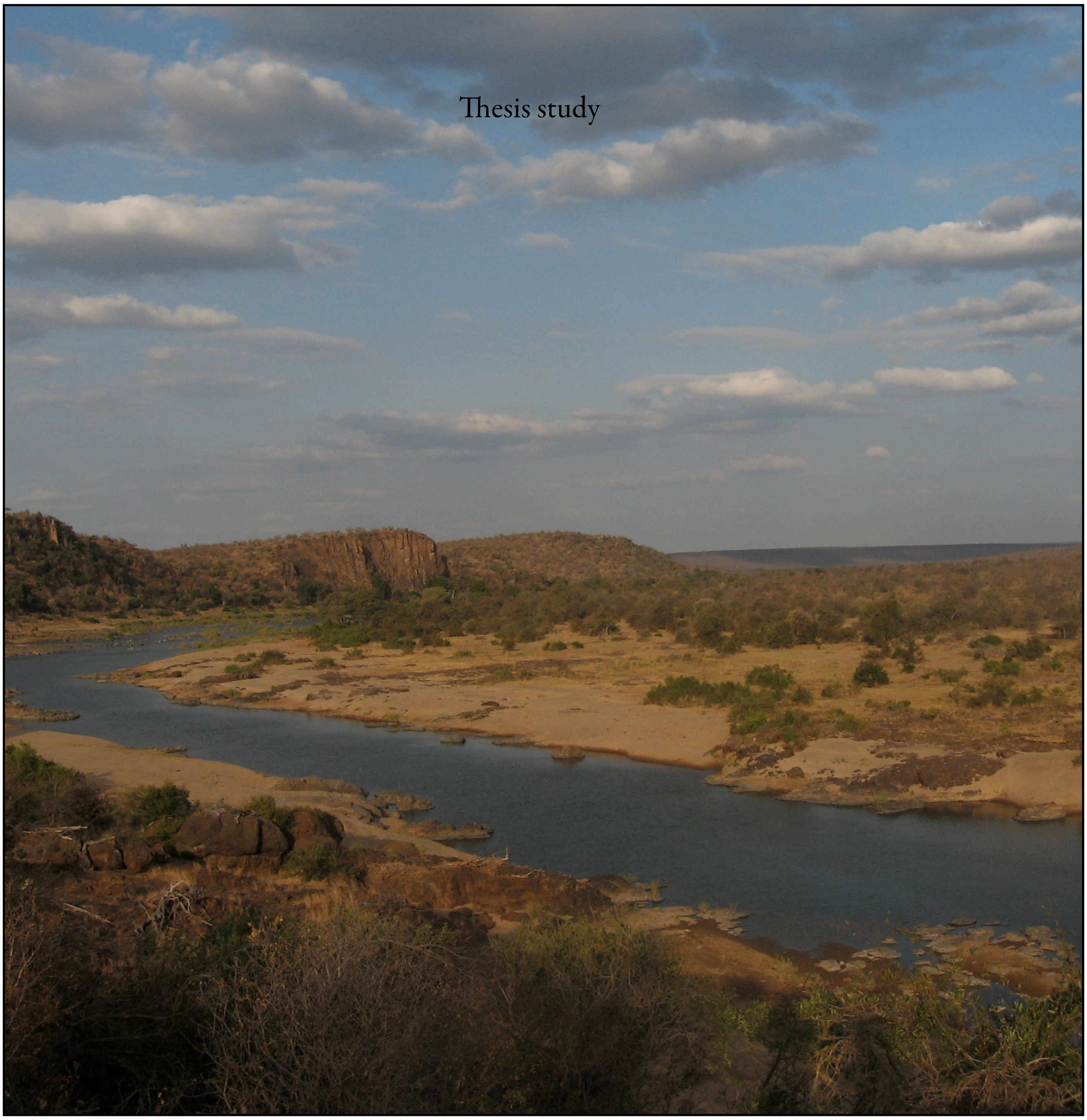
Validation & improving Smakhtin Environmental Flow Requirements Method



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Final Report

Validation & improving
Smakhtin Environmental Flow Requirements
Method

Thesis report

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"*We never know the worth of water till the well is dry*"

- Thomas Guller (1732) -

Preface

This research is a Master Thesis for the University of Twente (UT) and is part of the study Civil Engineering and management (main subject: Water Engineering and Management). This report describes an evaluation and improvement of a method that estimates the amount of water that is required by river ecosystems.

'If we knew what it was we were doing, it would not be called research, would it?'

Albert Einstein (1879 - 1955)

The quote indicates what characterizes research. Having a idea or being bewildered about something and the desire to find it out. Is it really as it is thought to be? Is there a snag? Before starting the thesis I had never heard of the term 'environmental flow requirements'. Did not know what to expect. So I just started to do the things and begin researching.
During the thesis someone told me that a thesis is like 'doing a road-cycling race without the route markers, you have to find your own way'. After continuous cycling and checking of the map, eventually I found the final straight and go across the line.

There are many who helped me during my 'ride'. In the preface they are usually mentioned by name, e.g. I would like to thank prof.dr.ir. Arjen Hoekstra en dr.ir. Denie Augustijn of 'University of Twente' for the patience, believe and of course for the advise, criticism and suggestions. These are the only two person that I mention by name.

And the rest? Though I do not mention you by name, I try to describe some of the ways in which your support helped me. You may have done it consciously or maybe unconsciously, still you supported me. And for that I am very grateful, thank you family and friends. Thank you because you have enabled me to go and study, had trust and believe in me, were realistic when needed and creative when wanted, made me smile and was there at the right moments, made it possible to visualize the numbers that i had and taught me how to do it, came with down to earth comments, prayers, just being there, saying a simple two-letter word, showing interest, distracting me in a good sense, smiling, made time to relax, encouraged and pushed me when needed and you ensured there was something called 'time for a (red) tea'.
If you do not recognize yourself in any of the above descriptions, don't worry. Apparently it is just as difficult to be complete with mentioning acts and events as it is to thank everyone by name. I still thank you for your support.

Paul Zeefat

Enschede, June 2010

Abstract

Rivers provide a range of valuable services to people. Besides people there is another water user, the river ecosystem itself. There are various economic and social methods to quantify the needs of people, while similar methods lack to describe the needs of ecosystems. Because the ecosystem is a so-called 'silent user', it is frequently left out of water allocation decision making and global water assessments. Smakhtin et al. (2004a) developed a method to estimate the ecological flow requirements (EFR) of a river system to keep it in a 'fair' condition and enable incorporation in global water assessments.

In accordance with the general accepted theory that EFR should be in line with the natural variability offlow regime, the Smakhtin method assigns two flow components: one to cope with the needs of the aquatic species throughout the year (a low flow requirement, LFR), the other to account for ecological processes that rely on flooding and desired channel maintenance (high flow requirement, HFR). Determinations offlow requirements are related to flow variability, in the Smakhtin method the flow parameter ratio Q_{90}/MAR is used to classify flow regimes, where low ratios indicate variable flow regimes and high ratios stable flow regimes, and is set as LFR. The HFR water recommendation is based on a Q_{90}/MAR ratio and it descends when the flows become more stable. When Q_{90} > 30% MAR no HFR is assigned. This study aims to validate the Smakhtin EFR method by using EFR case studies that determined flow requirements on local scale.

The EFRs are derived from ten case studies, located in Australia, the Netherlands and United States of America. In these studies the used EFR methods apply experts and/or computer models and pursue a sustainable river ecosystem. The recommended EFR is translated into a LFR and HFR component. The equivalent estimations of the Smakhtin method are constructed using associated recorded flow data. Through comparison of the LFR and HFR estimated by the Smakhtin method with the values derived from the case studies, the reliability of the Smakhtin method is evaluated. Trendlines and their correlation coefficients and a two-tailed t-test are used in the evaluation. Other flow parameter ratios, that characterize the variability in flow regimes are also used to examine their correlation with EFR.

Though only based on a limited number of case studies, the comparison showed that the Smakhtin LFR method did not describe a better correlation between LFR and Q_{90}/MAR than a trendline through the case study data. This is revealed by a statistical two-tailed t-test (10% significance level). The trendline, with similar weak correlation coefficient as the Smakhtin method, indicated a opposite approach than the one described by the Smakhtin method. Variable flows were considered, by the trend, to require larger volume of water than prescribed by Smakhtin LFR method, while stable flows need less. More than half of the other flow parameter ratios showed a similar, though weak, LFR trend. HFR trendlines also show an opposite trend than the one described by the LFR trendlines, with stable flows being assigned larger volume of water, and variable flows less. From the comparison of different flow parameter ratios it became clear that the flow regime of a river can be classified differently by these ratios.

Based on the performed comparisons, it is determined that the LFR allocations should be relatively higher for variable flows and lower for stable flows than suggested by Smakhtin. For a realistic EFR (= LFR+HFR) the HFR recommended by Smakhtin needs to be reversed to complement the new LFR model, leading to a new HFR model in which stable flows receive a high and variable flows a low HFR. The new HFR model is based on the flow parameter ratio that complied to this trend and gave the best correlation.

$$LFR = 35 * \left(\frac{Q_{90}}{MAR} * 100 \right)^{-0.42} \qquad HFR = 50 * \left(\frac{Q_{90}}{Q_{50}} \right)^{0.73}$$

Global application of the new EFR method, similar to the maps presented by Smakhtin et al. (2004a), showed that the new EFR model allocates lower volumes of water for EFR purposes than the Smakhtin method in basins where the Q_{90}/MAR is relatively high, i.e. rivers with stable flow regimes. It should be noted that in this study flow

parameters are based on actual flow data of regulated river systems while Smakthin's maps are based on simulated natural flows.
The comparison of local EFR studies shows that the assumption of Smakhtin that LFR = Q_{90}/MAR especially underestimates the low flow requirements for variable flows. In this study a new model is proposed for the LFR and subsequently the HFR. Since this model is only based on ten case studies with a limited range in flow variability and climatic conditions, more data is necessary to confirm the general trends found in this study.

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Glossary

EFR	term used in this study refers to the 'ecological flow requirement. It regards the water requirement of the ecology and does not incorporate the economic and social element regarding water demand.
FDC	Flow Duration Curve; curve presenting flow and the coexisting exceedence rate.
flow variability	the characteristic of a river; the variety in changes of flows within a river; stable flows have relatively small differences between the occurring flows. Increase in the existence of different flows and the relative difference in flow magnitudes lead to a more variable flow.
HFR	'high flow requirement'; flow assigned to comply the ecological processes (e.g. riparian vegetation) that rely on flooding and desired channel maintenance.
LFR	'low flow requirement'; flows assigned to comply the need of the aquatic species.
MAR	'mean annual runoff'; the average volume of river flow during a year expressed in volume per year, day or second (the term 'mean discharge' could also be used).
Q_{90}	flow that is exceeded 90 percent of the time.

1. Introduction

1.1. Environmental flow

*The Aral Sea once was the fourth largest inland lake in the world until from the 1960s the (former) Soviet Union commenced large-scale irrigation for agricultural plants in the Aral area. Irrigation water for the crops was ensured by withdrawing water from the Syr Darya River and the Amu Darya River, both major rivers feeding the Aral Sea. Combined with inefficient agricultural techniques this led to serious degradation of the rivers and the Aral Sea environments (*Whish-Wilson, 2002*). Pesticides were released in the ecosystem and river-, the delta-and the lake ecosystem deteriorated (*Micklin, 1994*). As a result of the large-scale irrigation projects and the neglecting of river system water demands the Aral Sea rapidly shrank leading to dust storms, a dramatic fall in commercialfishing, local climate change, reduction growing season, less drinking water and decrease in human health (*Whish-Wilson, 2002).

*The decline of the Aral Sea was not only predicted by the Soviet planners but, for reasons of economic growth, even justified. In 1987, when the drying of the Lake was clearly recognized, Soviet government water planners proclaimed: "May the Aral Sea die in a beautiful manner. It is useless" (*McCully, 1996*).*

The disappearing Aral Sea however is not unique. Water withdrawal led to environmental changes on various locations around the world. During the 1950s it was gradually recognized that environmental changes in the river systems were not only related to pollution, up till then considered as the most common reason of change. From the 1950s onwards river environmental degradation has also been related to flow regulation (King et al., 1999).

In order to meet the environmental needs of river ecology a minimum amount of water needs to be allocated to the river system. Various terms and definitions are used in describing this process, the most well known term being 'environmental flows' (others are for example 'instream water requirements', 'instream flows' and 'minimal flow'). During the 10th 'International Riversymposium and International Environmental Flows Conference[1] in Brisbane (2007), the term environmental flow has been defined and documented for the first time:

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

This definition considers the ecological, economic and social elements regarding river water demands. The requirements of pre-defined ecological objectives of the river system are presented in the 'ecological flow requirements' (EFR) (Marchand, 2003). For the economic and social elements similar flow requirements can be described. Combining all the requirements together will form, after some negotiations, an environmental flow (regime), hence the name 'environmental flow requirements'.

In general it is the environmental flow that is applied onto a river system. Several times studies and reports use the term EFR as an abbreviation of 'environmental flow requirements', although these studies do not take the economic or social elements into account. The requirements set in those studies are in fact ecological flow requirements. In this study EFR concerns the 'ecological flow requirements'. The EFR concerns the amount of water needed to ensure ecological sustainability of a river system, whereas environmental flow concerns the flow requirements in the whole range in order to come to a sustainable flow regime. In environmental flow the recommended flow does not directly represent the needs of ecological flow requirements, as they are an element of a larger set of flow requirements.

[1] Attended by over 800 scientists,economists, engineers, resource managers and policy makers from 57 nations.

1.2. EFR methods

Over the years various methods for ecological flow requirements (EFR) have been developed. Institutions, concerned or engaged in the topic, like International Water Management Institute(IWMI) and International Union for Conservation of Nature and Natural Resources (IUCN), have set up categorization tables of these various EFR methods. The categorization differs between IWMI and IUCN, regarding the label names and also (slightly) in the description and content of certain categories. For more information about the IWMI and IUCN categorization of EFR methods is referred to Tharme (2003) and Dyson et al. (1999) and eFlowNet.

The categorization table used in this study is mainly based on the IWMI table, except for the functional analysis method, which is extracted from the IUCN categorization table. The functional analysis is used as a substitute for the category 'holistic methods' which does not describe a method but rather a framework. The various EFR methods categories are briefly explained below. Table 1.1 summarizes the (dis)advantages of the used EFR methods.

Hydrological method
This EFR method is the most simple one and can be considered to act as a guideline. The ecological basis is minor or none, while the data requirements are low. The method uses primarily hydrological input, i.e. monthly or daily discharge data, to establish EFR. The recommendations of these methods can originate from more sophisticated EFR methods. Results of those methods are then remodeled as percentage annual flow or as a discharge similar to a flow that on average is exceeding a certain percentage of time during a year. Which is then used as a hydrological EFR method.
Examples: Tennant Method (Orth et al., 1981), Range of Variability Approach (RVA)(Richter et al., 1997)

Hydraulic rating method
This method is based on relatively simple hydraulic variables such as water width, depth, wetted perimeter and velocity at a (single) cross-section of a river channel. These variables are used as substitution for habitat factors of riverine biota. The assumption is that a combination of hydraulic variables can adequately represent the flow requirements for target species. Flow recommendations are presented as a minimum flow below which rapid loss of habitat is expected to occur.
Example: Wetted Perimeter Method (Gippel et al., 1998)

Habitat simulation method
This method has superseded the previous mentioned methods and is a step towards using computer models. It uses a similar approach as the hydraulic method. The models feature, among others, the possibility to incorporate more, and better relationships between indicative parameters and flow. It can use multiple river cross-sections and can also include out-of-channel components. Furthermore, it requires physical habitat data of the target species to indicate the suitability of an area. The flow recommendations are based on habitat areas that result from habitat-discharge curves. These curves show the suitability of an area for the various life stages or activities of selected key species.
Example: Physical Habitat Simulation Model (PHABSIM) (Bovee et al., 1998)

Functional analysis
Characteristic for this method is the attempt to understand (all) the links between hydrological and ecology aspects of the river system. It uses a broad perspective and covers many features of the river ecosystem. Information used in these methods include hydrological, hydraulic and biological data, as well as the considerable use of experts.
Example: Building Block Method (BBM) (King et al., 1998)

The hydrological and the hydraulic rating methods are usually applied in reconnaissance phases, whereas the habitat simulation and functional analysis methods are more suitable for more specific cases. However, the functional analysis methods could be applied in any phase, with the use of more expert(-ise) basis than general reconnaissance methods. The expertise needed for correctly interpreting the outcomes of the models increases with habitat simulation and functional analysis methods (see Table 1.1).

Table 1.1 Advantages and disadvantages of EFR methods adapted from Korsgaard (2006).

Method	Duration of assessment (months)	Major advantages	Major disadvantages
Hydrological	½	Low cost, limited data, rapid to use	Not site-specific, ecological links assumed
Hydraulic rating	2 - 4	Low cost, limited data, site specific	Ecological links assumed, single cross-section
Habitat simulation	6 - 18	Ecological links included, use of multiple sections	Extensive data collection and use of experts, high cost
Functional analysis	12 - 36	Covers most aspects within the system, use of multiple sections	Requires large scientific expertise and data, high cost

1.3. Problem definition

As mentioned before, awareness concerning EFR started around the 1950s, yet EFR and its application can still be considered a new area of expertise. This is illustrated by one of the outcomes of the River Symposium of 2007 in Brisbane that states that setting and implementing EFR is still 'learning by doing', regarding the relationship between flow alteration and ecological response (Brisbane declaration, 2007).

Not every time there are sufficient resources available to use the more sophisticated methods to develop EFR. Sometimes a lack of data is the constraint, while in other cases financial resources restricts the use of those methods. A simple method or model that could be applied worldwide without modification and still present specific and reliable EFR for each river does not exist and probably never will. Such a method would incorporate so many steps, it could hardly be considered 'simple'.

Smakhtin et al. (2004a) made a first attempt to developed an EFR model that could be applied globally. This EFR method will from this point onwards be referred to as the 'Smakhtin method'. The purpose of the method was to increase awareness of the necessity of EFR and attempt to develop an EFR method that could be included in global water resources assessments.

The Smakhtin method determines the EFR on the total river flow through a simple hydrological EFR method. A hydrological based EFR method could indicate, at first glance, whether current water withdrawals are below, passed or in acceptable level with regard to a fair ecological river system (Smakhtin, 2004a & 2007).
The flow requirements of the Smakhtin method are split into two parts. One part is to ensure an all year low flow (LFR), while another acts as a high(-er) flow that would normally occur in an annual flow regime (HFR). The low flow element is set at Q_{90}, i.e. the flow that is exceeded in 90% of the time. Smakhtin et al. (2004a) assume that Q_{90} is sufficient for ensuring a 'fair' condition of the river ecosystem. The HFR recommendation is an annual amount of water to be allocated. This volume decreases when river flow regime becomes more constant or stable. In general, stable flow regimes are expected to require lesser amounts of high flow water allocation, but do require large amount for 'low flow' allocation.

Smakhtin et al. (2004a) assume that the ecological system of a river, with characteristics of a variable flow regime, is adjusted to everyday (low) flow circumstances. This sounds very plausible, but it may not be so simple. Q_{90} is and will be the flow or discharge that is exceeded 90% of the time. When that flow, in case of a variable flow regime, appears to be relatively low compared to the average annual flow, it does not automatically offer a reason for the river ecosystem to act and cope well with drier periods. In fact, 90% of the time the system will endure higher flows. And so, it can be just as easily stated that the ecological system of the river is maybe 'badly' adapted to a Q_{90} low flow requirement. The river ecology may actually need a larger amount of water allocation.
In river systems with a variable flow regime the relative difference between Q_{90} flows and other occurring flows are large, and considerably larger than for more stable flow regimes. Therefore the LFR assumption of the Smakhtin method is questionable and requires an investigations towards its (adequate) applicability.

The underlying theory of the HFR sounds reasonable and states that a river with a constant flow, or stable flow regime, has no need for high flows. Such relatively higher flows do not occur frequently in those rivers. Variable flow regimes on the other hand are assigned a large HFR as result of frequent flow peaks.

The process of validation of the Smakhtin method with the EFRs derived for various rivers can show if the Smakhtin method assumptions are correct. If its recommendations are precise enough and whether it provides a reasonable estimate of the 'true' EFR. If the method does not correctly cope with flow requirements than the river ecology is still not adequately dealt with. The main focus will be on LFR and there will be looked at how the HFR relates to the LFR and wether it still makes 'ecological and sustainable' sense.

1.4. Research objective and report outline

The research objective of this thesis is stated as follows:

"*To validate and if necessary improve the current conceptual global ecological flow requirements of Smakhtin et al. (2004a) by comparing its estimations with those derived for specific river EFR case studies.*"

Achieving the objective of this thesis will be done through an investigation of the established Smakhtin method. The boundaries and interpretation of the method will be studied, together with the implications towards research data. Combined this will present the framework of the thesis, and is presented in chapter two. Research data is obtained from literature of case studies that have established EFR for rivers sections. Chapter three presents the investigation of the case studies.
After collecting the research data, chapter four focuses on the evaluation of the Smakhtin method with EFR case study data. Furthermore, an analysis on the case study EFR results and various flow parameters is performed to find a correlation with EFR recommendations a new method is proposed to estimate EFR based in the case study data. In chapter five an extra set of EFR is used to validate the new proposed method and improve its parameters.. Global application of the established EFR models on large river basins of the world is done in chapter six. Chapter seven discusses the critical points in this study and chapter eight presents the conclusions and recommendations of the research.

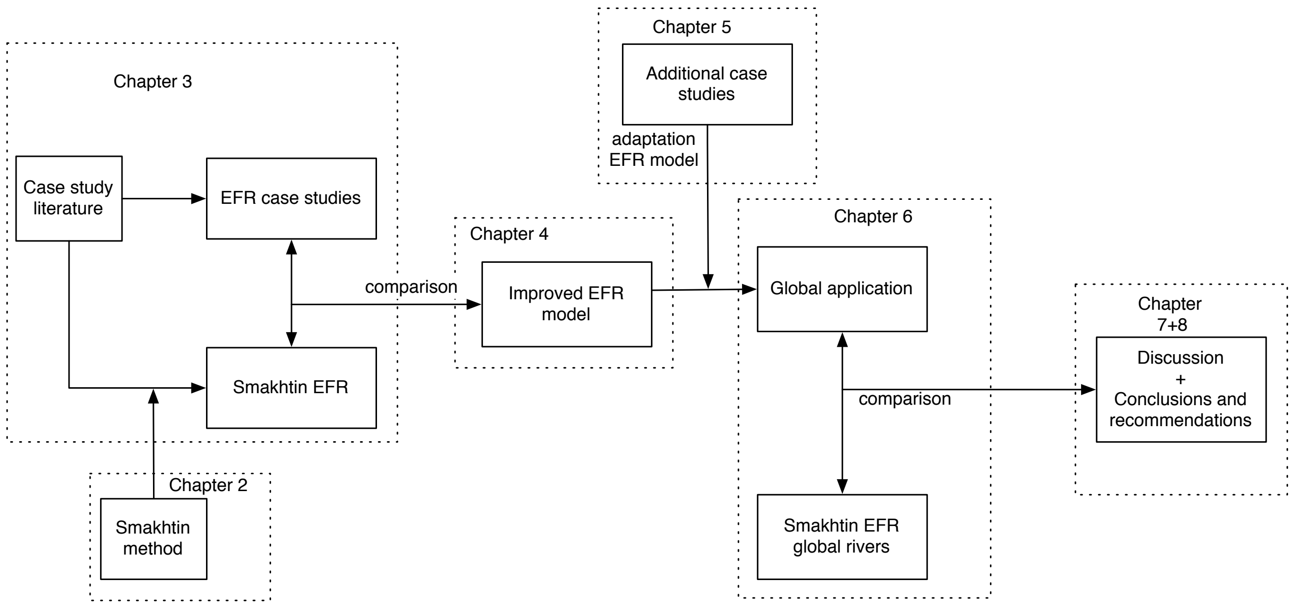


Figure 1.1 Research model.

