FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Environmental Flows Assessment for a Sustainable Management of Surface Water Bodies

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May, 2020

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A thesis submitted to the Faculdade de Engenharia da Universidade do Porto for the
PhD degree in Environmental Engineering

May 2020

Abstract

The future of freshwater biodiversity is dependent on efforts in order to stop the degradation of freshwater ecosystems, considered as the most threatened ecosystems in the world. Environmental flows are seen as a potential answer to this challenge, being defined as “the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being”. Even though, efforts have been pursued in order to define and provide environmental flows, being possible to perceive a huge progress within environmental flows science and water management, major challenges remain.

In this context, the main goal of this study is to evaluate the environmental flows required to achieve/maintain at least the good ecological status/potential of the water bodies considering the existing hydrological alterations. The achievement of good ecological status/potential is one of the main environmental objectives of the most influential piece of European water legislation – the Water Framework Directive. In order to achieve this goal, the key step is the formulation of hydrologic alteration-ecological responses relationships. Hence, through the development of these relationships, it is expected to define acceptable hydrological change limits, in order to achieve or maintain, at least, good ecological conditions.

The Cávado-Rabagão-Homem hydroelectric system, one of the most important systems in Portugal, located in the Cávado River Basin, was selected as study area. Nowadays, all dams included in this system, with exception of the Alto Cávado dam, are releasing environmental flows. In this context, EDP-Produção, responsible of managing this system, has been conducting monitoring campaigns in several locations in order to assess the ecological conditions. Within this study, in order to use this information (together with other information from additional monitoring campaigns), the selection of the same sites (in total, 19 sites throughout the Cávado-Rabagão-Homem river) was considered.

In order to achieve the proposed objective, the following main steps have been developed: i) the establishment of hydrologic foundation (i.e., the evaluation of natural and modified/current flow conditions) and hydrological alteration (resulting from the existence of the dams and their operations), ii) the evaluation of ecological conditions, and iii) formulation of hydrologic alteration-ecological responses relationship. It should be pointed out, that under the first point, it was necessary to perform hydrological modelling of the system under study. For this MIKE HYDRO River software was used (in total, 36 catchments were simulated).

Considering the main results, it was possible to perceive significant hydrological alterations in the studied sites (with most of the changes with a negative sign), and, for most of the sites, ecological conditions with: i) most of the values related with macroinvertebrates (IPtIN) with “Excellent” conditions, ii) fishes (F-IBIP) with values with a high variability (mainly due to the existence of a significant number of exotic species), iii) macrophytes (IBMR) always expressing “Excellent” conditions, and iv) chemical and physico-chemical elements with overall “Good” conditions. Also, it should be pointed out that, in quantitative terms, there is great variability in the response of indicators to environmental flows. In terms of hydrologic alteration vs. biological condition, it was possible to verify values scattered in different ranges of hydrological alteration and biological condition. The lack of a consistent cause-effect relationship between the hydrological alteration and the ecological condition precluded estimation of any potential threshold. Which in turn, prevent the definition of a hydrological alteration threshold, which hampered the establishment of environmental flows based on a cause-effect relationship between flows and ecology.

Keywords

Environmental Flows; Hydrological Alteration; Ecological Indicators; Hydrologic Alteration-Ecological Responses Relationships; Water Framework Directive; Water Bodies Status; Hydrological Modelling; MIKE HYDRO River; Cávado River.

Resumo

O futuro da biodiversidade dos ecossistemas de água doce depende dos esforços para travar a degradação destes ecossistemas, considerados como os ecossistemas mais ameaçados do mundo. Os caudais ecológicos são vistos como uma resposta potencial a este desafio, sendo definidos como "a quantidade, o timing e a qualidade dos caudais e níveis de água doce necessários para sustentar os ecossistemas aquáticos que, por sua vez, suportam as culturas humanas, as economias, os meios de subsistência sustentáveis e o bem-estar". Embora tenham sido desenvolvidos esforços no sentido de definir e implementar caudais ecológicos, sendo possível perceber um enorme progresso na ciência dos caudais ecológicos e na gestão da água, subsistem ainda grandes desafios.

Neste contexto, o principal objetivo deste estudo é avaliar os caudais ecológicos necessários para atingir/manter o bom estado ecológico/potencial das massas de água, tendo em conta as alterações hidrológicas existentes. A obtenção de um bom estado ecológico/potencial constitui um dos principais objetivos ambientais da legislação europeia mais influente no domínio da água - a Diretiva-Quadro da Água. Para alcançar este objetivo, o passo fundamental é a formulação de relações entre alterações hidrológicas e respostas ecológicas. Assim, através do desenvolvimento destas relações, espera-se definir limites aceitáveis de alteração hidrológica, a fim de alcançar ou manter, boas condições ecológicas.

O sistema hidroelétrico do Cávado-Rabagão-Homem, um dos mais importantes sistemas em Portugal, localizado na Bacia do Rio Cávado, foi selecionado como área de estudo. Atualmente, todas as barragens incluídas neste sistema, com excepção da barragem do Alto Cávado, estão a libertar caudais ecológicos. Neste contexto, a EDP-Produção, responsável pela gestão deste sistema, tem vindo a realizar campanhas de monitorização em diversos locais, com o objetivo de avaliar as condições ecológicas. No âmbito deste estudo, para a utilização desta informação (juntamente com outras informações de campanhas de monitorização adicionais), efetuou-se a seleção dos mesmos locais (no total, 19 locais em todo o rio Cávado-Rabagão-Homem).

Para atingir o objetivo proposto, foram desenvolvidos os seguintes passos principais: i) estabelecimento da base hidrológica (avaliação das condições naturais e modificadas/atuais) e da alteração hidrológica (resultante da existência das barragens e das suas operações), ii) avaliação das condições ecológicas, e iii) formulação das relações alteração hidrológica - respostas ecológicas. Deve salientar-se que, no primeiro ponto, foi necessário realizar a modelação hidrológica do sistema em estudo. Para tal, utilizou-se o software MIKE HYDRO River (tendo sido, no total, simuladas 36 bacias hidrográficas).

Considerando os principais resultados, foi possível verificar alterações hidrológicas significativas nos locais estudados (com a maioria das alterações com sinal negativo), e, para a maioria dos locais, condições ecológicas com: i) a maioria dos valores relacionados com macroinvertebrados ($IPtI_N$) com condições "Excelentes", ii) peixes (F-IBIP) com valores com elevada variabilidade (principalmente devido à existência de um número significativo de espécies exóticas), iii) macrófitas (IBMR) evidenciando sempre condições "Excelentes", e iv) elementos químicos e físico-químicos com condições globais de "Bom". De referir ainda que, em termos quantitativos, existe uma grande variabilidade na resposta dos indicadores aos caudais ecológicos. Em termos de alteração hidrológica vs. condição biológica, foi possível verificar valores dispersos em diferentes gamas de alteração hidrológica e condição biológica. Assim, a ausência de uma relação causa-efeito, consistente e evidente, entre a alteração hidrológica e a condição ecológica impediu a estimativa de qualquer limiar. O que, por sua vez, impediu a definição de um limiar de alteração hidrológica, o que impediu o estabelecimento de caudais ecológicos baseados numa relação causa-efeito entre os caudais e a ecologia.

Palavras-chave

Caudais Ecológicos; Alteração Hidrológica; Indicadores Ecológicos; Relações alteração hidrológica-resposta ecológica; Diretiva-Quadro da Água; Estado das Massas de Água; Modelação Hidrológica; MIKE HYDRO River; Rio Cávado.

Acknowledgements

Since the beginning of my PhD I had the contribution of a wide range of people who inspired and encouraged me, helping me to grow not only as a researcher and professional, but also, as a person. I am deeply thankful to all of them!

In the following lines, I want to express my gratitude to those who have contributed in a more remarkable way for the development of this thesis.

I am grateful to God for guiding me along my journey, teaching me to be happy with all that I have while pursuing my life goals.

To Professor Rodrigo Maia, I am grateful for the opportunity of developing this thesis, as well as, other work that we have developed together during the last 10 years. I thank him for trusting me, encouraging me to overcome the difficulties, telling me, as he said, to "*rematar à baliza*" ("shoot to the goal"). I am acknowledged for the wisdom, helping me to grow as a researcher and personally.

To Professor Nuno Formigo, I am thankful for all his support over the years, his knowledge transmission, motivation and optimism. Professor always pull me up to growth as a researcher and as a more self-confident person, telling me, as he said "*o difícil fazemos agora, os milagres demoram mais um bocadinho*" ("the hardest things we do now, the miracles take a little bit longer").

To Engineer Anabela Peres for her willingness for helping me, their dedication and kindness, transmitting me information and knowledge essential to the development of this work. I also thank the EDP team – Doctors João Pádua and João Ferreira, Engineers Nuno Portal, Miguel Oliveira and Marques Pinto – for their enthusiasm and commitment, without whom this work would not be possible.

I would also like to thank you the Professors, collaborators, colleagues and friends from FEUP for motivating me, being engaged in the process and being present in the hard times.

I also thank to Professors and colleagues from FCUP for giving me a place in the Lab 406 and for being so kind to me.

I am thankful to those who have crossed paths in my life during this process being very important in my life, cheering me up and helping me to grow, such as Amélia Sá, Conceição Maia and Nelson Oliveira.

I am thankful for having great friends, such as, Catarina, Sérgio, Sofia and Stephanie for supporting me, cheering me up and the usual laughs when we are together. I also thank my brother Arlon and my Angolan family for all the laughs and support.

Last but not least, I am thankful to all my family. I am deeply grateful to my parents and sister, for being always there for me, for their unconditional support, for the moments of happiness, for trust in me and motivation. I am deeply thankful to my parents, for all the efforts they made for raising me. I thank my little ones, Leonor, Tiago e Lara, for the happy and playful moments when we are together.

* * *

A special acknowledgment to the company EDP – Gestão da Produção de Energia, S.A. (EDP Produção), which besides the provision of essential information for the development of this thesis, supported, together with the Faculdade de Engenharia da Universidade do Porto (FEUP), the work herein presented through a research grant.

A major acknowledgement to DHI for sponsoring a MIKE Powered by DHI software license (covering the MIKE HYDRO River).

Thanks to IPMA, I.P. for providing precipitation records from the PT02 gridded precipitation dataset.

I would also like to thank ICNF (*Instituto da Conservação da Natureza e das Florestas*) for providing ecological information to this study (related with the AQUARIPORT Project).

I am also thankful to Professor Rui Cortes (UTAD) for his kind and helpful way giving me ecological information related with the 1st River Basin Management Plans.

“Success is not final, failure is not fatal: it is the courage to continue that counts.”

Winston Churchill

To my lovely grandmother Adelaide,
who taught me the meaning of perseverance

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Abbreviations and Symbols

a – a coefficient that varies with the annual heat index,

AC – Alto Cávado

APA – Agência Portuguesa do Ambiente

AR – Alto Rabagão

BF – baseflow

BG – Brufe and Gemesura

BOD – biochemical oxygen demand

CC – Concession Contracts

CD – Caniçada

$CK_{1,2}$ – time constants related with interflow and overland flow routing

CK_{BF} – Time constant for baseflow

CKIF – time constant for interflow

CPCA – Cabril, Penedo, Castanheiro, Abelheira

CQOF – overland flow runoff coefficient

CS_i – trophic value, indicator value of taxon i

d – Index of agreement

DHI – Danish Hydraulic Institute

D_m– number of days in the month

DO – Dissolved oxygen

DOSR – Dissolved oxygen saturation rate

E_a – actual/real rate of evapotranspiration

EC – European Commission

EDP – Energias de Portugal

EEA – European Economic Area

EFAs – Environmental Flows Assessments

E_i – coefficient of ecological amplitude of taxon i

ELOHA – Ecological Limits of Hydrologic Alteration

E_p – potential evapotranspiration

EPT – Number of families included in the Order Ephemeroptera, Plecoptera, Trichoptera

ETP_m – potential evapotranspiration in month m (mm)

Evenness – Pielou's index

F-IBIP – Índice Piscícola de Integridade Biótica para rios Vadeáveis de Portugal Continental

G – the remaining amount of infiltrating moisture

GRanD – Global Reservoir and Dam Database

H – Number derived from the Shannon-Wiener index

HA – Hydrologic Alteration

H_{0m} – daily mean possible duration of sunlight (hours) in that month

HMS – Habitat Modification Score

HQA – Habitat Quality Assessment

HS – Hydroelectric System

I – annual heat index

IASPT – Iberic ASPT Ibérico

IBMR – Índice Biológico de Macrófitos de Rio

ICNF (Instituto da Conservação da Natureza e das Florestas

IHA – Indicators of Hydrologic Alteration

IM – Instituto de Meteorologia

i_m – is the monthly heat index

INAG – Instituto da Água

IPMA – Instituto Português do Mar e da Atmosfera

IPS – Índice de Poluossensibilidae Específica

$IPtI_N$ – Índice Português de Invertebrados Norte

IWRM – Integrated Water Resources Management

K_i – scale of cover

L – lower zone storage

L/L_{max} – relative soil moisture content

L_{max} – the upper limit of the amount of water in the lower zone or root zone

ln S – neperian logarithm of the total number of species

MBE – the mean bias error

M_l – is the number of low flow events in the calibration period

M_p – is the number of peak flow events in the calibration period

MSs – Member States

N – is the number of time steps in the calibration period

NAM – Nedbør-Afstrømnings-Model

NFR – Natural Flow Regime

NGOs – Non-governmental Organizations

NH3-N – ammoniacal nitrogen

n_j – is the number of time steps in event j

N_m – an adjustment factor introduced to provide adjusted rates of potential evapotranspiration

NO_{3-} – nitrate

NSE – Nash-Sutcliffe coefficient

N° Taxa – Number of existent taxa

$\overline{OBS}$ – Average observed discharge

OBS_i – Corresponding observed discharge

OF – overland flow intensity

OF_{min} – upper limit for linear routing

PERSIANN-CDR (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks – Climate Data Record)

PL – Paradela

P_N – excess of water

PoMs – Programme of Measures

QOF – portion of P_N that contributes to overland flow

Q_{bypass} – bypass flows

Q_{eflows} – environmental flows

$Q_{flood\ discharges}$ – flood discharges

QIF – interflow contribution

$Q_{natural\ flows}$ – natural flows

$Q_{obs,i}$ – is the observed discharge at time i

Q_{other} – other flows

Q_{pumped} – pumped flows

$Q_{sim,i}$ – is the simulated discharge at time i

$Q_{total\ inflows}$ – total inflows

$Q_{total\ outflows}$ – total outflows

$Q_{turbine}$ – turbine flows

r – the correlation coefficient

R^2 – Coefficient of determination

RB – River Basin

RBD – River Basin District

RBMPs – River Basin Management Plans

RHS – River Habitat Survey

RMSE – root mean square error

RR – Rainfall – Runoff

SD – Salamonde

$\overline{SIM}$ – Average simulated discharge

SIM_i – Simulated discharge at time i

SNIAmb – Sistema Nacional de Informação de Ambiente

SNIRH – Sistema Nacional de Informação de Recursos Hídricos

TCPCA – Toco, Cabril, Penedo, Castanheiro, Abelheira

TG – root zone threshold value for groundwater recharge

TIF – root zone threshold value for interflow

$\overline{T}_m$ – monthly mean air temperature in month m

TOF – threshold value for overland flow

TP – total phosphorus

TRMM – Tropical Rainfall Measuring Mission

U – surface storage

U_{max} – the upper limit of the amount of water in the surface storage

VF – Vilarinho das Furnas

VN – Venda Nova

WFD – Water Framework Directive

ΔQ – total flows variation

θ – is the set of model parameters to be calibrated

1.INTRODUCTION

1.1 Motivation and relevance

Heraclitus, an ancient Greek philosopher, famously asserted that one can never step into the same river twice, introducing the physical metaphor for life’s constant change. The growth in human population and advances in technology in recent centuries have certainly changed rivers which are highly complex biophysical systems (Poff 2014). In 2002, Nobel Prize-winning chemist Paul Crutzen suggested that the world entered a new era – the Anthropocene – because of the global environmental effects of population growth and economic development (Zalasiewicz et al., 2008). Human impacts on rivers are extensive and pervasive, such is the case of the land-use change (i.e. urbanization and deforestation) and channel-spanning water infrastructure (i.e., dams) (Poff 2014). Dams are pointed out as responsible for the introduction of changes in the rivers through the alteration of flux of water, nutrients and sediments, modifying water temperatures, and blocking species movement. Nevertheless, dams play an important role in the control and management of water resources, including flood mitigation, water storage and hydroelectric power generation. The number of dams has being increasing during the last decades, which is highlighted on the global database – Global Reservoir and Dam Database (GRanD) – a collaborative international effort to collate existing dam and reservoir datasets, with the goal to provide a single, geographically and reliable database for the scientific community (Lenher et al., 2011, Beames et al 2019, GDW 2019). Based on this, it is possible to perceive that Portugal is one of the regions with a notable number of dams (Figure 1).

