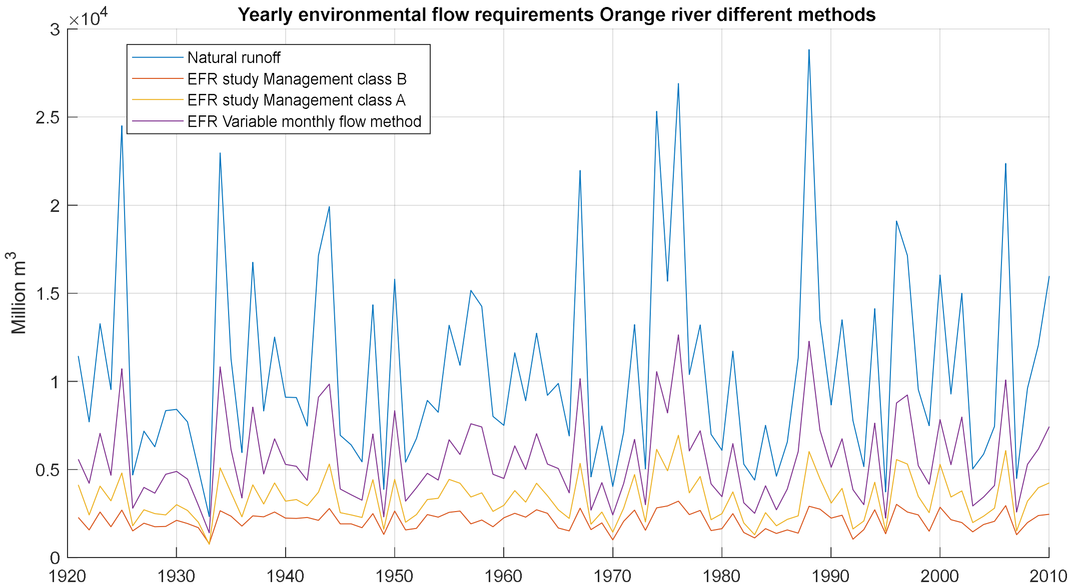

Figure 14: Natural runoff and environmental flow requirements for the Orange River basin

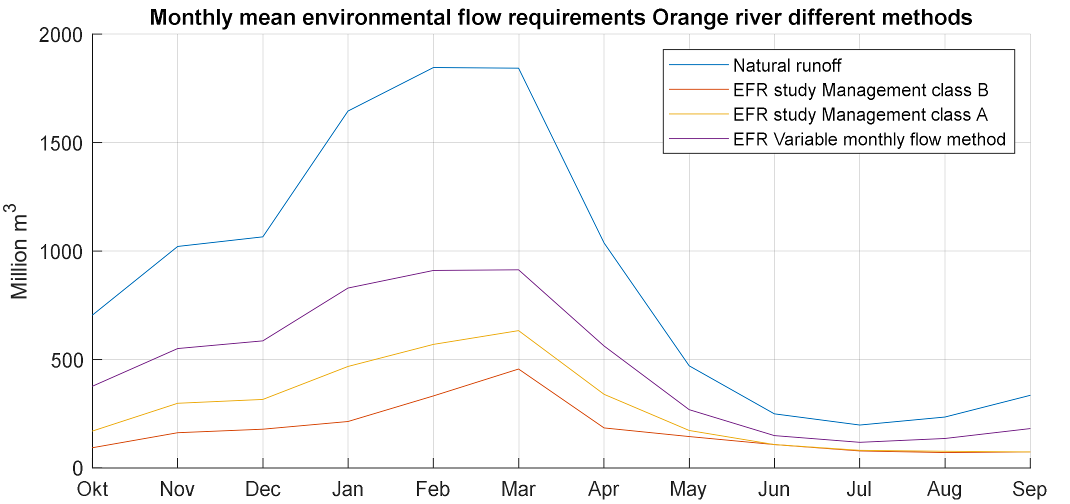

Figure 15: Natural runoff and environmental flow requirements for an average year in the Orange River basin

To compare the extrapolation of the EFRs to the level of sub-catchments the EFRs have been compared for a wet upstream sub-catchment in Lesotho and a dry upstream sub-catchment in the Lower orange region

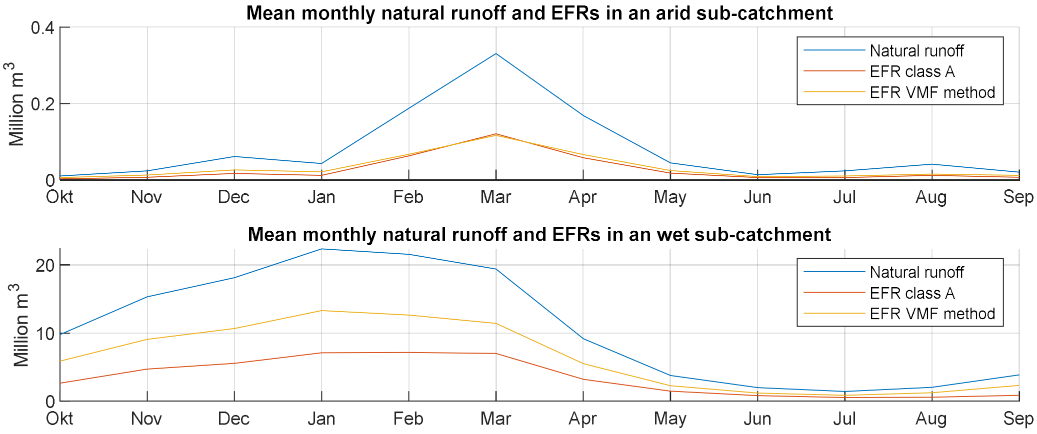

Figure 16: Comparison between the extrapolated EFRs and the VMF method for an arid and a wet sub-catchment in the Orange River basin. The period used is from 1920 to 2010.

From Figure 16 can be seen that the extrapolation method applied does result in realistic EFRs on the sub-catchment level since the pattern of the EFR of management class A look very similar to the pattern from the VMF method for two sub-catchments in different climate regions with different hydrological regimes.

4.3. Environmental sustainability of the historical blue water footprint

The environmental sustainability is assessed by first looking at the BWF, then analysing the effects of reservoirs on the BWA and next assessing the violation of the EFRs. Furthermore, the actual modelled runoff is compared with observed runoff to assess the uncertainty.

4.3.1. Blue water footprint accounting

The blue water footprint within the orange river basin has been accounted for 1990 till 2010.

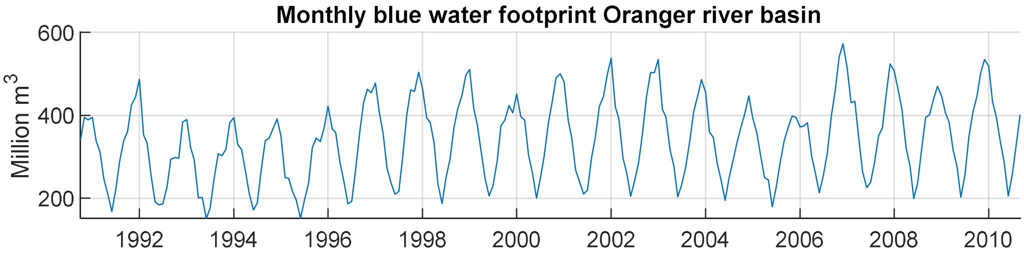

Figure 17: Monthly blue water footprint of the Orange river basin

From Figure 17 can be seen that there is a clear annual pattern in the BWF. The BWF in the summer is most of the time more than twice as high as it is during the winter. This pattern is mainly caused by the evapotranspiration pattern throughout the year, which increases the BWF of crops and reservoirs during the summer and decreases it during the winter.

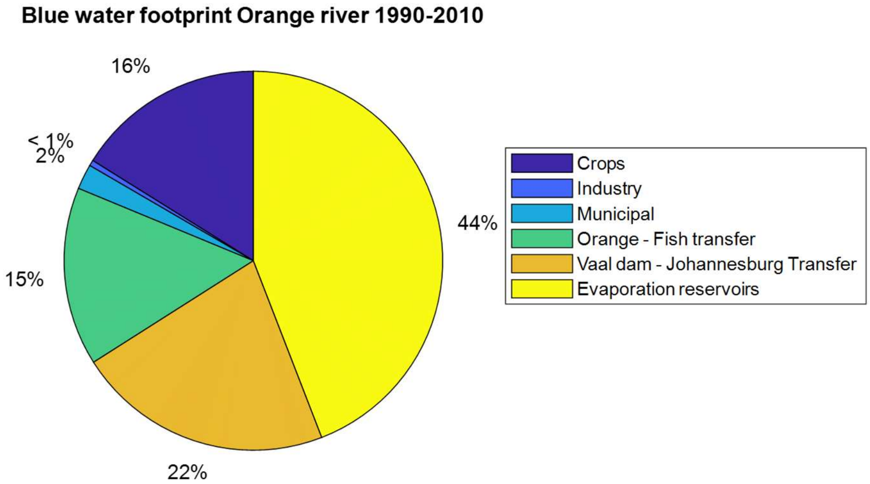

Figure 18: Contributors to the blue water footprint in the Orange river basin

The largest BWF is caused by evaporation of reservoirs (Figure 18), other large contributors are inter-basin water transfers out of the Orange river basin and irrigation of crops. There are also three water transfers into the orange river basin, but these are accounted for at the blue water availability analysis. The role of these transfers is to counteract the large transfer at the Vaal dam for Johannesburg and Pretoria. The municipal and industrial BWFs are very low.

To analyse the spatial variability of the BWF, the BWF of reservoirs is separated from the other BWFs. This is done because reservoirs perform a service role by releasing and storing water, which affects the BWA. Evaporation cannot be separated from this service. The spatial distribution of the average demand of the sectors is shown below.