2. Smakhtin method

This study is about validating the Smakhtin method. In this chapter the Smakhtin EFR method is described and discussed. It presents the concept of the method and interpretations that are made in this study concerning its application. This chapter will also show an approach to translate the EFR of the case studies into forms which can be compared with EFR results of the Smakhtin method.

2.1. Method description

The Smakhtin method can be characterized as an hydrological EFR method. It represents a global applicable method for allocating water to the river ecosystem (in a reconnaissance phase). It consists of a low flow recommendation (LFR) that is assumed to represent the minimum water requirement for the aquatic species for the entire year. And a high flow recommendation (HFR) that stands for the 'quickflow' component of a flow regime. It addresses channel maintenance, wetland flooding, vegetation recruitment and acts as stimulus for spawning and migration processes. The EFR is the summation of both flow requirements.

The EFR recommendations, specially the LFR, of the Smakhtin method are meant to keep the river ecosystem in 'fair' condition. In Smakhtin et al. (2004b) 'fair' is described as a condition that is considerably modified from its natural state. The biota of the system is disturbed and species have been lost and dominance of exotic species can occur.

In the Smakhtin method it is assumed that the ecology of the river system is adapted to its flow regime. Based on that, the LFR is assigned to the Q_{90} flow parameter; an indicator for (extreme) low flows. This is the flow that is exceeded 90 percent of the time. Its value is determined through the use of a flow durations curve (FDC). These curves present a cumulative distribution of the recorded river flow and sets the probability of occurrence rate of these flows (see Figure 2.1). More on development of FDCs is presented in chapter 3.

Table 2.1 Smakhtin conceptual EFR method (Smakhtin et al., 2004a).

Low Flow Requirement (Q_{90}; LFR)	High Flow Requirement (HFR)	Comment
If Q_{90} < 10% mean discharge (MAR)	then HFR = 20% MAR	Basin with very variable flow regimes. Most of the flow occurs as flood events during the short wet season.
If 10% MAR ≤ Q_{90} < 20% MAR	then HFR = 15% MAR	
If 20% MAR ≤ Q_{90} < 30% MAR	then HFR = 7% MAR	
If Q_{90} ≥ 30%MAR	then HFR = 0% MAR	Very stable flow regimes (e.g. groundwater dominated rivers). Flow is consistent throughout the year. Low flow requirement is the primary component.

A stepwise HFR recommendation is established based on the results of studies by Hughes et al. (2000) and Hughes (2000). The HFR is set in accordance with the flow regime variability of a river (see Table 2.1). This variability is established by a ratio Q_{90} and the mean annual runoff (MAR). Very stable flow regimes (high Q_{90}/MAR) are assigned no HFR as in those regimes such higher flows do not occur frequently. With increasing regime variability these higher flows become more distinctive and important, and thus the recommended HFR becomes higher.

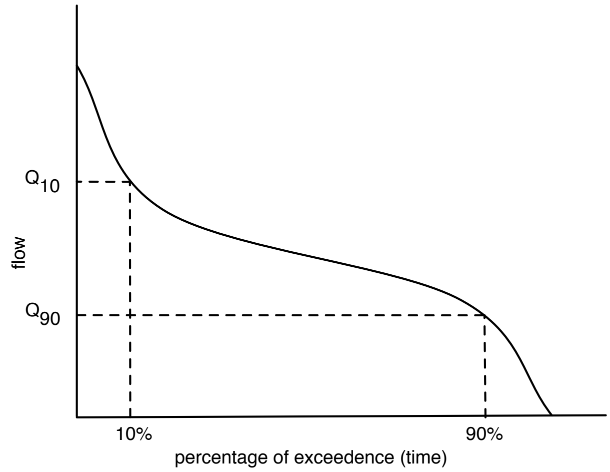


Figure 2.1 Example of a FDC and visualization of Q_{10} and Q_{90} flow.

2.2. EFR Interpretation

Table 2.1 describes the method of Smakhtin et al. (2004a). However, it can not be used without making some interpretations about its application. For example, the method does not explicitly mention any timing or period in which HFR flow should be allocated. Furthermore, there is no reference of how LFR and HFR relate to each other, specially when the latter is being applied. Two main issues are described below. These concern compensation of flows when the flow requirements could not be met and wether the HFR is to be considered an additional amount of water.

Flow compensation
Application of the LFR on a daily basis coincides with flows that are higher or lower. A Q_{90} automatically implies the occurrence of such circumstances, on average 10 percent of the discharges are lower. At those moments the question of compensation of flow is raised. When the natural flow appears to be lower than Q_{90}, it could be compensated on later dates with a higher discharge (see dotted line in Figure 2.2.c and d).

Set-up
The LFR can be viewed as a continues 'block' of flow with a duration of 365 days. At certain periods the HFR is superimposed, on the LFR, as a certain percentage of MAR. In that case the HFR is regarded as an additional flow (see Figure 2.2.b and d). With HFR not considered an additional flow, the LFR 'block' will be interrupted (see Figure 2.2.a and c).

Selected approach
In this study the use of a continues LFR flow is selected. This is based on the fact that Smakhtin et al. (2004a) states that EFR equals the summation of LFR and HFR. For the HFR there is no time period presented. In absence of such a period the LFR has to be considered as a continues 'block'. If it was not viewed as such, than a temporary interruption by the HFR would result in the LFR being lower than the percentage of the Q_{90}/MAR which Smakhtin states as being equal to LFR. The result in that case is an EFR that will not equal LFR plus HFR.
Here is chosen not to use 'flow-compensation'. Since Smakhtin et al. (2004a) state that Q_{90} equals the LFR, it implies that lower flows can occur. The applied flow is either the required flow or a lower natural occurring flow.

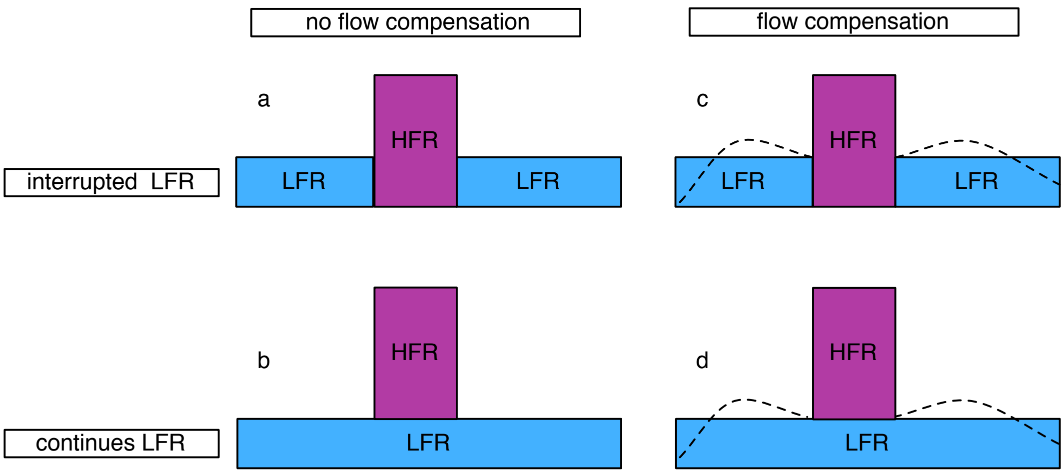
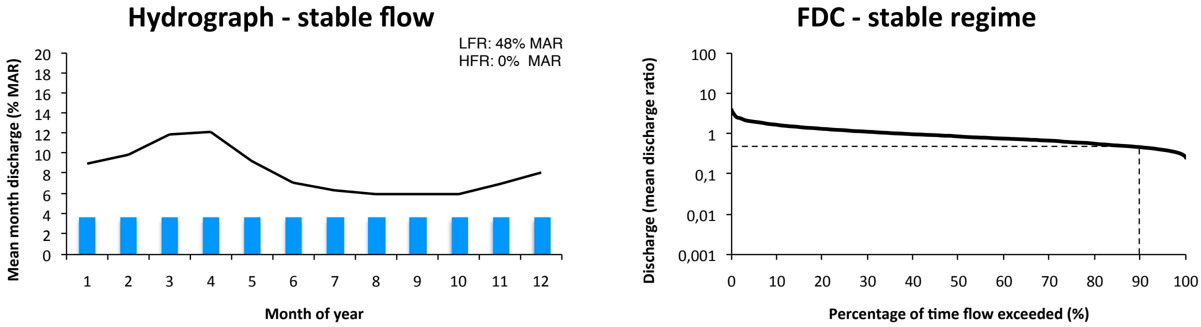


Figure 2.2 Schematization of possible interpretations of the LFR and HFR as defined by Smakhtin et al. (2004); LFR and HFR plotted for illustrative purposes only. The dotted line schematizes possible application of flow compensation for LFR.

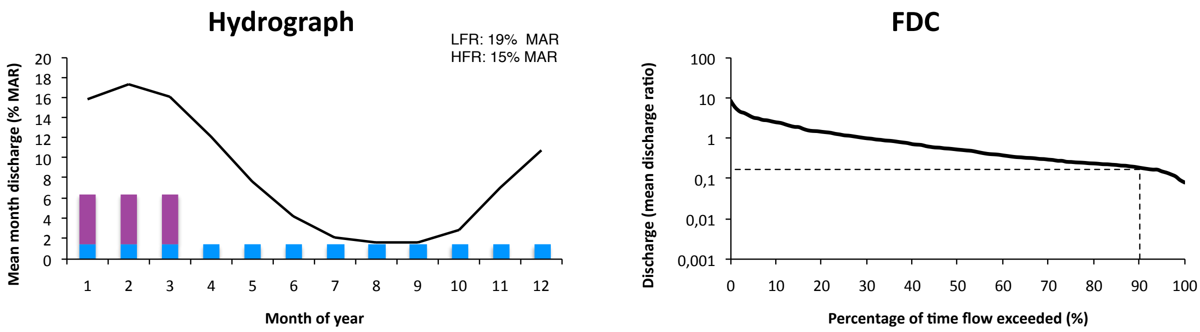
2.3. Application example

For illustrative purposes the Smakhtin method is applied on three example flow regimes (see Figure 2.3). The flow parameter Q_{90} and MAR are obtained from the FDCs and hydrographs and HFR can subsequently be derived by using Table 2.1. Note that the exceedence percentages of the FDC are plotted against a discharge divided by the mean discharge to enable comparison between curves.

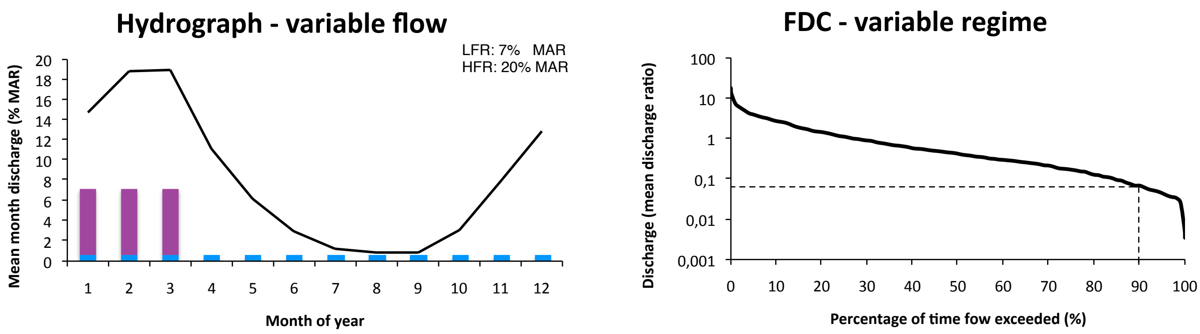
The example flow regimes start with a stable flow regime (Figure 2.3.a) and the regime becomes more variable in the other graphs (Figure 2.3. b and c). The hydrograph presents mean monthly flow values, while the FDC is constructed from data consisting of a list of daily discharges over a period of years. As it represents all the data and not merely an average, the FDC could show flow values higher and lower than those of the hydrograph.
The low blue colored bars represents the LFR and equals a conversion of the daily Q_{90} flow to a volume of water per year. This value is in this case divided by by twelve to obtain the monthly equivalent. Figures 2.3.b and c also have higher purple colored bars in the first three months. These columns represent the recommended HFR for those rivers. The Q_{90} of the stable flow is more than 40% of the MAR and as a result it not assigned any HFR. As the EFR graphs have only an illustrative purpose, no judgement should be made from the period and magnitude in which the HFR is applied; the HFR is distributed on a nonspecific number of months.



a.



b.



c.

Figure 2.3 Application of Smakhtin method on example FDCs; starting with a stable flow regime (a) the regimes becomes more variable with an intermediate (b) and variable (c) flow regime.

3. Case studies

Environmental flow methodologies have been recorded in use in over 40 countries. Not all countries have applied EFR methods with the same intensity. South Africa, United States of America and Australia are countries that have incorporated EFR in their policy (Tharme, 2003). This chapter introduces, among others, the researched EFR studies, used methods and approaches, considered parameters and the recommended EFR.
The EFR case studies used in this study are of an 'higher level' than a hydrological EFR method. A 'higher level' of EFR method is assumed to provide more 'reliable' EFR results.

3.1. Reading guide

Prior to the description of the EFR case studies a number of assumptions and approaches are explained. These concern the method and data used to attain required flow parameters, used descriptions, the way in which certain elements are presented and the location of the case studies.

Flow parameters
The flow parameters are obtained through a FDC. In Figure 2.3 the use of a FDC is already illustrated. Recorded daily flows are used as input for the FDC development. The recorded flow data were freely available.
After obtaining the recorded flow, the data of all the years are selected and ranked from high to low: the highest receiving number '1' and the lowest 'n'. The Weibull-Gumbel approach is used to establish the exceedence probability of a certain flow. This approach uses the following equation (Shahin et al., 1993):

$$P = 100 * \left(\frac{r}{n+1} \right)$$

P denotes the chance that a certain flow is exceeded in percentage; r stands for the rank that has been linked to the flow; n is the number of flow observations in the data set.
High flows are assigned lower change of being exceeded and lower flows higher chances. It should be noted that the Weibull-Gumbel approach can assign different flow exceedence ratios to similar flows.

All the FDC graphs in this study are plotted on logarithmic scale and against flow that is divided by the mean discharge, on the vertical axis. This procedure enables comparison between the FDCs of the different EFR case studies. The Q_{90} and MAR are expressed as annual volumes at the FDCs to illustrate the the annual allocation.

EFR description
Comparison of case study EFR with those of the Smakhtin method requires that the flow recommendations of a case study are converted into a LFR and HFR (see chapter 2). LFR and HFR are based on the flow objectives. Flows that are assigned to comply, in general terms, the needs of the aquatic species are considered to be characteristic for LFR. The main objective of the high flows concern for example channel maintenance and stimulating certain activities. In the 'Flow requirements tables' of chapter 3 the LFR and HFR are highlighted by a blue and purple color, respectively:

LFR HFR

On several occasions the EFR of the case studies presents a range of discharges and/or a duration for a flow event, e.g. 8-10 m^3/s for 4 to 6 days. This study aims to be cautious with the flow requirements. Therefore, in most of these occasions the maximum discharge and longest duration are selected for those events. Reflecting back to the previous example this means a flow of 10 m^3/s would be selected with a duration of 6 days.

The LFR and HFR of all case studies are presented in paragraph 3.11 and appendix I. The parameters needed to construct the LFR and HFR can all be obtained from the corresponding flow requirements table and FDC.

Case study locations
Worldwide spreading of cases is desired to explore global aspects concerning EFR application. It is about gathering information from various kinds of flow characteristics. Studies of rivers around the equator, between northern and southern tropic, would provide different flow regime characteristics than those around the north and south tropic flows.

Figure 3.1 Locations EFR case studies.

Figure 3.1 encircles the areas of the described case studies. The locations are:

- Bill Williams River, USA
- Border Meuse, NED
- Lower Thomson River, AU
- Lower Macalister River, AU

Reasons for selecting these studies are the distribution over the world and that it incorporates different climatic regions. The climatic regions are arid for the Bill Williams River, around the Tropic of Cancer, while the rest are in more temperate climates. The climatic conditions in the south-eastern part of Australia are more temperate than would be expected from the corresponding latitude.
Another major reason is a lack of publicly available EFR case studies and FDC data on Internet. Most studies consist of a incomplete annual EFR recommendation, only use an hydrological EFR method, do not present a EFR flow value but just a description of its EFR objectives in words; etc. This limited the number of studies that could be used, for this study.

3.2. Bill Williams River

3.2.1. River description

The Bill Williams River (BWR) runs through the western region of Arizona, USA (see Figure 3.2). It extends from the confluence of the Big Sandy and Santa Maria rivers to the Colorado River at Lake Havasu. The section portrayed in this study concerns the watercourse downstream of Lake Alamo to the Colorado River. Lake Alamo is a result of the construction of the Alamo Dam in 1963.

The BWR flows through terrain alternating between narrow canyons and wide valleys. Human activity along the river is minimal, though there are recreational activities like fishing, camping and wild life watching. Currently there is a single cotton farm and small patches of certain valleys are used for cattle grazing.

The climate characteristics of the region can be classified as resembling a desert climate, BWh typology of Köppen climate classification (Peel et al., 2007). The information used in this paragraph, and further on of BWR case study description is from Shafroth et al. (2006).

Figure 3.2 Location Bill Williams River in Arizona, USA (source: Shafroth et al., 2006).

3.2.2. Hydrology

Figure 3.3 presents the FDC of the BWR. The hydrological data is obtained from US Geological Service (USGS) and is publicly available on Internet (USGS). The data consists of measured discharges at a gauge station downstream of Alamo Dam, station number: 09426000.

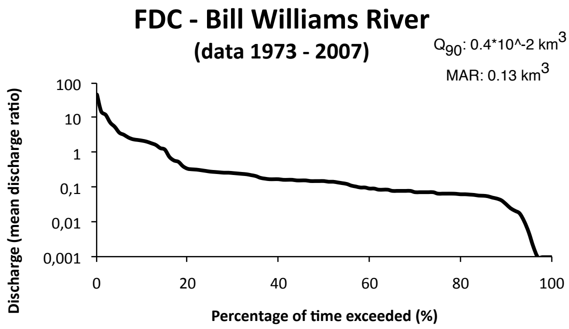


Figure 3.3 Flow duration curve of the BWR downstream of Alamo Dam.

3.2.3. EFR method

The EFR method can be categorized as a functional analysis method. The EFR is established through a workshop with experts. Three different habitat regions are considered (species examples are included):

- Aquatics (fish and aquatic macro-invertebrates and amphibians)
  - Longfin dace, speckled dace and roundtail chub
- Riparian-Bird (riparian vegetation and birds)
  - Southwestern willow fly catcher, western grebes (Aechmophorus occidentalis)

- Non-riparian (mammals, reptiles, amphibians and floodplain invertebrates)
    - ✳ Beaver, ground snake, southwestern toad

The latter two groups consider the vegetation, for its vital role in supporting fauna. Majority of the species appear to be dependent on cottonwood-willow habitat, forests and open floodplains are also considered an important factor.

3.2.4. EFR study

The main intention of the EFR is to maintain current aquatic habitat and riparian vegetation. Additional intend is to generate natural disruption circumstances as well as ensuring hostile circumstances for non-native species.
Eight cross sections have been selected along the length of the watercourse to represent different characteristics of the river. The effects on these cross sections of flows, ranging from zero to over 1000 m³/s, are modeled. The flow velocity, water depth and wetted perimeter are the parameters abstracted from these models. Based on these parameters the expert groups established the EFR for the entire length of the watercourse (see Table 3.1). The exact process of determining EFR is not clarified and can therefore not be enlightened.

3.2.5. Flow requirements

The baseflows preserve the riparian vegetation and the aquatic habitat, while higher flows are set to enable spawning of fish, creating disturbances, recruitment of materials and refreshing habitats.

Table 3.1 EFR Bill Williams River.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum baseflow: 0.6 m³/s; up to 2 months; rare; gradual rates of change											
Common baseflow: 0.6 – 1.4 m³/s											
	127.4-141.6 m³/s; 1 in 3 yrs; 7-10 days					28.3-56.6 m³/s; short (hours); rapid; 1 in 5 yrs					
	5.7-11.3 m³/s; 2-4 weeks; 1/yr					2.6-14.2 m³/s; short (hours); rapid; 1 in 2 yrs					
		283.2-849.6 m³/s; 2 day peak; gradual change rate (2-4 weeks); 1 in 5-10 yrs						> 849.6 m³/s; 1 in 25 yrs; <2 days; rapid change; best after 1 Oct			
> 849.6 m³/s; 1 in 25 yrs; <2 days; rapid change										This period also	

Note: Recommended flows have been converted from ft³/s.

3.3. Border Meuse

3.3.1. River description

Large part of the Border Meuse runs along the border between the Netherlands and Belgium (see Figure 3.4). The case study investigates the river section between the villages Borgharen and Stevensweert, the Netherlands. Upstream end of the section is bounded by a weir at Borgharen (see lowest purple dot in Figure 3.4). Further downstream there are no flow regulation constructions in this river section.

The Border Meuse is originally a pool riffle system with shallow fast flowing sections and deeper slower flowing water parts. Abrupt fluctuations in discharge, caused by upstream weirs and hydropower plant, result in flushing of certain macro-invertebrates and juvenile fish species. Former gravel excavation have lead to deep incisions of the main channel. The floodplains have agricultural functions and are rarely flooded.