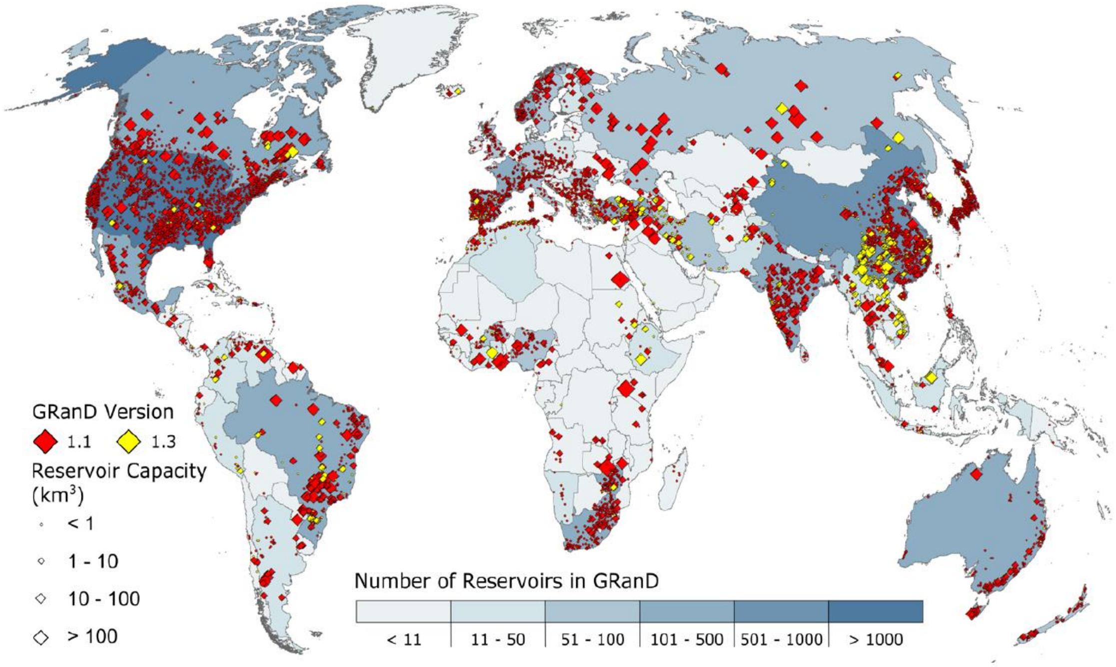

Figure 1 – Global distribution (by country) of large reservoirs in GRanD database (Beames et al 2019).

Freshwater ecosystems are the most threatened ecosystems in the world, with a decline in biodiversity faster than for any other ecosystem type (Dudgeon et al 2006). Threats to biodiversity decline can be divided into five categories: over-exploitation, water pollution, changes in flow regimes, habitat destruction and degradation, and invasion of exotic species. The combined effect of the interaction between these categories will further exacerbate the decline in the population and a decrease in freshwater biodiversity (Postel and Richter 2003, Vörösmarty et al 2010). Thus, the future of freshwater biodiversity is totally dependent on efforts to try to stop the degradation of these ecosystems, namely due to a growing interest of “restoring” regulated rivers by deliberately releasing reservoir water from dams to provide more reference-like flow conditions downstream (Poff 2014). Nevertheless, there are limits to the effectiveness of such efforts, due to the modifications associated with the existence of dams, which can lead to the existence of “novel ecosystems” that are far outside historical equilibrium boundaries and are therefore fundamentally not restorable to reference conditions (Acreman et al 2014a and 2014b, Poff 2014).

Twenty years ago, Richter et al (1997) asked “*How much water do rivers need?*”. Throughout the years many scientists and water managers have been working to try to provide answers to this question in almost every country. That in order to contribute to ecosystems restoration, optimizing social well-being and achieving a sustainable water management (Poff et al 2010, Arthington 2012). In this context, in order to provide answers to the previous question, different methods have being developed. Most of them – around 70% (Tharme 2003) either provide simple rules founded on hydrologic characteristics of surface water flows, or they quantify the flow volumes needed to maintain aquatic habitat characteristics (in terms of water depth, velocity and vegetal cover) for target species (usually fishes with commercial value). Around the late 1980s, river scientists working on the development of these methods, and a broader group interested in river ecology and restoration, pointed out the importance of different characteristics of the flow regime, not just the minimum flow required, which should exist to maintain critical habitats for aquatic species (Arthington 2012). These experts, from different countries, recognized the dynamic nature of river flows (Petts 1989, Poff and Ward 1990, Arthington et al 1992, Poff 1996, Richter et al 1996 and 1997), and shared a growing concern with the consequences for aquatic species and ecosystems with alterations of river flow magnitudes (discharge), seasonal patterns and temporal variability related with dams and other interventions. Hence, to protect freshwater biodiversity and maintain the ecosystem services of rivers, the idea that it is important to maintain natural flow variability came up. This brings up a broader "riverine ecosystem" perspective on the assessment of in-streams flows, and this term moved to more wide-ranging terms, such as "ecological and environmental water requirements", "ecological water demand", "environmental water allocations", "environmental flows" (e-flows) (Moore 2004, Song and Yang 2003, Arthington 2012). In 2007, the progress and direction of environmental flows science, practice, and policy was delineated, in the Brisbane Declaration and Global Action Agenda (The Brisbane Declaration 2007), during the 10th International River*symposium* and International Environmental Flows Conference held in Brisbane (Australia). This document – which brings a common vision and direction for environmental flows internationally – highlights the relevance of environmental water allocations for humans and freshwater-dependent ecosystems, being the first consensus document developed considering different experiences across regions and disciplines. After a decade, in 2017, this document was revisited within the 20th International River*symposium* and International Environmental Flows Conference held in Brisbane (Australia)[1], in order to update the declaration and action agenda to reflect recent developments and emerging challenges – which final version culminated in the "Brisbane Declaration and Global Action Agenda on Environmental Flows (2018)" (Arthington at al 2018). In this document, environmental flows are defined as *"the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being".* A more in-depth analysis of this definition, as well as, other suggested terminologies (e.g., the one provided in Horne et al 2017a, and, EC 2015), will be provided in the next chapter.

Even though concerted efforts have being pursued in order to define environmental flows, and a huge progress on environmental flows science and water management can be perceived, major challenges remain (i.e., Arthington 2012, Hart and Doolan 2017, Horne et al 2017b, Kennen

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[1] In which conference the author participated (Ramos et al 2017).

et al 2018) . In fact, it is possible to observe that environmental flow requirements have still not been adequately assessed for most aquatic ecosystems, and those have been implemented in even fewer (Moore 2004, Le Quesne et al 2010, Gillespie et al 2015, Harwood et al 2017) (Arthington et al 2018). Nevertheless, there are several water and environment research and development projects, as well implementation initiatives, that have tested and strengthened the scientific basis of environmental flows on-the-ground (as reviewed in Horne et al 2017b, Poff et al 2017). There is also an increase of efforts in order to conduct broader assessments from individual sites to whole river basin and regional scales (King and Brown 2010, Buchanan et al 2013, Hart 2016a and 2016b, O’Brien et al 2018, Stein et al 2017). In this context, it could be highlighted the Ecological Limits of Hydrologic Alteration (ELOHA) method, proposed by Poff et al (2010), which constitutes a framework for assessing environmental flow needs for many streams and rivers simultaneously, resulting from a consensus of a group of international scientists (a more in-depth description will be provided in the next chapters). This framework is a composed by a flexible 4-step process of analysing and synthesising scientific information concerning streamflows and the flow-related needs of riverine ecosystems. One of the main and crucial steps of the framework is the development of flow alteration – ecological response relationships (Arthington et al 2006, Poff et al 2010, Arthington 2012). The search for the establishment of these relationships by the scientific community has been increasing globally (Bunn and Arthington 2002, Lloyd et al 2003, Stewardson and Webb 2010, Webb et al 2013, Poff and Zimmerman 2010). However, although the principles of hydrological change are well accepted, there has been little success on the establishment of quantitative flow-ecology relationships, which allow to foresee the ecological responses to flow variability or flow regime change (Webb et al 2015).

1.2 Objectives

Environmental flows assessment can be defined as the process used to determine the environmental water requirement for targeted ecological endpoints (Webb et al 2017). These (for example, macroinvertebrates and fishes) are affected by landscape change and pollution in watersheds, being useful for watershed management (through metrics, such as species diversity, and/or through the combination of metrics into multimetric indices). Therefore, they are usually used for several purposes such as to assess or classify sites or water bodies (Rashleigh 2008).

In this context, the main goal of this work is to assess the environmental water required to achieve/maintain at least the good water bodies status/potential (as one of the main environmental objectives of the most influential piece of European water legislation, the Water Framework Directive), considering the existing hydrological alterations. To achieve this goal, the key step is the formulation of hydrologic alteration-ecological responses relationships. Through the development of these relationships it is envisaged the definition of acceptable hydrological change limits which are related with the achievement of environmental objectives (i.e. good water bodies status/potential). The establishment of these relationships involve: i) the development of hydrologic foundation (i.e. the evaluation of natural and modified/current flow conditions) and hydrological alteration (resulting from the existence of the dams and their operations) and ii) the evaluation of ecological conditions (in selected ecological endpoints within the case study). It was considered adequate to select, as a case study, the Cávado-Rabagão-Homem hydroelectric system, located in the Cávado River Basin. The selection of this case study is related to the fact that this is a highly regulated river system, where the implementation and evaluation of environmental flows were already taking place (before this work started). Furthermore, the hydroelectric system is located in Cávado River Basin, a river basin totally located in Portuguese river basin (i.e. is not a transboundary river basin which facilitates the evaluations).

It is envisaged that the output of this work could be an asset for EDP- Produção de Energia (Energias de Portugal) – as the Portuguese hydroelectric company responsible to manage the water resources of this river – as well as, for the APA (Agência Portuguesa do Ambiente) – as the Portuguese environmental agency and Water National Authority, with the role to plan and manage water resources. In fact, it is expected that the output of this work can be used by EDP: i) to assess the effects of hydrological modifications in the ecological condition, and ii) to adjust, if necessary, the environmental flows already defined and implemented for each dam of the system, in order to meet WFD objectives, and, consequently, its agreement with the Water National Authority.

1.3 Synopsis

This document is organized in seven main chapters: 1) Introduction, 2) Background of the study, 3) Study area, 4) Hydrological foundation and alteration, 5) Ecological characterization, 6) Formulation of hydrologic alteration-ecological responses relationships, 7) Conclusions, considerations and suggestions for future work.

The current chapter (Chapter 1), emphasizes the importance and the main goals of the present work. The background of the study (Chapter 2), provides information of the main topics important to understand and support the presented study.

The study area description and characterization, presented in Chapter 3, has the purpose to inform about: i) the Cávado River Basin, ii) the Cávado-Rabagão-Homem hydroelectric system located in this River Basin, iii) the stage of the implementation of environmental flows in the study area, and, iv) the selected sites for the assessment of environmental flows and for the evaluation of flow-ecology relationships.

Chapter 4 is developed to explain the methods and results linked with the establishment of a hydrologic foundation and the evaluation of the hydrological alteration. The following chapter, Chapter 5, presents the ecological characterization, i.e., a description of the information related with the main ecological surveys performed in the area, as well as, the methods and values of the ecological indicators used to assess the water bodies ecological status (based on WFD information). Chapter 6 give information about the formulation of hydrologic alteration-ecological responses relationships, which provide the key step in order to achieve the main goals of this study.

Finally, in Chapter 7, the main conclusions of this work and suggestions for future work are provided.

2. BACKGROUND OF THE STUDY

2.1 Introduction

Chapter 2 presents a literature review that constitutes the basis for the development of this study and the achievement of the study goals.

At the beginning of this chapter, a summary of the progress of environmental flows definitions, as well as some key concepts and topics, relevant for the understanding and framing of this study are provided (chapter 2.2). Then, in chapter 2.3, firstly, an overall picture of the main environmental flows assessment methodologies is provided, followed by an in-depth description of the some methods. One of the methodologies, included in the holistic environmental flows assessment methodologies group, the so-called “Ecological Limits of Hydrologic Alteration (ELOHA)” framework, is explained with a higher level of detail since some principles/steps of it are applied in this study. One of them is the definition of flow-ecology relationships, which are the key step to achieve the goals of this study. Hence, in chapter 2.4, an overview of key review studies – developed with the main purpose to understand and develop relationships between various kinds of flow alteration and ecological responses – is presented.

This study, developed over the Cávado RB (a Portuguese River Basin), is grounded within the Water Framework Directive (WFD) – one of the most influential pieces of European water legislation to date – which states that all water bodies, throughout the European Union, should achieve “good status”. Hence, chapter 2.5 presents an overall picture of the WFD, as well as, of environmental flows under WFD implementation.

At the end, in chapter 2.6, an overall picture on the topic of environmental flows in Portugal is provided.

2.2 How much water do rivers need?

2.2.1 A brief history of environmental flows – progress and definitions

The concept associated to the idea of "How much water do rivers need" has been evolving throughout the time. In the mid-20th century, together with the dramatic acceleration of the modern dam-building there was a growth on the history of environmental flows. According to Poff and Mathews (2013) environmental flows framework has "evolved from a relatively narrowly focused aquatic conservation strategy to a rather broad effort achieving social and ecological benefits from river management". Poff and Matthews (2013) identify three discrete periods of progress focusing on how environmental flows concept was developed and applied in practice over the last 25 years (by that time): i) a 1st period of emergence and synthesis (late-1980s through mid-1990s), ii) a 2nd period of consolidation and expansion (mid-1990s through mid-2000s), iii) a 3rd period of globalization and new challenges (mid-2000s to present, by the time of the study). Figure 2, presents a simplified illustration of environmental flows history (where it is possible to perceive approximate timelines, landmark achievements and events, scientific and technical challenges, and participants engaged in the environmental flows enterprise).

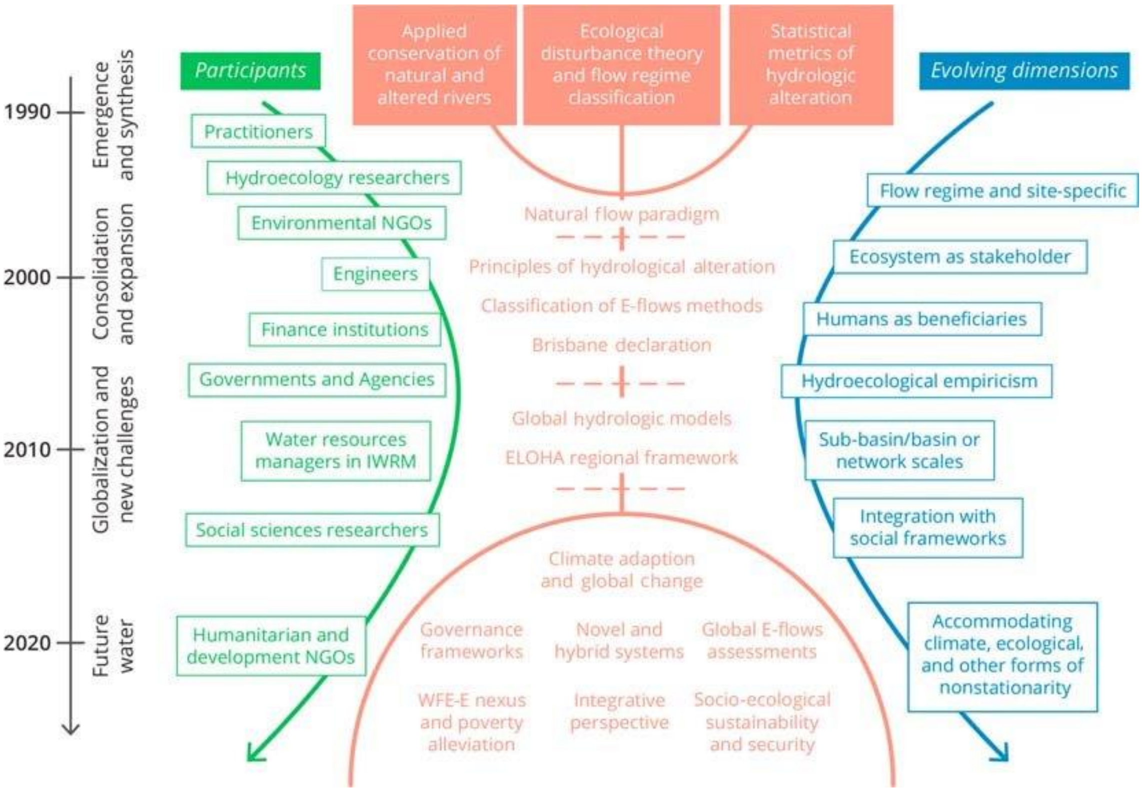


Figure 2 – Historical timeline for "modern" environmental water, showing emerging directions in the principles and concepts that underpin the science and growth in the number and diversity of engaged institutions and practitioners. Timelines are shown that fall into relatively discrete periods of types of activities. Timelines for participants engaged in environmental water over time are shown to the left, for benchmark achievements in the center, and for evolving dimensions of environmental water on the right. ELOHA, ecological limits of hydrologic alteration; IWRM, Integrated Water Resources Management; NGO, nongovernmental organization; WFE-E, water, food, and energy-environment nexus (source Poff et al 2017).