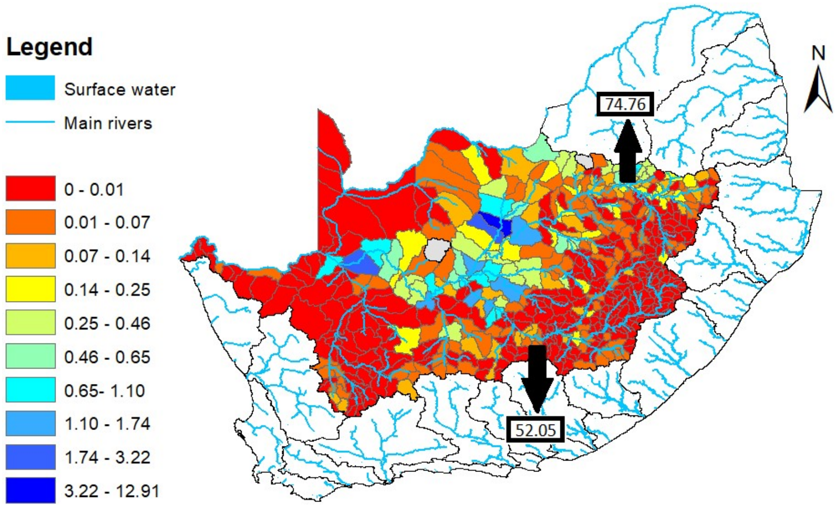

Figure 19: The average monthly BWF of the domestic, industrial, agricultural consumption and water transfers in million m^3. The upper arrow resembles the Johannesburg transfer and the lower arrow the Fish transfer. Period 1990 – 2010. (The data is shown in million m^3 instead of mm because the BWF is considered to be independent of the surface area)

Figure 19 shows that the current BWF has high spatial variability. However, most of the abstractions are done from the main rivers. When comparing this Figure 19 to Figure 10, the need for BWC allocation methods becomes apparent, as the water consumption mostly happens downstream of the regions with high locally generated runoff.

4.3.2. The effects of reservoirs on the BWA

Reservoirs have a key service role to better match the demand for water with the available water. In the following graphs is shown how they redistribute the BWA over time.

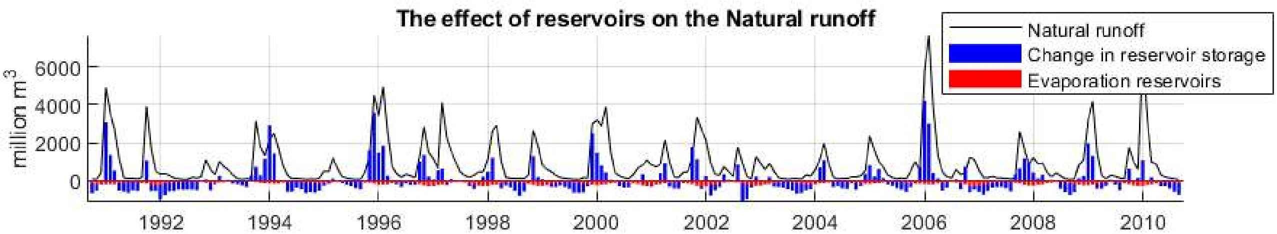

Figure 20: Change in reservoir storage vs natural runoff and evaporation

From Figure 20 can be seen that the reservoir's storage is mostly increased during peak flows and that this water is released during times of low flows.

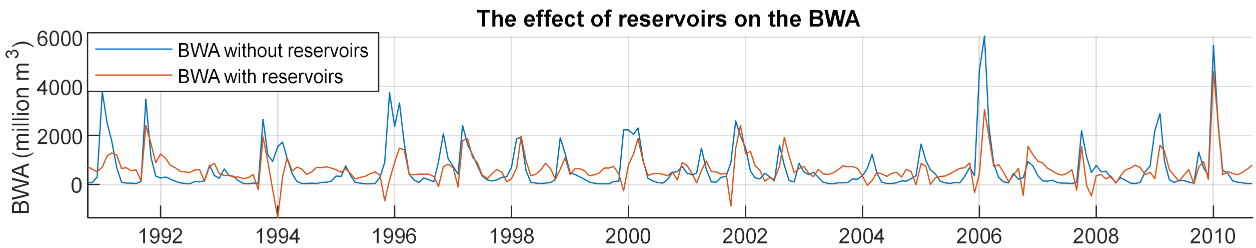

Figure 21: The effect of reservoirs on the BWA for the Orange River basin for the period 1990-2010

In Figure 21 the BWA in the Orange River basin is shown with and without reservoirs taken into account. From the graph can be seen that the peaks of BWA with reservoirs included are significantly smaller than they are without reservoirs included. Also, the reservoirs release a lot of water during the dry periods which will allow for more water consumption during these periods. There are also periods with negative BWA, this negative BWA means that the EFRs are violated by current reservoir management in these months. The evaporation of reservoirs results in a reduction in BWA of 2.8%.

4.3.3. Environmental sustainability of the blue water footprint

The environmental sustainability of the current BWF (including reservoirs) has been assessed below, by analysing the number of months in which the EFRs are violated.

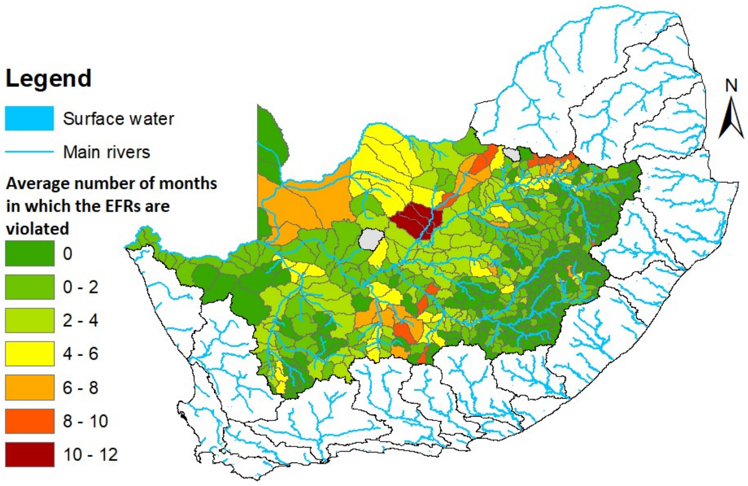

Figure 22: The average number of months per year that the Environmental flow requirements are violated, for the period 1990-2010. Comparison between modelled actual runoff and the EFRs.

From the map above can be seen that large areas have not violated the EFRs for a single month, these are mainly the upstream regions. The majority of sub-catchments along the main Vaal and Orange River violate the EFRs between 0 to 4 months of the year. The sub-catchments which violate the EFRs for more than 8 months of the year are mainly located in small tributaries in upstream areas.

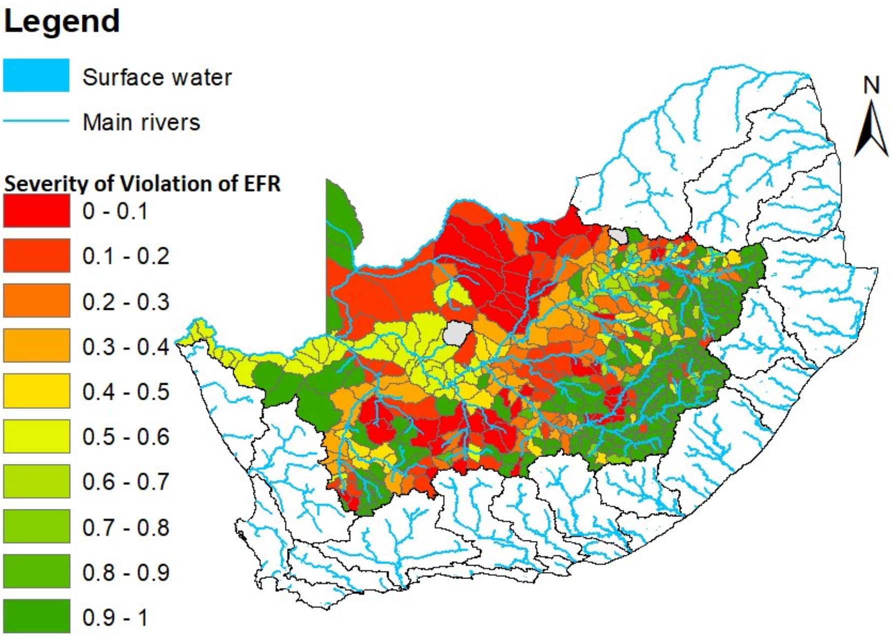

Figure 23: Severity of violation of the EFRs for the period 1990 – 2010.

In Figure 23 can be seen that when the Lower Orange River (yellow) violates the EFRs, on average half of the EFRs are met. Comparing Figure 22 with Figure 23 shows that areas which frequently violate the EFRs also on average severely violate them. Also, there are areas which do not frequently violate the EFRs, but when violation occurs they severely violate the EFRs. This new indicator can help analyse violation of EFRs.

4.3.4. Comparison of actual modelled runoff with observed runoff (uncertainty analysis)

Actual modelled runoff has been compared with observed runoff to check whether the model resembles reality.

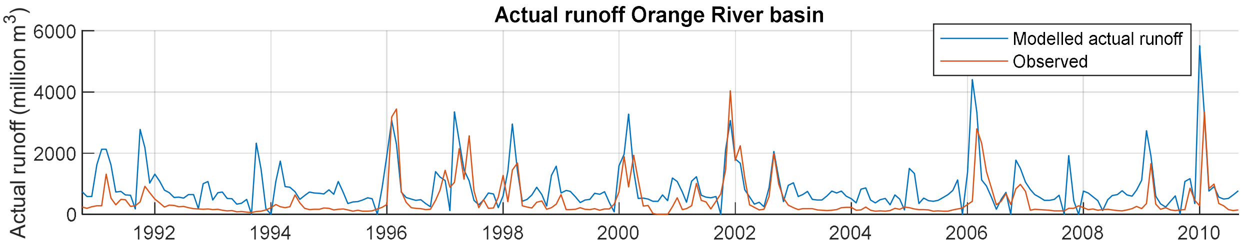

Figure 24: Actual monthly runoff orange river (location is just upstream of Namibia)

From Figure 24 can be seen that the observed actual runoff and modelled runoff follow some similar pattern, with some exceptional years such as 1994 and 2008. During these years the flow peak, which is observed upstream (Figure 25), is entirely stored in reservoirs. This storing of water is somewhat represented by the reservoir data, but this does not align perfectly resulting in some overestimation of actual runoff. Modelled actual runoff is also on average 27% larger than the actual observed runoff.