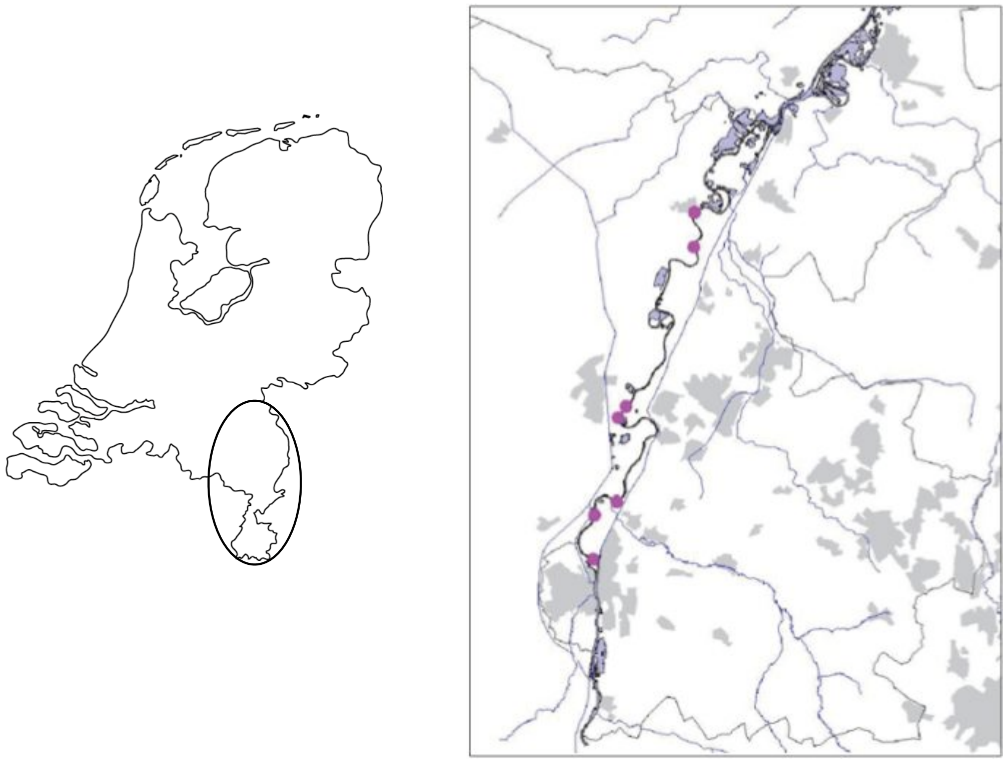


Figure 3.4 Study area Border Meuse (source: RWS-RIZA, 2006).

The climate can be characterized as a maritime temperate climate with precipitation in all seasons. Köppen climate classification is Cfb (Peel et al., 2007). The process and EFR results are described below and are obtained from RWS-RIZA (2006).

3.3.2. Hydrology

Figure 3.5 presents the FDC of the Border Meuse. The daily flow data is obtained from Waterstat, gauge station 'Borgharendorp' and is publicly available on Internet (Waterstat).

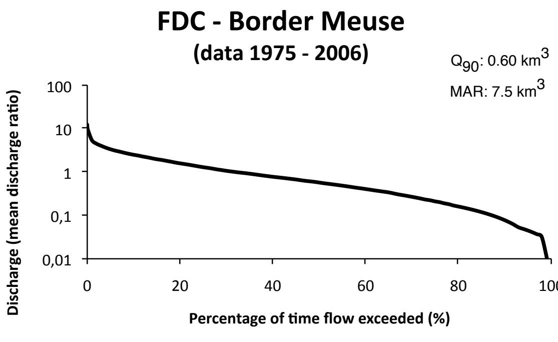


Figure 3.5 Flow duration curve Border Meuse at Borgharen (NED).

3.3.3. EFR method

The method RHASIM (River Habitat Simulation Model) (RWS-RIZA, 2006) is used, which can be categorized as a habitat simulation method. It is a two dimensional model based on the more well known PHABSIM (Bovee et al., 1998). The model consists of three modules:

- water motion;
- water quality;
- habitat suitability indices.

3.3.4. EFR study

The aim of the EFR study was to halt the current deterioration and to develop a sustainable river system in which characteristic species can develop and to better utilize the ecological potential of the Border Meuse. The Barbel ("Barbus Barbus") is selected as representative for these characteristic species. This species is highly dependent on flow velocity and water depth. It is assumed that when circumstances are suitable for the Barbel, it should also be suitable for the other characteristic species

For RHASIM the total river section was divided into cells and than incorporated in the model. The modules (see paragraph 3.3.3) are run for each individual cell. 'Water motion module' provides the flow velocity and water depth. Here this is supplied by WAQUA, a two dimensional water motion model.
The 'water quality module' requires input from field and laboratory measurements. The parameters used in RHASIM for water quality are suspended particles, temperature and oxygen level.
'Habitat suitability indices' describe the ecological requirements for each life stage of the Barbel. These needs regard flow velocity, water depth, substrate, water temperature and oxygen levels. Combined with the modeled data these ecological requirements of the Barbel result in describing the suitability of the habitat of each cell. By using different discharges in the model, a range of habitat suitability is developed from which the 'optimum' flow can be determined. An EFR is established for the entire length of the river section.

3.3.5. Flow requirements

Table 3.2 presents the EFR established for the Border Meuse. The EFR case study displays the flow requirements for each season. These have been converted into the following monthly periods: spring (Apr-Jun), summer (Jul-Sep), autumn (Oct-Dec) and winter (Jan-Mar).

Table 3.2 EFR Border Meuse.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
10 m^3/s			50 m^3/s – for certain locations up to 100 m^3/s			30 m^3/s			10 m^3/s		

Flow fluctuations have high impact on species that are less mobile. The juvenile Barbel and during the breeding phase the Barbel is vulnerable for these conditions. The breeding period is sensitive to flow fluctuations as they create unsuitable breeding locations; making them too deep or too shallow. Juveniles Barbels prefer shallow waters with relatively low flow velocity, while for adult Barbels lower flows result in less appropriate habitat.

3.4. Lower Thomson River

3.4.1. River description

Located in Victoria State in Australia, the Lower Thomson River flows from the Thomson Dam to its confluence with Latrobe River. Construction of the Thomson Dam started in 1976. Downstream of the dam there is a second regulation construction, the Cowwarr Weir which is constructed in 1957. Figure 3.6 shows the location and the reaches that have been investigated in the EFR study.
The climatic circumstances are characterized as a maritime temperate climate with significant precipitation in all seasons, Köppen classification symbol is Cfb (Peel et al., 2007). Information of this EFR case study is obtained from EarthTech (2003) and TMEFTF (2004) and are used in the study description as presented below.

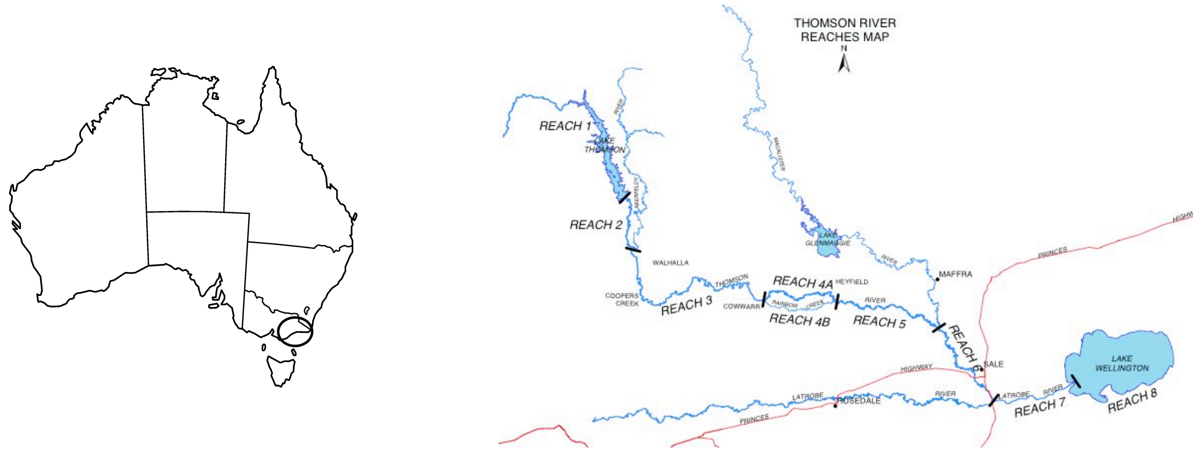


Figure 3.6 Location of Lower Thomson and Macalister River; Lower Thomson River study reaches (source: EarthTech, 2003).

3.4.2. EFR method

The FLOWS EFR method (NRE, 2002) can be characterized as a functional analysis method. A multidisciplinary technical panel is used to provide the resources for the FLOWS method and to make the interpretations to establish EFR. The panel consisted of experts on:

- geomorphology;
- hydrology;
- hydraulic modeling;
- riparian vegetation;
- macro-invertebrate and fish ecology.

3.4.3. EFR study

FLOWS uses two stages to establish EFR. The first stage comprehends collecting data in the study area concerning the ecological, geomorphology and hydrology aspects. Based on that information key reaches are identified. These reaches are regions of the study area that represent the characteristics of a section along the river. Sites are selected within these reaches to be representative for these specific ecological and hydrological features of the reach. Field assessments at the selected sites result in the establishment of flow objectives. These objectives concern the biodiversity and ecosystem processes.

The second stage of the FLOWS method consists of a survey at the selected sites to enable the construction of a hydraulic model. A cross-sections survey describes the channel in detail and also, to a lesser extent, the floodplain. 'HEC RAS' is used as hydraulic 1D model to visualize the hydraulic parameters for any given flow for the obtained

cross-sections. This model can also determine the flow that is required to meet the requirement of certain species, for example certain depth to ensure fish passage.
The output of 'HEC RAS' is used in the Flow Events Method (FEM). This method allows to identify the geomorphic and biological processes that are affected by flow variability (Stewardson et al., 2003). The use of GetSpells (EarthTech, 2003), a hydrological analysis tool, enables the analysis of the frequency, duration and start of flow events around the threshold flows. The technical panel interprets the results of the models and translates them into an EFR.

Though the EFR case study is conducted for in total six reaches, only four are used in this study. Lack of hydrological data restricted the use of reach 3 and 4b. Reaches 1, 7 and 8 are not presented in the EFR study. The following paragraphs present a short description of each reach, the hydrology and the results of the EFR study.

3.5. Reach 2 - Thomson Dam Wall to Aberfeldy River Junction

3.5.1. Reach description

The river is located downstream of the Thomson Dam, has high turbidity and flows through gorges, with bedrock controlling the channel form. Along the river the forest contains mixed species of Eucalyptus forests and invasive blackberry in disturbed areas. Recorded aquatic species contain brown trout, river blackfish, short finned eels, tupong, and macro-invertebrates which are mostly located in the shaded sections.

3.5.2. Hydrology

Figure 3.7 presents the FDC of reach two as measured at gauge station down stream of Thomson Dam, number 225112. The hydrological data is obtained from VWRDW, publicly available on Internet (VWRDW).

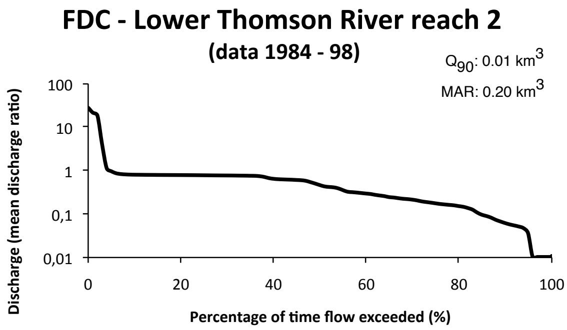


Figure 3.7 Flow duration curve reach 2 Lower Thomson River downstream of Thomson Dam.

3.5.3. Flow requirements

The general objective of the EFR is to establish an optimum habitat value for the developed flow objectives. This resulted in certain water depths and width which are correlated to discharges. In the following the EFR for reach 2 is described.

'FLOWS' distinguishes the following flow components: cease-to-flow, low flow, freshes[2], high flow, bankfull and overbank flow. The EFR recommendations follow a similar pattern (see Table 3.3), with the winter low flow considered to be part of the LFR.

[2] Freshes are small and short peak flow events.

The intention of the summer low flow is to restore and maintain the macro-invertebrates habitat and create enough fish habitat. Both habitats are based on water depth. Summer fresh ensures local fish movement, maintaining or enhancing native fish community and removal of accumulated fine sediment. The low flow in the winter period allows for permanent fish movement.

Table 3.3 EFR Lower Thomson River reach 2.

Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Low flow: > 1.4 m^3/s; (or natural)					Low flow: > 2.7 m^3/s (or natural)						
Fresh: > 2.7 m^3/s; 7/yr; min. 3 days					Fresh: > 9.3 m^3/s; 5/yr; min. 4 days						
								Bankfull Flow: > 23.1 m^3/s; 1 in 2 yrs; 3 days			

Note: Recommended flows have been converted from ML/day.

The objective of high flows and winter period freshes is to inundate the benches to recruit organic material, inundate riparian vegetation and act as a migration trigger for fish. Bankfull flows act as a disturbance flow and lead to channel maintenance. This flow prevents intrusion of riparian vegetation and maintains its diversity and structure. It could also act as a possible migration trigger.

For the majority of the other reaches the objective of the EFR (flow) components are similar to the one described for reach 2. If there is no further explanation towards the EFR for a specific reach, similar objectives are set for those reaches.

3.6. Reach 4a - Old Thomson (Cowwarr Weir to Rainbow Creek Confluence)

3.6.1. Reach description

In this section the river is highly sinuous, although the river has not migrated for the last 160 years, and contains long deep pools. The channel includes large woody debris, intrusion of vegetation and it is pressured by exotic weeds. The landscape is dominated by willows and the land is used for (intensive) agriculture activities.
A list of recorded fish species include native (6) and non-native (3) species. Channel clearing activities and daily flow fluctuations led to circumstances that are less suitable for the aquatic species.

3.6.2. Hydrology

Figure 3.8 presents the FDC of reach 4a as measured at gauge station Heyfield, number 225200. The hydrological data is obtained from VWRDW, publicly available on Internet (VWRDW).

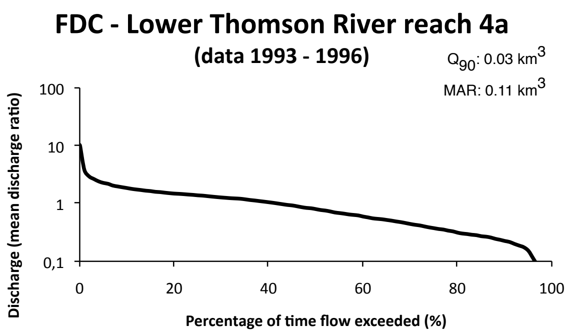


Figure 3.8 Flow duration curve reach 4a Lower Thomson River at Heyfield.

3.6.3. Flow requirements

The EFR for reach 4a in Table 3.4. has a similar setup as reach 2.

Table 3.4 EFR Lower Thomson River reach 4a.

Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Low flow: > 0.2 m^3/s; (or natural)					Low flow: > 0.5 m^3/s (or natural)						
Fresh: > 0.5 m^3/s; 4/yr; min. 7 days					Fresh: > 3.0 m^3/s; 7/yr; min. 4 days						
					Fresh: > 23.1 m^3/s; >1/yr; 4 days (1 in Aug-Sep)						

Note: Recommended flows have been converted from ML/day and rounded.

3.7. Reach 5 - Rainbow Creek Confluence to Macalister River Junction

3.7.1. Reach description

Due to upstream development of the Rainbow Creek this river section contains extra loads of sediment. The river meanders and the floodplain contains cut-offs and abandoned channels. Condition of the vegetation is at best classified as being moderate, with cattle grazing all around. Patches of eucalyptus species create a tall overstorey, with willows and wattles dominating most of the reach. Australian grayling, a vulnerable and protected fish species, has been recorded in this section of the river.

3.7.2. Hydrology

Figure 3.9 presents the FDC of reach 5 as measured at gauge station Wandocka, number 225212. The hydrological data is obtained from VWRDW, publicly available on Internet (VWRDW).

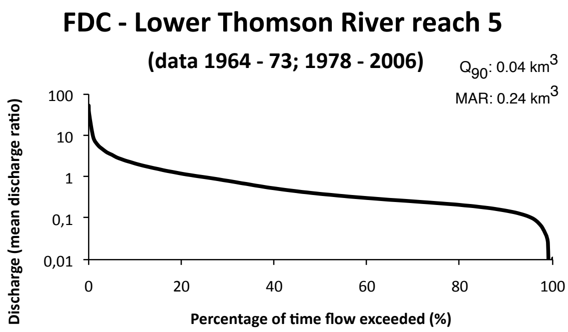


Figure 3.9 Flow duration curve reach 5 Lower Thomson River at Wandocka.

3.7.3. Flow requirements

This section has no separate flow requirement for the dry and wet part of the year. Instead there is an all year round low flow requirement (see Table 3.5). The objective and purpose for the EFR are the same as for reach 2. Bankfull flow has an extra function, which is to inundate the wetlands.

Table 3.5 EFR Lower Thomson River reach 5.

<table>
<tr><th>Dec</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th></tr>
<tr><td colspan="12">Low flow: > 0.8 m³/s; (or natural)</td></tr>
<tr><td colspan="5">Fresh: > 2.7 m³/s; 3/yr; min. 4 days</td><td colspan="7">Fresh: > 3.5 m³/s; 7/yr; min. 4 days</td></tr>
<tr><td colspan="12">Bankfull Flow: > 23.1 m³/s; 2/yr; min. 4 days (1 in Aug-Sep)</td></tr>
</table>

Note: Recommended flows have been converted from ML/day.

3.8. Reach 6 - Macalister River Junction to Latrobe River Junction

3.8.1. Reach description

In this section of the river, the channel becomes straight with some artificially straightened parts. A sinuous pattern will never evolve due to a unsuitable valley slope. The riparian zone is narrow, not continuous and contains Eucalyptus species and willows. Aquatic species are similar to those in reach 5.

3.8.2. Hydrology

Figure 3.10 presents the FDC of reach 6 as measured at gauge station Bundalaguak, number 225232. The hydrological data is obtained from VWRDW, publicly available in the Internet (VWRDW).

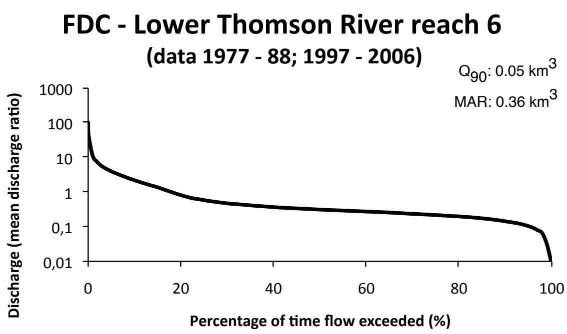


Figure 3.10 Flow duration curve reach 6 Lower Thomson River at Bundalaguak.

3.8.3. Flow requirements

The EFR for reach 6 is similar to reach 5, as it also contains a single low flow requirement (see Table 3.6). For this reach the bankfull flow is also intended to inundate the floodplain wetlands.

Table 3.6 EFR Lower Thomson River reach 6.

<table>
<tr><th>Dec</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th></tr>
<tr><td colspan="12">Low flow: > 1.2 m³/s; (or natural)</td></tr>
<tr><td colspan="5">Fresh: > 4.1 m³/s; 3/yr; min. 4 days</td><td colspan="7">Fresh: > 25.5 m³/s; 3/yr; min. 10 days</td></tr>
<tr><td colspan="5"></td><td colspan="7">Bankfull Flow: > 110.0 m³/s; 2/yr; min. 4 days (1 in Aug-Sep)</td></tr>
</table>

Note: Recommended flows have been converted from ML/day.

3.9. Lower Macalister River

3.9.1. River description

The Lower Macalister River flows in the state Victoria, Australia. It runs from Lake Glenmaggie to its confluence with the Lower Thomson River. Lake Glenmaggie developed due the construction of the Glenmaggie Dam in 1926. Several water abstraction activities take place at Lake Glenmaggie, e.g. the Macalister Irrigation District.

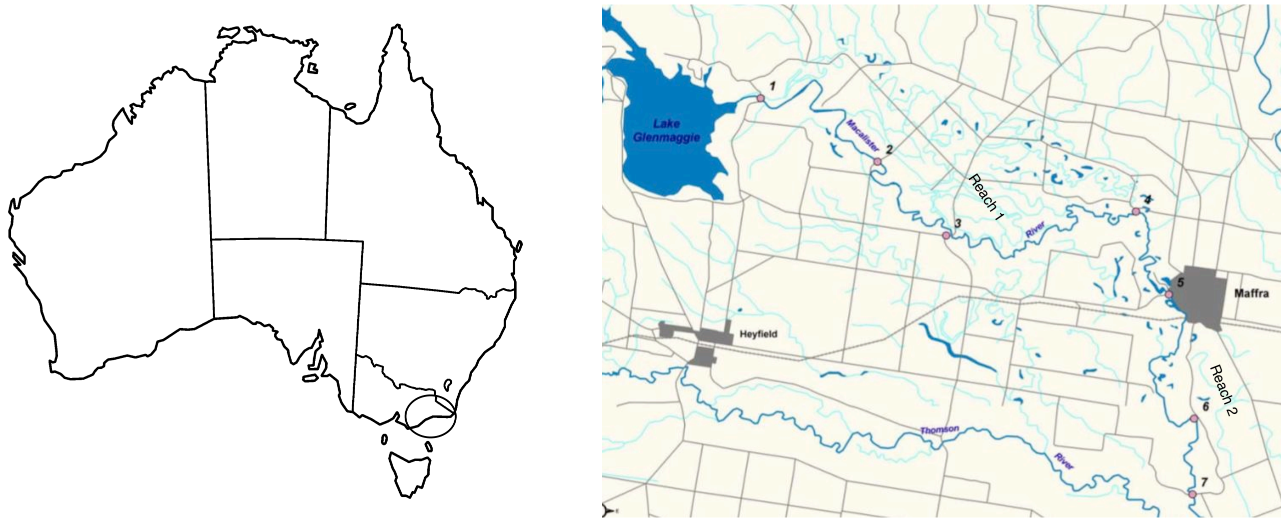


Figure 3.11 Study reaches Lower Macalister River (source: SKM, 2003a).

The locations of the river sections that haven been investigated in the study are presented in Figure 3.11.They are located in the same region as the Lower Thomson River.
Climatic circumstances are characterized as maritime temperate, with significant precipitation in all seasons with Köppen classification symbol is Cfb (Peel et al., 2007).

3.9.2. EFR method

The method used in this study, FLOWS, is similar to the Lower Thomson River (see paragraph 3.4.2).

3.9.3. EFR study

Though the study area has been divided into two reaches, only the first reach is used. Lack of hydrological data restricted the use of reach 2. The FEM model has not been used in this study. Application of the method is similar to the one of the Thomson River (see paragraph 3.3.4). The description and result below are obtained from SKM (2003a) and TMEFTF (2004).

3.10. Reach 1 – Downstream of Lake Glenmaggie to Maffra Weir.

3.10.1. Reach description

The river is a sinuous lowland channel with large floodplains containing abandoned channels. At some locations there are eroding riverbanks and vegetated mid-channel bars. During the 1950s the area has been cultivated by removal of material from the channel and clearing of the floodplains.

Habitats in this section comprise aquatic and overhanging vegetation. The riparian zone contains willows and Eucalyptus, and has pasture grasses as ground cover. Within the channel there is little emergent vegetation and along the water edge there are knotweeds. Recorded fish species contain native migrating species, like Short-Finned Eel and Tupong. Exotic species like Carp are recorded as well. The macro-invertebrates community was considered to be in a poor condition.

3.10.2. Hydrology

Figure 3.12 presents the FDC of reach 1 as measured at gauge station Glenmaggie tail gauge, number 225204. The hydrological data is obtained from VWRDW, publicly available on Internet (VWRDW).