In the late 1940s, environmental flows assessments began in earnest in snowmelt streams and rivers of the western United States, having as a main goal to protect valuable cold-water fisheries. (Poff and Matthews 2013). In the 1970s, there was a rapid progress mainly due to a new environmental and freshwater legislation (Water Act 1972) coupled with an increasing need for quantitative assessments of flows to protect aquatic species impacted by dam construction (which was at a peak in the United States) (Poff et al 2017). In fact, prior the 1980s, environmental flows were practiced in a “reductionist” mode (i.e., to secure minimum flows for singles species – usually a valued game fish) downstream individual large dams, mainly in the USA. Based on Poff and Matthews (2013) the foundation of the today’s environmental flows framework can be outlined mainly due to three discrete sources of scientific and conservation activity. The first was related with efforts by the environmental flows practitioners in Australia (Arthington et al 1992) and South Africa (King and Tharme 1994) to focus on multiple ecological targets, instead of only in individual species of fish valued by society. These efforts were: i) led by ecological principles and mainly informed by expert opinion, ii) focused in specific sites requiring restoration or conservation. The second source was mainly linked with academic interest in characterizing the natural flow regime and its role in ecosystems of largely unmodified, free-flowing rivers. This was build up from the increasingly recognized role that natural disturbance plays in regulating the structure and function of riverine ecosystems from both ecological and geomorphic perspectives (Resh et al 1988, Hill et al 1991). These principles were then used in a comparative context to perceive how ecosystem structure might vary across broad hydroclimatic and geographic extents (Poff and Ward 1990). The third source reveal an explicit focus on how humans change natural flows. This began in the early to mid-1990s and represented a move toward a joining approach that bridged academic and pragmatic approaches. In this context, could be highlighted the development of a framework – in USA by the Nature of Conservancy – for classifying the ecologically relevant flow variability at individual sites of interests. In this, there is a comparison between a pre-impact (pre-dam) flow period, or reference condition, with a post-impact flow period in order to quantify the extent of alteration of ecologically relevant flow metrics, due to the dam (Richter et al 1996 and 1997). In mid-1990s, the three perspectives were merged and synthesized with some publications such as, a publication of the natural flow regime concept (Poff et al 1997, Richter et al 1997) and the indicators of hydrologic alteration method (Richter et al 1996). A more in-depth description about this will be provided in the sub-chapter 2.2.2. It should be highlighted that during mid-1990s, most of the focus was scientific and technical mainly concerning in a conceptualization and measurement of natural flow variability and dam-induced alteration. These activities mainly occurred in developed countries with a high scientific capacity and significant water management capacity (such as USA, Western Europe, South Africa and Australia).

The second period (Figure 2), “Consolidation and Expansion” (mid-1990s through mid-2000s), was mainly focused on efforts of scientists and practitioners working on environmental flows on how to manage rivers in an ecologically sustainable fashion. A key contribution of this period, as pointed out by Poff and Matthews (2013) was “the articulation of principles of flow alteration, combined with documented examples of ecological effects that could be understood by water infrastructure managers (Bunn and Arthington 2002)”. Within this period, an important argument for the conservation status of freshwaters advanced in which ecosystems should be denoted as “stakeholders” that should have “ethical consideration on par with human sectors and livelihoods with ethical ‘rights’ to legitimate water needs” (Poff and Matthews 2013, Acreman 2001, Naiman et al 2002). In fact, sustainability started to be analysed in terms of balancing of competing needs of humans and ecosystems (Baron et al 2002, Poff et al 2003). Also during this period, a noteworthy publication that expanded the environmental flows relevance and increased public and broad scientific awareness related with the global loss of freshwater ecosystems integrity and biodiversity was the book of Postel and Richter (2003). The growing engagement of conservation non-governmental organizations (NGOs) and interest in environmental flows “facilitated engagement with institutions involved at national, sectorial, and global applications of water resources development and operation” (Poff and Matthews 2013). Furthermore, environmental flows began to be seen as a policy tool that could be incorporated on watershed management approaches, such as Integrated Water Resources Management (Bernhardt 2006). Moreover, during this period could be highlighted, the exploration by water resources engineers on how dam operation schemes might be modified based on flow alteration principles to allow for downstream ecological benefits beyond minimum flows (Eheart 2004, Suen and Eheart 2006, Vogel et al 2007, Gao et al 2009). As previously referred (in Chapter 1), the progress and direction of environmental flows science, practice, and policy was delineated, through the elaboration of the 2007 Brisbane Declaration (2007) – which constitutes the culminating document in the consolidation and expansion period. This document (Brisbane Declaration 2007) bringing a common vision and direction for environmental flows internationally, provided a widely recognized definition of environmental flows (sometimes referred as e-flows): “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”.

As previously referred (Figure 2), Poff and Mathews (2013) also highlight a 3rd period of globalization and new challenges (mid-2000s to mid-2010s, by the date of their study). With global awareness of environmental flows growing, major new audiences were engaged, and new challenges appeared. In fact, several studies appeared in order to evaluate integrated environmental threats and address questions, such as: i) trade-offs between water supply for agricultural water demand and supply to natural ecosystems (Smakhtin et al 2004), ii) the implications of climate change and human population growth for management of regulated versus unregulated rivers (Nelson et al 2009), and iii) the implications of multiple stressors on biodiversity conservation in the world's rivers (Vörösmarty et al 2010). During this period, academics and practitioners started to re-examine some of the basic scientific assumptions used in environmental flows practice, namely: i) the strength of evidence for ecological response to specific types of hydrologic alteration (Lloyd et al 2003, Poff and Zimmerman 2010), and ii) biological adaptations to historic flow variability (Lytle and Poff 2004). It was considered necessary a solid empirical grounding behind the assumed ecological impairments associated with degrees of flow alteration. Hence, a method to classify flow regimes based on natural patterns of historic variation was proposed by Arthington et al (2006), providing a method to support flow standards for streams and rivers that lack extensive historical hydrologic and ecological data. In this context, with the collaboration of a large cross-section of the global environmental flows community (academics, NGOs, agency scientists) a synthesis on environmental flows science and practice was produced, named as Ecological Limits of Hydrologic Alteration (ELOHA) (Poff et al 2010). A more in-depth description of this will be provided in Chapter 2.3.2. Some publications that document the firm establishment of the global reach of e-flows theory and practice are special journal issues (Acreman et al 2014b, Arthington et al 2010) and a book (Arthington 2012).

In short, as described by Poff and Mathews (2013), over the last 25 years (period 1990 to mid-2010s), it was evident an expansion of environmental flows and a transition from an "era of aquatic conservation and ecological integrity to a period of explicit 'social-ecological sustainability'", due to new challenges and emerging audiences and users.

It should be highlighted that Poff and Mathews (2013) nominated as a pivotal statement and synthesis by these last 25 years of environmental flows history, the 2007 Brisbane Declaration, which brought together the experiences of environmental flows practitioners across regions and disciplines, setting an internationally common vision and direction for environmental flows. The environmental flows definition presented in this Declaration has been cited in several books and hundreds of journal publications showing "a consolidated, widely accepted statement of the essence and vital purpose of environmental flows". After this definition, within the scientific community, some suggestions arise, being one of them the replacement of the term "environmental flows" to "environmental water" or to "water for the environment" (Arthington et al 2018). As expressed by Horne et al (2017a) the use of the term "environmental water" (a water volume) instead of "environmental flow" (a discharge) should be favoured as the first concept is "applicable across both ponded bodies such as wetlands, and flowing water bodies such as rivers and estuaries". Another terminology is used, for example, by the EC (2015), which uses the term "ecological flows" and defines it in terms of "hydrological regimes" to halt the ecological deterioration of aquatic systems and achieve good ecological status. As previously referred, in chapter 1, after 10 years of the 2007 Brisbane Declaration, within the 20th International River*symposium* and Environmental Flows Conference (held in September 2017), a renewal of this influential document started culminating in the 2018 Brisbane Declaration. Here (as described in Arthington et al 2018), the term "environmental flow" is still used and a new definition is provided. In fact, even though the authors of the 2018 Brisbane Declaration support the use of other terminologies to embrace "all surface and groundwater-dependent aquatic ecosystems, whether flowing or standing" in their view, ceasing to use the widely accepted term "environmental flows" could "disconnect the 2018 Declaration from the 2007 Declaration, as well as from the vast body of environmental flows knowledge and implementation exercise published before and since 2007 (Arthington et al 2018). Nevertheless, the definition provided in this 2018 Declaration provides a definition embracing "all aquatic ecosystems and their coupled human systems dependent upon flowing, standing or ground water": "Environmental flows describe the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being". It should be highlighted that in this definition "aquatic ecosystems" include "rivers, streams, springs, riparian, floodplain and other wetlands, lakes, coastal waterbodies, including lagoons and estuaries, and groundwater-dependent ecosystems".

Throughout this study, it was chosen to use the term "environmental flows" instead of the term "ecological flows" (used namely in EC 2015) or the "environmental water regime" (used in Horne et al. 2017a), because of the widely used of the former term "environmental flows".

Following, due to the focus and scope of this study, some key definitions presented in Horne et al 2017a will be provided: i) "environmental flows assessment", ii) "environmental allocation mechanisms", iii) "environmental water release" and iv) "environmental water management". "Environmental flows assessment" is the "process used to determine the environmental water requirement for targeted ecological endpoints (Tharme 2003)", which can be assessed through the combination of hydrological, hydraulic, ecological, and social knowledge (through the use of expert knowledge and opinion). Regarding the term "environmental allocation mechanisms" these are the "policy mechanisms available to provide environmental water. There are two general approaches: 1) those that impose regulations on the behaviours of other users (i.e. caps, conditions on storage reservoirs, or conditions on license holders) and 2) those that provide the environment a direct right to water (environmental reserve or environmental water rights) (Horne et al 2017a). Concerning the concept "environmental water release", this is, as described by Horne et al. (2017a) a "release from storage made specifically for the purposes of meeting a downstream environmental objective. The environmental water regime can be delivered through a combination of environmental flow releases and exogenous flows, including unregulated inflows and releases for other water uses (i.e. agriculture or hydropower)." Finally, as stated by Horne et al. (2017a) the concept of “environmental water management”, comprises “the process of determining, allocating, implementing and managing environmental water”. This is one component of integrated water resource management. The management of rivers for environmental outcomes should settled within a holistic water resource planning (Figure 3). Environmental water management is located on a spectrum from passive to active water management. The former type is associated with “establishing long-term plans and rules that do not require further action to provide environmental water”. The latter type of management refers, as highlighted by Horne et al. (2017a) to “those allocation mechanisms that require ongoing decision making concerning when and how to use environmental water to achieve the desired outcomes”.

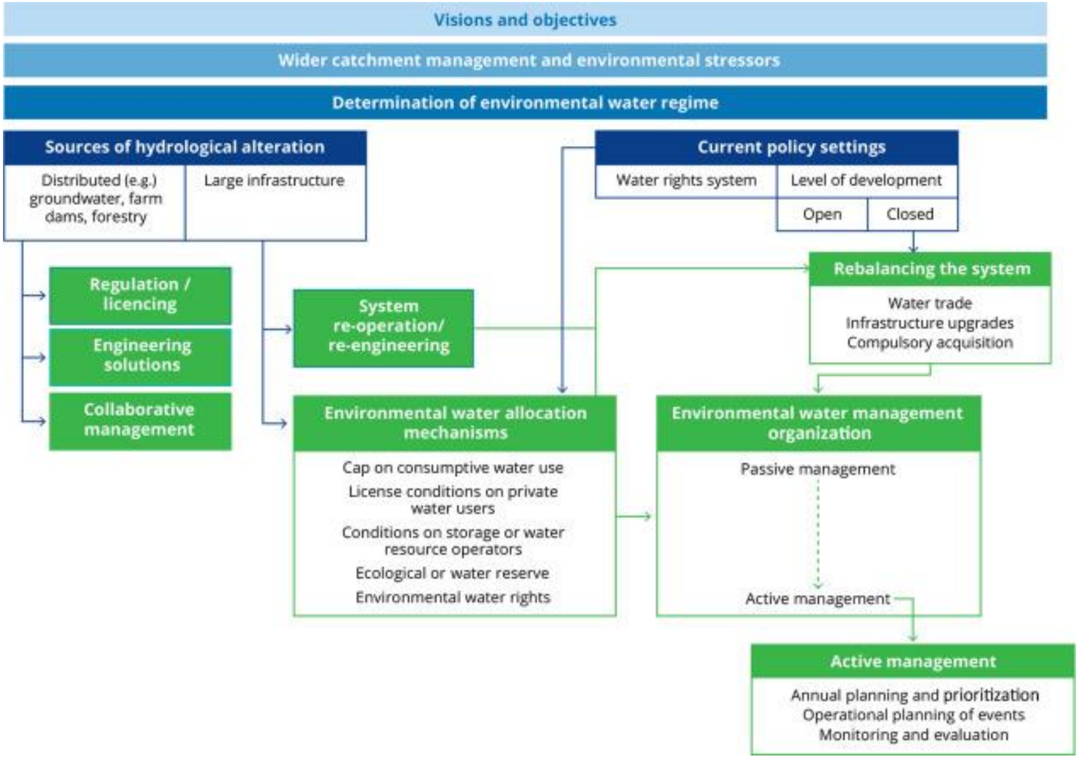


Figure 3 – Environmental water management within water resource planning (Horne et al 2017a).

2.2.2 The natural flow regime paradigm and facets of river flow regimes

In 1997, a paradigm for the restoration and conservation of rivers – *The Natural Flow Regime Paradigm* emerged (Poff et al. 1997). This paradigm highlights that streamflow – “which is strongly correlated with many critical physicochemical characteristics of rivers, such as water temperature, channel geomorphology and habitat diversity“– constitutes the “master variable” that “limits the distribution and abundance of riverine species and regulates the ecological integrity of flowing waters”. One of the main ideas introduced by this concept is related with the fact that the natural variation of flows creates and maintains “the dynamics of in-channel and floodplain conditions and habitats that are essential to aquatic and riparian species”. This concept has an important role in the context of environmental flows, leading to the perception that environmental flows should reflect and mimic the natural flow variability (Arthington 2012).

The flow regime can be described by five ecologically relevant characteristics (or facets), i.e, five facets considered critical for the ecological processes: i) magnitude, ii) frequency, iii) duration, iv) timing and v) rate of change of flows (Richter et al 1996, Poff et al 1997). These facets can be used to characterize the entire range of flows (the hydrologic signature of the river), as well as, specific hydrologic events decisive for biota and the ecological functioning of river ecosystems (such as droughts and floods). Considering these facets, it is possible to perceive and quantify the hydrologic and associated ecological consequences of certain human activities that change the natural flow facets of the flow regime. Following, a summary of each one of the facets is provided (Poff et al 1997, Arthington 2012):

i. Magnitude: is “the amount of water moving past a fixed location per unit of time”, being expressed, for example, in m^3 per second). This facet can refer to the quantity of flow relative to some river property, such as the volume of water needed to provide an adequate water depth in a stream riffle important for fish passage, or to inundate an area of floodplain.

ii. Frequency: refers to “how often a flow of a given discharge occurs over some nominated time period”.

iii. Duration: is “the length (period) of time associated with a particular discharge event”, such as, a flood that inundates the floodplain during some weeks or months. It is relevant to understand the duration (namely, the total number of days or months in sequence) to study the ecology of a river, in order to perceive if a specific flow condition persists (as for example, a period in which there is no surface flow).

iv. Timing: refers to the period of time, the “regularity”, with which a “particular event is likely to occur”.

v. Rate of change: is “the rate at which stream discharge changes from one magnitude to another”. Usually, a stream hydrograph is composed by periods of high flow divided by longer periods of low flows. Typically, differences in the rates of these processes can reveal different types of streams. For example, more *stable* rivers (Figure 4a) express a very steady pattern of flows, which in turn will lead to slow changes. By other side, *flashy* streams (Figure 4b) reveal very rapid rates of rise (and often fall) in discharge.