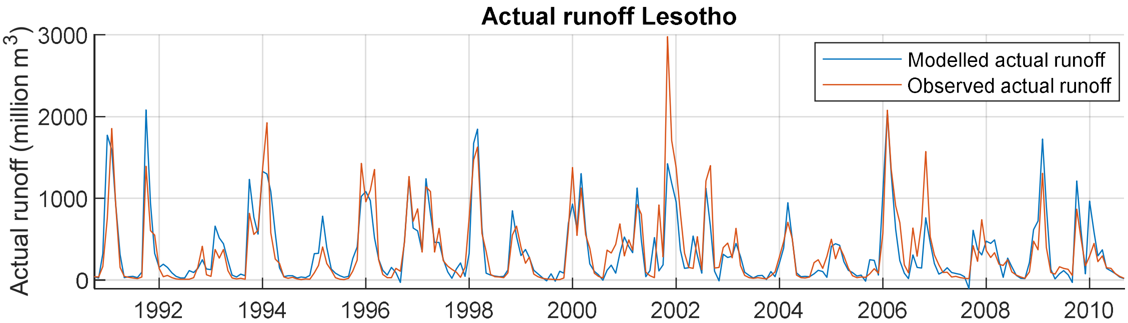

Figure 25: Actual runoff downstream Lesotho

In Figure 25 the actual runoff just downstream of Lesotho is shown. This location is chosen since the domestic, agricultural and industrial BWFs of Lesotho are very low, also the reservoir and water transfer only effect one of many tributaries so their influence is low as well. This means that the major component for predicting actual runoff is the WRSM/Pitman model performance.

From Figure 25 can be seen that modelled and observed actual runoff look very similar, the model only underestimates the total amount of runoff by 2%, The timing of the flow peaks looks also correct, indicating that there is no large snow build-up during the winter. However, the size of the flow peaks is not always accurate, especially in 2002 and 2007 the observed flow peaks are more than twice as high than the modelled flow peaks. This is most likely caused by inaccurate precipitation measurements since the model does perform well in other years.

The overestimation of modelled actual runoff in Figure 24 is most likely caused by the following factors: underestimation of the BWF, neglection of small reservoirs and neglection of evaporation and seepage along the river channel. Comparing the observed runoff (Figure 24) with the EFRs results in an average violation of 8.35 months per year, while the previous the actual modelled runoff only violates the EFRs for 1.80 months per year. This large difference can be explained by the uncertainties in the estimation of actual runoff mentioned before. This also means that the violation of the EFRs previously assessed is most likely much worse.

4.4. Formalization of blue water footprint caps

Formulation of the BWCs is done by first testing the methodology, furthermore, a first-come-first-served allocation strategy is adopted and evaluated.

4.4.1. Determining the maximum allowed consumption per sub-catchment

First, the BWCs are set on the 50th percentile of locally generated BWA for all the sub-catchments. Assumed is that the BWF is equal to the BWC with no reservoirs and water transfers.

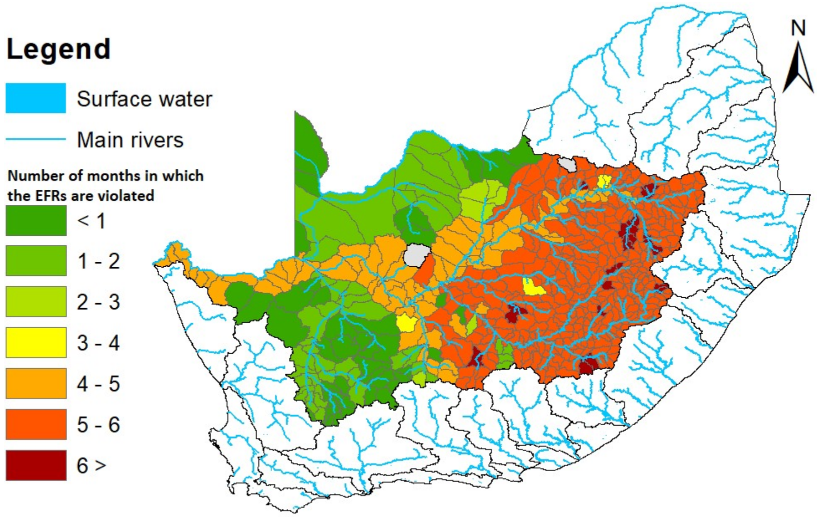

Figure 26: Average number of months per year in which the EFRs are violated. BWF is equal to the BWC. BWC is set on the 50th percentile of locally generated BWA. Period 1920-2010.

Above can be seen that especially the arid western part has large green areas. This can be explained by the fact that the western dessert part has almost no locally generated water which does result in a BWC of zero for most months of the year, which means that this cap never violates the EFRs. At the mouth of the river, the EFRs are violated for an average of 4.85 months per year. From Figure 26 can also be seen that there are certain sub-catchments which violate the EFRs for more than the anticipated average of 6 months per year. These are never the most upstream sub-catchments but the sub-catchments just below them. This is caused by the flow accumulation, e.g. if two sub-catchment both violate the EFR for half of the time, combining these runoffs and EFRs can result in a violation of the EFRs for more than half of the time. This doesn't have to be problematic in practice as the maximum occurred violation is an average of 6.3 months per year, but it shows the percentile does not directly translate to the maximum occurring violation of EFRs.

Second, the BWCs are set on the 50th percentile total BWA (including inflow from upstream) for all the sub-catchments. Assumed is that the BWF is equal to the BWC with no reservoirs and water transfers.

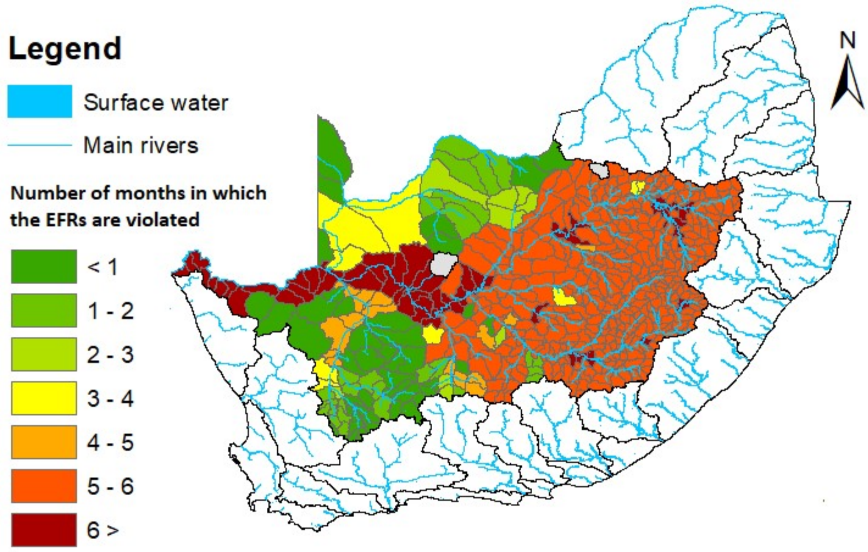

Figure 27: Average number of months per year in which the EFRs are violated. BWF is equal to the BWC. BWC is set on the 50th percentile of total BWA. Period 1920-2010.

in Figure 27 can be seen that especially the Lower Orange river violates the EFRs more than the predicted 6 months on forehand. This is because at the confluence of the Vaal and the Upper orange the combination of accepted environmental flow violation causes together an unacceptable violation of environmental flow, this is explained in more detail below by analysing the month of January.

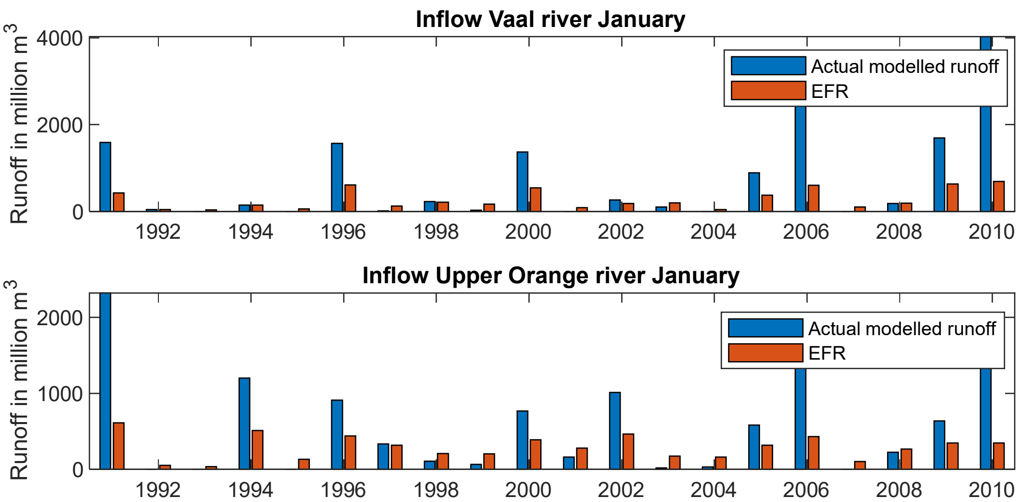

Figure 28: Violation of the EFRs for the Vaal and the Upper Orange, BWF=BWC set on 50th percentile of total BWA. both violate the EFRs 10 of the 20 months (50%).

In Figure 28 can be seen that the Violation of the EFRs occurs in both the Vaal and the Upper Orange for half of the Januaries, which is logical for a BWC set on the 50th percentile. In Figure 29 the runoff and EFRs from Figure 28 are added together. This results in a violation of the EFRs for 11 of the 20 months (55%), this explains the violation of the EFRs in the Lower Orange River in Figure 27.