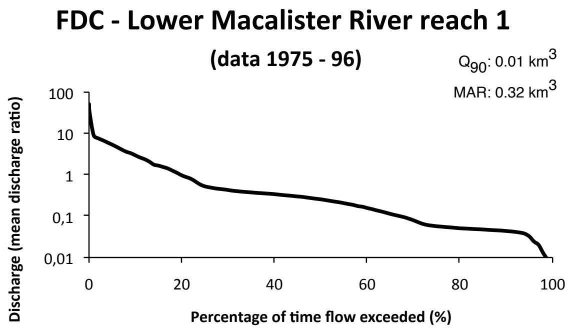


Figure 3.12 Flow duration curve reach 1 Lower Macalister River downstream of Glenmaggie Dam.

3.10.3. Flow requirements

Table 3.7 shows the outcome of the EFR study for reach 1. The general objective is to maintain the current condition or restore and rehabilitate it back to natural conditions. In some cases the impact of certain threatening activities are aimed to be limited. None of the recorded species are explicitly linked in reference to certain flow recommendations.

Table 3.7 EFR Lower Macalister River reach 1.

Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Low flow: min. 0.4 m^3/s						Low flow: min. 3.7 m^3/s					
Fresh: > 4.1 m^3/s; 3/yr; 7 days						Fresh: > 17.4 m^3/s; 3/yr; 9 days					
						Bankfull Flow: > 115.7 m^3/s; 1/yr; 2 days					

Note: Recommended flows have been converted from ML/day.

The drier period runs from December till May and the wet season from June till November. Basics for the recommended flows are in general similar to those of the Lower Thomson River. However, the low flow in the dry period has also the function to dry the streambed to allow accumulation of organic matter on the exposed channel section. The low flow in the wet period has an extra function, which is suppressing the encroachment of terrestrial vegetation that may have occurred in the dry period.

3.11. EFR summary

As described in the 'Reading guide' in 3.1, the flow recommendations of the case studies need to be divided in LFR and HFR to enable comparison with the Smakhtin method. These flows are highlighted with respectively blue and purple colors in the 'flow requirements tables'. The results are summed up in this paragraph and Table 3.8.

LFR

The EFR of the Bill Williams River presents a flow range describing the flows that are regarded as LFR. Both baseflows, 'minimum' and 'common' need to take place. In these ranges the maximum flows are chosen, i.e. minimum baseflow: 0.6 m^3/s and common baseflow: 1.4 m^3/s. Besides choosing the maximum flows, also the length of the flow event is maximized.
In the Border Meuse the lowest flow, 10 m^3/s, is selected as LFR. It retains the current quality of the river system and complies with the LFR definition mentioned in paragraph 3.1.
The EFR of the Lower Thomson and Macalister Rivers present clear formulation of required flows. The EFR case study Lower Thomson River labels the flow in the winter/spring period as 'high flow'. However, it is concluded that the flow objectives better suits the LFR definition. These flows have therefore been labelled 'low flow' in this study.

HFR

The Smakhtin method presents an annual value for the HFR, therefore in this study a similar annual approach should be used. High flow recommendations with a frequency of once every two years, or more frequent, are taken into account for determining an annual HFR. It needs to be stressed that other 'high flows' that not taken into HFR, are not considered unimportant. The importance of those flows are highly recognized and need to be maintained in their individual case.

For the Bill Williams River the high flow is set at the maximum discharge and length, i.e a flow of 11.3 m^3/s for a period of 4 weeks. High flows of the Border Meuse suggests a range of flows. Some locations require the highest flow (100 m^3/s) while the others a lower flow (50 m^3/s). A compromise between the two flows is considered an adequate representation of the requirements of the region; 75 m^3/s for 3 months. In the remaining case studies the high flow recommendations are used as they are presented and (color) labelled in those studies.

EFR

In Figure 2.2.b is illustrated how the LFR and HFR should be converted into EFR. When necessary, it is essential to lengthen the LFR period to an annual length, as e.g. in the Border Meuse case study. The HFR is established by deducting the high flow recommendations with the (daily) LFR flow. When there are multiple LFR flows during a year, like with the Lower Macalister River, it is necessary that the high flow is deducted by the LFR flow that occurs in the same period. In appendix I these LFR and HFR calculations are presented. Table 3.8 presents the EFR and its components of each study. Included are also the EFR recommendations according to the Smakhtin method.

Table 3.8 Summary EFR case studies .

Location	Case study (in % MAR)			Smakhtin method (in % MAR)		
River	LFR (%MAR)	HFR (%MAR)	EFR (%MAR)	LFR (%MAR)	HFR (%MAR)	EFR (%MAR)
Bill Williams River	30	18	48	3	20	23
Border Meuse	4	9	13	8	20	28
Lower Thomson River						
reach 2	34	9	43	6	20	26
reach 4a	11	13	24	23	7	2830
reach 5	11	20	31	15	15	30
reach 6	10	39	49	14	15	29
Lower Macalister River						
reach 1	20	18	38	4	20	24

Note: flow requirements are rounded

4. Evaluation of Smakhtin method

Previous chapter showed the flow requirements of river specific EFR case studies. Research into the (cor-)relation between flow recommendations and the flow parameters is the basis of this chapter. The Smakhtin EFR method is being evaluated based on case study EFR. And (also) other indicators of flow variability are used for examining a (cor-)relation with the case study EFR.

4.1. Validating Smakhtin method

The flow parameters in this validation process are mainly derived from FDCs. The FDC is constructed as described in paragraph 3.1. and is based on daily river flow discharges. To compare flow requirements of case studies with those of the Smakhtin method requires the following parameters: Q_{90}, MAR and an EFR separated into LFR and HFR elements. All the data can be acquired from the FDCs that are plotted in the case study descriptions in chapter 3 and table 3.8.

Q_{90} flow parameter is the Smakhtin method equivalent of the case study LFR. Plotting case studies LFR data against the Q_{90}/MAR ratio enables comparison with the Smakhtin method. Figure 4.1.a shows the LFR data (dots) and the Smakhtin LFR method, which is visualized by a linear line.
Smakhtin HFR method is also related to the Q_{90} parameter. Therefore the HFR of the case studies are plotted against the same Q_{90}/MAR ratio as the LFR. A schematic step-wise line representing the Smakhtin HFR is presented in Figure 4.1.b.

Visually, the LFR data from the case studies can be more or less divided into two groups. One runs a little lower but parallel to the Smakhtin method, while another is much higher. The HFR data shows a similar picture. Half of the data is reasonably similar to the Smakhtin HFR recommendations. As for the rest: two HFR data points are lower and one is much higher compared to the Smakhtin method.

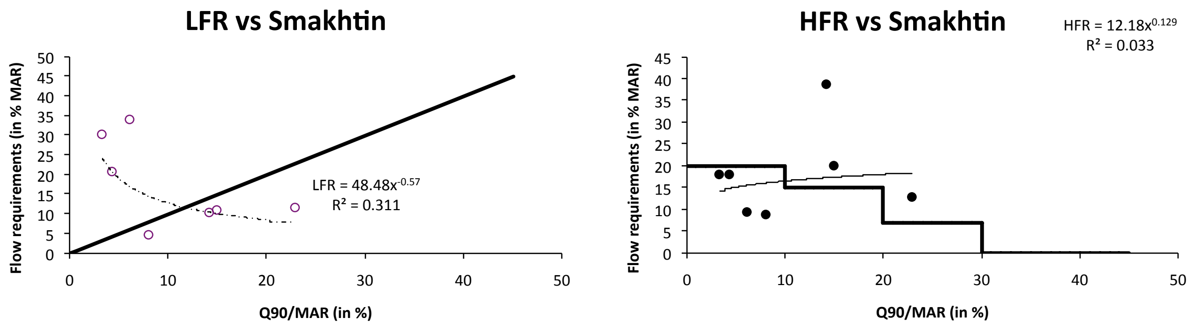


Figure 4.1 Comparison EFR results case studies and Smakhtin method with annual Q_{90} values.

The trendlines through the data of the case studies are plotted in Figure 4.1 and can be used to estimate flow requirements at various Q_{90}/MAR ratios. They are constructed by a least-squares power regression method. This type of regression equation avoids that the trendline crosses the x or y-axis. In case the trendline would cross one of the axes, it would imply either a negative flow requirement or flow regime variability; neither of which is possible. As a result the locations of axis-crossing would then state a minimum or maximum of flow requirements, or a flow regime that would not require a LFR or HFR. Both statements are presumed too premature to consider at this stage.

The 'goodness of fit' of the trendline is illustrated by its correlation coefficient (R^2). The score of the coefficient is established by (Davis, 2002):
$R^2 = SS_R/SS_T$
SS_R: sum of squares due to regression
SS_T: total sum of squares (difference with the overall mean)

The R^2 score can vary from 0 to 1. A score of 1 suggests that the trendline perfectly predicts or fits the data. While zero implies no relationship between data and trendline.
Although normally a R^2 is determined for a trendline, the best fit, here a R^2 is also established for a line that already exists, the Smakhtin LFR method. The result is a score of 0.4 for the Smakhtin LFR method, and thus relative similar to the trendline in Figure 4.1.a (see also appendix II)

A statistical significance test (Davis, 2002), a two-tailed t-test, has been conducted to determine wether there is evidence that would suggest that the Smakhtin method is not a good estimator. The initial hypothesis is, that the Smakhtin method is a good LFR estimator. Results of the t-test will indicate if there is reason for a rejection of this initial hypothesis. The data set appeared to be too small to show any indication of such rejection with a significance level of 10% or better (the t-test is described in appendix II).[3]

Preliminary view is that several rivers, with the characteristic of a variable flow regime (i.e. low Q_{90}/MAR), require a LFR that consists of a large MAR percentage. A relatively larger LFR is needed for those rivers than for more stable regimes. This is opposite to the assumption of Smakhtin et al. (2004a).
Simple drawing of a trendline resulted in a correlation coefficient equal to the Smakhtin LFR method. This raises reasonable doubt and room for further study about the adequacy of the Smakhtin LFR method, and as the LFR and HFR form an unity, the whole EFR method.

4.2. Deriving LFR and HFR predictors

4.2.1. EFR comparison

In this study a correlation between flow regime variability and EFR, as stated in Smakhtin et al. (2004a), is still presumed valid. The river flow regime is represented by using 'simple' flow parameters. This approach ensures the simplicity and global practice of the EFR method. However, the results of paragraph 4.1 show that the representation by the Smakhtin method of this correlation is open for discussion. Therefore different ways in describing regime variability are used to see wether there are possible better (clear) patterns visible between regime variability and the flow requirements. Brodie et al. (2008) and Smakhtin (2001) present, among others, the following ratios to characterize flow regime variability:

- Q_{90}/MAR
- Q_{50}/MAR
- Q_{90}/Q_{50}
- Q_{20} - Q_{80}

The flow parameters represent different sections of a flow regime. According to Smakhtin (2001) the Q_{90} and Q_{80} flow parameters are indicators for (extreme) low flow. The Q_{50} equals the median flow and lies in the transition region of high(-er) and low flows and Q_{20} is considered a high(-er) flow.

In general these ratios illustrate how low flows relate to the high flows, in a similar way that the Smakhtin method uses the Q_{90}/MAR ratio. Large magnitude differences between the flow parameters indicates a steeper curve of the FDC. In those instances the low flows are of a considerably smaller size than the high flows or annual runoff. This is characteristic for regimes with higher flow variability (see Figure 2.3.c).
The principle of the first three ratios is that low values correspond with variable regimes. For Q_{20} - Q_{80} there is an opposite relation. In this ratio stable flows are assigned lower values, as the FDC slope is less steep (see Figure 2.3.a). To enable comparison between the case studies results, (Q_{20} - Q_{80}) is divided by its mean flow or MAR. Results of all the comparisons are presented in Figure 4.2.

[3] This test is not conducted for the generated trendlines, because they are not independent from the data.

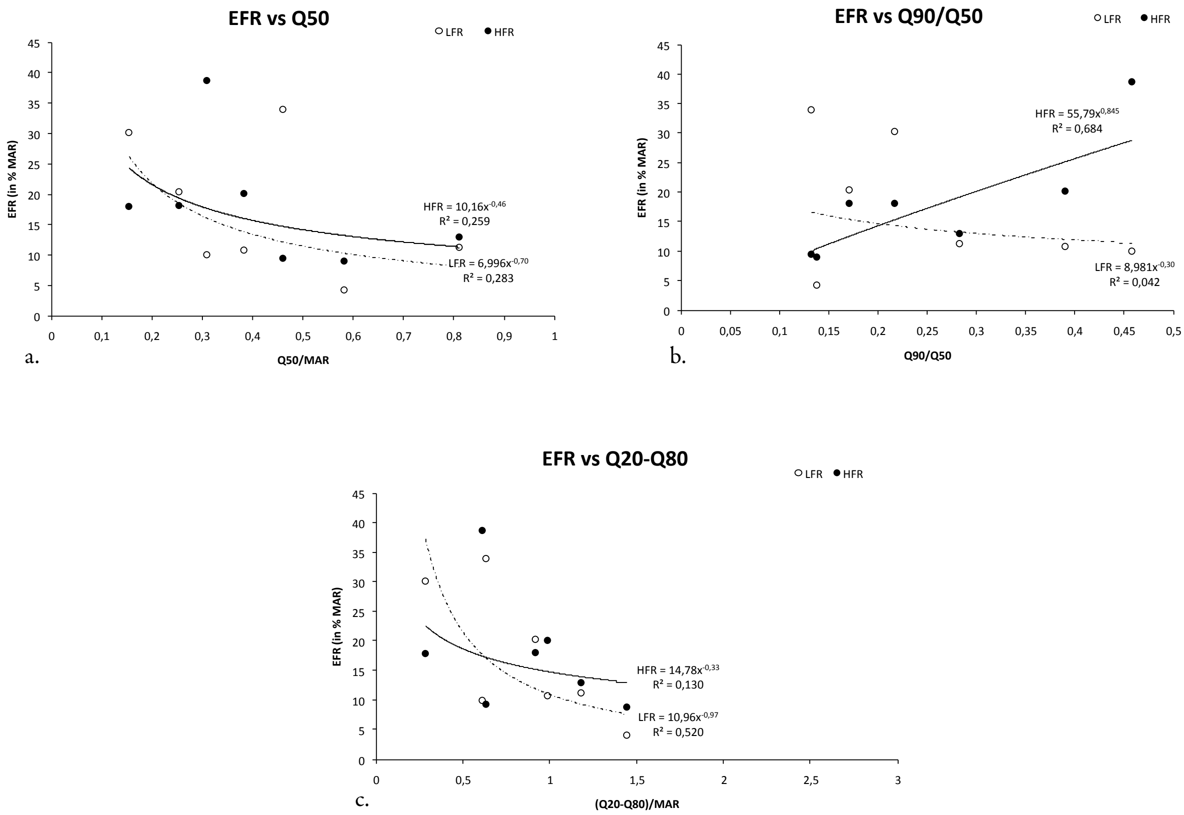


Figure 4.2 Analysis correlation between flow parameters and LFR and HFR (with power regression trendlines).

4.2.2. Observations

Figure 4.1. and 4.2 display different patterns of the trendlines. Some suggest a LFR or HFR trend that is similar to the Smakhtin method, e.g. a variable flow being assigned low LFR and high HFR, while others show an opposite trend. In table 4.1 the tendency of the trendlines of each investigated ratio is presented.

Table 4.1 Trendline comparison with Smakhtin LFR and HFR tendency.

EFR flow element	Trendline tendency	
	resembling Smakhtin method	not resembling Smakhtin method
LFR	Q_{20} - Q_{80}	Q_{90}/MAR; Q_{50}/MAR; Q_{90}/Q_{50}
HFR	Q_{50}/MAR	Q_{90}/Q_{50}; Q_{20}-Q_{80}; Q_{90}/MAR

Almost all the plots display a R^2 score thats is relatively weak. Only the R^2 scores of the HFR trendline of Q_{90}/Q_{50} can be considered relatively strong, and the LFR trendline Q_{20} -Q_{80} as moderate.

There is an additional aspect that can be observed from Figure 4.1 and 4.2, besides the different tendency of each trendline. It is the manner in which the flow regime variability is illustrated and classified. This is not uniform with each ratio; there are differences. Where some classify a certain flow regime as 'variable' an other labels it as a 'stable' flow regime and vice versa. All plots in Figure 4.2 show some points that undergo such a transition. These shifts result in uncertainty when considering the appropriate manner to address regime variability; which ratio provides afitting and reliable way in classifying the variability of a flow regime.

4.3. Adapted EFR model

Paragraph 4.1 illustrates that there is room for adjusting the Smakhtin method. The correlation between data and Smakhtin flow requirements is weak. On the other hand, paragraph 4.2 shows that the examined flow ratios are also inconclusive about their correlation of EFR and flow regime variability. The latter is best illustrated by the LFR plot of Q_{90}/MAR. The trendline as well as the Smakhtin method give similar R^2 scores, but they approach the LFR completely different (see Figure 4.1).

Examining Figure 4.1 and 4.2 shows that the R^2 score of the LFR trendline of Q_{20} - Q_{80} is larger than for all the others. At the same time there is uncertainty concerning its suitability to be used to describe flow regime variability. As mentioned in paragraph 4.2 there uncertainties in in classifying the flow regimes. For this ratio the transitions in classification, compared to the others, are considered to be most apparent.

In the end, the ratios of Q_{90}/MAR and Q_{90}/Q_{50} are selected to describe LFR and HFR. The selection of these ratios is partially based on R^2 scores, ecological and hydrological grounds. Most of the ratios show a tendency that is opposite to the Smakhtin method. However, their R^2 scores are low and of these ratios the Q_{90}/MAR is the highest. The tendency of the Q_{90}/MAR trendline is similar to the hypothesis described in paragraph 1.3.

This means that, according to the EFR case studies, variable flow regimes should be allocated a larger amount of flow as LFR than merely a Q_{90}. A flow that is likely to be exceeded over 300 days a year is therefore possibly not an appropriate recommendation for LFR. As mentioned in paragraph 1.3, it is probable that stressed rivers, i.e. highly variable regimes, do not receive a sustainable amount of flow with the Q_{90}. These regimes have characteristically steep FDCs, specially at the lower end (flows with high exceedence change). This makes it sensitive to an assignation of Q_{90} as LFR.

The Smakhtin HFR method is changed to ensure that the total EFR still makes ecological sense. The Q_{90}/MAR trendline assigns lower LFR for more stable flow regimes. Keeping the original Smakhtin HFR method could result in stable flow regimes being recommended no EFR flows at all. Therefore it is necessary to adapt the HFR model, and most likely to reverse its recommendations: stable flow regimes receiving higher HFR allocations. Although this seems to contradict with the general assumption to mimic the flow regime, it is essential to ensure the allocation of sustainable flows. For the HFR the majority of the ratios also point in a direction opposite to the Smakhtin method; Of them the Q_{90}/Q_{50} trendline gives the highest R^2 score.

The following models are derived from the trendlines in Figure 4.1 and 4.2 to form an EFR model. From this point onwards this newly adapted EFR model is referred to as 'new EFR model'. In the LFR model the x-axis consists of Q_{90} divided by MAR presented as a percentage; therefore it is multiplied by 100 to obtain percentage values. The HFR x-axis consists of the ratios Q_{90} and Q_{50} as presented by the FDC.

$$LFR = 48.5 * \left(\frac{Q_{90}}{MAR} * 100 \right)^{-0.57} \qquad HFR = 55.8 * \left(\frac{Q_{90}}{Q_{50}} \right)^{0.85}$$

For the application of the new EFR model it needs to be noted that the investigated rivers, according to their Q_{90}/MAR ratio, appear to be variable flows regimes. Almost none of the Q_{90}/MAR ratios of the case studies exceeds 20%. The implications is a rise of uncertainty in EFR predictions when it is applied for rivers with Q_{90}/MAR ratios higher than 20% MAR.

4.4. EFR application methods

4.4.1. LFR application

Smakhtin et al. (2004a) do specifically not mention any time period, frequency or characteristic in which the EFR should be applied. This is because its primary attempt is to establish an annually volume of water that needs to be allocated for ecological purposes. Smakhtin's LFR is set at Q_{90}, which application frequency and timing is clear. It equals a daily discharge (m^3/s) that is considered as a minimum flow that should be applied during a year except in periods where natural supply flow is less than the LFR. For the HFR these timing and frequency are not clear.

In the new EFR model the LFR is no longer set as a daily flow parameter (Q_{90}), but is merely represented by an annual volume of water. Therefore three potential techniques are presented to transform this annual LFR into LFR suited for smaller time steps, e.g. a monthly LFR:

- LFR divided equally over all months;
- LFR as a percentage of every month's discharge;
- LFR separation into two periods (wet and dry).

HFR can be utilized in similar fashion. However, as can be established from the EFR case studies, during a year the HFR is applied at multiple and sometimes single periods. The length of these periods are divers and not uniform with each case study. Therefore only the LFR is discussed here.

The first technique involves dividing the established LFR by twelve. The effect is that each month is presented a similar amount of MAR that should be allocated as LFR. It resembles a continuous flow requirement that is applied throughout the year. This is also shown in several EFR case studies that are used in this study.
At certain moments the flow requirements could be higher than the occurring flows, especially in rivers with variable flow regimes. In Figure 4.3 this technique is applied. During the months of low flow the LFR is nearly equal to the mean monthly discharge. This indicates that during those periods there is only little surplus of water.
The white bars illustrate the mean annual monthly discharge of an example flow and the blue-bars the corresponding LFR. Both values are presented as a percentage of MAR.

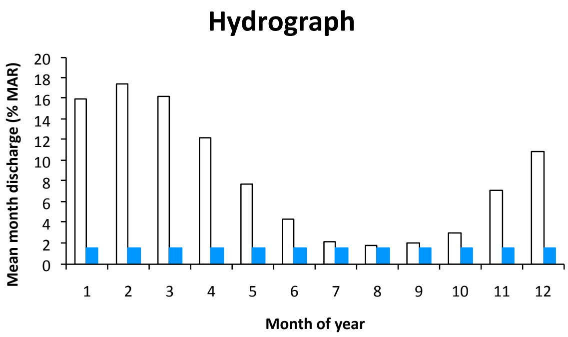


Figure 4.3 Example equal LFR for each month.

The second technique assigns the LFR as a percentage of a monthly flow that should be allocated. If the LFR is set at, for example 18% MAR, then in that case the LFR would become 18% of the mean flow of each individual month. This technique mimics the original flow, but at a lower level. It raises the possibility that the required flow actually occurs. However, it also indicates that in every month water abstraction is allowed. With this technique even (extremely) variable flow regimes and maybe even stressed river systems might be considered to have a surplus of water every single month.

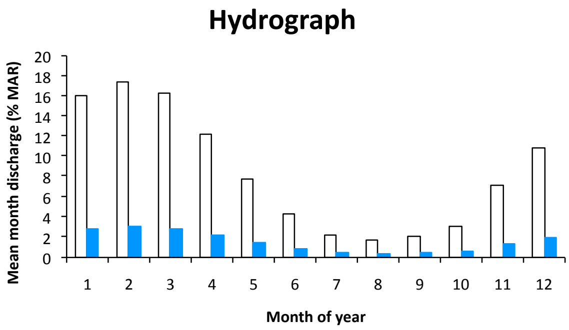


Figure 4.4 Example equal LFR percentage for each month.