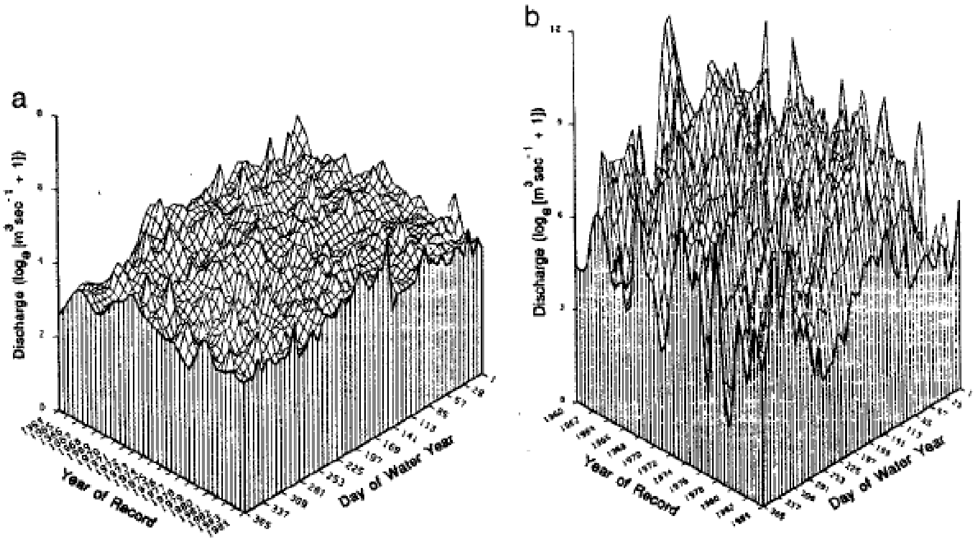


Figure 4 – Daily mean discharge records showing the inter and intra-annual flow variation for a) Augusta Creek – Michigan, and b) Satilla River – Georgia (Poff et al 1997).

The different flows facets, i.e. the different aspects of flow regimes, can be characterized by using a very wide range of hydrologic statistics/metrics. Throughout the time, researchers have been working on the definition of several hydrologic metrics that are capable to express different flow regimes and have a main role on the ecosystem functions (i.e. ecologically relevant hydrologic metrics). After the elaboration of several studies (such as, Hughes and James 1989, Poff and Ward 1989 and 1990, Poff 1996, Richter et al 1996, 1997, 1998) a wide number of hydrologic statistics describing the facets of flows were defined. In this context, Olden and Poff (2003) highlight the relevance of selection of the metrics to guarantee that redundant metrics could be selected. In fact, based on a group of 171 hydrologic metrics defined, they search for a subset of these metrics that can be used to represent the main features of the hydrological regime, while minimizing redundancy (i.e. multicollinearity). Accordingly with these authors, the obtained results reveal that the metrics obtained based on IHA (Indicators of Hydrologic Alteration) ecohydrological software tool (which was developed by The Nature Conservancy) “adequately represent the majority of the variation explained by the entire population of 171 indices and thus capture the majority of the information available. Furthermore, the IHAs represent almost all of the major components of the flow regime, and therefore provide a good balance between objective selection of high information indices and accessibility in terms of computation”. Also, two solvable shortcomings of the IHAs are highlighted within Olden and Poff (2003) study. In summary, the authors pointed out that “the Indicators of Hydrologic Alteration can provide a powerful tool for the calculation of high information, non-redundant indices describing the major components of the flow regime; however, like the case with all the indices, only a subset of the IHAs should be used in any analyses”. Besides, it is emphasized by Olden and Poff (2003) that “although we have examined a total of 171 hydrologic indices derived from a number of published studies, additional indices may have to be developed to account for question-specific aspects of the hydrograph". Table 1 presents the 33 IHAs metrics/ ecohydrological indices, grouped into five categories that represent major regime characteristics.

Table 1 – The 33 IHA metrics (adapted from The Nature Conservancy 2009).

Facets of flows	Group number	IHA metric		Number of metrics
Magnitude of monthly water conditions	1	Mean or median value for each month of the year		12
Magnitude and duration of annual extreme water conditions	2	Annual minima	1-day mean	12
			3-day-means	
			7-day means	
			30-days means	
			90-days means	
		Annual maxima	1-day mean	
			3-day-means	
			7-day means	
			30-days means	
			90-days means	
		Number of zero-flow days		
		Base flow index		
Timing of annual extreme water conditions	3	Julian data of each annual	1-day maximum	2
			1-day minimum	
Frequency and duration of high and low pulses	4	Number of	low pulses within each water year	4
			high pulses within each water year	
		Mean or median duration (days) of	low pulses	
			high pulses	
Rate and frequency of water condition changes	5	Rise rates: Mean or median of all positive differences between consecutive daily values		3
		Fall rates: Mean or median of all negative differences between consecutive daily values		
		Number of hydrologic reversals		
Total				33

2.3 Environmental flows assessment methodologies

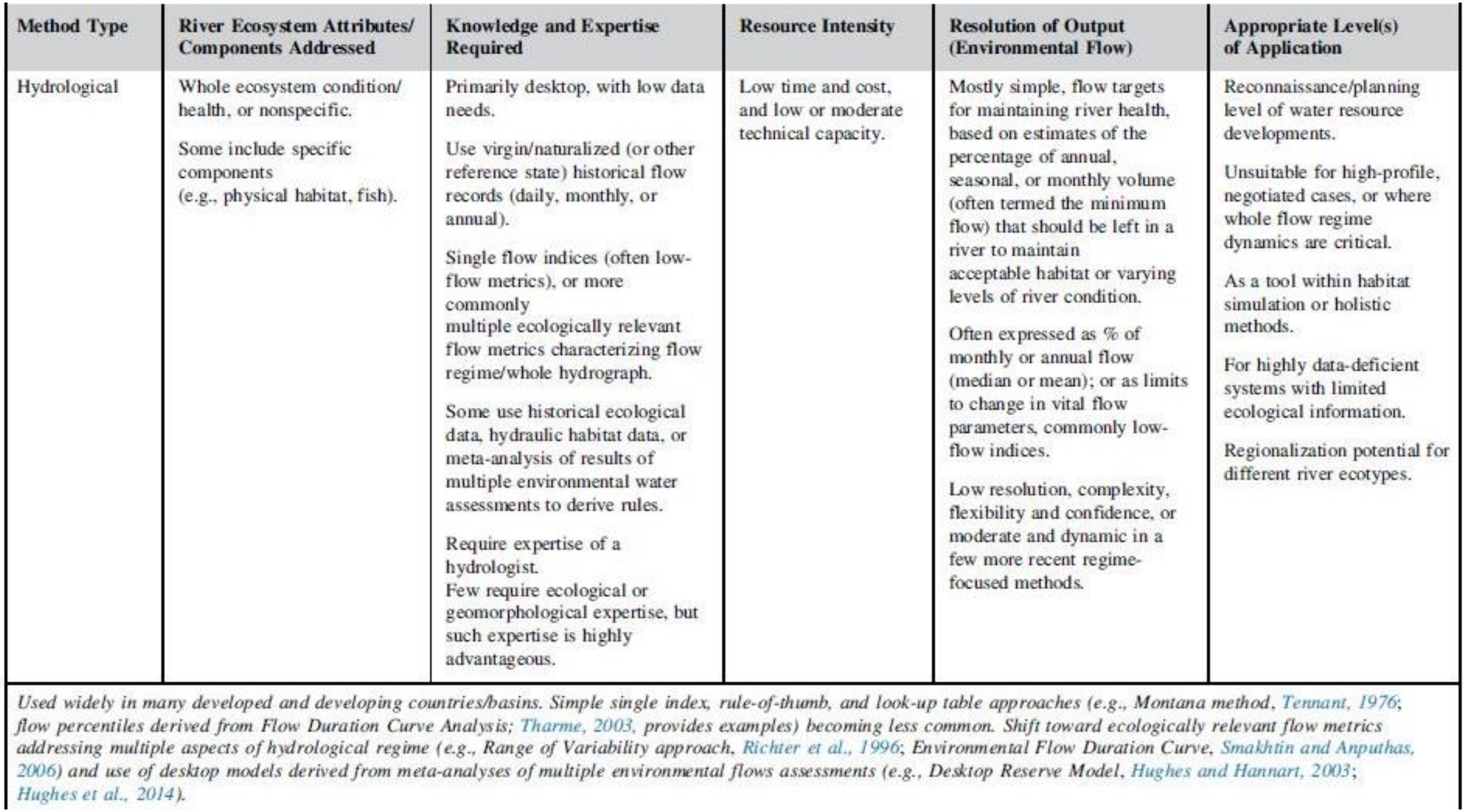
2.3.1 Main types of environmental flows assessment methodologies

The assessment of environmental flows is carried out for different contexts of water resources management, spatial scales and diverse biophysical systems.

Throughout the years, more than 200 environmental flows assessment methodologies were developed to address particular issues and special situations (Tharme 2003, Acreman and Dunbar 2004, Arthington 2012).

There are four main categories of environmental flows assessment methods: i) hydrological, ii) hydraulic rating, iii) habitat simulation, and iv) holistic methods. These groups, that made early by Tharme (1996 and 2003), and are widely accepted, remain relevant today, existing a notorious expansion of holistic approaches (Poff et al 2017). Even though Tharme (2003) recognized four relatively discrete categories of methods, it should be emphasized that during more demanding environmental flows assessments (EFAs), combinations of several methods are frequently applied (category of "combined" methods), and many statistical techniques (category "other") are used to evaluate data for input to EFAs (Arthington 2012). Also it could be emphasized that Dyson et al. (2003) provided alternative terms to refer to the categories identified by Tharme (2003), respectively considering the group order previously referred: i) lookup tables, ii) desktop analysis, iii) habitat modelling, and iv) functional analysis methods. Nevertheless, due to the widely use and acceptance of the categories provided by Tharme (2003), the names of the former categories are used herein. Throughout the years, the referred methods have been improving due to usual applications on the ground and through continuous advances in science. Despite the fact, most of the methods continue to focus widely on rivers, many of them are applicable (with some modifications) to other types of water bodies (such as, standing waters) (Arthington 2012, Poff et al 2017). As emphasized by Poff et al (2017) "methods tend to be applied hierarchically (Tharme 1996), from hydrology-based approaches – common and more appropriate in a precautionary, low-resolution framing of environmental water requirements at a water resources planning level – to increasingly comprehensive assessments using holistic methods". In Poff et al (2017), a generalized comparison between the main types of methods to assess environmental flows is provided (Table 2 – a, b, c, d, e).

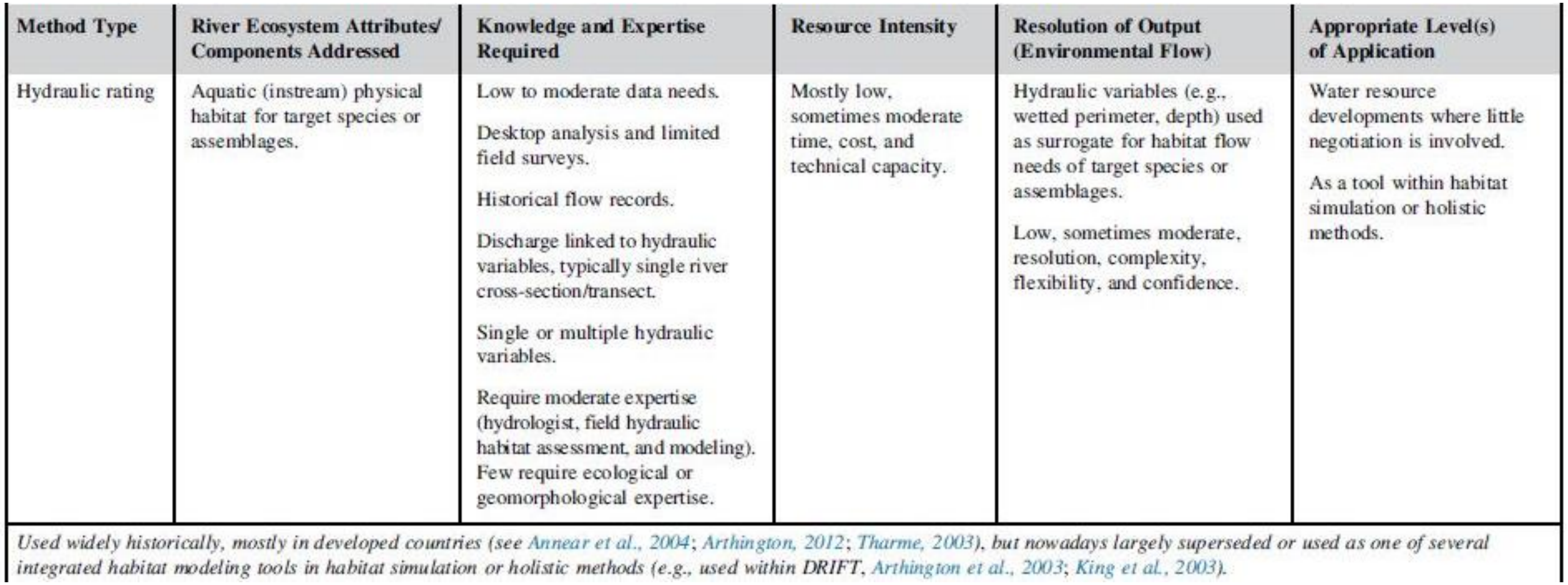
Table 2a – Generalized comparison of the four main types of methods and frameworks used worldwide to estimate environmental water regimes for rivers from site to regional levels (source Poff et al 2017).



Method Type	River Ecosystem Attributes/ Components Addressed	Knowledge and Expertise Required	Resource Intensity	Resolution of Output (Environmental Flow)	Appropriate Level(s) of Application
Hydrological	Whole ecosystem condition/ health, or nonspecific. Some include specific components (e.g., physical habitat, fish).	Primarily desktop, with low data needs. Use virgin/naturalized (or other reference state) historical flow records (daily, monthly, or annual). Single flow indices (often low-flow metrics), or more commonly multiple ecologically relevant flow metrics characterizing flow regime/whole hydrograph. Some use historical ecological data, hydraulic habitat data, or meta-analysis of results of multiple environmental water assessments to derive rules. Require expertise of a hydrologist. Few require ecological or geomorphological expertise, but such expertise is highly advantageous.	Low time and cost, and low or moderate technical capacity.	Mostly simple, flow targets for maintaining river health, based on estimates of the percentage of annual, seasonal, or monthly volume (often termed the minimum flow) that should be left in a river to maintain acceptable habitat or varying levels of river condition. Often expressed as % of monthly or annual flow (median or mean); or as limits to change in vital flow parameters, commonly low-flow indices. Low resolution, complexity, flexibility and confidence, or moderate and dynamic in a few more recent regime-focused methods.	Reconnaissance/planning level of water resource developments. Unsuitable for high-profile, negotiated cases, or where whole flow regime dynamics are critical. As a tool within habitat simulation or holistic methods. For highly data-deficient systems with limited ecological information. Regionalization potential for different river ecotypes.

Used widely in many developed and developing countries/basins. Simple single index, rule-of-thumb, and look-up table approaches (e.g., Montana method, Tennant, 1976; flow percentiles derived from Flow Duration Curve Analysis; Tharme, 2003, provides examples) becoming less common. Shift toward ecologically relevant flow metrics addressing multiple aspects of hydrological regime (e.g., Range of Variability approach, Richter et al., 1996; Environmental Flow Duration Curve, Smakhtin and Anputhas, 2006) and use of desktop models derived from meta-analyses of multiple environmental flows assessments (e.g., Desktop Reserve Model, Hughes and Hannart, 2003; Hughes et al., 2014).