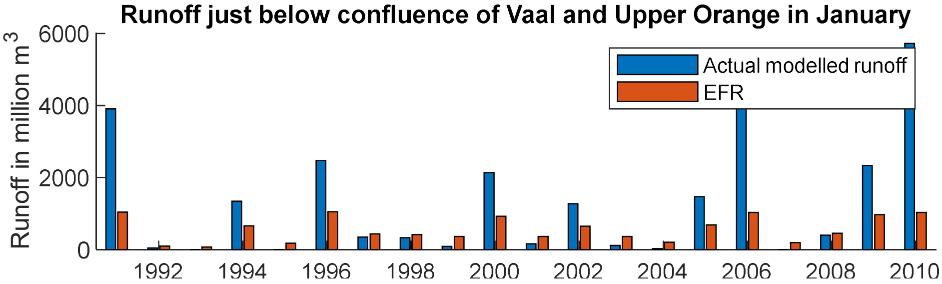

Figure 29: Violation of the EFRs for just below the confluence of the Vaal and the Upper Orange River, violation occurs in 11 of the 20 months (55%)

From Figure 26 and Figure 27 is seen that both approaches towards setting a BWC based on a percentile of BWA can result in a slightly higher violation of the EFRs than anticipated on forehand. In Table 7 the size of the BWC and violation of the EFRs for different percentiles and both approaches are shown. The method which sets the BWC on a percentile of total BWA allows for much more water consumption while maintaining similar levels of EFR violation, especially in the arid Lower Orange region.

Table 7: Environmental flow violation and size of the BWC for the different BWC methods

		BWC set on a percentile of locally generated BWA			BWA set on a percentile of total BWA		
	percentile	50	25	5	50	25	5
Average violation of the EFRs in the percentage of time	Upper Orange	47	21	3	48	24	5
	Vaal	47	22	4	49	24	5
	Lower Orange	19	4	0	25	9	1
Worst EFR violation in the percentage of time	Upper Orange	51	26	5	51	25	5
	Vaal	52	26	5	51	26	5
	Lower Orange	50	25	5	52	25	5
Average BWC in million m^3 per month	Upper Orange	197	97	39	238	130	66
	Vaal	83	38	20	139	64	33
	Lower Orange	1	0	0	41	13	13
	Total	281	136	59	419	207	112
	Percentage increase	-	-	-	49%	52%	90%

In Figure 30 the relation between the violation of the EFRs and size of the potential BWC is shown, it shows that the 2nd method allows for much more water consumption on every percentile.

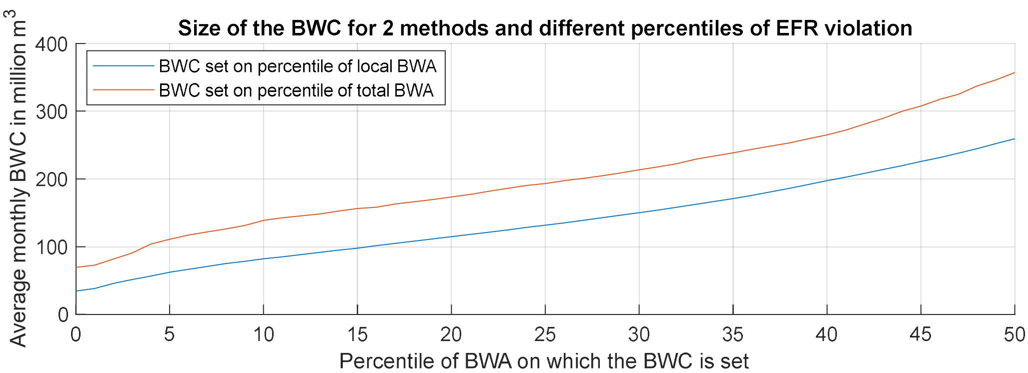

Figure 30: Relation between the size of the BWC and the violation of EFRs for two methods

4.5. Analysing the effect of reservoirs on BWCs

In this paragraph, the proposed BWCs are analysed for situation A and B which represent the allocation strategy with and without reservoirs respectively. Situation C represents the current situation.

Table 8: Evaluation of the proposed BWCs. Situation A is without reservoirs, situation B is with two reservoirs and situation C is the current situation

	situation A			Situation B			Situation C
Percentile of BWA on which the BWC is set	5	25	50	5	25	50	-
Required reduction of the current BWF in percentage	59.5	45.2	34.8	22.2	19.9	17.4	0
Average guarantee of supply BWC in percentage of time	99.8	97.7	93.3	99.8	97.9	93.5	81.7
Average violation of the EFRs for the worst sub-catchment in percentage of time	5	25	50	5	25	50	95

In Table 8 can be seen that the stricter the percentile of allowed violation of the EFRs is set, the more the current BWF has to be reduced. On the other hand the stricter the percentile of allowed violation of the EFRs is set, the higher the guarantee of supply becomes. Both situations A and B stay within the expected violation of the EFRs. Situation B performs equal or better than situation A for every assessment criteria. In particular the reduction of the current BWF, is much lower in situation B than in A. This can be explained by the redistributing effect of reservoirs. Furthermore, the difference in the required reduction of the BWF is also much lower in situation B, ranging from 17.4 % to 22.2 %, while scenario A ranges from 34.4 % to 59.9 %. This means that reservoirs can make the trade-off between utilizing BWA and violation of the EFRs less pronounced.

For the spatial analysis of the criteria situation B is chosen with the BWC set on the 25th percentile of BWA.

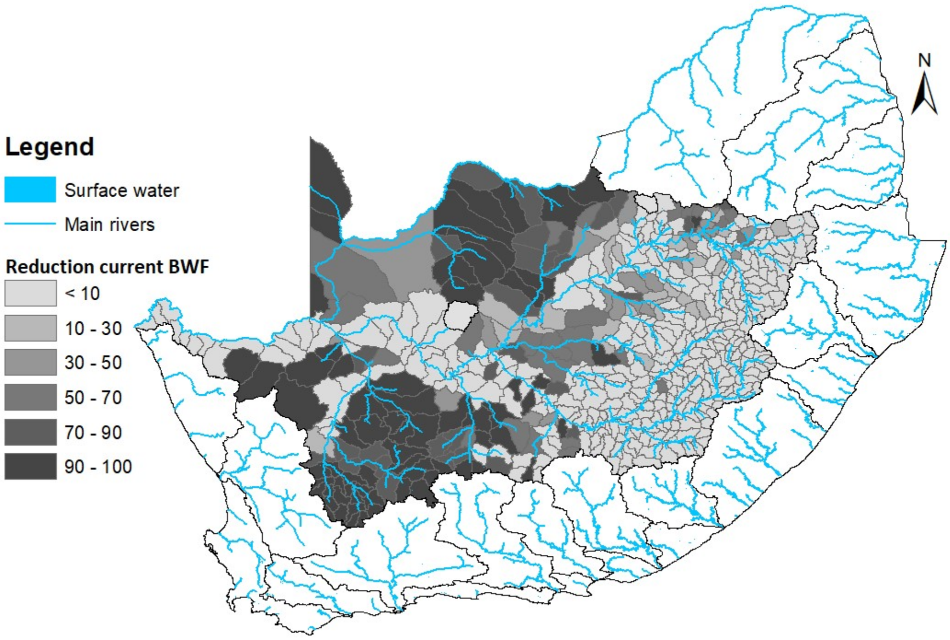

Figure 31: Required reduction in the percentage of the current BWF by the BWC set on the 25th percentile of BWA with two reservoirs included for the period 1990-2010.

In Figure 31 can be seen that the current BWF does not have to be reduced much in the upstream areas in the east, this is because the BWF was already low compared to the BWA. Furthermore, along the main Lower Orange River the BWF does not have to be reduced, as it is supplied by the Gariep dam. The main reduction of the BWF takes place in the small tributaries in the arid regions. This was to be expected as these regions have almost no locally generated BWA which results in a BWC of zero for many if not all months of the year, this could already be seen in Figure 26 and Figure 27.

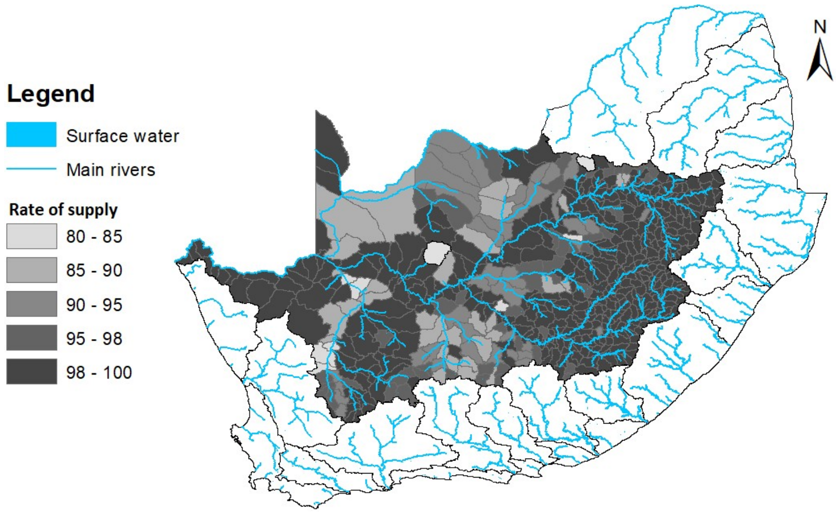

Figure 32: Guarantee of supply of the BWC set on the 25th percentile of BWA with two reservoirs included for the period 1990-2010.

In Figure 32 can be seen that the overall guarantee of supply is very high (above 80 %), the guarantee of supply is relatively low in the small tributaries. Although some of these tributaries will have a BWC of zero which has a 100% supply rate, which is a limitation of this criteria.