Dividing the LFR into two separate blocks, one LFR for the dry- and another for the wet-period, is a sort of compromise between the two previous techniques. It is similar to the one used in the EFR case study of the Lower Thomson River. It has the benefit of a rigid LFR combined with the possibility to set lower flow requirements in drier periods if needed. There is difficulty in determining the ratio between the dry- and wet-period LFR. This is most likely to vary between river systems.

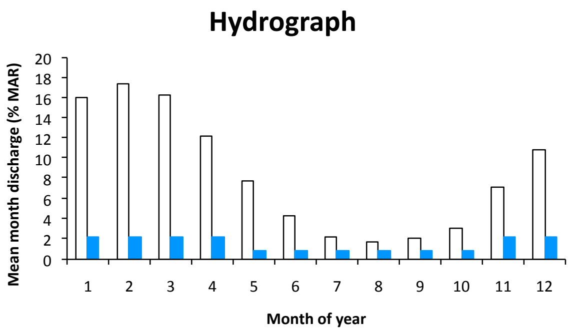


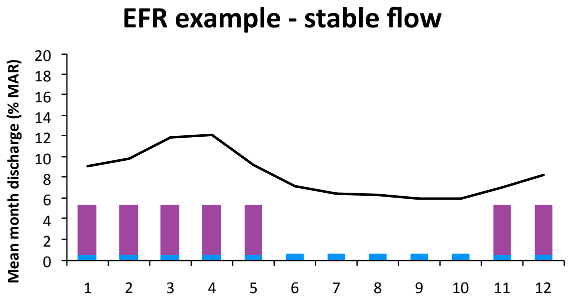
Figure 4.5 Example two separate LFR periods within a year.

With all three techniques there is the possibility that at certain moments the flow is, due to natural circumstances, lower than the requirements. In those cases the natural flow should be used.

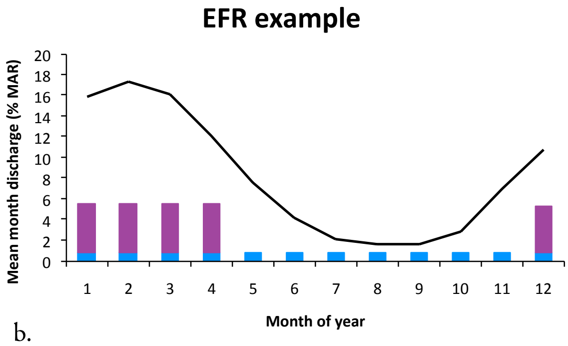
4.4.2. Example EFR applications

The new EFR model is set up and the various manners in which it can be applied are described. Figure 4.6 illustrates the application of the new EFR model on the example flows of chapter 2. The technique of evenly distributing the LFR over each month is used to illustrate the monthly LFR. The HFR is distributed over several months. The plots are for illustrative purposes.
The LFR is illustrated by the lower blue-bars and HFR by the purple-bars, on top of the LFR. The line above represents the hydrograph of the example flows.

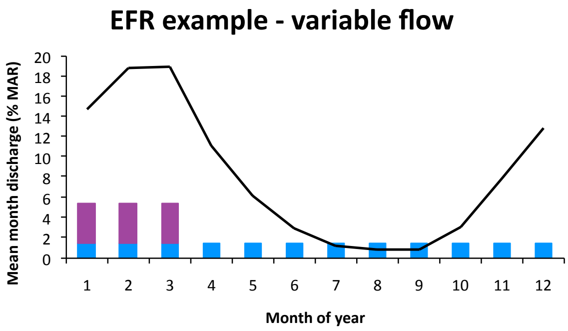
In the new EFR model, the LFR recommendations for rivers with variable flow regimes are raised. Looking at mean monthly flow scale, it is likely that they are even higher than the lowest mean month flow (see Figure 4.6.c). The latter is not so much a problem, but merely shows the importance of EFR. The HFR is clearly lower for these rivers than those allocated to a river with a more stable flow regime. For stable flows the LFR is lower than in the Smakhtin method. A part of that is compensated by the allocation of a HFR, though there are still periods during a year in which the flow requirements are (relatively) low.
The example graphs in Figure 4.6 show that the total water reservation for the ecological system is in some cases minor, compared to the average annual discharge; leading to a surplus of water for alternative uses.



a.



b.



c.

Figure 4.6 Application of the new EFR model on flow examples.

5. Review new EFR model

The accuracy of the new EFR model constructed in previous chapter is examined in this chapter. This is done by using three extra EFR case studies that are obtained after the development of chapter 4. Comparison between the predicted EFR and the actual EFR from the studies shows the suitability and sensitivity of the new EFR model.

5.1. EFR case studies

The studies concern the Barwon and Moorabool River. Both rivers are located in the state of Victoria, Australia (location: see Figure 5.1). The EFR method used in these studies is the FLOWS method, similar to the one described in paragraph 3.4. Each case study and its results is described below.

Figure 5.1 Locations of the three case studies encircled (State Victoria; Australia).

5.2. Barwon River

5.2.1. River description

The river catchment is located in State Victoria, Australia (see Figure 5.1 and 5.2). There are various tributaries located within the study area. Three of these are included in the EFR study. The river is regulated by the West-Barwon Dam, which is constructed in 1964. More than eighty percent of the area is grassland or cleared land. The EFR study states that the river condition is marginal or poor, with only 7 percent of the rivers and streams in the catchment being considered as 'good'.
The climatic circumstances characterize a maritime temperate climate with significant precipitation in all seasons, with Köppen climate classification Cfb (Peel et al., 2007).

The information in this section and below is obtained from the documents CMA (2005; 2006) and Lloyd Environmental (2005). For further information is referred to these documents.

5.2.2. EFR method

The FLOWS method used in this study is similar to the Lower Thomson River EFR case study. For more information is referred to paragraph 3.4. and its references, as well as CMA (2005; 2006) and Lloyd Environmental (2005).

5.2.3. EFR study

The study area of the Barwon River catchment contains 9 reaches. Reaches 2, 3, 8 and 9 are recommended EFR that are higher than MAR. This indicates that the ecology requires a larger amount of water than the MAR can deliver. It could be considered that the river is regulated to such an extent that there are no natural conditions. It is assumed that EFR can never exceed the MAR and therefore these reaches are not included in this study.
Discharge data for reaches 4, 6 and 7 contained many periods of (too long) unexpected no-flow and/or comprised by too few years of data. Reach 5 concerns an estuary, which generally requires other specifications to establish EFR. This left only reach 1 to be used.

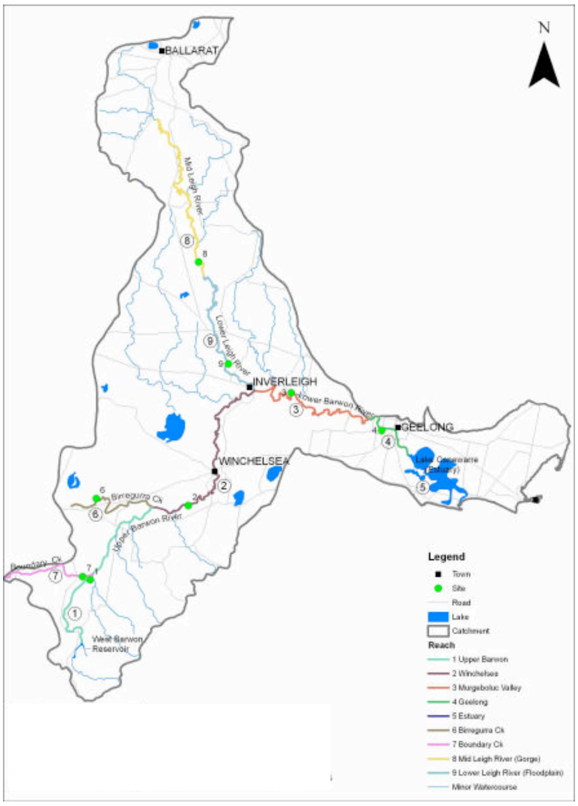


Figure 5.2 Study area Barwon River (source: CMA, 2006).

5.3. Reach 1 – Barwon River at Upper Barwon

5.3.1. Reach description

This reach runs from West Barwon River Reservoir to the Birregurra Creek junction. The upper part the river is a narrow channel, flowing through foothills and has a floodplain with steep valley walls. It is characterized by a pool and riffle system. Further downstream, the foothills progresses into a flat-bottomed valley and the stream widens. This section has a wetland character, including ponds and old meander channels. Additionally, a part of the stream is channelized and a drain is constructed.

Drainage and land clearing activities resulted in little native vegetation on the floodplains. Under natural circumstances this reach would likely be an extensive and continuous wetland habitat. Nowadays there are, between the pasture grasses, wetland herbs (e.g. Tall Sedge, Persicaria descipiens, Cyperus eragrostis) and emergent macrophytes (e.g. Common Reed, Tall Spike-sedge, Juncus procerus).

Flora and fauna within the channel is summarized by:

- aquatic plants (e.g. Azolla filiculoides and Lemna minor)
- native fish; twelve species recorded (e.g. Mountain Galaxias, Short Finned Eel, Southern Pigmy Perch.)
- exotic fish;three species recorded (e.g. Brown Trout, Redfin Perch.)

Low species diversity of macro-invertebrates are caused by poor living conditions. These conditions do not meet the required SEPP[4] objectives.

5.3.2. Hydrology

Figure 5.3 shows the FDC for reach 1 of the Barwon River. The hydrological data is obtained from VWRDW, publicly available on Internet, gauge station number 233224 at Ricketts Marsh (VWRDW).

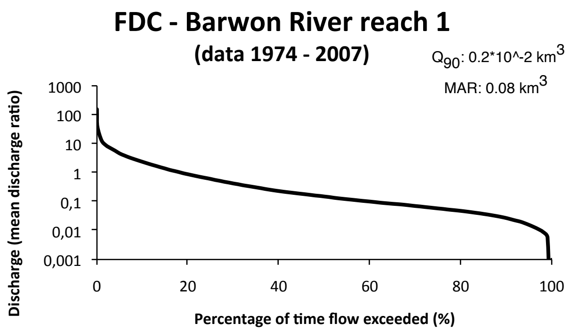


Figure 5.3 Flow duration curve Barwon River reach 1 at Ricketts Marsh.

5.3.3. Flow requirements

There are no ecological functions identified for a period of drought, so-called 'cease-to-flow' event. A summer low flow is assigned to ensure a pool depth for permanent (small) fish and aquatic macro-invertebrates habitats. Growth of floodplain bushes is supported by maintaining a shallow water table under the floodplain. Summer freshes maintain the aquatic macrophytes by inundation of the floodplain. Winter low flow is assigned for seasonal growth of aquatic species, fish movement and inundation of wetlands and floodplains. Complete inundation of the floodplain is generated by the high flow. These higher flows further enable sediment transport and macro-invertebrates habitats. It flushes the system, recruits plant species and creates breeding habitat for fish species.

Table 5.1 EFR Barwon River reach 1.

Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Low flow: > 0.06 m^3/s (or natural)					Low flow: > 0.6 m^3/s (or natural)						
Fresh: >2.5 m^3/s; 3/yr, 2 days					Fresh: > 1.8 m^3/s; 3/yr, 5days						
					Large Fresh: >18.5 m^3/s; 1/yr, 10 days						

Note: Recommended flows have been converted from ML/day.

[4] Science & Environmental Policy Project

5.4. Moorabool River

5.4.1 River description

This catchment consists of two main branches, on the east and west. The river flows through confined valleys and confluences near Morrisons (see Figure 5.4). After the confluence the channel valley broadens, with now and then a narrow section. The land use is mainly agricultural; sheep and cattle grazing. The flow is regulated by various dams and the main reservoirs in the catchment are the Moorabool and Lal Lal Reservoir (SKM, 2003b).

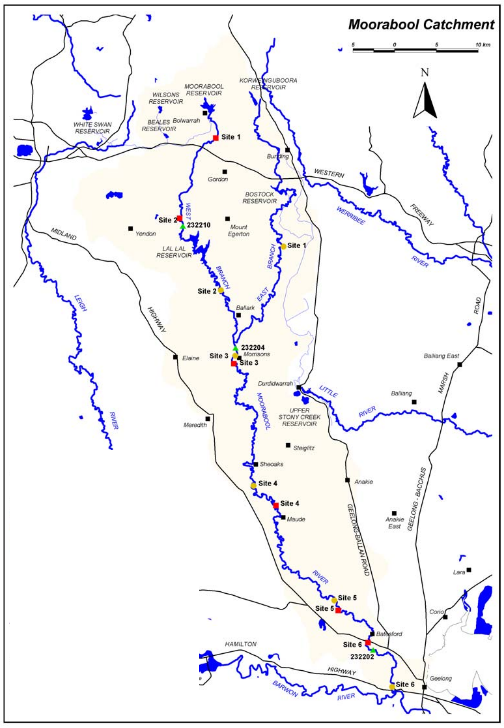


Figure 5.4 Study area Moorabool River (source: SKM, 2003b).

5.4.2. EFR method

The method used in this study, FLOWS, is the same as for the Lower Thomson River. For more information is referred to paragraph 3.4 and its references, as well as SKM (2003b).

5.4.3. EFR study

In total four reaches are studied, of which reach 2 and 3 are used. The reason that the other reaches are not used is lack of available flow data or EFR recommendations that exceed MAR.

5.5. Reach 2 - West Moorabool River between Moorabool and Lal Lal Reservoir

5.5.1. Reach descriptions

Characteristic for the river is a narrow and contracted channel meandering through lands that are covered with pasture grasses. Extensive land clearing activities have altered the riparian vegetation. It led to the rise of exoticflora on the riverbanks such as willows and pasture grasses. The area features only a few habitats.
The little fish data that exist for this reach point in the direction of exotic species domination, e.g. like Redfin, Brown Trout and Tench. Only one native specie was recorded; Mountain Galaxias. Fish mobility in the reach is reduced by the Moorabool Reservoir (upstream) and Lal Lal Reservoir (downstream).

5.5.2. Hydrology

Figure 5.5 presents the FDC of reach two as measured at gauge station Mount Doran, number 232211. The hydrological data is obtained from VWRDW, publicly available on Internet (VWRDW).

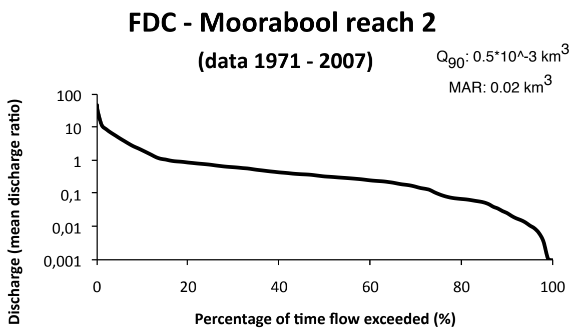


Figure 5.5 Flow duration curve Moorabool River reach 2 at Mount Doran.

5.5.3. Flow requirements

A cease-to-flow event acts as a disturbance to maintain the diversity of macrophytes and macro-invertebrate species and prevent channel intrusion of (exotic) pasture grasses.
Low flow in the dry period will wet the channel bottom to ensure minimum habitat conditions. The water depth is sufficient to enable fish passage between high and low flow habitats and to leave the benches exposed. Freshes flush the system to ensure water quality. Furthermore, it increases the connectivity between pools and variety in habitats. The frequency of the freshes are increased because its effects are short-lived.
High flows will fill the channel and inundate all benches. This will disturb riparian vegetation and ensure sediment transport.

Table 5.2 EFR Moorabool River reach 2.

Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Cease-to-flow: 0 m^3/s;2/yr, 8 days						Low flow: 0.3 m^3/s (or natural)					
Low flow: 0.05 m^3/s (or natural)						Fresh: > 0.5 m^3/s;min. 3/yr, 10 days					
Fresh: > 0.08 m^3/s;min. 4/yr, 7 days						High flow: 6.1 m^3/s;1/yr, 2 days					

Note: Recommended flows have been converted from ML/day.

5.6. Reach 3 West Moorabool River below Lal Lal reservoir to Sharp Road, She Oaks

5.6.1. Reach description

The channel has pool and riffle system and its layout varies between constricted and shallow wide sections. In general the area is or has been subjected to farming (stock access), avulsion of benches and willow removal. Some parts of the channel border a national park which results in the presence of valuable habitats.
Riparian vegetation along the channel consists, among others, of River Red Gum, Silver Wattle and Woolly Tea-Tree. Instream channel habitats contain a high diversity of (healthy) macro-invertebrates communities, Common Reed, rush and various fish species such as: Tupong, Australian Grayling, Spotted Galaxias, River Blackfish and Australian Smelt.

5.6.2. Hydrology

Figure 5.6 presents the FDC of reach two as measured at gauge station Morrisons, number 232204. The hydrological data is obtained from VWRDW, publicly available on Internet (VWRDW).

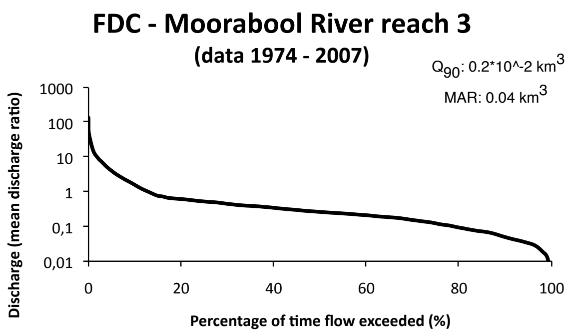


Figure 5.6 Flow duration curve Moorabool River reach 3 at Morrisons.

5.6.3. Flow requirements

The EFR for reach 3 in Table 5.3 has a similar setup as reach 2. Only flow requirements with different EFR objectives are further described in this section.

The summer fresh is also assigned as a migration trigger for certain fish species (e.g. Australian Grayling). The winter low flow allows fish movement and suppresses encroaching terrestrial vegetation. An additional objective of the high flows is a migration cue for fish species. Overbank flows are not recommended due to absence of any noteworthy wetlands.

Table 5.3 EFR Moorabool River reach 3.

Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Cease-to-flow: 0 m^3/s;1/yr, 10 days						Low flow: 1.0 m^3/s (or natural)					
Low flow: 0.23 m^3/s (or natural)						Fresh: > 1.7 m^3/s;2/yr, 5 days					
Fresh: > 0.36 m^3/s;min.4/yr, 7 days						High flow: 36.1 m^3/s;1/yr, 2 days					

Note: Recommended flows have been converted from ML/day.

5.7. Comparison new EFR model

LFR and HFR of the case studies are created in a similar way as is in chapter 3 (see also appendix I). These flow requirements are used to research how precise the predictions of the new EFR model are. Table 5.4 shows the LFR and HFR predictions by the new EFR model and the actual flow requirements assigned by the case studies. The comparison shows very different predictions for the LFR, while the HFR estimations are comparable to those of the case studies.

Table 5.4 Comparison newly EFR model recommendation and case studies.

	Barwon River	Moorabool River	
LFR	reach 1	reach 2	reach 3
Q_{90} (ML/yr)	2E+03	4E+02	2E+03
MAR (ML/yr)	8E+04	2E+04	4E+04
LFR $_{\text{newly EFR model}}$ (% MAR)	27	32	19
LFR $_{\text{case study}}$ (% MAR)	14	20	49
HFR	reach 1	reach 2	reach 3
Q_{90} (ML/d)	6	1	5
Q_{50} (ML/d)	35	22	28
HFR $_{\text{newly EFR model}}$ (% MAR)	13	5	14
HFR $_{\text{case study}}$ (% MAR)	16	7	19

Note: values are rounded.

The LFR and HFR data are imported into the graphs of chapter 4 which results in Figure 5.7; encircled are the new data of the three case studies. Although the R^2 scores slightly change, a total shift of the trendline does not occur., The extra data supports the trend described by the 'new EFR model'.
For the Smakhtin LFR method a R^2 score is again established; a R^2 of 0.25. Also a two tailed t-test is conducted, with again the hypothesis that the Smakhtin LFR method is a good estimator. This time the result of the test indicates that the hypothesis, and thus the Smakhtin LFR method, can be rejected with a significance level of (at least) 10% (see appendix II).

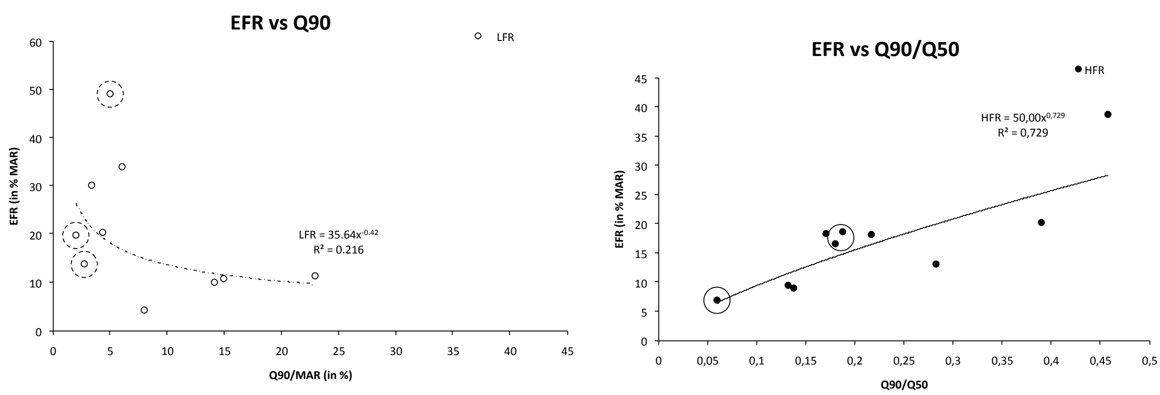


Figure 5.7 LFR and HFR trendline plots with validation EFR case studies

The new EFR model was based on a limited number of cases studies. Therefore the new case studies are used to develop new trendlines to present LFR and HFR estimation models (see Figure 5.7). The LFR and HFR trendlines result in the following models[5]:

$$LFR = 35.6 * \left(\frac{Q_{90}}{MAR} * 100 \right)^{-0.42} \quad HFR = 50.0 * \left(\frac{Q_{90}}{Q_{50}} \right)^{0.73}$$

From this point onwards these models will be used and referred to as the 'new EFR model'.

[5] Note the equations in Figure 5.7 are used.

6. Global EFR application

Comparison between the Smakhtin method and the new EFR model of chapter 5, is the central point in this chapter. By applying both methods on world's major river basins a map is created to illustrate the effects of the new EFR model.

6.1. Data of major river basins

A river basin, or watershed, is the area of land where precipitation drains downhill into a waterbody, i.e. river, lake or sea. These basins are separated by geographical barriers that obstruct water flowing to other regions. Smaller sub-basins and watersheds are ultimately a part of a large river basin. The basins used in this chapter are considered primary or major river basins and are obtained through the World Resources Institute (WRI) (Revenga et al., 1998). This list consists of over a hundred river basins (see appendix III). A number of the basins included in the list are of a smaller size than some sub-basins. However, only the listed major river basins are used because of a lack of sub-basin information.