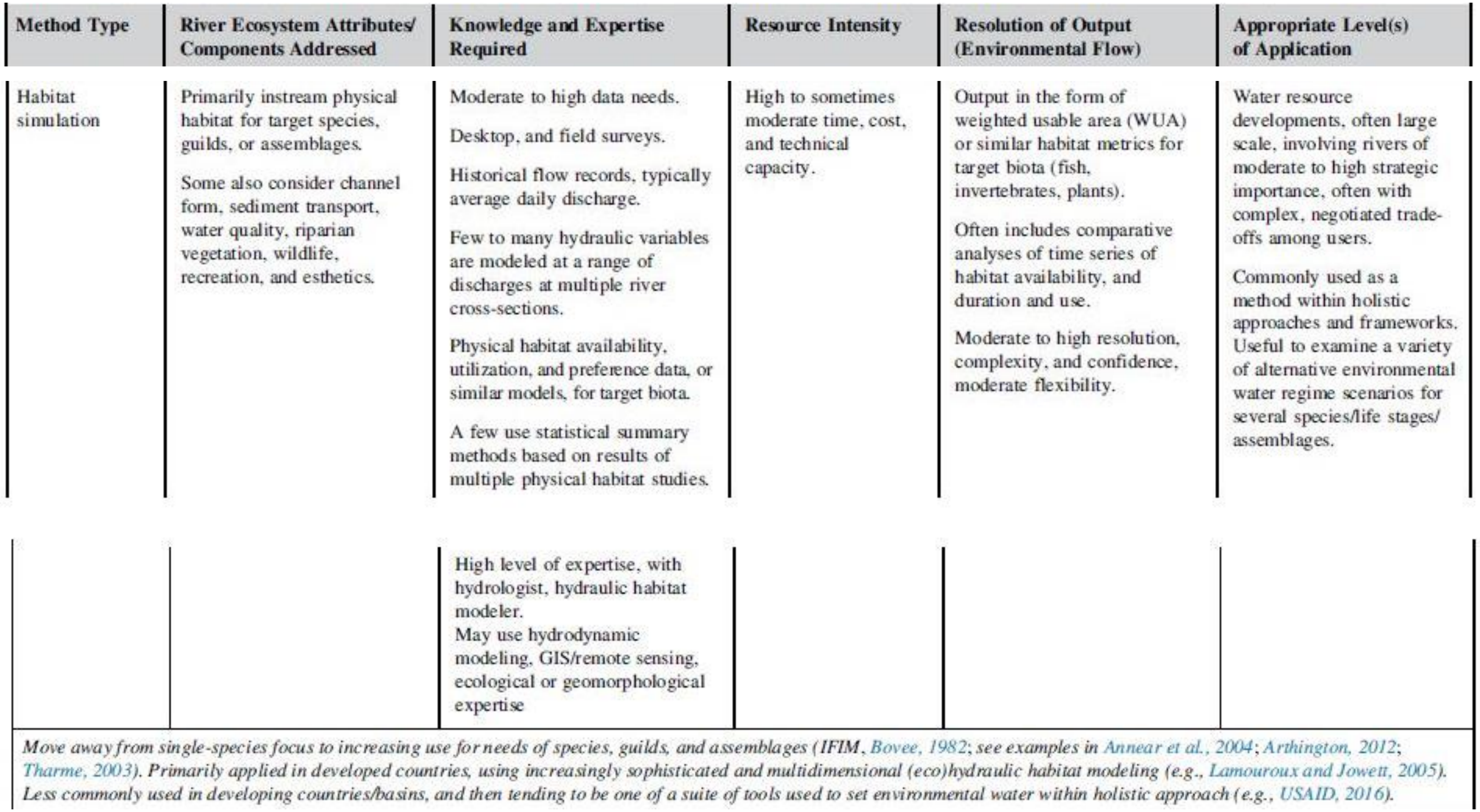
Table 2b – Generalized comparison of the four main types of methods and frameworks used worldwide to estimate environmental water regimes for rivers from site to regional levels (source Poff et al 2017).



Method Type	**River Ecosystem Attributes/ Components Addressed**	**Knowledge and Expertise Required**	**Resource Intensity**	**Resolution of Output (Environmental Flow)**	**Appropriate Level(s) of Application**
Hydraulic rating	Aquatic (instream) physical habitat for target species or assemblages.	Low to moderate data needs. Desktop analysis and limited field surveys. Historical flow records. Discharge linked to hydraulic variables, typically single river cross-section/transect. Single or multiple hydraulic variables. Require moderate expertise (hydrologist, field hydraulic habitat assessment, and modeling). Few require ecological or geomorphological expertise.	Mostly low, sometimes moderate time, cost, and technical capacity.	Hydraulic variables (e.g., wetted perimeter, depth) used as surrogate for habitat flow needs of target species or assemblages. Low, sometimes moderate, resolution, complexity, flexibility, and confidence.	Water resource developments where little negotiation is involved. As a tool within habitat simulation or holistic methods.

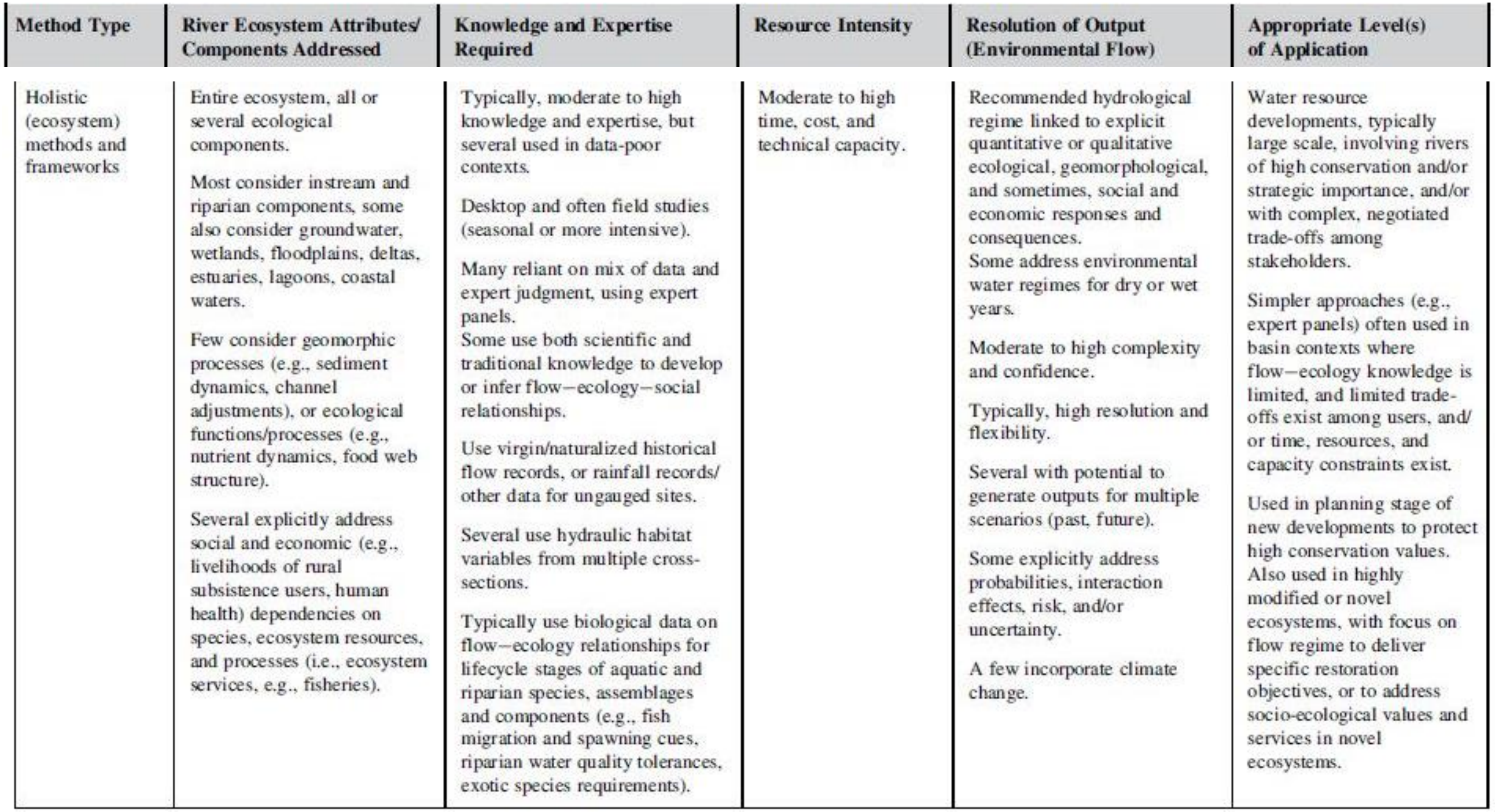
Used widely historically, mostly in developed countries (see Annear et al., 2004; Arthington, 2012; Tharme, 2003), but nowadays largely superseded or used as one of several integrated habitat modeling tools in habitat simulation or holistic methods (e.g., used within DRIFT, Arthington et al., 2003; King et al., 2003).

Table 2c – Generalized comparison of the four main types of methods and frameworks used worldwide to estimate environmental water regimes for rivers from site to regional levels (source Poff et al 2017).



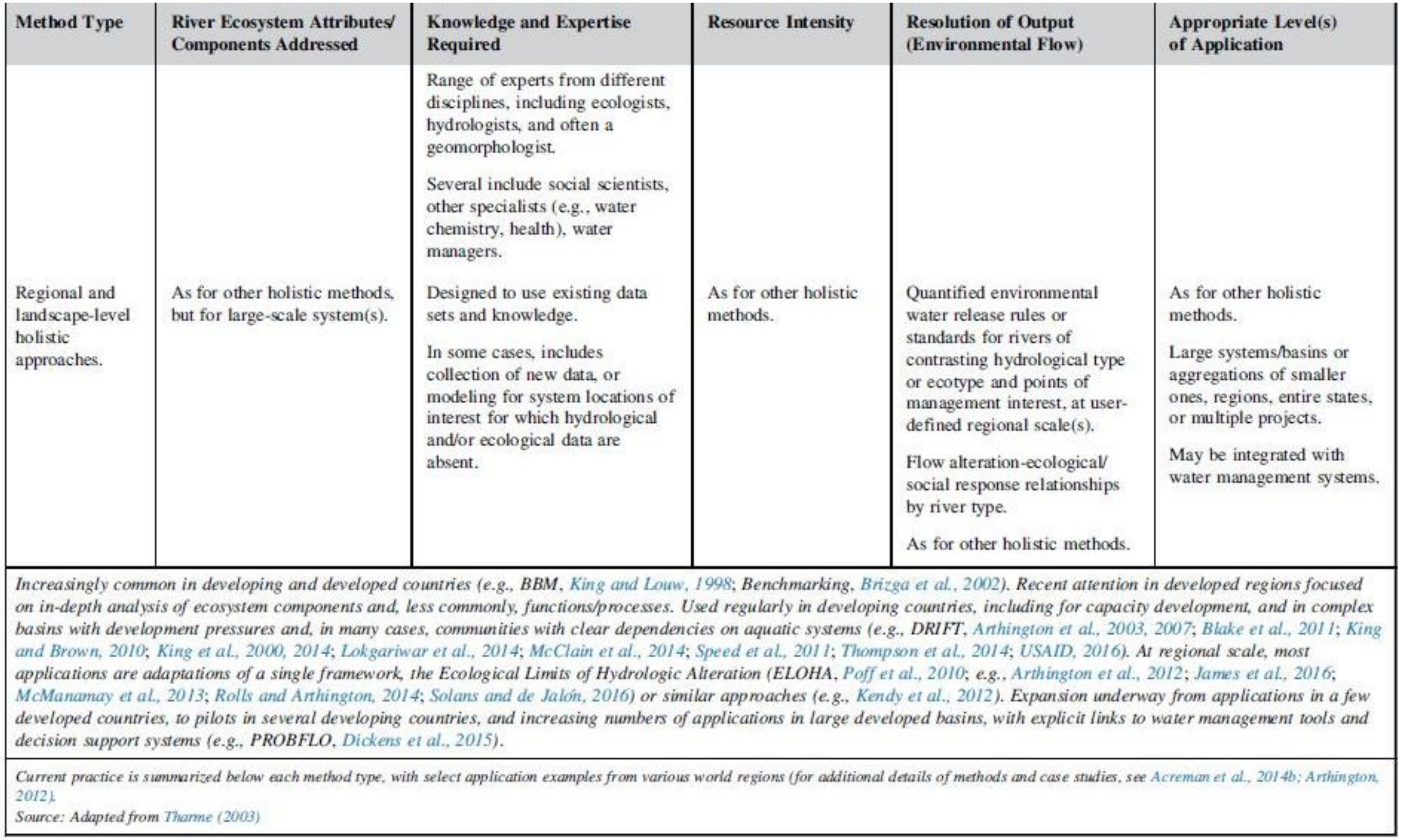
Method Type	**River Ecosystem Attributes/ Components Addressed**	**Knowledge and Expertise Required**	**Resource Intensity**	**Resolution of Output (Environmental Flow)**	**Appropriate Level(s) of Application**
Habitat simulation	Primarily instream physical habitat for target species, guilds, or assemblages. Some also consider channel form, sediment transport, water quality, riparian vegetation, wildlife, recreation, and esthetics.	Moderate to high data needs. Desktop, and field surveys. Historical flow records, typically average daily discharge. Few to many hydraulic variables are modeled at a range of discharges at multiple river cross-sections. Physical habitat availability, utilization, and preference data, or similar models, for target biota. A few use statistical summary methods based on results of multiple physical habitat studies. High level of expertise, with hydrologist, hydraulic habitat modeler. May use hydrodynamic modeling, GIS/remote sensing, ecological or geomorphological expertise	High to sometimes moderate time, cost, and technical capacity.	Output in the form of weighted usable area (WUA) or similar habitat metrics for target biota (fish, invertebrates, plants). Often includes comparative analyses of time series of habitat availability, and duration and use. Moderate to high resolution, complexity, and confidence, moderate flexibility.	Water resource developments, often large scale, involving rivers of moderate to high strategic importance, often with complex, negotiated trade-offs among users. Commonly used as a method within holistic approaches and frameworks. Useful to examine a variety of alternative environmental water regime scenarios for several species/life stages/ assemblages.
Move away from single-species focus to increasing use for needs of species, guilds, and assemblages (IFIM, Bovee, 1982; see examples in Annear et al., 2004; Arthington, 2012; Tharme, 2003). Primarily applied in developed countries, using increasingly sophisticated and multidimensional (eco)hydraulic habitat modeling (e.g., Lamouroux and Jowett, 2005). Less commonly used in developing countries/basins, and then tending to be one of a suite of tools used to set environmental water within holistic approach (e.g., USAID, 2016).					

Table 2d – Generalized comparison of the four main types of methods and frameworks used worldwide to estimate environmental water regimes for rivers from site to regional levels (source Poff et al 2017).



Method Type	River Ecosystem Attributes/ Components Addressed	Knowledge and Expertise Required	Resource Intensity	Resolution of Output (Environmental Flow)	Appropriate Level(s) of Application
Holistic (ecosystem) methods and frameworks	Entire ecosystem, all or several ecological components. Most consider instream and riparian components, some also consider groundwater, wetlands, floodplains, deltas, estuaries, lagoons, coastal waters. Few consider geomorphic processes (e.g., sediment dynamics, channel adjustments), or ecological functions/processes (e.g., nutrient dynamics, food web structure). Several explicitly address social and economic (e.g., livelihoods of rural subsistence users, human health) dependencies on species, ecosystem resources, and processes (i.e., ecosystem services, e.g., fisheries).	Typically, moderate to high knowledge and expertise, but several used in data-poor contexts. Desktop and often field studies (seasonal or more intensive). Many reliant on mix of data and expert judgment, using expert panels. Some use both scientific and traditional knowledge to develop or infer flow—ecology—social relationships. Use virgin/naturalized historical flow records, or rainfall records/ other data for ungauged sites. Several use hydraulic habitat variables from multiple cross-sections. Typically use biological data on flow—ecology relationships for lifecycle stages of aquatic and riparian species, assemblages and components (e.g., fish migration and spawning cues, riparian water quality tolerances, exotic species requirements).	Moderate to high time, cost, and technical capacity.	Recommended hydrological regime linked to explicit quantitative or qualitative ecological, geomorphological, and sometimes, social and economic responses and consequences. Some address environmental water regimes for dry or wet years. Moderate to high complexity and confidence. Typically, high resolution and flexibility. Several with potential to generate outputs for multiple scenarios (past, future). Some explicitly address probabilities, interaction effects, risk, and/or uncertainty. A few incorporate climate change.	Water resource developments, typically large scale, involving rivers of high conservation and/or strategic importance, and/or with complex, negotiated trade-offs among stakeholders. Simpler approaches (e.g., expert panels) often used in basin contexts where flow—ecology knowledge is limited, and limited trade-offs exist among users, and/ or time, resources, and capacity constraints exist. Used in planning stage of new developments to protect high conservation values. Also used in highly modified or novel ecosystems, with focus on flow regime to deliver specific restoration objectives, or to address socio-ecological values and services in novel ecosystems.