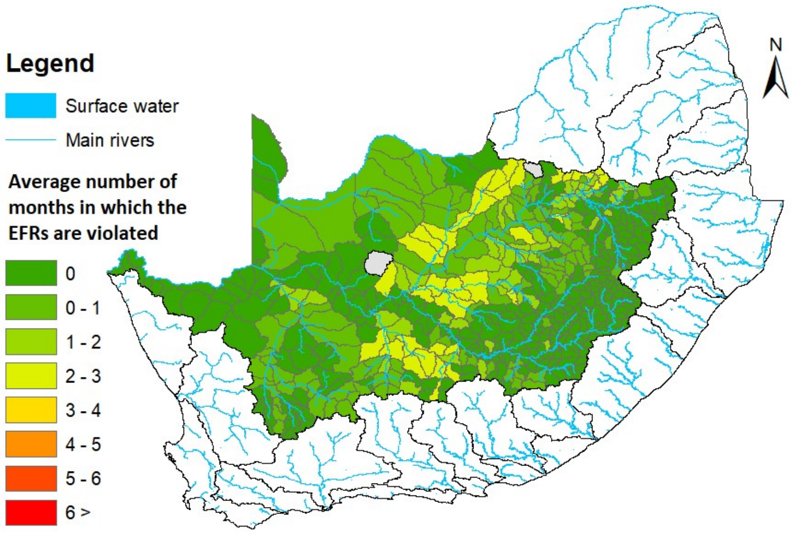

Figure 33: Violation of the EFRs by the BWC set on the 25th percentile of BWA with two reservoirs included for the period 1990-2010.

From Figure 33 can be seen that the average violation of the EFRs stays within expected bounds, all sub-catchments remain under 3 months of violation of the EFRs.

4.5.1. Detailed analysis of the effect of reservoir management on the BWC

From Table 8 was seen that reservoirs can increase the BWC, this can be explained by the fact that reservoirs can redistribute water throughout the year to better match the demand (Figure 34).

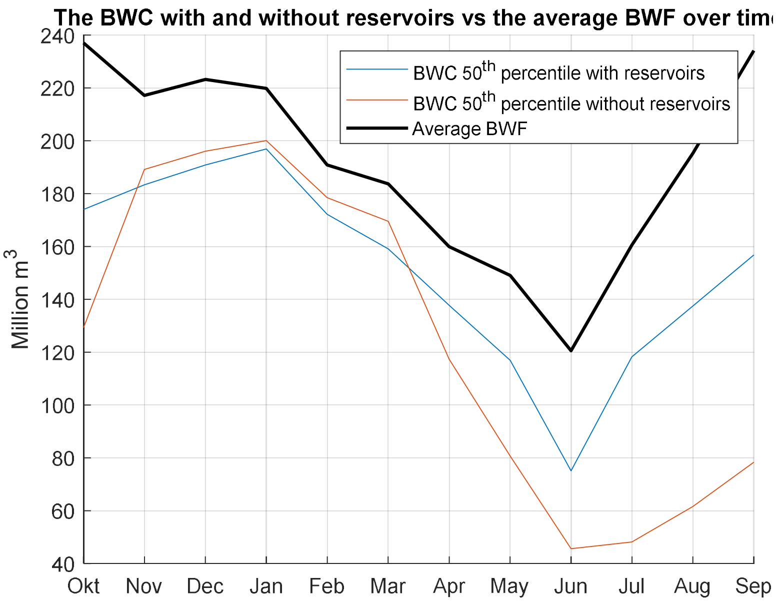

Figure 34: The size of the total BWC set on the 50th percentile of BWA with and without reservoir management

From Table 8 was also seen that reservoirs can make the trade-off between utilizing BWA and violation of the EFRs less pronounced. To show how they make this trade-off less pronounced, a cumulative distribution function (CDF) is shown for both the Vaal and Gariep dam. A month is chosen where the total outflow for the situation with and without reservoirs is roughly equal, to allow for proper comparison.

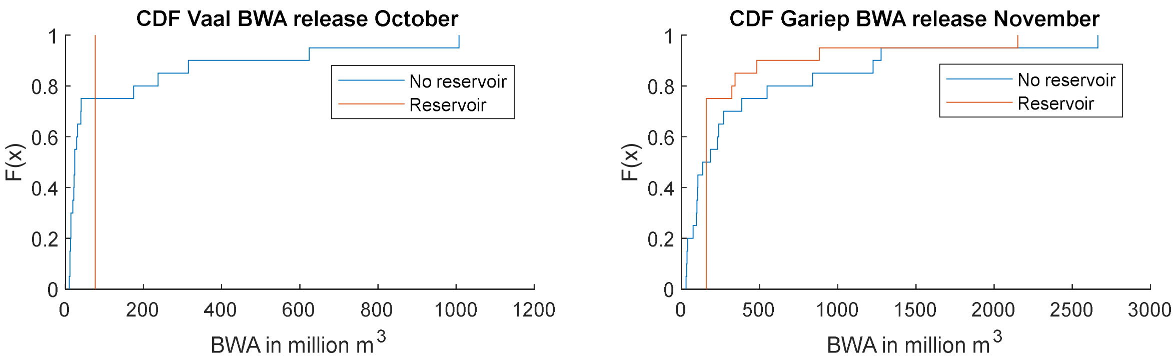

Figure 35: Cumulative distribution function (CDF) of BWA for the Vaal and the Gariep dam.

From Figure 35 can be seen that the Vaal dam changes the CDF. The shape of the curve has changed shape and has become a straight line. The Vaal dam can eliminate inter-annual variability between Octobers. It can meet the EFRs and supply 76 million m^3 every October. By having a reservoir the otherwise unutilized flow peaks become usable. This does come at a cost of evaporation, which is on average 39 million m^3 in October. The tipping point is on the 75th percentile, but setting a BWC which violates the EFRs 75% of the time should not be an ambition of policymakers. At the Gariep dam, a similar pattern is seen, although this reservoir is not able to fully store the flow peaks resulting in spillage and thus unutilized BWA. The stricter the percentile is set the larger the advantage of using reservoirs becomes. If a reservoir is unable to store the flow peaks due to limitation in the capacity than this advantage is reduced. If the advantage of reduced inter-annual variability outweighs the reduction of evaporation is reservoir dependent and on the percentile on which the BWC is set (tipping point).

5. Discussion and recommendation

In this chapter, the most important limitations and shortcomings of this thesis are discussed and recommendations are made for further research.

5.1. River flow

The Pitman/WRSM2000 model is calibrated by Royal HaskoningDHV. From the comparison between the observed and modelled actual runoff of Lesotho, was seen that some peak flows were highly underestimated or overestimated. This difference was most likely caused by inaccurate rainfall data. Overestimation in runoff will result in an overestimation of the BWC, which can then cause more environmental flow violation than accepted by the BWC. This shows the importance of accurate rainfall measurements.

Once runoff or groundwater enters a stream or river the hydrological components of a river come into play. Hydrological components such as evaporation of river flow, water consumption by riparian vegetation and flow time are all neglected. Especially the assumption that upstream water is available downstream in the same month is problematic. Water released from the Vanderkloof Dam takes 4 to 6 weeks to reach the estuaries (Matthews, 2015). About a third of the sub-catchments are even further upstream than the Vanderkloof Dam. To better represent reality flow from one sub-catchment to another should be delayed, but due to the current model using a monthly time step the minimal delay is one month. For further research, I would suggest using a daily runoff model to set monthly BWCs per sub-catchment.

In this study, it is assumed that all the water consumed is abstracted from surface water, while in reality, this is 84% surface water, 16% groundwater (UNESCO, 2006). Water consumption is now limited to the amount of river flow, while in reality more can be consumed depleting groundwater reserves. These lower groundwater levels will reduce future river flow which will reduce future BWA. Neglecting this, results in predicted future BWA levels to be higher than they will be which increases the chances of violating the EFRs.

Alien vegetation and afforestation are seen as accepted changes which influence the runoff, it would be better if they were accounted as a BWF. Production forests are a BWF as they are created by humanity, alien vegetation is often indirectly caused by humans and therefore also belongs to humanity’s appropriation of the freshwater resource. This would allow policymakers to analyse if the benefits outweigh the costs of clearing out alien vegetation.

The last limitation regarding modelled runoff has to do with the arid regions (Kalahari desert). Many small rivers in these regions contain water for only a week a year if not less. Now the BWC is set on zero for most if not all months of the year. This can be problematic for the people living in these areas. I would suggest focusing only on groundwater in these regions as runoff is too unpredictable to be utilized.

5.2. Environmental flow requirements

For this study the EFRs are assumed to be the minimum amount of river flow for a sustainable river ecology, for the saltmarshes and estuaries at the mouth of the orange river, it is important that the mouth closes two to four times in ten years (Matthews, 2015). mouth closure is achievable if river flows during the low-flow season could be sufficiently reduced and timed to coincide with high-wave sea conditions when sand is washed into the estuary and deposited in the mouth. The river mouth hasn’t closed since the 1990s, the main reason for this is that dam releases have elevated low-flows during the dry season and drought periods (Matthews, 2015).

EFRs are seen as threshold values to sustain freshwater and estuarine ecosystems (Pastor et al., 2014), but it remains questionable if this threshold value really exists. This opinion is supported by the wide variety of developed EFR assessment methodologies of over 200 (Tharme, 2003), all these methodologies inherit the developer's ideas on requirements for a healthy riverine ecosystem. This translate to very different results, for the case of the Orange River basin 31 % of Natural runoff estimated by Orasecom (2010), 52 % estimated by the VMF method and 27 % estimated by Smakhtin et al. (2004). On the other hand, this thesis has reasoned that some violation of the EFRs is required to allow for some consumption. This would mean that any BWC set is therefore environmentally unsustainable.

There are also other factors which affect the health of a riverine ecosystem. Reservoirs have well-known detrimental effects by the impoundment of free-flowing river habitat, blockage of fish migration (Jager & Smith, 2008). Water quality also affects the ecosystem. It could be reasoned that there will also be a trade-off between the violation of the water quality standards and allowed pollution of the river due to uncertainty in the predicted runoff.

I propose the development of a tool which can quantitively assess the health of a riverine ecosystem and can incorporate the effects of both the quantity and quality of water on the ecosystem as well as the blockage of reservoirs and weirs. This tool should deliver a grade for the health of the ecosystem per sub-catchment. For example, a scoring system could be developed which better indicates the health of a river ecosystem like the figure below.