In Smakhtin et al. (2004a & b) the EFR method is applied on major river basins by using modeled flow data. Such data were not available for this study. Therefore the comparison between Smakhtin method and the new EFR model is carried out using measured flow records.
The hydrological data for the basins is acquired from various publicly on Internet available discharge data sets. In this study the following databases are used: GRDC, GRDW, R-Hydronet, RivDIS v1.1 and Unesco-Shiklomanov. Databases GRDC and RivDISv1.1 also present the contours of various large river basins including the general river pattern and tributaries.

With a few exceptions most of the river basins contain multiple gauge stations and thus various flow records. The majority of the flow records that are used come from the most downstream located stations. It is assumed in this study that the most downstream stations resemble the total river basin. And as such, represent the total amount of water that flows through the river basin. The consequence of using downstream located station is that the data will consist of fewer extreme values than can be observed in flow data of more upstream regions. In case the downstream stations provide too few years of data a more upstream station is used. And in absence of a main channel station, one in a tributary is used. In the end there are 86 river basins suitable for application of the new EFR model..

The length of flow records vary from 3 to over 100 years and contain mean month flows (in m^3/s). Various stations show incomplete years within the flow records. These records miss some months of data during a year and in some cases even complete years. In the application of the EFR methods only years containing flow data for each month, i.e. complete flow years, are used.

6.2. Global application

To apply the new EFR model, described in paragraph 5.7, onto the major river basins requires to link the gauge station locations and river basins together. For each gauge station, and thus river basin, a FDC is created to obtain the required flow parameters and the new EFR model is applied (see appendix IV).
It should be noted that the use of river basins from around the world will result in application of the new EFR model on a wide range of flow regimes. By using a much wider range of flow regimes the new EFR model is applied to rivers with different flow regimes than those used in the construction of the new EFR model; i.e. Q_{90} > 20% MAR. Therefore, the results of the new EFR model may be more uncertain for those situations.

Figure 6.1-3 presents the flow recommendations of the Smakhtin method (6.1) and the new EFR model (6.2), as well as the differences (6.3) between them. In Figure 6.3. the blue colored (positive) areas indicate that the Smakhtin method recommendations are higher than those of the new EFR method. While the yellow-red scale highlight the

regions in which the Smakhtin method recommends lower EFR than the new EFR model. In all three maps the river basins for which no flow data were available remain white.
In appendix V a map with the Q_{90}/MAR is presented. Combined with Figure 6.3 it reveals that the Smakhtin method describes relatively higher EFR estimations in regions with variable flows (high Q_{90}/MAR). The new EFR model shows higher estimations for variable regimes (low Q_{90}/MAR). Although there are regions with large relative differences between both EFR estimations, almost half of the river basins displays a difference that lies in the range of 0-5%.

In appendix V the EFR map of the world, as presented in Smakhtin et al. (2004a), is also shown. The recommendations on this map, based on modeled flow data, are compared to the Smakhtin map created in this study. A comparison between measured and modeled flow data. Because the original Smakhtin map used modeled flow data it shows an EFR for more locations. The measured flow data map shows one EFR 'color' for an entire basin. Due to differences in detail of the maps, not the entire river basins are compared. Depending on the location within the basin where the measured flow data are collected, it can be stated wether that section of the basin has relatively similar EFR recommendations.
Major differences are not observed between the two maps. There are individual cases with clear differences, like e.g. the river Nile. In case of modeled flow data the main part of the Nile basin is assigned 20-25% MAR, against 30-35% with measured flow data. Though in general it is conceivable that the modeled flow data shows a slightly lower EFR recommendation.

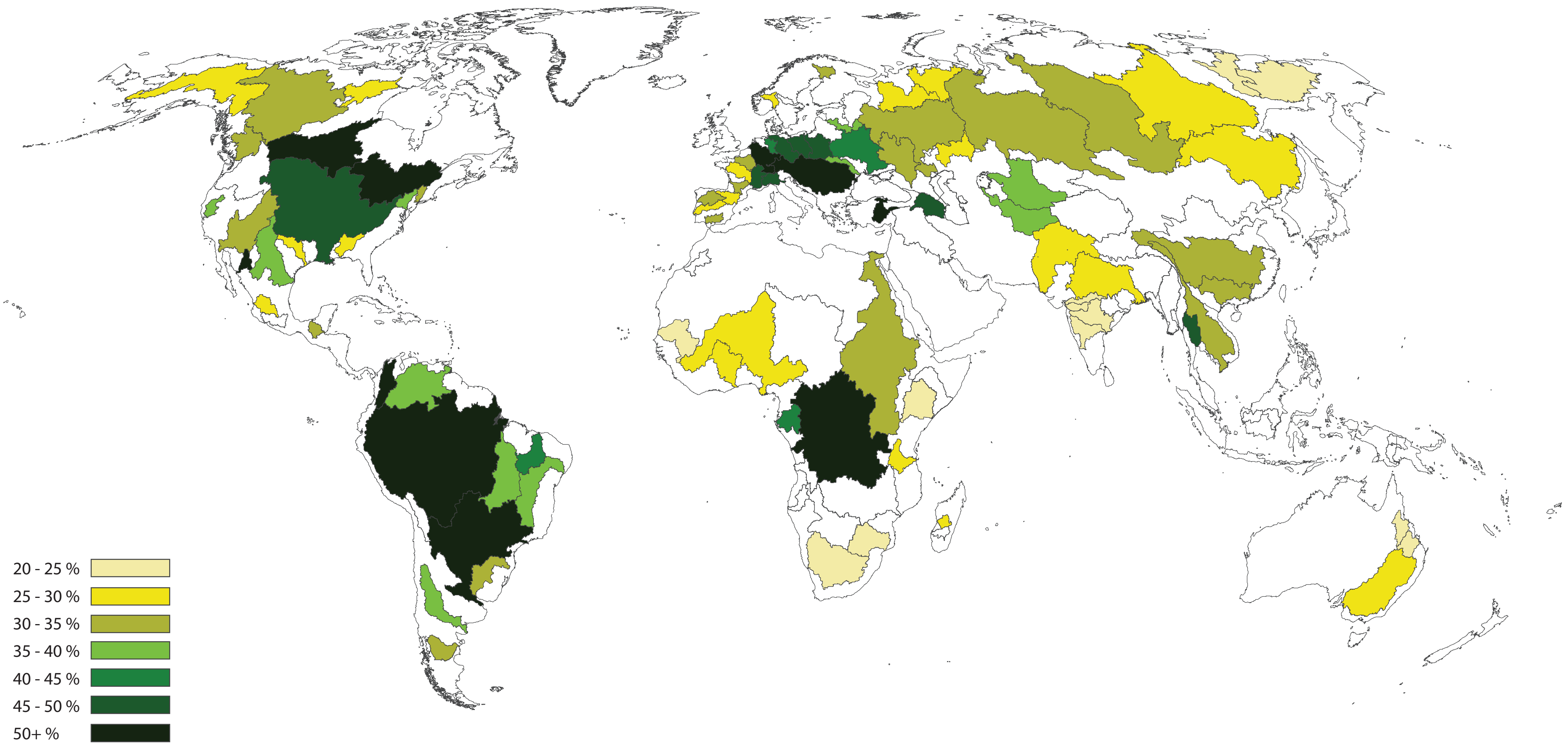


Figure 6.1. Application of Smakhtin method on major river basin using recorded flow data at a single gauge station. EFR presented in percentage of MAR (source basins map: WRI, World Resources Institute).

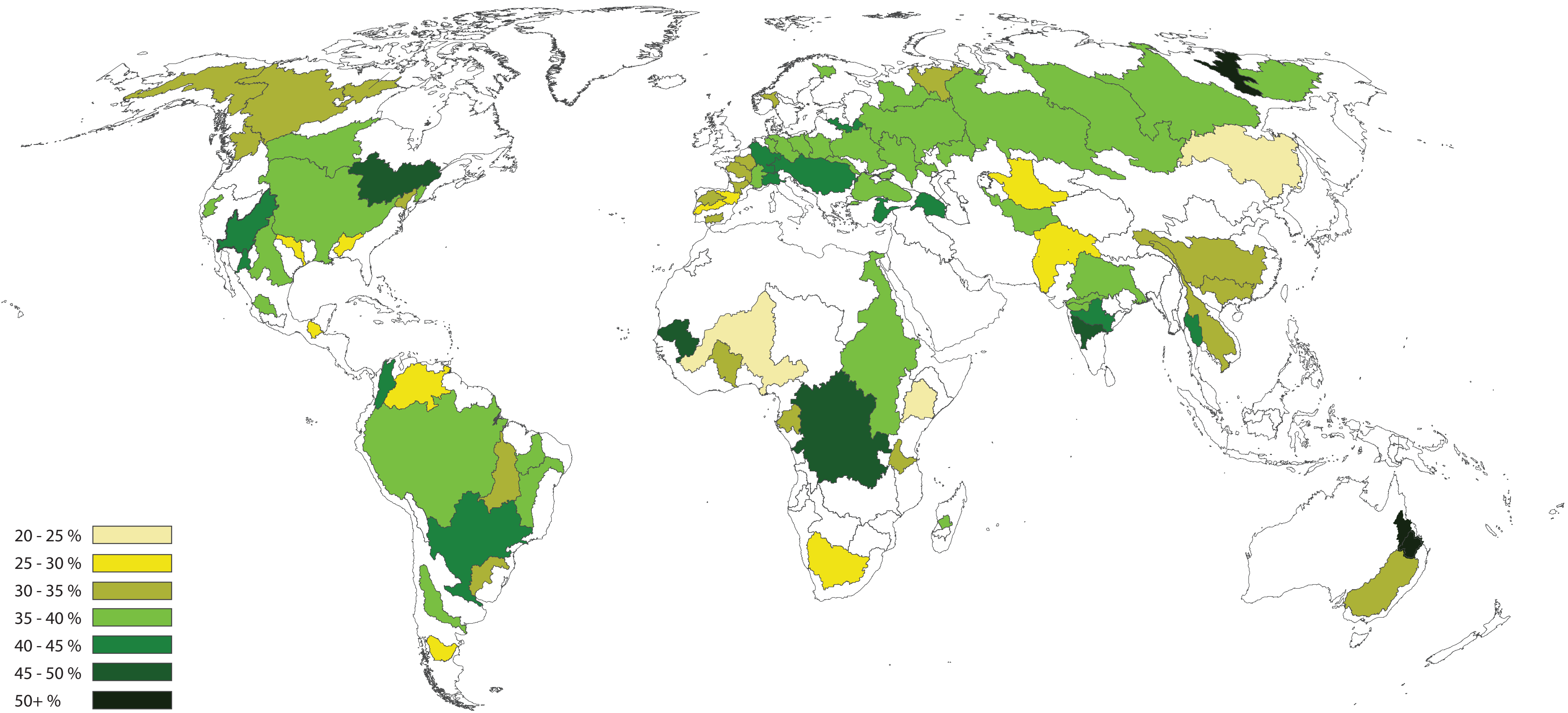


Figure 6.2. Application of new EFR model on major river basin using recorded flow data at a single gauge station. EFR presented in percentage of MAR (source basins map: WRI, World Resources Institute).

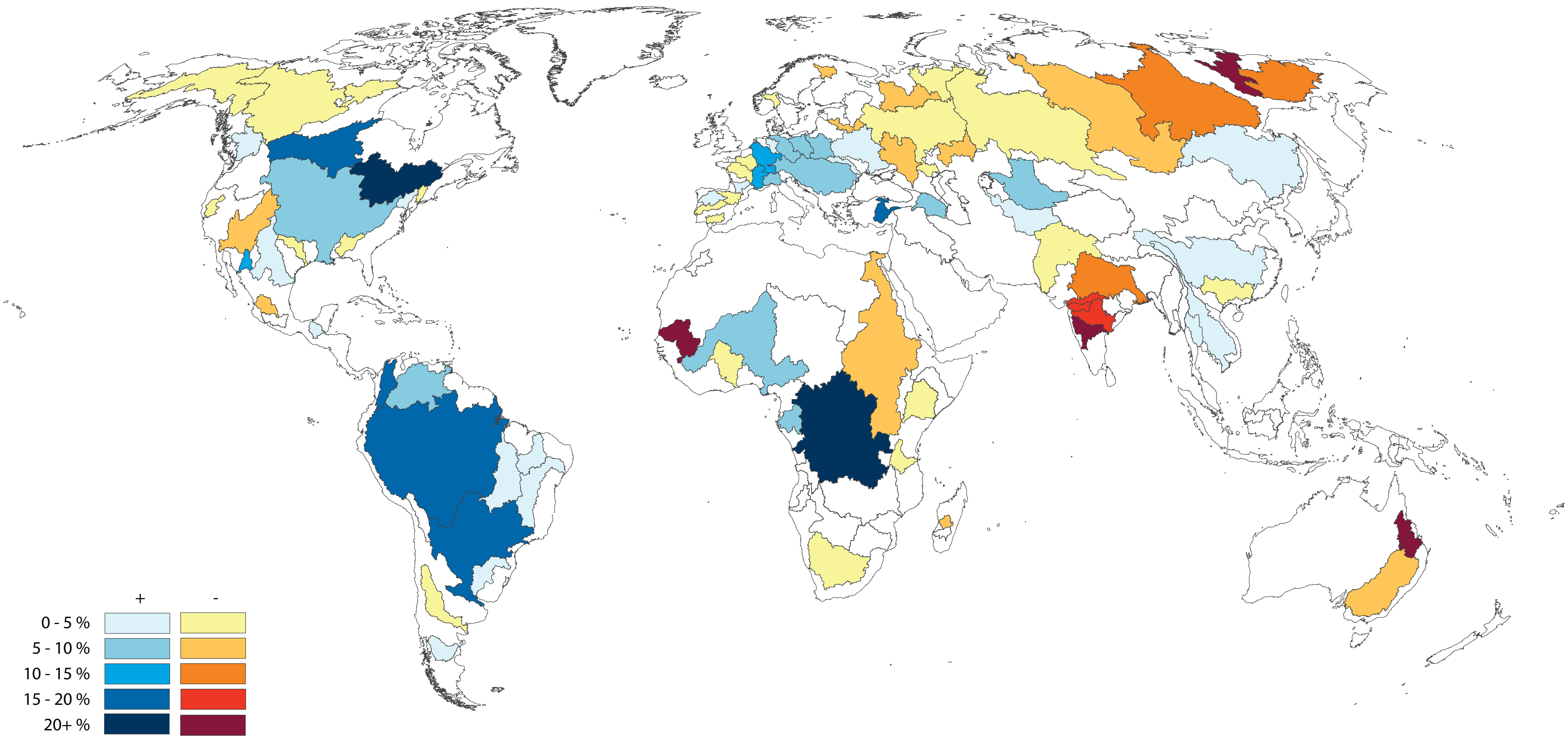


Figure 6.3. Comparison between Smakhtin method and new EFR model after validation. Positive labels indicate that Smakhtin EFR is higher than EFR recommendation of the new EFR model. Negative labels indicate that Smakhtin method EFR is lower than EFR recommendations of the new EFR model. Differences presented in percentages of MAR (source basins map: WRI, World Resources Institute).

7. Discussion

7.1. General results

The results of the validation study of the Smakhtin method, as presented in chapter 4, suggest that it could be improved. It reveals that another EFR model can present predictions with similar accuracy regarding the LFR and HFR. However, the new EFR model contains some issues regarding low precision (correlation coefficient) of the LFR and the meaning for the use of the HFR.
The difference between the Smakhtin LFR method and the case studies, and thus also the new LFR model, can well be the result of the 'fair condition' principle of the Smakhtin method. EFRs of the case studies aim for a more sustainable ecosystems. For a variable flow regime the new EFR model assigns relative large amounts of water to ensure the low flow part of EFR. And for more stable flow regimes it estimates lower amounts of LFR. The new HFR model is selected so that it assigns a larger HFR where the LFR is low; i.e. HFR is high when the flow regime is stable. The new HFR therefore does not fully relate to the definition of Smakhtin et al. (2004a), who considers the HFR to be a 'quickflow' response to precipitation. Especially for stable regimes, that are assigned larger HFRs, it contradicts this definition.

Besides Smakhtin et al. (2004a), literature states that the EFR recommendations should include or mimic natural flow events of a flow regime (Richter et al.,1997; NRE, 2002; O'Keeffe et al., 2009). This means incorporating droughts, low and high flow, flood events etc. All the used EFR case studies have incorporated such events. It is for this reason that the LFR and HFR are considered in the Smakhtin method and the new EFR model has incorporated them also.

Some of the above mentioned flow events, and thus mimicking the flow, could be achieved by the LFR. As a daily flow, the recommended LFR either occurs or there is a lower flow. In the latter case the flow variety steps in. At those moments the natural flow is accepted as the low flow (as described in paragraph 2.2) and thus it leads to a series of possible different flows instead of one single (low) flow that is defined by LFR.
With a higher daily LFR flow, the possibility of this sort of flow variety increases. In this way the flow variety could be included in the LFR. Note that only when the flow is lower as a result of natural occurrence or circumstances it is considered a temporary LFR replacement. In all other cases the recommended LFR is still perceived as the required flow.
The new LFR model could be practiced in a similar way. It assigns a relatively larger LFR to variable flow regimes. Therefore, a part of the flow variety that would otherwise be created by the HFR, could be handled by the LFR. And in this way tackle the characteristic of the new HFR model. The sum of both flow requirements still appears to present a sustainable EFR.

7.2. Limitations

Besides a different interpretation of LFR and HFR as described above, there are aspects within the validation process that result in limitations of the study results; concerning prior steps of the development of the new EFR model. These aspects are divided into two parts; one regarding the used data and an other regarding the model results of the EFR comparisons.

7.2.1. Data

The required flow parameters, for comparison with the Smakhtin method, are obtained by using measured flow data. The use of recorded flow data means that the flows have possibly lost some of its natural characteristics due to regulation activities and flow alterations. One of the possible consequences is a decrease of low flow occasions. During the wet season low flows can be used to fill reservoirs. In the dry season these flows are released for irrigation purposes (King, 2002). Another possible consequence is a shift in flow regime, a Q_{95} flow can become a Q_{90} flow (Bragg et al., 2005). The use of regulated flow does not necessarily present a natural flow.

A second aspect is data irregularities concerning certain flow records of the case study rivers and major river basins. These errors express themselves as no actual documentation of any flow data and long periods of no-flow during a season when such flows are highly unlikely to occur. In those cases the entire year in which the error occurred is discarded, which leads to non-continues flow records. The result of such non-continuous data is that certain characteristic flow years may not be included in the data set. And thus lead to missing possible important flow events, which will influence the flow parameters and form of the FDC.

7.2.2. Model results

In the development of the new EFR model a limited number of EFR case studies is used; in total 10 case studies. This leads to uncertainty in the chosen model, which is best illustrated by the weak R^2 scores. The distribution around the globe of these studies is marginal and majority are Australian based. The rivers of the studies are of a relative small size.
Combined with the limited case study data and its global distribution, this leads to only a few flow regimes being represented in the new EFR model. According to the Q_{90}/MAR method, the rivers of the case studies are more likely variable than stable regimes. So the new EFR model is established while covering only a small part of the possible range of flow regimes. It is for those regions that the model is most likely to describes a better fitting EFR.

Related to the incorporation of a limited range of regime variability is the uncertainty of the keywords: 'flow regime variability'. Transitions of individual points (rivers) are observed during different classifications of the flow regimes. One approach to describe regime variability classifies a river as variable while another states that the same river has more stable flow regime characteristics. So for given flow requirements and river flow data, the ratios present (weak) trendlines tendencies that can be opposite to each other. This transitions increases the uncertainty in establishing which trend describes the EFR in the most reliable way. This uncertainty of the new EFR model is expressed by its general weak R^2 score, especially for the LFR. The Smakhtin method has similar weak scores.
How all this eventually affects the developed new EFR model, regarding any under or overestimation of EFR, can not be determined. What can be stated is that a LFR model could, just as the HFR of the Smakhtin method, be derived from flow parameters and therefore The LFR does not have to be a Q_{90}. In fact this points in the direction of a possible improvement of the Smakhtin method.

8. Conclusion and recommendations

8.1. Conclusions

Representing the ecological water demands in global water assessments requires an EFR method that provides a set of flow requirements that can easily be established and serves as an reliable set of flows. The EFR method of Smakhtin et al. (2004a) is developed to be such a method. The main objective of this study was to look into the precision of the LFR (low flow requirements) and HFR (high flow requirements) recommendations of the Smakhtin EFR method when these are compared to EFR established in EFR case studies for rivers.

Based on the outcome of ten EFR case studies, a two-tailed statistical t-test and correlation coefficient scores, it appeared that the Smakhtin LFR method of Q_{90} flow can just as well be replaced by another model. The LFR estimations of the Smakhtin method, Q_{90} flow, were generally lower than the LFR established by the case studies. A new EFR model is established:

$$LFR = 35 * \left(\frac{Q_{90}}{MAR} * 100 \right)^{-0.42} \qquad HFR = 50 * \left(\frac{Q_{90}}{Q_{50}} \right)^{0.73}$$

Rivers with variable flow regimes (low Q_{90}/MAR) are, in the new LFR model established in this study, allocated a relatively higher percentage of MAR than in the method by Smakhtin et al. (2004a). The HFR method defined by Smakhtin decreases when flow regimes become more stable. Preserving this HFR approach would eventually lead to rivers with a stable flow regime being allocated (almost) no water volume. The new HFR model increases the amount of water being allocated when flow regimes become more stable. Now the EFR, LFR plus HFR, still presents a ecological sustainable estimation.

Comparison of the new EFR model with the Smakhtin method shows that, when applied on major river basins, the new EFR model has the tendency of having lower EFR estimations for regions characterized by stable flow regimes. In variable flow regimes it is reverse, and the new EFR model shows (some) higher EFR estimations. For the other, intermediate regimes there are less differences.
However, the manner in which flow regime variability is described appears to be not as straightforward as expected. Classification of the flow regimes has different results for each approach that is used in this study, which leads to uncertainty.

An answer to the question wether the EFR recommendations by the Smakhtin method are reliable enough to be considered an adequate EFR method can not be answered with a simple 'yes or no'. The results of this study brought to light that a 'fair' Q_{90} Smakhtin LFR does not provide sufficient protection in the case studies with variable flow regimes. At the same time its HFR does not present major discrepancies. However, the fact that the LFR estimations did not suffice the case studies shows that the Smakhtin method needs improvement of its LFR method. As the LFR and HFR are related to each other the HFR also requires further improvement. The new EFR model developed in this study show the direction in which these improvements can be made.

8.2. Recommendations

This study illustrates that the Smakhtin method does not necessarily describes the EFR matter in a correct manner. With its limited resources this study gives reason to engage a future research of this topic.
Before collecting more data to further improve the Smakhtin method, there are other things that need to be investigated. The main assumption in this study and in Smakhtin et al. (2004a) is the existence of a correlation between flow regime variability of a river and the recommended amount of flow for EFR. This study shows uncertainties and transitions in the process of describing the variability of a flow regime. Research should be done into the most adequate manner to address and indicate the variability of a river regime; which ratio presents reliable

regime variability descriptions. When the flow regimes can be classified by using a reliable technique, the findings of the research to the correlation between flow regime variability and EFR become more reliable.
Once the flow regime variability can be described in a reliable way, more EFR case studies should be collected. A data set that incorporates different sizes of river and different flow regimes, so that the EFR model can eventually be applied on to a wider range of rivers while retaining confident results.