Table 2e – Generalized comparison of the four main types of methods and frameworks used worldwide to estimate environmental water regimes for rivers from site to regional levels (source Poff et al 2017).



Method Type	River Ecosystem Attributes/ Components Addressed	Knowledge and Expertise Required	Resource Intensity	Resolution of Output (Environmental Flow)	Appropriate Level(s) of Application
Regional and landscape-level holistic approaches.	As for other holistic methods, but for large-scale system(s).	Range of experts from different disciplines, including ecologists, hydrologists, and often a geomorphologist. Several include social scientists, other specialists (e.g., water chemistry, health), water managers. Designed to use existing data sets and knowledge. In some cases, includes collection of new data, or modeling for system locations of interest for which hydrological and/or ecological data are absent.	As for other holistic methods.	Quantified environmental water release rules or standards for rivers of contrasting hydrological type or ecotype and points of management interest, at user-defined regional scale(s). Flow alteration-ecological/ social response relationships by river type. As for other holistic methods.	As for other holistic methods. Large systems/basins or aggregations of smaller ones, regions, entire states, or multiple projects. May be integrated with water management systems.
Increasingly common in developing and developed countries (e.g., BBM, King and Louw, 1998; Benchmarking, Brizga et al., 2002). Recent attention in developed regions focused on in-depth analysis of ecosystem components and, less commonly, functions/processes. Used regularly in developing countries, including for capacity development, and in complex basins with development pressures and, in many cases, communities with clear dependencies on aquatic systems (e.g., DRIFT, Arthington et al., 2003, 2007; Blake et al., 2011; King and Brown, 2010; King et al., 2000, 2014; Lokgariwar et al., 2014; McClain et al., 2014; Speed et al., 2011; Thompson et al., 2014; USAID, 2016). At regional scale, most applications are adaptations of a single framework, the Ecological Limits of Hydrologic Alteration (ELOHA, Poff et al., 2010; e.g., Arthington et al., 2012; James et al., 2016; McManamay et al., 2013; Rolls and Arthington, 2014; Solans and de Jalón, 2016) or similar approaches (e.g., Kendy et al., 2012). Expansion underway from applications in a few developed countries, to pilots in several developing countries, and increasing numbers of applications in large developed basins, with explicit links to water management tools and decision support systems (e.g., PROBFLO, Dickens et al., 2015).					
Current practice is summarized below each method type, with select application examples from various world regions (for additional details of methods and case studies, see Acreman et al., 2014b; Arthington, 2012). *Source: Adapted from Tharme (2003)*					

2.3.2 Ecological Limits of Hydrologic Alteration – ELOHA

As previously referred, this study is based on some steps of the Ecological Limits of Hydrologic Alteration (ELOHA) framework/methodology, which reflects the consensus and the acquired experiences, over several decades, of various researchers, through scientific knowledge and practical application of environmental flows. This flexible methodology arises from a synthesis of various hydrological techniques and methods for environmental flows assessments, which can be used to support regional water resources management, with the determination of environmental flows for multiple sites throughout a region. ELOHA framework has been applied in several geographical and political contexts around the world (The Nature Conservancy 2017). It should be highlighted that ELOHA framework can be included in the holistic methods (at a regional level), more specifically in the often termed "top-down" approaches (Arthington 1998). As pointed out by Arthington (2012) "top-down methods define environmental flows in terms of acceptable levels of change from the natural flow regime and the natural (before alteration) structure/functioning of the riverine ecosystem. They enable consideration of many scenarios vis-à-vis the relationships between flow regime alteration and ecological consequences, while associated decision-making processes are able to select a final recommended flow regime for implementation (King et al 2003)."

The ELOHA framework (presented in Poff et al 2010) extended the approach presented by Arthington et al (2006) by formalizing a scientific and social process that can be used for setting environmental flows, as presented on Figure 5.

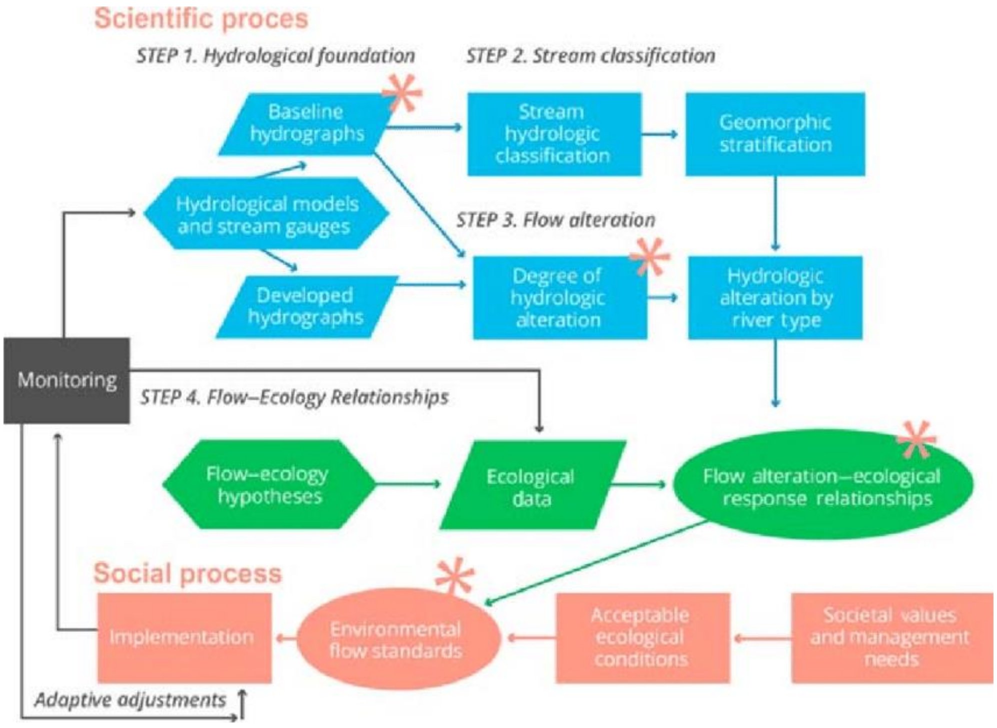


Figure 5 – ELOHA framework for determining environmental flows for multiple sites throughout a region (river network/s). The steps where the assumption of stationarity is implicit are indicated with a "star" (source Poff et al 2017).

As illustrated by Figure 5, the scientific process foreseen four main steps: i) building a hydrologic foundation (of baseline hydrographs for stream and river segments along the study region), ii) defining a stream classification – based on hydrologic classification (i.e. the consideration of a few distinctive flow regime types which are expected to have different associated ecological characteristics, that could be defined through the use of a set of ecologically relevant flow variables) and, also, in relevant geomorphic features, iii) assessing the deviation of current-condition flows from baseline-condition flows (i.e. the degree of flow alteration), and iv) developing flow – ecology and flow alteration – ecological response relationships for stream types. These relationships, as stated in Poff et al (2017), "can be compiled from existing data, or new data collected along a flow regulation gradient, and tested statistically to determine the form (e.g., threshold, linear) and degree of ecological change (positive or negative) associated with a particular type of flow regime alteration (Arthington et al. 2006)". It should be emphasized that, as described in Poff et al (2010), the assessment of relationships between flow alteration and ecological responses could begin by the elaboration of hypotheses that should be based on expert knowledge and on awareness of the hydroecological literature. Table 3, presents some examples of hypotheses to describe expected ecological responses to flow alteration (Poff et al 2010, Arthington 2012).

As pointed out by Poff et al (2017), considering Poff et al (2010), "a guiding principle of ELOHA is that ecological responses to particular features of the altered flow regime can be interpreted most robustly and usefully when there is some mechanistic or process-based relationship between the ecological (or social) response and the particular flow regime component". Having this in consideration, Poff et al (2010), provided some ecological indicators considered to be useful for the development of flow alteration – ecological response relationships, Table 4.

Table 3 – Examples of hypothesis to describe expected ecological responses to flow alteration, formulated by the authors of ELOHA (Poff et al 2010, Arthington 2012).

Flow characteristic	**Hypothesis**
Extreme low flows	Depletion of extreme low flows in perennial streams and subsequent drying will lead to rapid loss of invertebrate and fish diversity and biomass due to declines in wetted riffle habitat, lowered residual pool area depth when riffles stop flowing, loss of connectivity between viable habitat patches, and poor water quality.
Low flows	Depletion of low flows will lead to progressive reduction in total secondary production as habitat area becomes marginal in quality or is lost. Augmentation of low flows will cause a decline in richness and abundance of species with preferences for slow-flowing, shallow habitats.
Small floods and high-flow pulses	Lessened frequency of substrate-disturbing flow events will lead to reduced benthic invertebrate species richness as fine sediments accumulate, blocking substratum interstitial spaces.
Large floods	Increases in floodplain inundation frequency will enhance productivity in riparian vegetation species through increased microbial activity and nutrient availability, up to a point of waterlogging, after which productivity will decline due to anaerobic soil conditions.

Table 4 – Ecological indicators useful in developing flow alteration-ecological response relationships formulated by the authors of ELOHA (Poff et al 2010, Arthington 2012).

Criteria	**Indicator**
Mode of response	Direct response to flow (e.g., spawning or migration). Indirect response to flow (e.g., habitat-mediated).
Habitat responses linked to biological changes	Changes in physical (hydraulic) habitat (width-depth ratio, wetted perimeter, pool volume, bed substrate). Changes in flow-mediated water quality (sediment transport, dissolved oxygen, temperature).

	Changes to in-stream cover (e.g., bank undercuts, root masses, woody debris, fallen timber, overhanging vegetation).
Rate of response	*Fast versus slow* Fast: appropriate for small, rapidly reproducing, or highly mobile organisms. Slow: long life span. *Transient versus equilibrial* Transient: establishment of tree seedlings, return of long-lived adult fish to spawning habitat. Equilibrial: reflecting an end-point of recovery to some equilibrium state.
Taxonomic groupings	Algae and aquatic vegetation; riparian vegetation; macroinvertebrates; amphibians; fish; terrestrial species (arthropods, birds, water-dependent mammals, etc.) Composite measures, such as species diversity; Index of Biotic Integrity.
Functional attributes	Production; trophic guilds; morphological, behavioural, life-history adaptations (e.g., short-lived versus long-lived, reproductive guilds); habitat requirements and guilds; functional diversity and complementarity.
Biological level of response (process)	Genetic; individual (energy budget growth rates, behaviour, traits); population (biomass, recruitment success, mortality rate, abundance, age-class distribution); community (composition, dominance, indicator species, species richness, assemblage structure); ecosystem function (production, respiration, trophic complexity).
Social value	Fisheries production; clean water and other ecosystem services or economic values; protection of endangered species. Recreational opportunities (e.g., rafting, swimming, scenic amenity); indigenous cultural and spiritual values.

After the scientific process (see Figure 5), as highlighted by Arthington (2012) “interpretation of these hydro-ecological relationships and thresholds shall occurs in a consensus context where stakeholders and decision makers explicitly evaluate acceptable risk as a balance between the perceived value of the ecological goals (and ecosystem services), the economic costs involved, and the scientific uncertainties in functional relationships between ecological responses and flow alteration (Poff et al. 2010)”. In fact, the developed relationships provide scientific input to a social process in which a balance between environmental values with societal values and goals has been carried out.

2.4 Flow-ecology and flow alteration-ecological response relationships

As highlighted in Poff et al (2017) “At the core of environmental water science and assessment is the relationship between attributes of the flow regime and ecological responses to natural flow variability and to flow alterations, so-called flow-ecology relationships or flow alteration-ecological response relationships, respectively (Arthington et al 2006, Poff et al 2010).”

One of the major challenges for environmental water science is to develop robust and, if possible, transferrable flow-ecology relationships. In fact, generalization and transferability of these relationships have been recognized as matters of concern, due to the different ways that flow variables and ecological variables can be (and have been) defined and associated between them, at a several spatial and temporal scales (Poff et al 2017).

As previously referred, a key working assumption in environmental flows assessments has been that flow is a master variable leading to significant ecological responses, when there is an alteration of the flow regime. In fact, as supported by ecological theory (Bunn and Arthington 2002, Monk et al 2007, Poff and Ward 1989, Poff et al 1997) the so-called ecologically relevant components of a flow regime should be retained or restored. Indeed, as highlighted by Poff et al (2017), “in the absence of quantitative understanding of how specific levels of magnitude, frequency, duration, and timing can be combined to achieve a desired level of ecological response, the principle of mimicking aspects of the NFR is often invoked from the conservation perspective of the so-called precautionary principle (*sensu* Myers 1993)”. Nevertheless, a full restoration of the natural flow pattern is hardly achievable or necessarily desirable bellow all dams (Horne et al 2017c). Consequently, the main question appear, as pointed out by Poff et al (2017) “how much flow conservation (protection) or restoration is needed to effectively preserve or restore the ecosystem to some stated or desired level of condition?”. Within environmental flows science, the answer to this question has been a topic of concern (Richter et al 1997, Poff et al 2010, Acreman et al 2014a, The Brisbane Declaration 2007, The Brisbane Declaration on Environmental Flows 2018). In order to set specific restoration targets it is important to have, as previously expressed, an understanding related with the relationship between flow alteration and ecological response, and whether there are or not critical thresholds above or below which key functions or elements of the ecosystem are impaired or lost. In fact, as emphasized by Arthington (2012) "ecological responses to flow alteration may vary from no change to linear or to a threshold response (Anderson et al 2006, Arthington et al 2006), and the response may be positive or negative, depending on the selected ecological variable(s), the specific flow metric(s), and the degree of alteration for a given river type" (Figure 6).

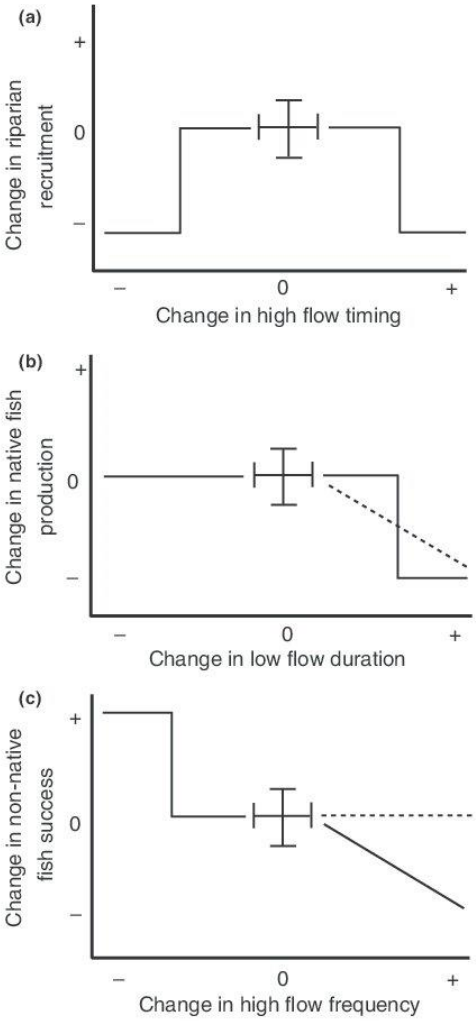


Figure 6 – Flow alteration-ecological response relationships for three river types: a) snowmelt, b) groundwater-fed, and c) flashy. Change in the flow metric (x-axis) ranges from negative to positive, with no change representing the reference condition. The response of the ecological variable (y-axis) to the flow alteration measured across a number of altered sites ranges from low to high. The bracketed space in the center of the graph represents the natural range of variation in the flow variable and ecological variable at the reference sites (source Poff et al 2010).