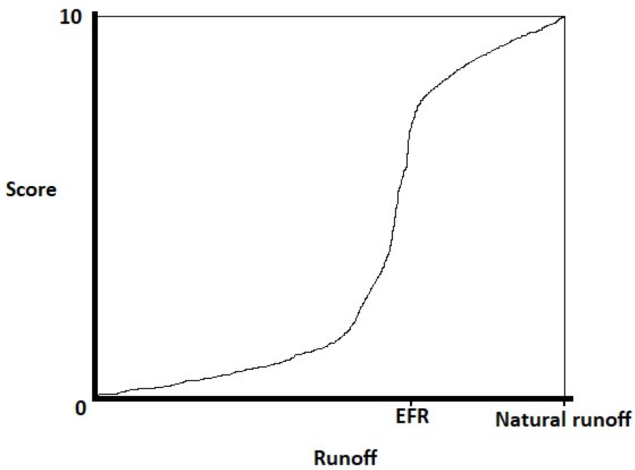

Figure 36: An example of a scoring system, which could indicate the effects of measures on an ecosystem in a better way

This would allow policymakers to analyse the effects of different measures on the ecosystem of a river in a better way. This is similar to the different management classes South Africa uses for describing a riverine ecosystem, but it is yet unknown what the difference between class A and B is. Therefore policymakers cannot know what impact their measures will have on the ecosystem.

5.3. Blue water footprint

The accounted BWFs are compared with water footprint data of national production of Hoekstra and Mekonnen (2012). Second, the BWFs within the Orange river basin are compared with the findings of two report (Orasecom, 2007), (Hoekstra and Mekonnen, 2011) and a paper (Lange et al., 2007).

Table 9: The blue water footprint of national production in South Africa for the period 1996-2005 (average values) (million m^3/year) and average annual water use within the Orange river basin.

BWFs whole of South Africa	**Hoekstra and Mekonnen (2012)**		**Results of this thesis**
Crop production	6412		3370
Industrial production	38		67
Domestic water supply	390		374
Animal water supply	282		-
BWFs within the Orange River basin	**Orasecom (2007)**	**Lange et al. (2007)**	**Results of this thesis**
Crop production	1800	1757	661
Other Agricultural usages	-	90	-
Industrial production	-	75	20
Domestic water supply	-	130	88
Mining	40	10	-
Orange – Fish Transfer	-	575	625
Vaal – Johannesburg transfer	-	550	897
Evaporation reservoirs	1750	-	1809
Total	4974[1]		4100
[1] Combination of both studies mean value taken if both studies provide data.			
Total (Hoekstra and Mekonnen, 2011) (includes agriculture, industrial and domestic BWF)	2144		769

From Table 9 can be seen that the annual BWFs of most sectors are very similar to the literature values, except for crop production. First of all the estimated BWF of crop production for the whole of South Africa by Hoekstra and Mekonnen (2012) is almost twice as large as the estimation in this thesis with the data from Hogeboom et al. (unpublished data). Both data sources use different methods to estimate the BWF of crops. These methods have a different approach to estimating the BWF of crops. The dataset of Hogeboom et al. (unpublished data) analyses the BWFs for a selection of 36 crop types. These crop types are compared to data of harvested area from each crop type (FAO, 2016) and this showed the 36 crop types cover 96% of the harvested area. This shows that the smaller selection in crops does likely not explain the large difference in BWF of crop production. The large difference is thus likely caused by the high uncertainty level in BWF estimations of crop production based on satellite data.

When looking at the BWF of crop production within the orange river (Table 9), the difference between the literature and the approach of this thesis becomes even larger. It is unclear how the data from the literature should be interpreted. Both studies determine the abstractions per region based on a water balance (water consumption = observed inflow – observed outflow). It could thus be argued that Orasecom (2007) and Lange et al. (2007) have likely included evaporation of small farm dams in the crop production value. This evaporation of small farm dams could explain a certain portion of the difference. However, it is still certain that BWF data of crops is uncertain.

Evaporation has been estimated for the larger reservoirs, but the smaller farm dams are neglected. These small farm dams might have a small individual impact which is unknown, but Mantel et al. (2017) estimated that the Orange River basin contains 58 906 of these small farm dams. Currently, evaporation causes 44 % of the BWF, but this might be a lot higher.

The uncertainty in this BWF affects the sustainability assessment of the current situation, but for the formulation of BWCs, the lack of certainty is not problematic. The spatial distribution of the BWF seemed to follow logical patterns and it thus gave a realistic picture of the demand not taking place at the location where the runoff was generated.

5.4. Forecasting runoff

From an environmental standpoint, BWCs are ideally formed dynamically, such that the cap is stricter in relatively drier months and less strict in relatively wet months (Hogeboom et al., 2020). Long-term predictions of runoff have significant uncertainties. In this thesis, the future runoff is predicted solely based on historical runoff, but this is not the best method to predict future runoff. To better predict runoff climate predictions together with historical runoff data could be used (Gelfan & Motovilov, 2009). Runoff predictions can especially improve by using climate predictions as South Africa is affected by El Niño Southern Oscillation (ENSO) (Lindesay, 1988). For the accuracy of climate predictions, the required lead-time becomes important. I would recommend research to be done on which lead times for a BWC would be appropriate for each different sector.

5.5. Allocation strategy

The applied allocation strategy is surrounded by limitations, neglection of 38 large reservoirs and assuming evaporation to be independent of the storage is a large step away from reality. Together with the optimization technique of a calculated guess makes this allocation strategy not useful for policymakers.

There are at least two boundary conditions to be added to the allocation strategy. The water act of the Republic of South Africa (1998) made aquatic ecosystems along with basic human needs the only two sectors with a legitimate right to water. This water act does not describe what should happen when the basic human needs conflict with the aquatic ecosystems needs. Falkenmark and Widstrand (1992) consider basic human needs a sacred right and give them top prioritization. Basic human needs could be assigned as boundary conditions of which an allocation strategy should at least suffice. Flood protection could be considered as another basic human need. The reservoirs in the Orange River basin play a vital role in flood protection (Matthews, 2015). Therefore I would recommend adding this to the reservoir management strategy, such that the reservoir can fulfil the required safety standards. This is again a trade-off between safety and utilisation of reservoir capacity, but this has usually been decided by the government.

The Global Water Partnership defined Integrated Water Resource Management as a *“process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems”* (Global Water Partnership, 2000). From the literature study was found that equity is always an ambiguous concept, but maximisation of the resultant economic and social welfare is also difficult. Determining the social welfare and resultant economy of an allocation strategy is not only dependent on the size of the total water consumption allowed, other factors such as variability of the BWC throughout the year is also important. E.g. a farmer cannot take advantage of a BWC which is high in a few months and low in others. Further research should be done for designing an objective function which can quantify the social and economic welfare of a certain allocation strategy and research on which optimization techniques are most suitable for water allocation problems.

5.6. Toward policy uptake

The most important factor is creating awareness for the environmental problems related to unsustainable water consumption. This awareness should translate to electing policymakers who are willing to preserve the riverine ecosystem. These policymakers create the demand for BWC allocation strategies with appropriate criteria.

Second, prove is needed that implementation of BWCs helps to preserve the riverine ecosystem. It is yet unclear how a reduction in the frequency of violation of the EFRs from e.g. 50 % to 25 % affects the actual ecosystem. Therefore efforts should be made to implement BWCs in some small river basin in the world just to test the procedure and prove of works.

Third, assumed that a farmer gets an assigned BWC of 100 units of water for the coming season. One could argue that since historically his BWF was 80% of what he withdrew from the river that he is now allowed to withdraw 125 units of water from the river. The farmer wants to use this limited amount of water as efficiently as he can. He might use a better irrigation technique, which could increase his BWF resulting in a BWF of above 100 and might result in violation of the EFRs.

There are countless of more hurdles to be overcome, such as a possible differentiation between a groundwater cap and surface water cap (Hogeboom et al., 2020). Therefore I would recommend for future research to investigate what steps have to be taken from determined BWCs towards policy uptake.

6. Conclusion

Humans and nature share the limited blue water resources. The continuous rise in human water consumption has a tremendous impact on global biodiversity (Vörösmarty et al., 2010). The blue water footprint in the Orange River basin is shown to violate the EFRs in many regions for 0 to 4 months of the year and some regions for more than 6 months of the year. A new severity of violation indicator was proposed to analyse the severity of violation of the EFRs and it showed that most sub-catchments which frequently violated the EFRs also severely violated the EFRs. Currently, the water resources of the Orange River basin are unsustainably used and capping water consumption is urgent to prevent overexploitation.

The objective of this thesis is to provide a methodology for formulating blue water caps on the spatial scale of sub-catchments taking inter and intra annual variability into account, which incorporates reservoirs, water transfers, the current blue water footprint while respecting the environmental flow requirements.

A methodology has been proposed which is shown to be able to quantify BWCs. This methodology uses a water balance model which was able to include water transfers and reservoirs on the level of sub-catchments. The BWCs were set on a monthly time scale to account for intra annual variability and either more precautionary or more risk-taking choices can be made in setting these monthly BWCs, reflecting inter annual variability. This choice can be made considering the identified trade-off between violation of the EFRs and utilization of available blue water. The objective has been reached and is visualised by the flow diagram in paragraph 3.4.

The maximum allowed consumption in a sub-catchment was shown to be higher when upstream inflow was taken into account compared to determining it based solely on the locally generated runoff. The total size of the BWC was shown to increase by 49% to 90% for 50% and 5% allowed violation of the EFRs respectively.

An allocation strategy which focuses on maximisation of consumption was adopted. The applied allocation strategy including reservoir management showed that the current BWF has to be reduced by 17.4% to 22% for 50% to 5% allowed violation respectively. Reservoirs were also shown to make the trade-off between utilizing BWA and violation of the EFRs less pronounced. They do this by making the otherwise not utilizable flow peaks available for consumption. Storing these flow peaks was shown to increase the BWC despite losses due to evaporation for the Vaal and the Gariep dam.

The added value to science from this thesis is that methodology has been provided on how BWCs can be set on the level of sub-catchments. This could be adopted by other water allocation models such as MEQAA (Farriansyah et al., 2018), WRAP (Wurbs, 2005) and CWAM (Wang et al., 2008). It is a middle step between Hogeboom et al. (2020) their quantification for entire river basins and personalised BWCs per household and company.