The following steps or elements are recommended in the process to create an EFR model that can be used in global water assessments and for individual cases:

- research into an appropriate and reliable technique to describe flow regime variability by flow parameters, e.g. MAR, Q_{90}.
- extend the package of EFR case studies; with studies that are more widespread over the world.
- include studies on larger rivers to make the model more applicable for different sizes and kind of rivers.

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Appendix I: EFR case studies

The numbers and figures of the flow data used to construct the LFR and HFR comparison are presented here.[1]
1 ML/d = 1000/(3600*24) ≈ 1.157 E-02 m^3/s
1 ft^3/s ≈ 2.832 E-02m3/s

Bill Williams River - gauge station downstream of Alamo Dam, station number: 09426000

LFR
(0.566 m^3/s * 61 days + 1.416 m^3/s * 304 days) * 86,400 s/day = 40,172,771 m^3 (≈ 0.302 MAR)
HFR
(11.327–1.416) ft^3/s * 28 days) * 86,400 s/day = 23,976,441 m^3 (≈ 0.180 % MAR)
EFR: 64,149,212 m^3 (≈ 0.482 MAR)
mean: 4.219 m^3/s MAR: 365 * mean * 86400 s/day
Q_{90}: 0.141 m^3/s Q_{80}: 0.272 m^3/s Q_{50}: 0.651 m^3/s Q_{20}: 1.472 m^3/s

Border Meuse - gauge station 'Borgharendorp'

LFR
10 m^3/s * 365 days * 86,400 s/day = 315,360,000 m^3 (≈ 0.042 MAR)
HFR
((30–10) m^3/s * 92 days + (75–10) m^3/s * 91 days) * 86,400 s/day = 670,032,000 m^3 (≈ 0.090 MAR)
EFR: 985,392,000 m^3 (≈ 0.132 MAR)
mean: 236.94 m^3/s MAR: 365 days*mean* 86400 s/day
Q_{90}: 19 m^3/s Q_{80}: 39 m^3/s Q_{50}: 138 m^3/s Q_{20}: 380 m^3/s

Lower Thomson River

reach 2 - gauge station down stream of Thomson Dam, number 225112

LFR
125 ML/d * 151 days + 230 * 214 days = 68,095 ML (≈ 0.340 MAR)
HFR
(230–125) ML/d * 21 days + (800–230)ML/d * 20 days + (2,000–230)ML/d * 3 days = 18,915 ML (≈ 0.094 MAR)
EFR: 87,010 ML (≈ 0.434 MAR)
mean: 549.121 ML/d MAR: 365 days * mean
Q_{90}: 33.511 ML/d Q_{80}: 82.472 ML/d Q_{50}: 253.133 ML/d Q_{20}: 430.001 ML/d

[1] rounded

reach 4a - gauge station Heyfield, number 225200

LFR
20 ML/d * 151 days + 45 ML/d * 214 days = 12,650 ML (≈ 0.113 MAR)
HFR
(45–20) ML/d * 28 days + (260–45) ML/d * 28 days + (2,000–45) * 4 days = 14,540 ML (≈ 0.130 MAR)
EFR: 27,190 ML (≈ 0.243 MAR)
mean: 306.103 ML/d MAR: 365 days * mean
Q_{90}: 70.097 ML/d Q_{80}: 97.489 ML/d Q_{50}: 247.873 ML/d Q_{20}: 458.662 ML/d

reach 5 - gauge station Wandocka, number 225212
LFR
70 ML/d * 365 days = 25,550 ML (≈ 0.108 MAR)
HFR
(230–70) ML/d * 12 days + (300–70) ML/d * 28 days + (5,000–70) ML/d * 8 days = 47,800 ML (≈ 0.202 MAR)
EFR: 73,350 ML (≈ 0.309 MAR)
mean: 649.695 ML/d MAR: 365 days * mean
Q90: 97.3405 ML/d Q80: 134.799 ML/d Q50: 249.0395 ML/d Q20: 773.928 ML/d

reach 6 - gauge station Bundalaguak, number 225232
LFR
100 ML/d * 365 days = 36,500 ML (≈ 0.100 MAR)
HFR
(355–100) ML/d * 12 days + (2,200–100) ML/d * 30 days + (9,500–100) ML/d * 8 days = 141,260 (≈ 0.387 MAR)
EFR: 177,760 ML (≈ 0.487 MAR)
mean: 999.56 ML/d MAR: 365 days * mean
Q_{90}: 141.13 ML/d Q_{80}: 195.45 ML/d Q_{50}: 308.62 ML/d Q_{20}: 807.34 ML/d

Lower Macalister River

reach 1 - gauge station Glenmaggie tail gauge, number 225204

LFR
35 ML/d * 182 days + 320 ML/d * 183 days = 64,930 (≈ 0.204 % MAR)
HFR
(350 - 35) ML/d * 21 days + (1,500 - 320) ML/d * 27 days + (10,000 - 320) ML/d * 2 days = 57,835 ML (≈ 0.182 MAR)
EFR: 122,765 ML (≈ 0.386 MAR)
mean: 872.133ML/d MAR: 365 days * mean
Q_{90}: 37.937 ML/d Q_{80}: 44.196 ML/d Q_{50}: 221.986 ML/d Q_{20}: 844.575 ML/d

Barwon River

reach 1 - gauge station Ricketts Marsh, number 233224
LFR
5 ML/d * 151 days + 50 ML/d * 214 days = 11,455 ML (≈ 0.138 MAR)
HFR
(215–5) ML/d * 6 days + (153–50) ML/d * 15 days + (1,600–50) ML/d * 7 days = 13,655 ML (≈ 0.165 MAR)
EFR: 82,792 ML (≈ 0.360 MAR)
mean: 226.828 ML/d MAR: 365 days * mean
Q_{90}: 6.293 ML/d Q_{80}: 11.155 ML/d Q_{50}: 34.814 ML/d Q_{20}: 202.967 ML/d

Note: 7 instead of 10 days of large fresh flow; cause fish species required maximum 7 days of this flow.

Moorabool River

reach 2 - gauge station Mount Doran, number 232211
LFR
0 ML/d * 16 days + 4 ML/d * 166 days + 22 ML/d * 183 days = 4,690 ML (≈ 0.198 MAR)
HFR
(7–4) ML/d * 28 days + (40–22) ML/d * 30 days + (525–22) ML/d * 2 days = 1,630 ML (≈ 0.069 MAR)
EFR: 23739 ML (≈ 0.266 MAR)
mean: 65.037 ML/d   MAR: 365 days * mean
Q_{90}: 1.323 ML/d Q_{80}: 4.359 ML/d Q_{50}: 22.079 ML/d Q_{20}: 57.825 ML/d

reach 3 - gauge station Morrisons, number 232204
LFR
0 ML/d * 10 days + 20 ML/d * 172 days + 83 ML/d * 183 days = 18,629 ML (≈ 0.491 MAR)
HFR
(31–20)ML/d * 30 days + (146–83) ML/d * 10 days + (3,115–83) ML/d * 2 days = 7,024 ML (≈ 0.185 MAR)
EFR: 37,935 ML (≈ 0.676 MAR)
mean: 103.933 ML/d   MAR: 365 days * mean
Q_{90}: 5.196 ML/d Q_{80}: 9.803 ML/d Q_{50}: 27.667 ML/d Q_{20}: 64.800 ML/d

Appendix II: Statistical test

Statistical test (R^2)

$\hat{y}_i$ = 'estimated regression line' ; LFR = Q_{90}
y_i = case study LFR (observed LFR)

$$SS_R = \sum_{i=1}^{n} \hat{y}_i^2 - \frac{\left(\sum_{i=1}^{n} \hat{y}_i\right)^2}{n}$$

$$SS_T = \sum_{i=1}^{n} y_i^2 - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n}$$

$$R^2 = \frac{SS_R}{SS_T}$$

These scores presented in this study are obtained through Excel, which uses the same method as mentioned above.

	Smakhtin estimation (values in % MAR)		case study data (values in % MAR)	
	LFR: $\hat{y}_i$		LFR: y_i	
	$\hat{y}_i$	$\hat{y}_i^2$	y_i	y_i^2
Bill Williams River	3.36	11.26	30.19	911.70
Border Meuse	8.02	64.30	4.22	17.81
Lower Macalister River reach1	4.35	18.92	20.40	416.04
Lower Thomson River reach 2	6.10	37.24	33.97	1,154.27
Lower Thomson River reach 4a	22.90	524.40	11.32	128.19
Lower Thomson River reach 5	14.98	224.47	10.77	116.09
Lower Thomson River reach 6	14.12	199.39	10.01	100.11
Moorabool River reach 2	2.03	4.14	19.76	390.34
Moorabool River reach 3	5.00	24.99	49.11	2,411.51

Barwon River reach 1	2.77	7.70	13.84	191.43

With the first seven cases (Bill Williams River to Lower Thomson River reach 6) the following SSR and SST results are obtained (n=7) for LFR:
SSR: 244.05
SST:756.50
R^2: 0.32

With all the ten case studies (Bill Williams River to Barwon River reach 1) the following SSR and SST results are obtained (n=10) for LFR:
SSR: 338.01
SST: 1692.67
R^2: 0.20

two-tailed t-test

use of STDEV formula in Excel to derive standard error () .
Excel uses the following equation:

$$\sigma = \sqrt{\frac{\sum\left(x - \bar{x}\right)^2}{n-1}}$$

with ‘x’ being the difference between $LFR_{case\ study}$ and $LFR_{Smakhtin\ method}$.

H0 = the hypothesis (μ)
H1 = alternative hypothesis
alpha = level of significance
X = average value data set

$$z = \frac{\bar{X} - \mu_0}{\sigma}\sqrt{n}$$

Hypothesis is that there is no difference between Smakhtin LFR and case study LFR; difference is expected to be zero ($\mu_0 = 0$).

$H_0 : \mu_0 = 0$
$H_1 : \mu_1 \neq 0$

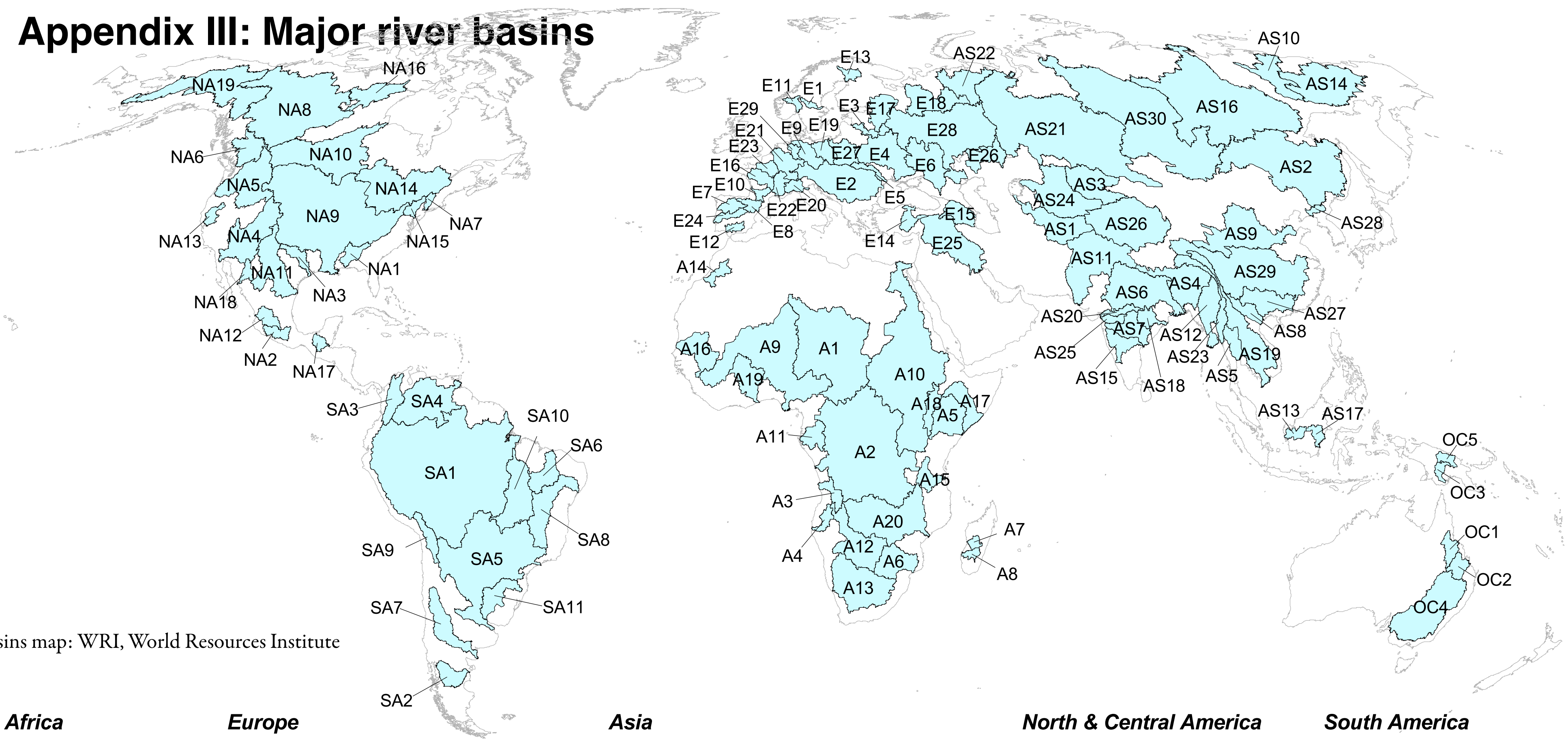
with n = 7 (Bill Williams River to Lower Thomson River reach 6):
X = 6.78
standard error = 16.37
z = 1.09

with n = 10 (Bill Williams River to Barwon River reach 1):
X = 12.03
standard error = 17.83
z = 2.13

critical region for n = 7 with alpha = 10% (two-tailed); degrees of freedom: 6 (n-1)
z = 1.94
critical region for n = 10 with alpha = 10% (two-tailed); degrees of freedom: 9 (n-1)
z = 1.83
critical region for n = 10 with alpha = 5% (two-tailed); degrees of freedom: 9 (n-1)
z = 2.26

LFR			(x)
	Smakhtin	case study	case study – Smakhtin
Bill Williams River	3.36	30.19	-26.84
Border Meuse	8.02	4.22	3.80
Lower Macalister River reach1	4.35	20.40	-16.05
Lower Thomson River reach 2	6.10	33.97	-27.87
Lower Thomson River reach 4a	22.90	11.32	11.58
Lower Thomson River reach 5	14.98	10.77	4.21
Lower Thomson River reach 6	14.12	10.01	4.11
Moorabool River reach 2	2.03	19.76	-17.72
Moorabool River reach 3	5.00	49.11	-44.11
Barwon River reach 1	2.77	13.84	-11.06

Appendix III: Major river basins



source basins map: WRI, World Resources Institute

Africa

A1 Lake Chad
A2 Congo
A3 Cuanza
A4 Cunene
A5 Jubba
A6 Limpopo
A7 Mangoky
A8 Mania
A9 Niger
A10 Nile
A11 Ogooue
A12 Okavango
A13 Orange
A14 Oued Draa
A15 Rufiji
A16 Senegal
A17 Shaballe
A18 Turkana
A19 Volta
A20 Zambezi

Europe

E1 Dalalven
E2 Danube
E3 Daugava
E4 Dnieper
E5 Dniester (Nistru)
E6 Don
E7 Duero
E8 Ebro
E9 Elbe
E10 Garonne
E11 Glomma-Laagen
E12 Guadalquivir
E13 Kemijoki
E14 Kizilirmak
E15 Kura-Araks
E16 Loire
E17 Lake Ladoga
E18 North Dvina
E19 Oder
E20 Po
E21 Rhine & Maas
E22 Rhone
E23 Seine
E24 Tagus
E25 Tigris & Euphrates
E26 Ural
E27 Vistula
E28 Volga
E29 Weser

Asia

AS1 Amu Darya
AS2 Amur
AS3 Lake Balkhash
AS4 Brahmaputra
AS5 Chao Phrya
AS6 Ganges
AS7 Godavari
AS8 Hong (Red River)
AS9 Huang He (Yellow River)
AS10 Indigirka
AS11 Indus
AS12 Irrawaddy
AS13 Kapuas
AS14 Kolyma
AS15 Krishna
AS16 Lena
AS17 Mahakam
AS18 Mahanadi
AS19 Mekong
AS20 Narmada
AS21 Ob
AS22 Pechora
AS23 Salween
AS24 Syr Darya
AS25 Tapti
AS26 Tarim
AS27 Xun Jiang
AS28 Yalu Jiang
AS29 Yangtze
AS30 Yenisey

North & Central America

NA1 Alabama & Tombigbee
NA2 Balsas
NA3 Brazos
NA4 Colorado
NA5 Columbia
NA6 Fraser
NA7 Hudson
NA8 Mackenzie
NA9 Mississippi
NA10 Nelson
NA11 Rio Grande
NA12 Rio Grande de Santiago
NA13 Sacramento
NA14 Saint Lawrence
NA15 Susquehanna
NA16 Thelon
NA17 San Pedro & Usumacinta
NA18 Yaqui
NA19 Yukon

South America

SA1 Amazon
SA2 Chubut
SA3 Magdalena
SA4 Orinoco
SA5 Paraná
SA6 Parnaiba
SA7 Rio Colorado
SA8 São Francisco
SA9 Lake Titicaca & Salar de Uyuni
SA10 Tocantins
SA11 Uruguay

Oceania

OC1 Burdekin-Belyando
OC2 Dawson
OC3 Fly
OC4 Murray-Darling
OC5 Sepik

Appendix IV: EFR application major river basins

EFR North-America

Database numbers represent the following databases (as mentioned in references list):
1) RivDISv1.1 & GRDC
2) GRDW
3) Unesco-Shiklomanov
4) R-Hydronet

North-America									EFR - Case study			EFR-Smakhtin				
nr	River Basin	Station	Data base	ID-num ber	Dataset years	Mean flow [m³/s]	Q_{90} [m³/s]	Q_{50} [m³/s]	LFR (% MAR)	HFR (% MAR)	EFR (% MAR)	LFR (% MAR)	HFR (% MAR)	EFR (% MAR)	Difference Smakhtin - Case study	EFR Smakhtin document
1	Alabama	Coffee-Ville L&D nr Coffee-Ville, A	2	2955	1961-92	8,70E+02	1,10E+02	4,80E+02	12,0	17,6	29,7	13,2	15,0	28,2	-1,4	-
2	Balsas	-		-	-	-	-	-	-	-	-	-	-	-	-	-
3	Brazos	Rosharon, TX	2	313	1924-92	1,40E+02	1,10E+01	6,50E+01	15,3	13,4	28,7	7,5	20,0	27,5	-1,3	-
4	Colorado	Lees Ferry, Ariz.	1	360	1911-1960	5,10E+02	1,40E+02	2,50E+02	8,8	33,4	42,2	27,9	7,0	34,9	-7,3	27
5	Columbia	-		-	-	-	-	-	-	-	-	-	-	-	-	33
6	Fraser	Hope	1	272	1913-84	2,70E+03	7,50E+02	1,90E+03	8,9	25,0	33,9	27,6	7,0	34,6	0,7	-
7	Hudson	Green Island, N.Y.	1	1052	1947-83	3,90E+02	1,30E+02	3,00E+02	8,2	27,1	35,3	33,5	0,0	33,5	-1,9	-
8	Mackenzie	Norman Wells	1	267	1967; 1969-72; 1974-79; 1982-84	8,30E+03	2,60E+03	6,80E+03	8,4	24,8	33,2	30,9	0,0	30,9	-2,3	35

9	Mississippi	Vicksburg, Miss.	1	385	1965-67; 1969-78; 1983-82	1,70E+04	7,80E+03	1,50E+04	7,2	31,4	38,5	45,7	0,0	45,7	7,2	42
10	Nelson	Above Bladder Rapids	3	-	1959-84	2,30E+03	1,30E+03	2,20E+03	6,6	32,7	39,4	54,7	0,0	54,7	15,3	-
11	Rio Grande	Laredo, Tex.	1	365	1901-14; 1923-72	1,10E+02	3,40E+01	7,70E+01	8,6	27,5	36,0	29,8	7,0	36,8	0,8	28
12	Rio Grande de Santiago	Santiago at El Capomal	3	-	1956-81	2,70E+02	3,60E+01	9,60E+01	12,0	24,4	36,4	13,5	15,0	28,5	-7,9	-
13	Sacramento	Sacramento, California	1	351	1949-78; 1980-83	6,90E+02	2,70E+02	5,00E+02	7,7	31,9	39,5	38,7	0,0	38,7	-0,9	-
14	Saint Lawrence	Massena,New York	2	413	1861-1981	6,90E+03	5,80E+03	6,90E+03	5,5	44,5	50,0	84,8	0,0	84,8	34,8	-
15	San Pedro & Usumacinta	Boca Del Cerro	3	-	1949-83	1,90E+03	5,60E+02	1,60E+03	8,5	23,6	32,1	30,0	7,0	37,0	4,9	-
16	Thelon	Thelon at Above Beverly Lake	3	-	1971-88	2,50E+02	1,60E+01	9,20E+01	16,4	13,9	30,3	6,4	20,0	26,4	-3,9	-
17	Susquehanna	Harrisburg, Pa.	2	412	1891-1983	9,70E+02	1,80E+02	7,10E+02	10,5	18,1	28,6	18,3	15,0	33,3	4,7	-
18	Yaqui	El Novillo	1	1105	1976-79	7,90E+01	4,20E+01	6,90E+01	6,7	34,6	41,3	53,3	0,0	53,3	12,0	-
19	Yukon	Pilot Station	2	3872	1976-92	6,40E+03	1,40E+03	4,30E+03	9,9	21,6	31,4	21,3	7,0	28,3	-3,2	-

EFR Africa

Africa									EFR - Case study			EFR-Smakhtin				
nr	River Basin	Station	Data base	ID-number	Dataset years	Mean flow [m³/s]	Q_{90} [m³/s]	Q_{50} [m³/s]	LFR (% MAR)	HFR (% MAR)	EFR (% MAR)	LFR (% MAR)	HFR (% MAR)	EFR (% MAR)	Difference Smakhtin - Case study	EFR Smakhtin document
1	Lake Chad	-	-	-	-	-	-	-	-	-	-	-	-	-	-	24
2	Congo/Zaire	Kinshasa	1	1534	1903-83	4,00E+04	3,00E+04	3,80E+04	5,8	42,1	47,9	74,8	0,0	74,8	26,9	31