Nevertheless, as pointed out by Poff et al (2017), "many flow-ecology relationships are better expressed as continuous curves, and, therefore, pose greater challenges in identifying potential thresholds of change to guide management decisions". In fact, as previously referred, a major requirement is the development of "robust and, if possible, transferrable flow-ecology relationships" which has been a challenge and difficult to obtain due to the several ways flow variables and ecological responses can be defined and combined (Carlisle et al 2011, Lloyd et al 2003, Olden et al 2014, Poff and Zimmerman 2010, Webb et al 2015). This was described by some of the referred studies, which had as main goal the establishment of flow alteration – ecological response relationships through the evaluation of a significant number of published literature. This was the case of Lloyd et al (2003) in which through the analysis of 70 studies it was proved impossible to identify any simple linear or threshold relationship between the size of ecological change and the size of the hydrologic alteration. As stated by Arthington (2012), there were some constraints in the referred attempts to derive quantitative relationships, mainly due to the revision of disparate literature, including "lack of control or reference sites for unaltered conditions, other environmental changes occurring in the ecosystem (e.g., sediment flux, temperature change), and no possibility of comparing ecological conditions before and after most of the hydrologic alteration took place. Given that alteration of flow regimes is typically confounded with changes in the other environmental drivers of aquatic ecosystems, unambiguous relationships between single measures of flow alteration and ecological response may be difficult to extract (Konrad et al 2008)." Another factor that was pointed out as a difficulty to perceive ecological responses was the presence of exotic species that generate direct and indirect impacts on native species and ecosystems (Bunn and Arthington 2002, Arthington 2012). In order to detect more robust relationships, Lloyd et al (2003) proposed that a larger dataset spanning a broader range of hydrologic alterations (i.e., not just flow volume) and types of ecosystem response might be a solution.

Poff and Zimmerman (2010) developed a review of the literature (in total 165 papers) on ecological responses to alteration of natural flow regimes. This study revealed a particular attention to the type of quantitative relationships, which, as referred before, could be, for example: linear, curvilinear or "thresholds" of responses to flow alterations. In fact, the latter type of relationships are extremely useful within ecosystems management, since the thresholds might reveal, as highlighted by Arthington (2012) "when an ecosystem or valued ecological attribute has been shifted to the limits of resiliency and when collapse or a shift to an alternative and often undesirable ecological state is likely to occur (Folke et al 2004)." Table 5 provides some of the main information reported in the work developed by Poff and Zimmerman (2010).

Table 5 – Some of the main information reported in the work developed by Poff and Zimmerman (2010) (this table was build based on information presented on Arthington 2012).

Reported:		**Of the 165 studies reviewed:**
Environmental drivers	Only flow modification	70 %
	Sediments	14 %
	Temperature	11 %
	Sediment-temperature interactions	5 %
Source of flow regime change	A dam	88 %
	Water diversions	17 studies
	Groundwater abstraction	6 studies
	Levees	7 studies
	Weirs, road construction, or channelization	some studies
	Unspecified multiple factors affecting the flow regime	some studies
	Did not report a source	32 studies
Flow regime alteration	Magnitude	99 studies
	Duration	25 studies
	Timing	16 studies
	Frequency	16 studies
	Rate of change	5 studies
	Did not specify a flow component	4 studies
Ecological responses to flow regime alteration	In terms of population or community change of riparian vegetation, aquatic primary producers, macroinvertebrates, fish, birds, and amphibians	145 studies

As presented on Table 5, the ecological responses to flow regime alteration were reported on 145 papers, being analysed considering several groups of organisms (as shown on Figure 7).

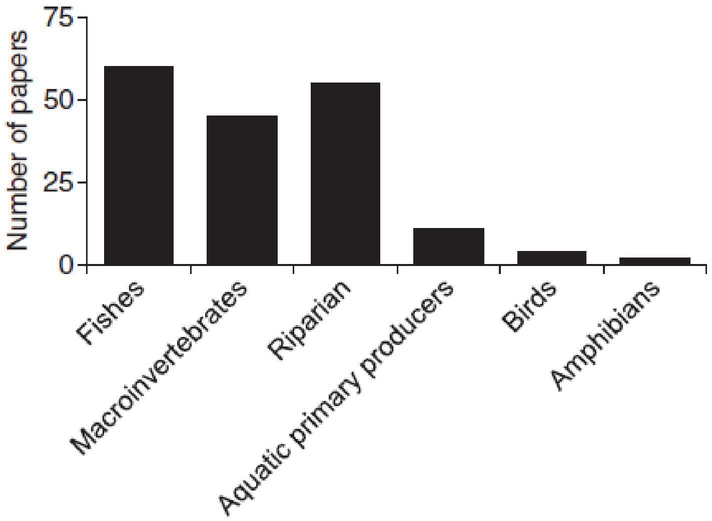


Figure 7 – Number of papers (out of a total of 145 papers) that measured population or community responses to flow alteration, by organism category. Some papers reported on multiple categories of organisms; thus the number of papers across categories adds up to more than 145 (source Poff and Zimmerman 2010).

Some results will be following provided, in terms of the quantitative responses of the most studied organisms in the papers evaluated by Poff and Zimmerman (2010), It was possible to perceive that macroinvertebrate abundance and diversity both generally declined in response to alteration in flow magnitude (whether there is an increase or a decrease in the alteration of flow magnitude). This can be noticed on Figure 8. Furthermore, it is possible to identify that usually most of the flow changes are near -100% or +100%, existing few intermediate values. This is a common challenge in the establishment of relationships, since the rare existence of intermediate values between the referred ranges, turns out very difficult the recognition of any threshold. As highlighted by Poff and Zimmerman (2010) "there was no consistent difference in direction or magnitude of macroinvertebrate response in terms of source of flow magnitude alteration."

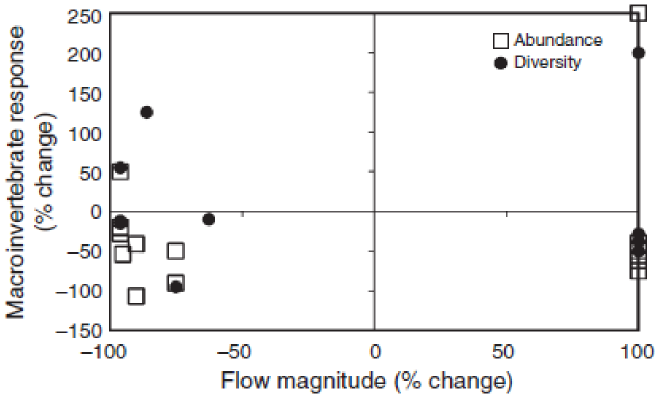


Figure 8 – Percent change in macroinvertebrate abundance and species diversity (and/or richness) with respect to percent alteration of flow magnitude. Percent change for both macroinvertebrates and flow magnitude represents alteration relative to a pre-impact or "reference" condition. Alteration in flow magnitude includes changes in peak flow, total or mean discharge, baseflow, or hourly flow. [Note: one extreme value for a change in abundance (+3000%) is plotted at +250% for presentation purposes] (source Poff and Zimmerman 2010).

Regarding fishes, according with Poff and Zimmerman (2010), it was possible to perceive "consistent negative responses to alteration in flow magnitude, whether measured by changes in abundance, population demographic parameters or diversity of assemblages" (Figure 9). Furthermore, it was possible to identify, as for macroinvertebrates, a lack of flow alteration points in the moderate ranges, limiting the "estimation of any potential threshold response and limited inference on lower levels of alteration that may not have negative impacts on fish species and assemblages". Moreover, it was possible to understand based on the revision of the 165 papers, conducted by Poff and Zimmerman (2010), that "The two specific types of flow alteration reported for these papers were changes in average discharge and short-term variation, for which both increases and declines in flow magnitude were reported".

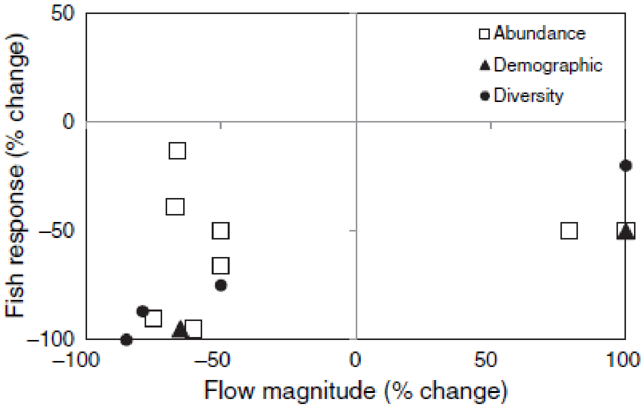


Figure 9 – Percent change in fish abundance, demographic parameters and species diversity (and/or richness) with respect to percent alteration of flow magnitude. Percent change for both fishes and flow magnitude represents alteration relative to a pre-impact or "reference" condition. Alteration in flow magnitude includes changes in peak flow, total or mean discharge, baseflow or hourly flow (source Poff and Zimmerman 2010).

In relation to the riparian communities (Figure 10), according with Poff and Zimmerman (2010), "All of the riparian studies recorded changes in peak flows", hence the riparian responses "can be associated with decreases in flood peaks, leading to reduction or elimination of overbank flooding".

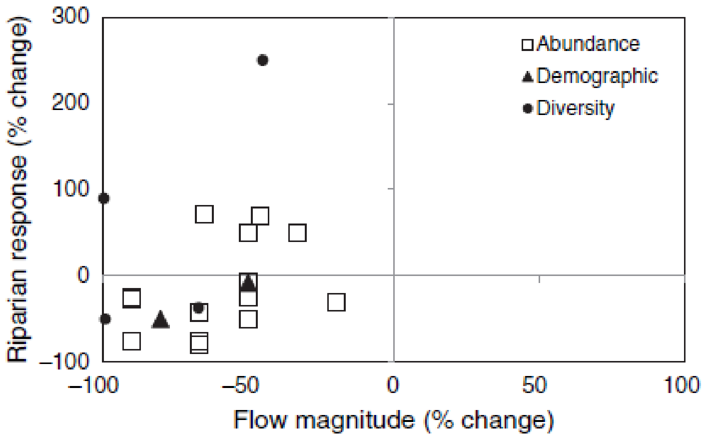


Figure 10 – Percent change in riparian abundance, demographic parameters and species diversity (and/or richness) with respect to percent alteration of flow magnitude. Percent change for riparian species and communities and flow magnitude represents alteration relative to a pre-impact or "reference" condition. Alteration in flow magnitude represents changes in peak flow only (source Poff and Zimmerman 2010).

As emphasized by Arthington (2012), Poff and Zimmerman (2010) suggested several factors that could constrain their evaluation: "the wide variety of ecological metrics and types of flow alteration reported; the different measures of flow alteration; different ways of measuring ecological response (e.g., upstream-downstream comparisons versus site-specific change relative to historical records); the problem of multiple hydrologic alterations (such as magnitude and seasonal timing); and interactions of flow change with other environmental characteristics, such as temperature regime, sedimentary processes, hydraulic habitat structure and dynamics, life-history processes, and the like (Konrad et al 2008, Olden and Naiman 2010, Stewart-Koster et al 2010)". Poff and Zimmerman (2010) enhance the need to develop hydrologic alteration-ecological response relationships, through: targeted monitoring along gradients of flow regime change and before-after dam construction as well as through flow release experiments (e.g., King et al 2010) and analysis of existing datasets.

A common problem either in Lloyd et al (2003), either in Poff and Zimmerman (2010), was that the reviewed studies did not provide as explicitly as is necessary the information necessary to achieve the quantification of hydroecological relationships in undisturbed and regulated river systems. Furthermore, another constraint pointed out by Arthington (2012) on both meta-analyses developed, was that "the studies reviewed ranged across river types, bioregions, and climatic zones, and the number of reported studies was insufficient to stratify the data to take into account these geographic and climatic influences on flow regime and ecosystem characteristics."

Following the two referred systematic reviews, Webb et al (2013) tried to overcome some of the perceived difficulties using the so-called Eco Evidence method and software to analyse the 165 studies evaluated by Poff and Zimmerman (2010). As highlighted by Webb et al (2013), "Eco Evidence provides a rule set and standardised list of terms to assist reviewers to interpret consistently the results of disparate studies. The companion software assists with the synthesis of this information to reach transparent and repeatable conclusions regarding cause-effect hypotheses of ecological responses to environmental drivers". Eco Evidence software is free available at www.toolkit.net.au/tools/eco-evidence (Norris et al 2012, Webb et al 2011 and 2012a), which has been positively used in topic-specific systematic reviews (such as Harrison 2010, Grove et al 2012, Webb 2012b).

Within this study (Webb et al 2013) it was found, in general terms, a "consistent sensitivity to changes in flow regime for both fish and riparian vegetation across a variety of performance metrics." For the case of macroinvertebrates, it was possible to assess that "While macroinvertebrates responses varied among performance metrics (e.g., abundance was negatively affected by increases or decreases in flows, diversity was only negatively affected by flow decreases, and assemblage structure was affected by neither), they were largely consistent within these metrics."

As it was possible to perceive through the above referred studies, the establishment of flow-ecology relationships is a challenge. In fact, as highlighted by Poff et al (2017), the flow-ecology relationships that emerge from literature reviews could be referred as noisy flow-ecology relationships, since there are other key drivers of ecological processes and patterns, such as temperature (Olden and Naiman 2010), sediment (Wohl et al 2015) and species interactions (Shenton et al 2012) that could confound the established relationships. In fact, the establishment of relationships between flow, thermal and sediment alterations raise further challenges, besides their implementation in terms of environmental water management. Indeed, as pointed out by Poff et al 2017 "Environmental water has primarily and deliberately focused on flow management, because preventing or reversing flow alteration is a necessary condition to sustain or restore the ecological integrity of riverine species and ecosystems. Moreover, reregulation of the flow regime below a dam is relatively easily achieved compared to other types of environmental modification such as altered thermal and sediment regimes."

2.5 Water Framework Directive (WFD)

The Water Framework Directive (WFD), one of the most important and ambitious pieces of European Environmental legislation to date (Boeuf and Fritsch 2016), was adopted on 23 October of 2000 (EC 2000). Its main objective is to protect and enhance freshwater resources having as main defined goal achieving at least a good water status/potential in all EU water bodies, by 2015, unless there was ground for exemptions (i.e., specific and justified situations provided by Member States) (Maia 2017). Now, MSs have the chance to achieve this goal at least in 2021, or, at the latest, by 2027, which is the final deadline to meet WFD objectives (EC 2017a). WFD establishes a set of coordinated objectives to be accomplished, in a specific timeframe (Wilby et al 2006) with key milestones within WFD implementation. The river basin management planning process is framed on a six-year revolving actions and review cycle, on which the River Basin Management Plans (RBMPs) and the accompanying

Programme of Measures (PoMs) are key instruments for the implementation of the WFD and the achievement of environmental objectives (EC 2017a and b, Ramos et al. 2017 and 2018).

WFD goals are due to be implemented by the current 28 European Union Member States (plus Norway, which is implementing the WFD under a specific timetable agreed pursuant to the Agreement on the European Economic Area, EEA) (EC 2017b). For MSs, the WFD establishes a set of coordinated objectives to be accomplished.

2.6 Environmental flows in Portugal

During the years, the topic of environmental flows has been also increasing in Portuguese legislation.

In 1987, the Basic Law on the Environment (*Lei de Bases do Ambiente*, Law nº 11/87 of April 7) highlighted the need to include environment protection and conservation in planning, management and use of the water domain. This legislation was the legal basis that allowed, since 1989, to include in the licensing of new hydraulic systems, the obligation to maintain a minimum flow downstream of the dam to minimize negative impacts on aquatic ecosystems. In 1994, the Decree-Law nº 46/94, of February 22, emerged with the goal to bring together, in a coherent way, the uses of the water domain, public and private, subject to licensing and under the jurisdiction of the Water Institute (*Instituto da Água*). Thus, this legislative document, establishing the licensing regime for the use of the water domain, states in the "Content of the titles of water abstraction for hydroelectric power generation" (*Conteúdo dos títulos de captação de água para produção de energia hidroelétrica*), the need to establish environmental flows and in the "Content of the license for the construction of public works" (*Conteúdo da licença para a construção de obras públicas*), the obligation to install the necessary devices to release these flows (and also the so-called reserved flow – *caudal reservado* – which corresponds to the flow that should be guaranteed downstream of the hydraulic systems, for the maintenance of existing uses, namely water irrigation). The need to implement environmental flows to protect and restore ecosystems is also highlighted in the Decree-Law nº 45/94, of February 22, a document that was framed to regulate water resources planning process, as well as, the preparation and approval of the basin plans before the entry into force of the WFD (Directive 2000/60/EC of 23 October 2000).

With the WFD – which established a framework for action in the public domain of water policy – the importance of defining and implementing environmental flows to achieve WFD environmental objectives (such as good water status) is implicitly recognized (Alves and Bernardo 2002).

WFD was transposed to Portuguese legislation to the so-called Water Law (*Lei da Água*, Law nº 58/2005, December 29) and the Decree-law nº 77/2006, March 30 (which complements the former one). These legislative documents were altered, respectively, for the Decree-Law nº 130/2012 and Decree-Law nº 103/2010. These changes were mainly due to the reorganization of the services and bodies with competence in the field of water resources management, namely by the creation of the Portuguese Environment Agency, I.P., which assumed functions of national water authority. Within the scope of these legal documents, whose primary purpose is the protection and sustainable water resources management, all activities that have a significant impact on water bodies status, may only be exercised through a permit to use water resources (article 56º). These uses, when carried out based on the water resources of the public water domain, are named as Licenses or Concessions (Decree-Law nº 226-A/2007 – currently modified by the Law nº 44/2012 – and Ordinance nº 1450/2007). The Concession of water resources of the public water domain for private uses is provided under a concession agreement, which must be establish between the administration and the concessionaire, referring the concession conditions (APA 2016).