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Appendix A: Comparison of flow duration curves

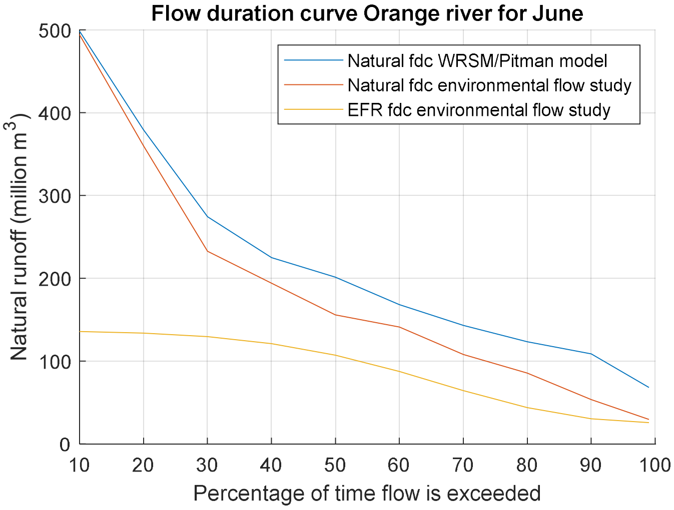

Figure 37: Flow duration curves (fdc) for June

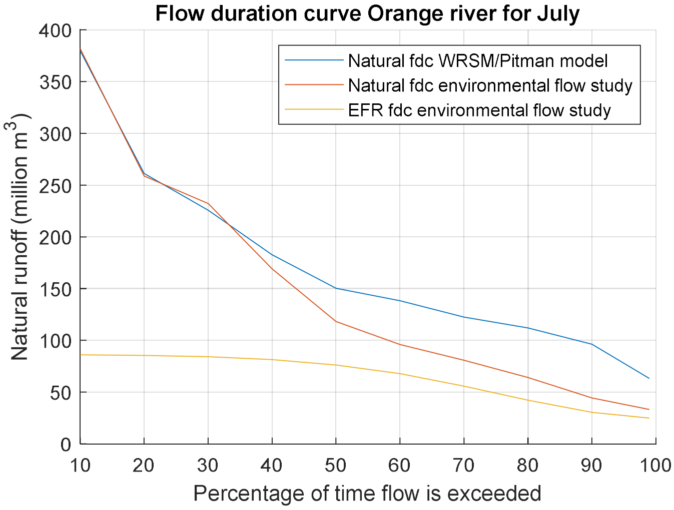

Figure 38: Flow duration curves (fdc) for July

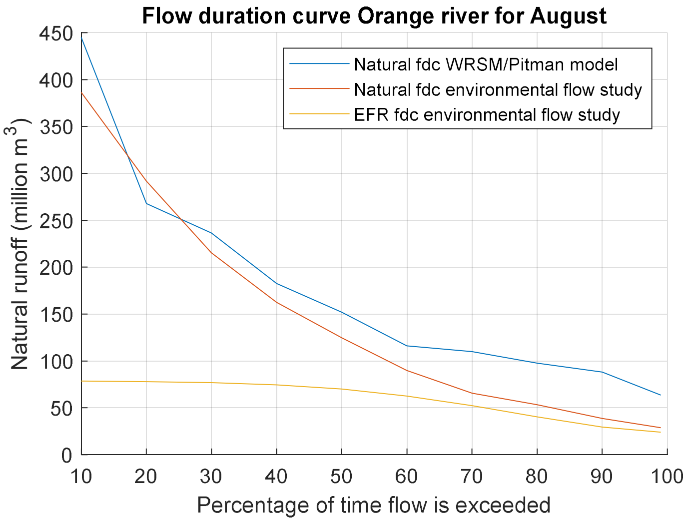

Figure 39: Flow duration curves (fdc) for August

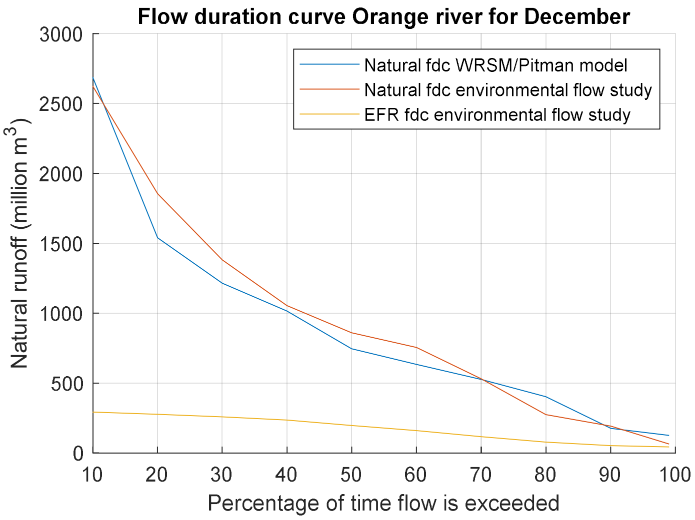

Figure 40: Flow duration curves (fdc) for December

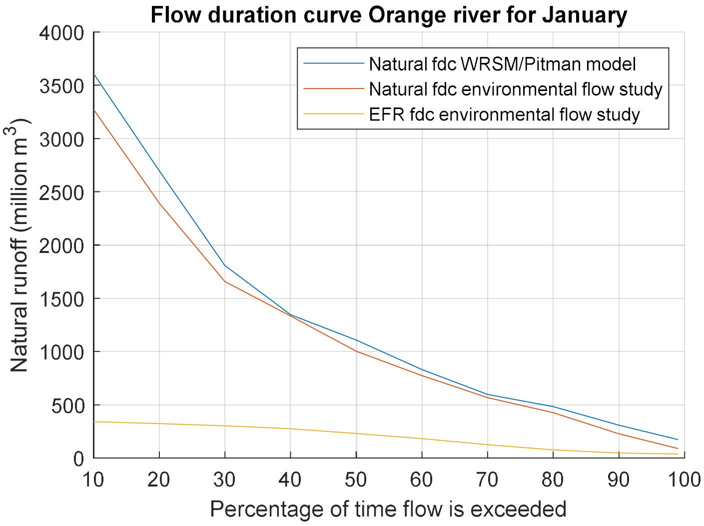

Figure 41: Flow duration curves (fdc) for January

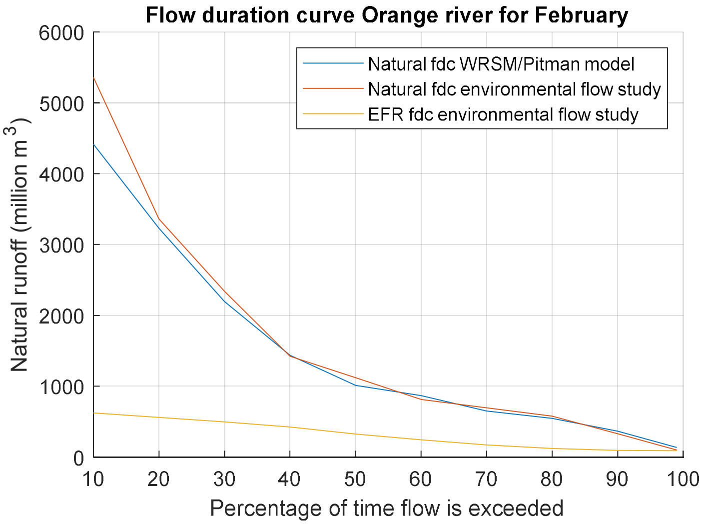

Figure 42: Flow duration curves (fdc) for February

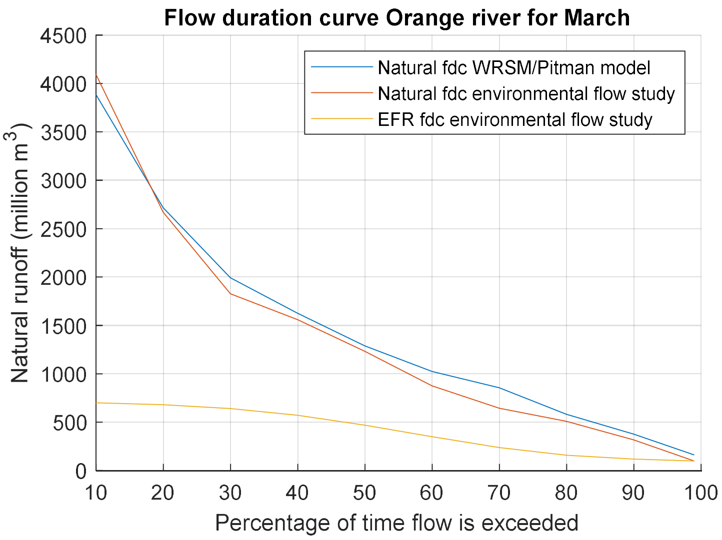

Figure 43: Flow duration curves (fdc) for March

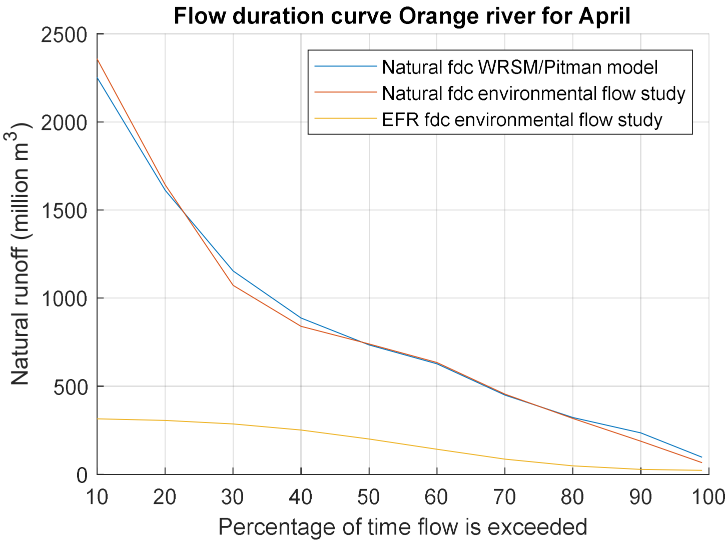

Figure 44: Flow duration curves (fdc) for April

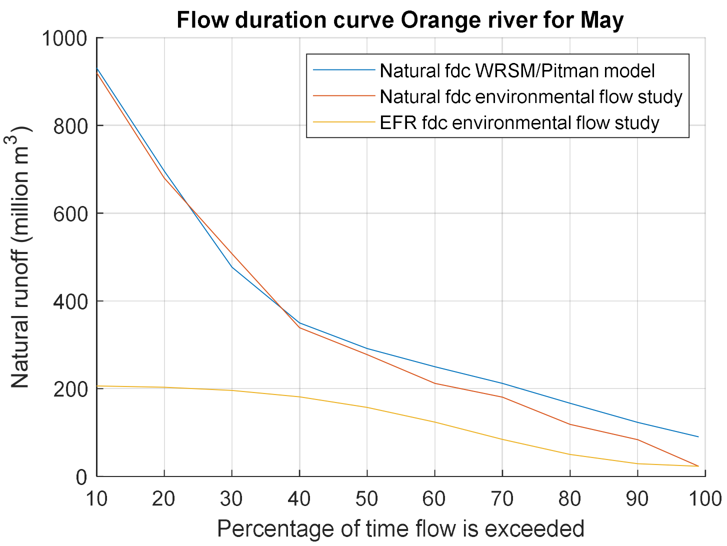

Figure 45: Flow duration curves (fdc) for May

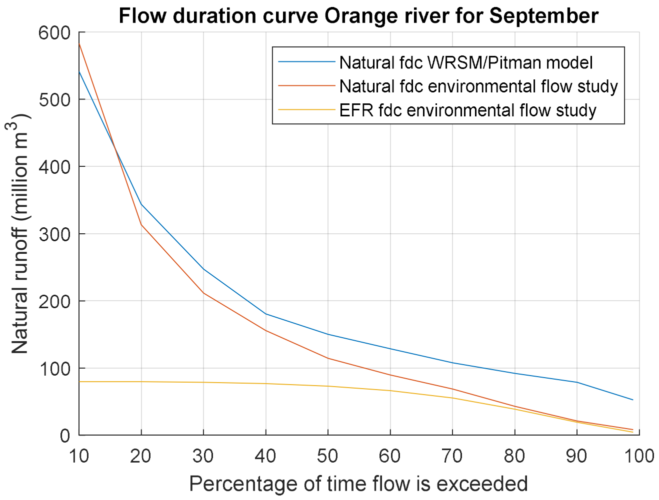

Figure 46: Flow duration curves (fdc) for September

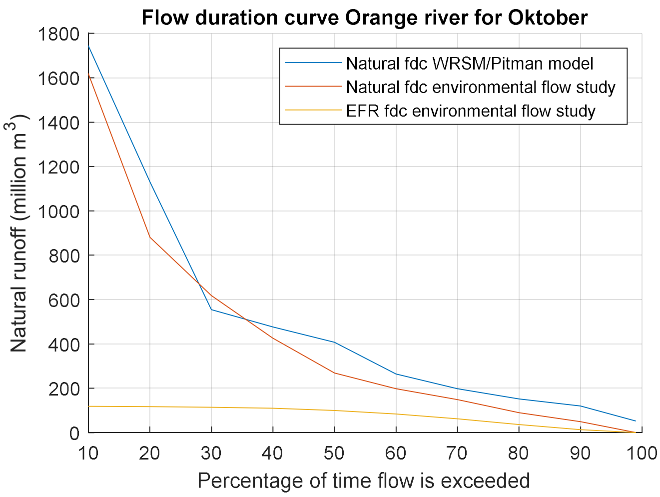

Figure 47: Flow duration curves (fdc) for October

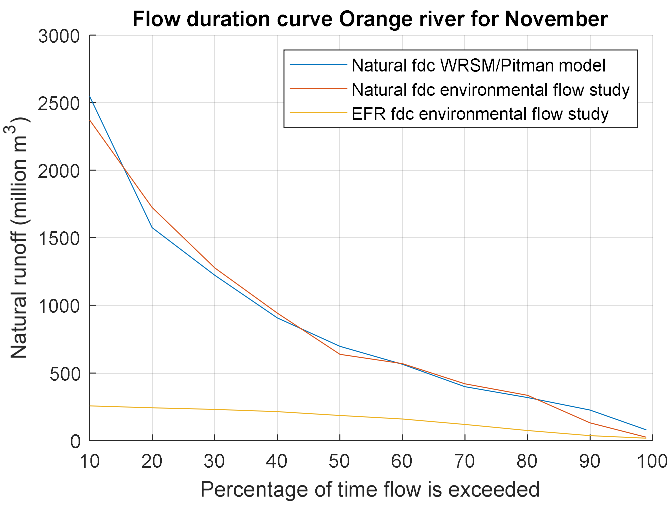

Figure 48: Flow duration curves (fdc) for November

From the previous figures 38 to 49 can be seen that the flow duration curves for natural runoff from the WRSM/Pitman model (Water Resources of South Africa, 2012) and the one retrieved from the environmental flow study (Orasecom, 2007) look visually very similar.

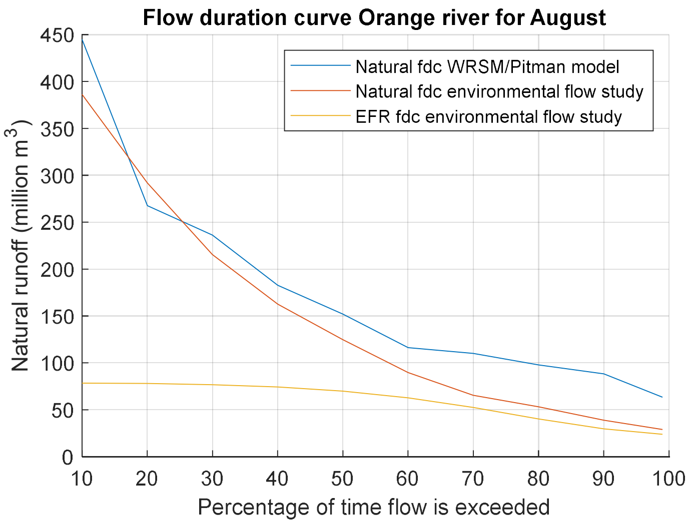

Figure 49: Flow duration curves (fdc) for August (winter)

In figure 50 above one of the largest differences between the natural flow duration curves is shown.

E.g. a month of august with natural runoff of 100 million m^3. The WRSM/Pitman model (Water Resources of South Africa, 2012) shows this flow is exceeded 80% of the time, while the model from the EFR study (Orasecom, 2007) says it is exceeded only 60% of the time. Therefore what the WRSM/Pitman model describes as extremely low flow is seen by the EFR study as slightly low flow. This can have implications on the EFRs.