3	Cuanza	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	Cunene	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	Jubba	Afgoi	1	1550	1952; 1945-59; 1961-72	4,50E+01	1,80E+00	4,50E+01	19,9	4,8	24,7	4,0	20,0	24,0	-0,7	-
6	Limpopo	Beitbridge Pump-station C/s	-	-	-	-	-	-	-	-	-	-	-	-	-	**25**
7	Mangoky	Bevoay	1	59	1952-1970; 1972; 1974-75; 1982	5,20E+02	7,40E+01	2,10E+02	11,7	23,6	35,3	14,1	15,0	29,1	-6,2	-
8	Mania	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	Niger	Malanvilla	1	1466	1953-60; 62-64;70-72;74-77; 79	1,20E+03	1,40E+02	1,40E+03	12,6	9,0	21,7	11,9	15,0	26,9	5,2	28
10	Nile	Dongola	1	76	1912-84	2,60E+03	6,50E+02	1,40E+03	9,3	28,6	37,8	24,8	7,0	31,8	-6,0	24
11	Ogooue	Lam-barene	1	17	1930-49; 1954-75	4,70E+03	2,00E+03	4,50E+03	7,4	27,4	34,8	42,1	0,0	42,1	7,3	-
12	Okavango	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	Orange	Vioolsdrif	1	1459	1965;67-70;72;78-80	1,60E+02	5,80E+00	9,10E+01	20,6	6,7	27,3	3,7	20,0	23,7	-3,6	27
14	Oued Draa	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	Rufiji	Stiegeler's Gorge	1	1526	1955-58; 61;71;77-78	8,20E+02	1,90E+02	5,10E+02	9,6	24,2	33,7	22,9	7,0	29,9	-3,9	-
16	Senegal	Bakel	1	70	1951-84	6,70E+02	4,10E+00	1,60E+02	43,6	3,5	47,2	0,6	20,0	20,6	-26,5	23
17	Shaballe	-	-	-	-	-	-	-	-	--	--	-	-	-	-	-
18	Turkana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

19	Volta	Bamboi	1	1494	1951-73	2,60E+02	2,30E+01	1,00E+02	14,2	16,8	31,1	8,9	20,0	28,9	-2,1	28
20	Zambezi	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

EFR Asia

Asia									EFR - Case study			EFR-Smakhtin				
nr	River Basin	Station	Data base	ID-number	Dataset years	Mean flow [m³/s]	Q_{90} [m³/s]	Q_{50} [m³/s]	LFR (% MAR)	HFR (% MAR)	EFR (% MAR)	LFR (% MAR)	HFR (% MAR)	EFR (% MAR)	Difference Smakhtin - Case study	EFR Smakhtin document
1	Amu Darya	Chatly	1	1252	1938-73	1,30E+03	4,00E+02	9,50E+02	8,6	26,5	35,1	29,8	7,0	36,8	1,7	27
2	Amur	Kom-somolsk	1	932	1933-84	9,70E+03	1,10E+03	8,40E+03	12,8	11,6	24,3	11,5	15,0	26,5	2,2	28
3	Lake Balkhash	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	Brahmmaputra	-	-	-	-	-	-	-	-	-	-	-	-	-	-	27
5	Chao Phraya	Nakhon Sawan	1	888	1976-84	7,80E+02	3,60E+02	5,90E+02	7,1	35,2	42,2	47,0	0,0	47,0	4,8	-
6	Ganges	Farakka	1	863	1949-60; 1965-73	1,20E+04	1,80E+03	3,90E+03	11,6	28,0	39,6	14,6	15,0	29,6	-10,0	23
7	Godavari	Pola-varam	1	858	1902-10; 1912-60; 1965-74; 1976-79	3,20E+03	7,20E+01	3,70E+02	25,2	15,3	40,5	2,3	20,0	22,3	-18,3	24
8	Hong	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	Huang He	-	-	-	-	-	-	-	-	-	-	-	-	-	-	31
10	Indigirka	Voron-tsovo	1	936	1937-68; 1972-84	1,60E+03	9,70E+00	1,40E+02	43,6	7,3	50,9	0,6	20,0	20,6	-30,3	-

11	Indus	Kotri	3	-	1937-55; 1967-70; 1976-79	2,90E+03	1,70E+02	1,10E+03	17,0	12,4	29,4	5,8	20,0	25,8	-3,6	25
12	Irriwaddy	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	Kapuas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	Kolyma	Sredne-kolymsk	1	937	1927-31; 1934-57; 1964-84	2,20E+03	5,90E+01	4,00E+02	23,5	12,4	35,8	2,7	20,0	22,7	-13,1	-
15	Krishna	Vijaya-wada	2	856	1901-19 60; 1965-74; 1976-79	1,60E+03	1,00E+01	2,40E+02	43,9	5,0	48,8	0,6	20,0	20,6	-28,2	24
16	Lena	Kusur	1	930	1935-84	1,70E+04	1,30E+03	3,60E+03	15,0	24,0	39,0	7,9	20,0	27,9	-11,1	-
17	Mahakam	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	Mahandi	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19	Mekong	Muk-dahan	1	1248	1925-87	8,00E+03	1,50E+03	4,40E+03	10,4	22,9	33,2	18,9	15,0	33,9	0,7	28
20	Narmada	Garu-deshwar	1	846	1949-60; 1965-74; 1976-79	1,20E+03	3,80E+01	1,70E+02	22,0	17,1	39,1	3,1	20,0	23,1	-16,0	-
21	Ob	Salekh-ard	1	835	1930-84	1,20E+04	3,20E+03	7,60E+03	9,1	26,6	35,7	25,7	7,0	32,7	-2,9	38
22	Pechora	Ust - Tsilma	1	829	1932-84	3,40E+03	4,90E+02	1,50E+03	11,6	21,7	33,3	14,3	15,0	29,3	-4,0	-
23	Salween	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
24	Syr Darya	Tyumen-Aryk	1	832	1930-35; 1940-43; 1949-84	5,40E+02	1,10E+02	4,70E+02	10,1	17,1	27,2	20,0	15,0	35,0	7,8	27
25	Tapti	Kathore	1	845	1950-53; 1957-60; 1965-74; 1976-79	4,10E+02	5,00E+00	9,40E+01	32,7	5,9	38,6	1,2	20,0	21,2	-17,3	-
26	Tarim	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

27	Xung Jiang	Wuzhou	1	898	1976-83	7,10E+03	1,70E+03	5,30E+03	9,5	21,4	30,9	23,4	7,0	30,4	-0,5	30
28	Yalu Jiang	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
29	Yangtze	Datong	3	-	1950-86	2,80E+04	9,80E+03	2,70E+04	8,0	23,9	31,9	34,9	0,0	34,9	3,0	-
30	Yenisey	Igarka	1	880	1936-84	1,80E+04	4,30E+03	9,20E+03	9,4	28,6	38,0	24,1	7,0	31,1	-6,9	-

EFR Oceania

Oceania									**EFR - Case study**			**EFR-Smakhtin**				
nr	**River Basin**	**Station**	**Data base**	**ID-number**	**Dataset years**	**Mean flow [m³/s]**	**Q_{90} [m³/s]**	**Q_{50} [m³/s]**	**LFR (% MAR)**	**HFR (% MAR)**	**EFR (% MAR)**	**LFR (% MAR)**	**HFR (% MAR)**	**EFR (% MAR)**	**Difference Smakhtin - Case study**	**EFR Smakhtin document**
1	Burdekin-Belyando	Clare	1	423	1965-68; 1973-84	3,60E+02	1,50E+00	3,10E+01	51,4	5,6	57,0	0,4	20,0	20,4	-36,6	-
2	Fitzroy East (Dawson)	The Gap	1	421	1965-68; 1973; 1976-84	1,70E+02	5,00E-01	1,70E+01	59,4	3,8	63,2	0,3	20,0	20,3	-42,9	-
3	Fly	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	Murray-Darling	Lock 9 Upper	1	422	1965-68; 1973-84	2,60E+02	2,60E+01	9,60E+01	13,5	19,3	32,8	10,1	15,0	25,1	-7,7	-
5	Sepik	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

EFR Europe

Europe									**EFR - Case study**			**EFR-Smakhtin**				
nr	**River Basin**	**Station**	**Data base**	**ID-number**	**Dataset years**	**Mean flow [m³/s]**	**Q_{90} [m³/s]**	**Q_{50} [m³/s]**	**LFR (% MAR)**	**HFR (% MAR)**	**EFR (% MAR)**	**LFR (% MAR)**	**HFR (% MAR)**	**EFR (% MAR)**	**Difference Smakhtin - Case study**	**EFR Smakhtin document**

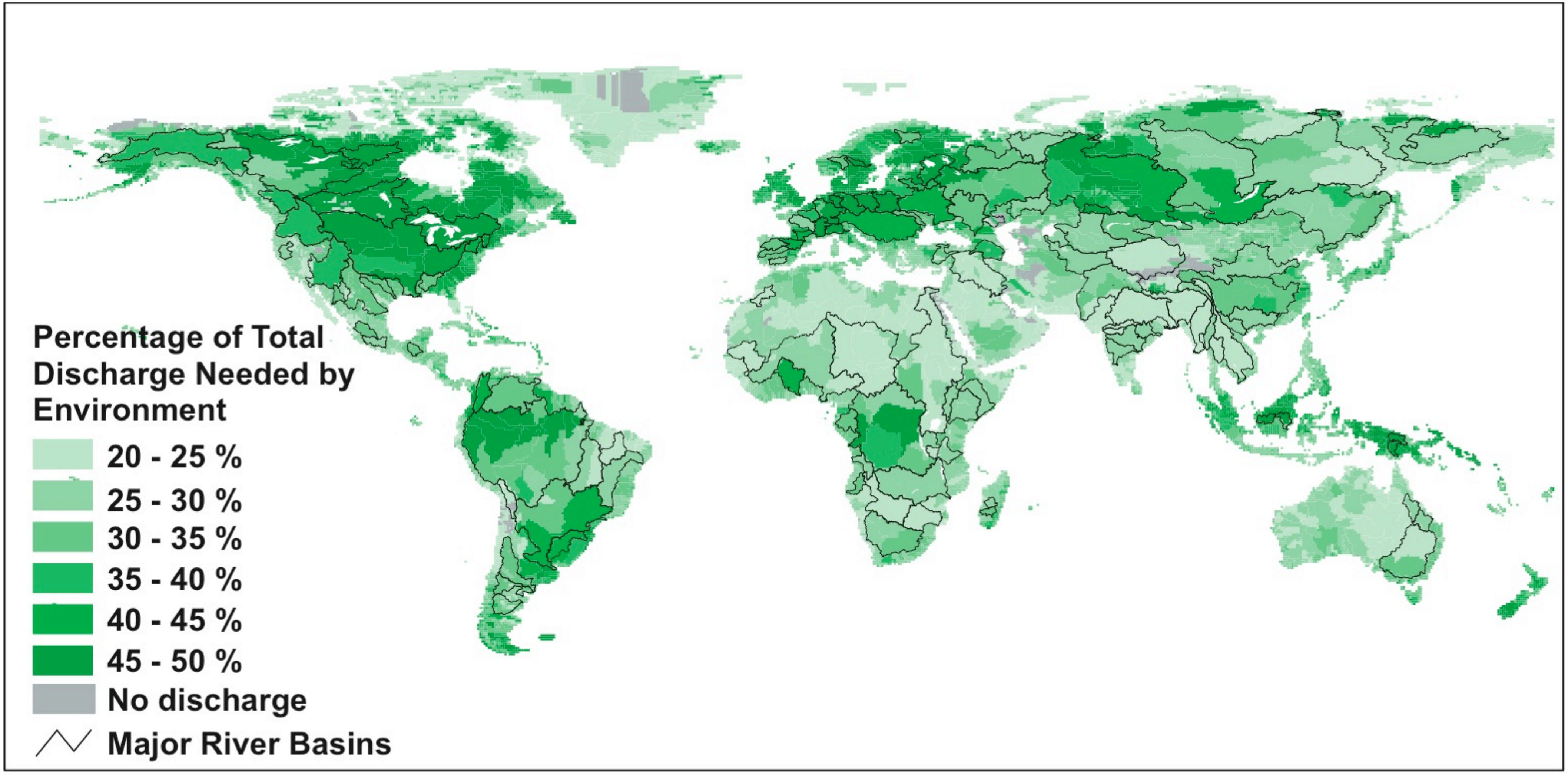
1	Dalaven	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	Danube	Ceatal Izmail	1	765	1921-1984	6,50E+03	3,60E+03	6,20E+03	6,6	33,5	40,1	54,8	0,0	54,8	14,7	40
3	Daugava	Daugav-pils	1	780	1965-84	3,90E+02	1,10E+02	2,00E+02	8,7	32,6	41,3	29,0	7,0	35,9	-5,4	-
4	Dnieper	Dniepr Power Plant	1	805	1952-84	1,50E+03	6,40E+02	1,20E+03	7,3	31,2	38,5	43,4	0,0	43,4	4,9	34
5	Dniester	Bendery	1	776	1965-84	3,80E+02	1,50E+02	3,10E+02	7,6	29,0	36,7	38,9	0,0	38,9	2,3	-
6	Don	Razdors-kaya	1	815	1891-1917; 1919-21; 1925-26; 1928-84	7,90E+02	1,90E+02	4,40E+02	9,3	27,8	37,0	24,6	7,0	31,6	-5,4	-
7	Duero	Regua	1	994	1933-68	5,40E+02	1,00E+02	2,90E+02	10,3	23,6	33,9	19,1	15,0	34,1	0,2	-
8	Ebro	Tortosa	1	735	1913-62; 1965-1974; 1976-1983	1,30E+03	2,60E+02	1,10E+03	10,0	18,0	28,0	20,6	7,0	27,6	-0,4	-
9	Elbe	Witten-berge	1	759	1969-84	7,40E+02	3,50E+02	6,40E+02	7,0	32,4	39,4	47,5	0,0	47,5	8,1	45
10	Garonne	Mas d'Agenais	1	736	1921-74; 1976-79	6,10E+02	1,50E+02	4,60E+02	9,2	22,1	31,4	24,8	7,0	31,8	0,4	-
11	Glomaa-Laagen	Solberg-foss	1	760	1902-84	6,70E+02	1,50E+02	4,90E+02	9,8	20,6	30,4	21,6	7,0	28,6	-1,8	-
12	Gualdalquivir	Alcala del Rio	1	983	1913-30	6,80E+02	1,60E+02	4,60E+02	9,4	23,2	32,6	23,7	7,0	30,7	-2,0	-
13	Kemijoki	Taival-koski	1	781	1911-84	5,40E+02	1,60E+02	3,50E+02	8,5	28,4	36,9	30,0	0,0	30,0	-6,9	-
14	Kizilirmak	Inozu	1	804	1976-83	2,00E+02	1,20E+02	1,80E+02	6,4	36,9	43,3	58,3	0,0	58,3	15,0	-
15	Kura-Araks	Surra	1	818	1930-69; 1970-84	5,50E+02	2,60E+02	4,50E+02	7,0	33,9	40,8	48,4	0,0	48,4	7,6	-
16	Lake Ladoga	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

17	Loire	Montjean	1	737	1863-74; 1976-79	8,40E+02	1,90E+02	6,30E+02	9,7	20,4	30,1	22,1	7,0	29,1	-0,9	-
18	North Dvina	Ust-Pinega	1	820	1882-1985	3,30E+03	7,00E+02	1,80E+03	9,9	25,3	35,1	21,0	7,0	28,0	-7,1	-
19	Oder	Goz-dowice	1	763	1901-86	5,40E+02	2,60E+02	4,70E+02	7,0	32,2	39,2	47,9	0,0	47,9	8,8	47
20	Po	Ponte-lagoscuro	1	751	1918-79	1,50E+03	7,50E+02	1,30E+03	6,9	33,4	40,3	49,4	0,0	49,4	9,1	-
21	Rhine	Rees	1	745	1936-84	2,30E+03	1,20E+03	2,10E+03	6,7	33,3	40,1	52,7	0,0	52,7	12,6	44
22	Rhone	Beaucaire	1	740	1921-74; 1975-79	1,70E+03	8,40E+02	1,60E+03	6,9	31,8	38,7	49,4	0,0	49,4	10,7	40
23	Seine	Paris	1	739	1928-74; 1977-79	2,70E+02	6,50E+01	1,70E+02	9,4	24,4	33,7	24,0	7,0	31,0	-2,7	37
24	Tagus	V.V. de Rodao	1	986	1913-68	3,10E+02	2,10E+01	1,30E+02	15,9	13,2	29,1	6,8	20,0	26,8	-2,3	-
25	Tigris & Euphrates	-	-	-	-	-	-	-	-	-	-	-	-	-	-	26
26	Ural	Kushum	1	826	1915-17; 1921-84	3,00E+02	3,90E+01	1,00E+02	12,1	24,6	36,7	13,0	15,0	28,0	-8,7	32
27	Vistula	Tczew	1	764	1901-86	1,10E+03	4,80E+02	9,00E+02	7,2	31,4	38,5	45,2	0,0	45,2	6,6	-
28	Volga	Volgograd Power Plant	1	817	1879-1935; 1953-58; 1961-84	8,10E+03	2,60E+03	5,50E+03	8,2	29,1	37,3	32,6	0,0	32,6	-4,7	35
29	Weser	Intschede	1	747	1921-84	3,20E+02	1,30E+02	2,60E+02	7,4	30,5	37,9	41,7	0,0	41,7	3,8	-

EFR South-America

South-America									EFR - Case study			EFR-Smakhtin				
nr	River Basin	Station	Data base	ID-number	Dataset years	Mean flow [m^3/s]	Q_{90} [m^3/s]	Q_{50} [m^3/s]	LFR (% MAR)	HFR (% MAR)	EFR (% MAR)	LFR (% MAR)	HFR (% MAR)	EFR (% MAR)	Difference Smakhtin - Case study	EFR Smakhtin document
1	Amazon	Obidos	1	514	1928-46; 1972-78; 1980-82	1,60E+05	9,00E+04	1,60E+05	6,5	32,7	39,2	58,2	0,0	58,2	19,1	40
2	Chubut	Los Altares	4	5161	1944-93	5,00E+01	1,30E+01	4,30E+01	9,0	20,9	29,9	26,2	7,0	33,2	3,3	-
3	Magdalena	Puerto Berrio	1	447	1969-72; 1976-84	2,50E+03	1,50E+03	2,40E+03	6,4	35,4	41,8	60,4	0,0	60,4	18,7	-
4	Orinoco	Cdad` Bolivar	3	-	1926-32; 1935-62	2,50E+04	7,50E+03	2,40E+04	8,6	21,5	30,1	29,7	7,0	36,7	6,6	-
5	Parana	Corrientes	3	-	1905-82	1,60E+04	9,20E+03	1,60E+04	6,5	34,3	40,8	56,7	0,0	56,7	15,9	-
6	Parnaiba	Porto Formoso	1	1146	1976-81	8,40E+02	3,40E+02	6,10E+02	7,6	32,3	39,9	40,0	0,0	40,0	0,1	-
7	Rio Colorado	Pichi Mahuida	3	-	1949-52; 1965-71	1,10E+02	4,10E+01	7,90E+01	7,8	31,1	38,9	37,7	0,0	37,7	-1,1	-
8	Sao Francisco	Juazeiro	1	519	1929-75; 1977-79	2,80E+03	1,10E+03	2,10E+03	7,6	31,2	38,8	39,4	0,0	39,4	0,5	-
9	Lake Titicasa & Salar-Uyuni	-		-		-	-	-	-	-	-	-	-	-	-	-
10	Tocantins	Itupiranga	3	-	1976-81	1,10E+04	3,30E+03	9,10E+03	8,7	23,9	32,6	28,9	7,0	35,9	3,3	-
11	Uruguay	Concordia	1	459	1969-79	5,50E+03	1,80E+03	4,70E+03	8,2	24,8	33,0	33,3	0,0	33,3	0,3	-

Appendix V: Smakhtin EFR



Application of the Smakhtin method using modeled flow data. Map originates from Smakhtin et al. (2004a)

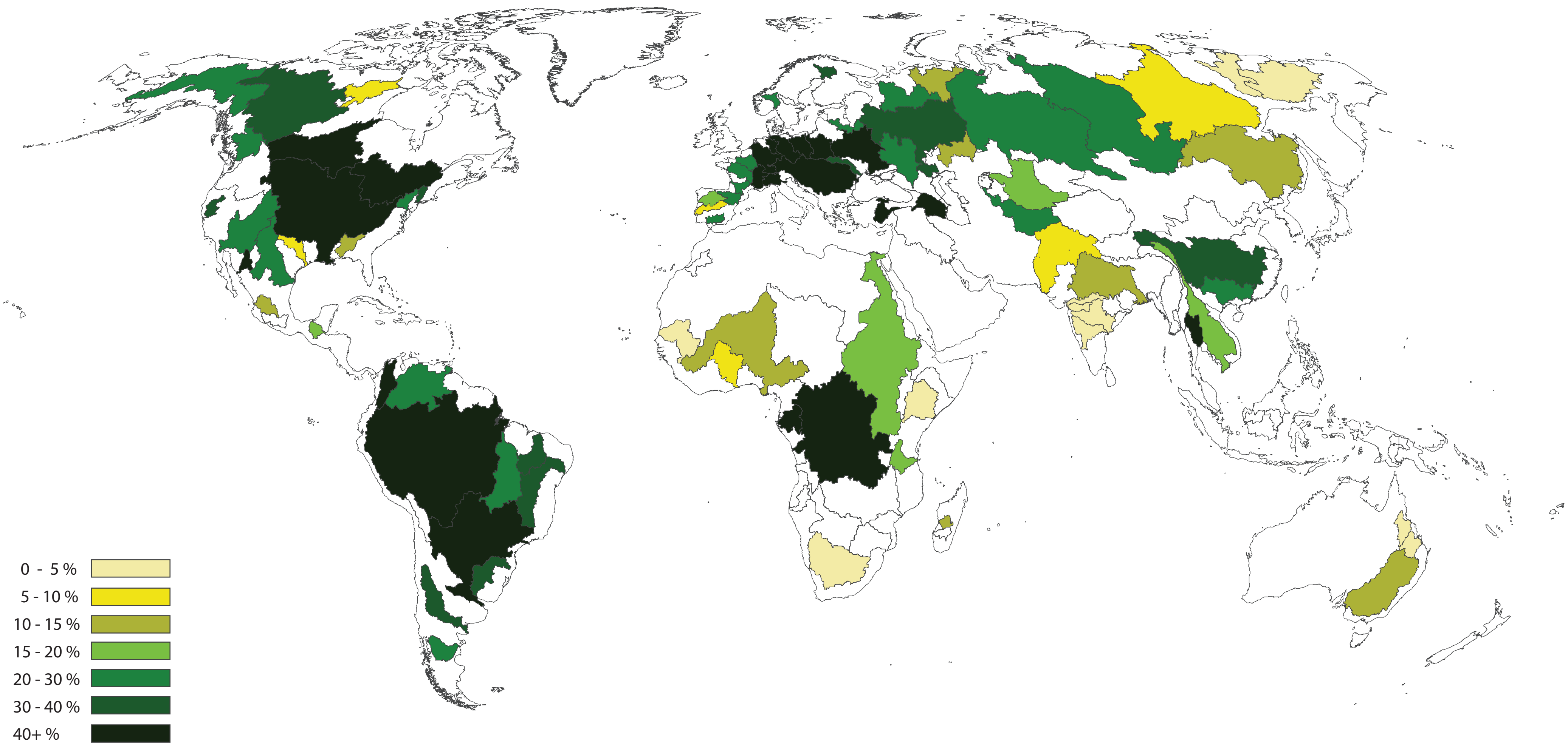


Illustration of the Q_{90} flow as a percentage of the MAR for major river basins (source basins map: WRI, World Resources Institute).