Another point is that the FDC does not go below 10%, This means that in terms of EFR set no difference is made between a flow which occurs 10% of the time or a flow which only occurs 1% of the time. Thus the decision is made to apply the VMF method to compare the EFRs during high flows

Appendix B: Capacity table of Orange River reservoirs

Table 10: Capacities of the reservoirs in the orange river basin for which data has been provided by the Department of water and sanitation (DWS, 2019).

Code	Name	Start Date	End date	Region	Capacity (million m^3)
D3R002	Gariep	1971	2019	Upper Orange	4903.5
D3R003	Vanderkloof	1977	2019	Upper Orange	3092.4
C8R003	Sterkfontein	1974	2019	Vaal	2616.9
C1R001	Vaal	1936	2019	Vaal	2603.5
D1R002	Katse	1996	2019	Upper Orange	1519.1
C9R002	Bloemhof	1968	2019	Vaal	1242.9
D1R003	Mohale	2003	2019	Upper Orange	843.5
C1R002	Grootdraai	1980	2019	Vaal	349.5
C5R002	Kalkfontein	1938	2019	Vaal	325.1
C4R002	Erfenis	1959	2019	Vaal	206.1
C4R001	Allemanskraal	1976	2019	Vaal	174.5
D2R006	Knellpoort	1989	2019	Upper Orange	130.0
D6R002	Smart Syndicate	1922	2013	Lower Orange	101.1
C5R003	Rustfontein	1955	2019	Vaal	72.1
C5R004	Krugersdrift	1970	2019	Vaal	71.5
C3R006	Taung	2015	2019	Vaal	61.4
C3R002	Spitskop	1975	2019	Vaal	57.8
C2R008	Luciana Barage	2018	2019	Vaal	55.4
C9R001	Vaalharts	1940	2019	Vaal	50.7
C7R001	Koppies	1920	2019	Vaal	42.3
C5R001	Tierpoort	1923	2019	Vaal	34.0
C8R008	Fika-Patso	1999	2019	Vaal	29.4
C2R001	Boskop	1958	2019	Vaal	21.0
D4R004	Setumo	1995	2019	Lower Orange	20.7
D7R001	Boegoeberg	1983	2019	Lower Orange	20.6
C9R003	Douglas Storage	1977	2019	Vaal	16.2
C8R004	Saulspoort	1971	2019	Vaal	15.7
D4R003	Disaneng	1988	2019	Lower Orange	14.1
C2R005	Klipdrift	1972	2019	Vaal	13.3
D2R002	Armenia	1955	2019	Upper Orange	13.2
C5R005	Groothoek	1981	2019	Vaal	11.9
D1R001	Sterkspruit	2006	2019	Upper Orange	9.5
D2R001	Egmont	1938	2019	Upper Orange	9.1
C2R003	Klerkskraal	1969	2019	Vaal	7.9
C2R007	Rietspruit	1976	2019	Vaal	7.3
C2R002	Johan Neser	1923	2019	Vaal	5.7
D2R004	Welbedacht	1976	2019	Upper Orange	5.4
C2R004	Potchefstroom	1968	2019	Vaal	2.0
C2R006	Elandskuil	1976	2019	Vaal	1.2
D4R001	Leeubos	1948	2019	Lower Orange	1.0
				Total	18778.5