In this context, in 2008, the company EDP – Gestão da Produção de Energia, (hereinafter referred as EDP Produção) has signed new concession contracts for the use of the surface water abstractions to produce hydroelectric energy.

3.STUDY AREA

3.1 Introduction

This chapter will provide information about the study area. In sub-chapter 3.2, a general description about the Cávado River Basin is provided, for instance: i) information related with Cávado River Basin location, ii) the climatic conditions (namely in terms of yearly drought conditions), iii) the main geological formations and land cover/uses. Sub-chapter 3.3, presents information regarding the main structures and functioning of the Cávado-Rabagão-Homem hydroelectric system, most relevant for this study. In sub-chapter 3.4, a picture of the environmental flows in the study area is given. Particularly, how the environmental flows, to be released by the main dams included in the Cávado-Rabagão-Homem, have been defined. Moreover, information is provided concerning the characteristics of the environmental flows release devices (installed in recent years), as well as, the time period on which the operation (EDP) started to release the environmental flows. Finally, in sub-chapter 3.5, information related with the sites/locations selected for this study to assess environmental flows effects, as well as, to look for a definition of flow-ecology relationships. It should be highlighted that these sites correspond to the ones of the sampling network of ecological conditions used by EDP.

3.2 Cávado River Basin

The Cávado – Rabagão – Homem hydroelectric system, the one selected for this work, is located in the Cávado River Basin. This River Basin (RB), Figure 11, located in the northwest region of mainland Portugal, has an area of around 1600 km^2, being the bigger river basin included in the River Basin District nº 2 – RBD2 (which comprises three River Basins: Cávado, Ave e Leça) (APA 2016).

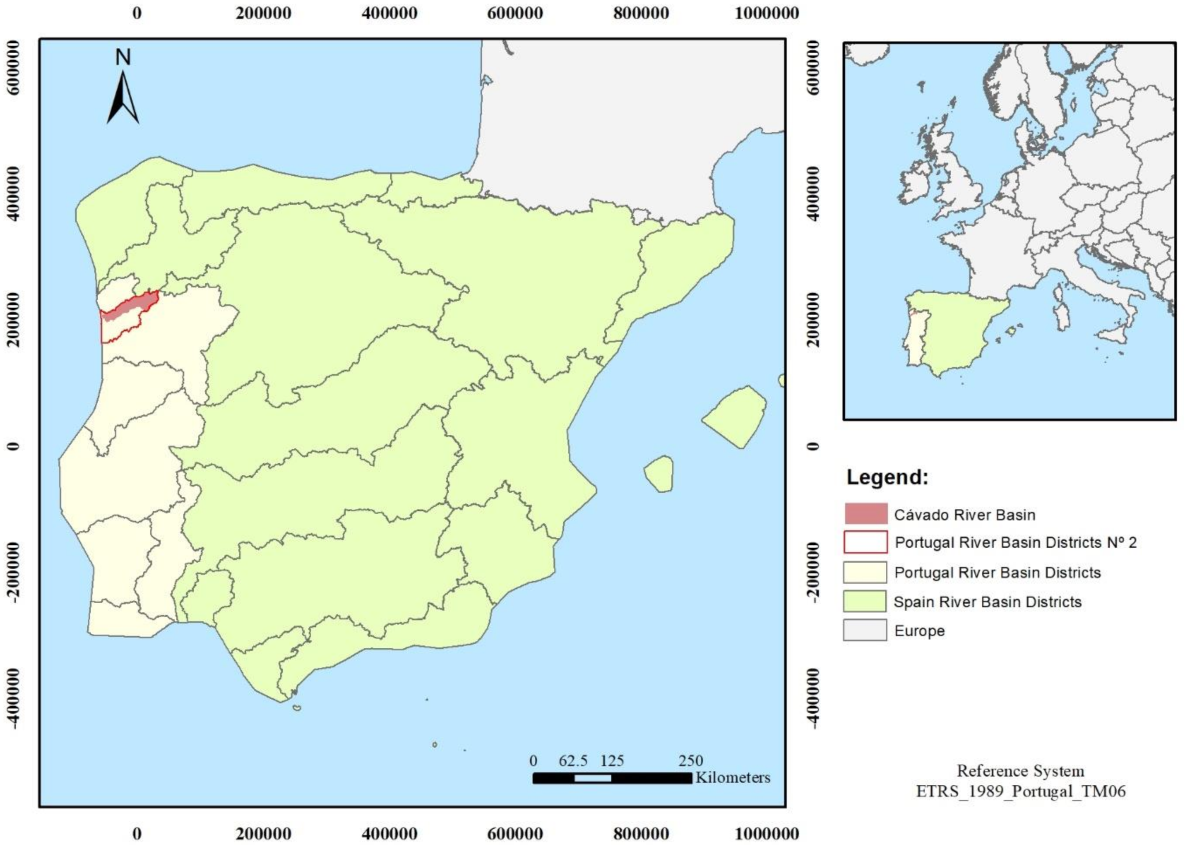


Figure 11 – Cávado River Basin location and River Basin Districts in the Iberian Peninsula.

Cávado River Basin, with bordering limits with Spain, totally or partially intercepts fourteen portuguese counties: Amares, Barcelos, Boticas, Braga, Cabeceiras de Basto, Esposende, Montalegre, Ponte da Barca, Ponte de Lima, Póvoa do Lanhoso, Póvoa de Varzim, Terras de Bouro, Vieira do Minho e Vila Verde (Figure 12). Information on actions carried out to delineate Cávado River Basin is available at sub-chapter 4.3.1.1.

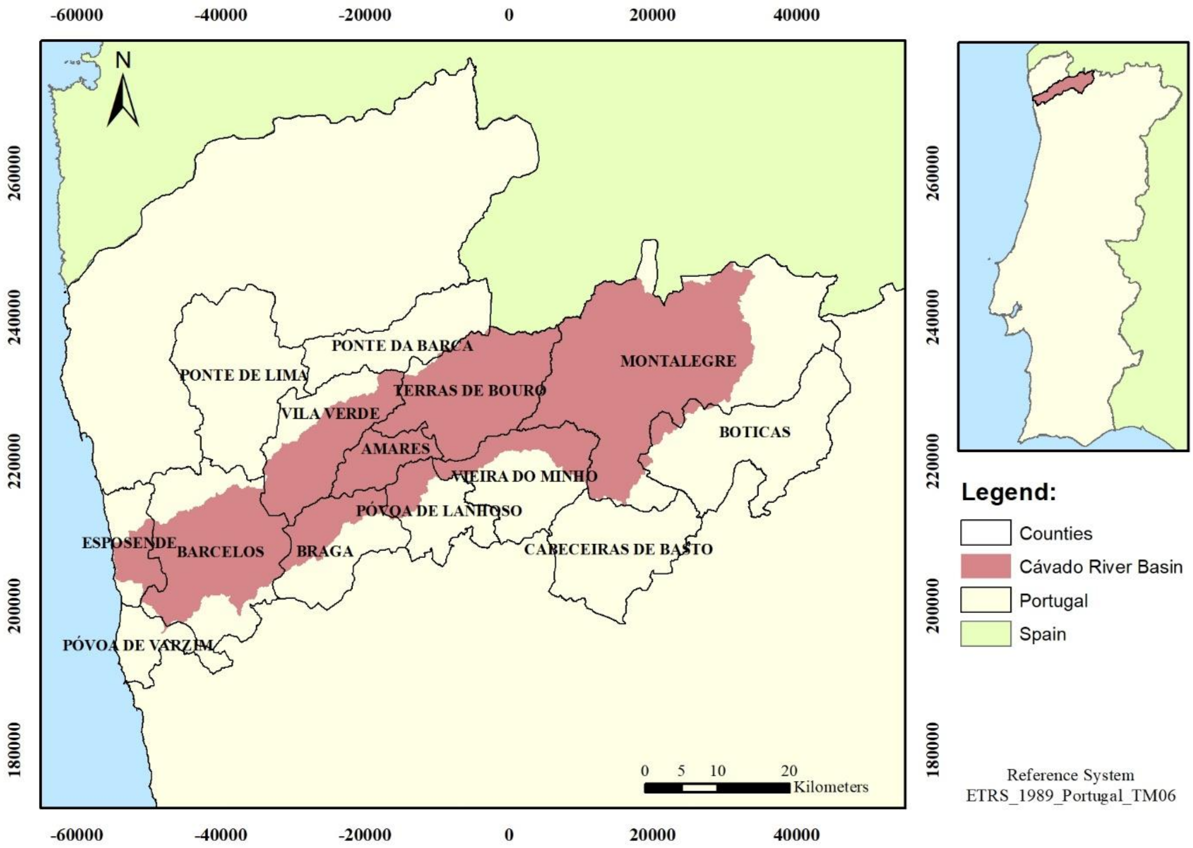


Figure 12 – Cávado River Basin and totally and partially intercepted counties.

The Cávado River, with approximately 129 km of extension, has its river spring in the Larouco Mountain (in an altitude of nearly 1520 m) and its river mouth in Esposende. Cávado River has two main tributaries: i) the Homem River (in the right river bank) – with a drainage area of around 260 km^2, has an extension of 45 km and its river spring is located in the Gerês Mountain – and ii) the Rabagão River (in the left river bank) – with a drainage area of nearly 250 km^2, has an extension of 37 km and its river spring is located between Barroso and Larouco Mountains (APA 2012, APA 2016).

According to IPMA (2019a), the values of the last available climate normals (the average values that characterize the climate of the region from 1971-2000) allowed the identification of the type of climate of the region, according with the Köppen-Geiger climate classification. Based on this, the climate in the Cávado River Basin is temperate continental (Type C), more specifically of the subtype Csb. For instance, a temperate climate with dry and mild summer (IPMA 2019a).

According with the 2nd River Basin Management Plan (RBMP) of the RBD2, (APA 2016), the Cávado RB presents annual mean precipitation values, ranging between 900 and 4200 mm, with a decreasing tendency of precipitation values from upstream to downstream areas of the RB (with values under 1500 mm per year, near the coastal RB area).

The analysis of the occurrence of drought periods was made based on the values of Standardized Precipitation Index (SPI). SPI was developed by McKee et al. (1993) and is based only on precipitation. One of the unique features of this index is it can be used to monitor conditions on a variety of time scales (NDMC 2019). Mathematically, the SPI corresponds to the cumulative probability of a given precipitation event occurring in a season. Table 6 presents the SPI classification system used to classify the SPI 12-months presented on Table 7, which corresponds to the characterization of drought conditions in a hydrological year for the period 2000-2018.

Table 6 – SPI classification for drought and wet periods and corresponding probability of occurrence (based on IPMA 2019b).

SPI	**Classification System**		**Probability**
	Description	**Color**	**(%)**
≥ 2.00	Extreme wet	🟦	2.3
1.50 a 1.99	Severe wet	🟦	4.4
1.00 a 1.49	Moderate wet	🟩	9.2
0.99 a 0.50	Mild wet	🟩	15.0
0.49 a -0.49	Normal	🟨	38.2
-0.50 a -0.99	Mild drought	🟨	15.0
-1.00 a -1.49	Moderate drought	🟧	9.2
-1.50 a -1.99	Severe drought	🟫	4.4
≤ -2.00	Extreme drought	🟫	2.3

Table 7 – SPI 12-months for Cávado RB (based on IPMA 2019b).

Year	**SPI 12-months for Cávado**
2000	-0.44
2001	2.11
2002	-1.37
2003	0.16
2004	-0.90
2005	-1.44
2006	-0.59
2007	0.10
2008	-1.11
2009	-1.25
2010	0.57
2011	-0.83
2012	-1.36
2013	1.39
2014	0.99
2015	0.30
2016	1.43
2017	-0.54
2018	0.29

In order to perceive the overall land cover/land uses of the Cávado River Basin, the Copernicus Global Land Service, Pan-European Component (https://land.copernicus.eu/pan-european) was used to download information relative to CORINE Land Cover 2012, the 4th CLC inventory in Europe. CLC2012 data provides information on the biophysical characteristics of the Earth's Surface for 2012. The CORINE Land Cover (CLC) nomenclature is a 3-level hierarchical classification system and has 44 classes at the third and most detailed level. Herein, in order to have an overall picture of land cover/land use for the Cávado River Basin, an analysis of the information based on level 1 information was done (EEA 2017). As it is possible to perceive (Figure 13) most of the region is covered by forest and semi natural areas (1- Artificial surfaces, 2 – Agricultural areas, 3 – Forest and semi natural areas, 4 – Wetlands, 5 – Water bodies).

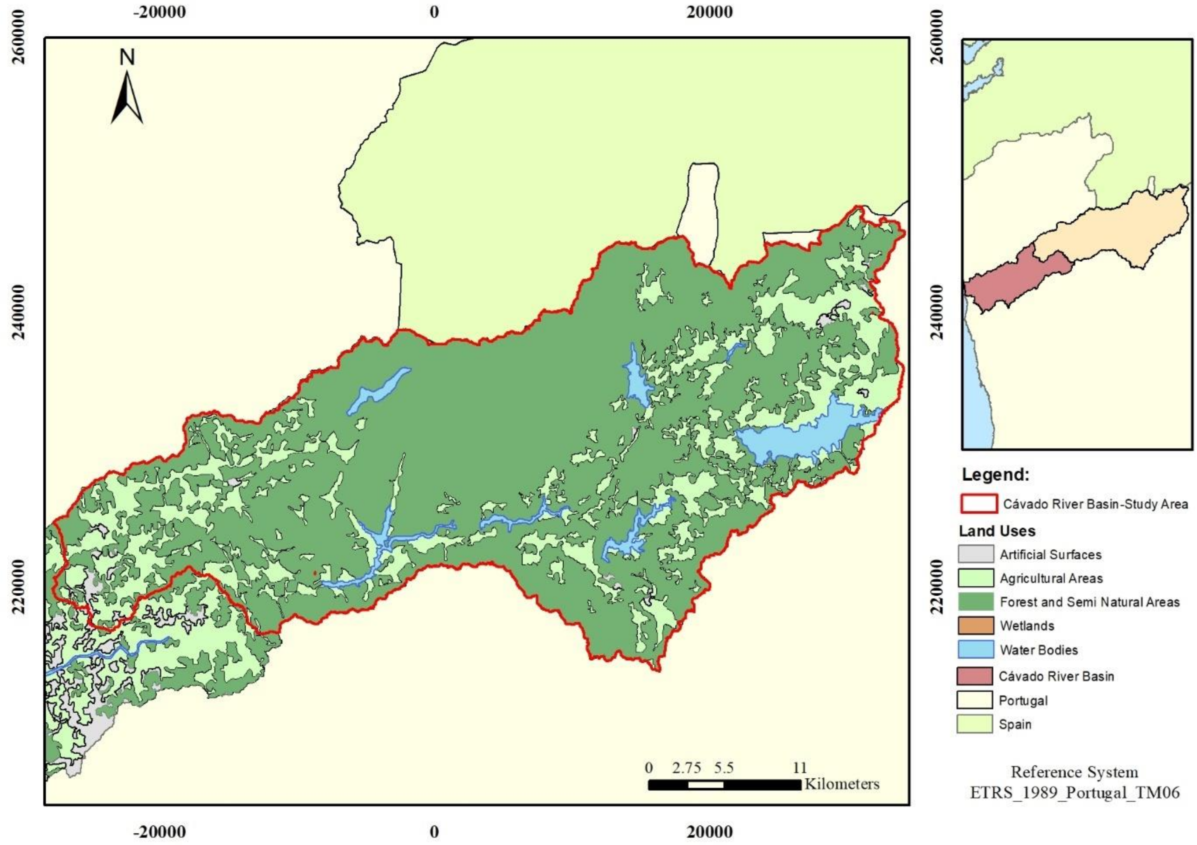


Figure 13 – Land cover/land use (developed in this study based on information from CLC2012 version 18_5).

The Cávado RB has a high hydric potential, which combined with the profile of its rivers led to the construction of several dams for hydroelectric production, the so-called Cávado – Rabagão – Homem hydroelectric system (HS), which has an essential role for the strategic water and energy storage (APA 2016).

3.3 Cávado- Rabagão- Homem hydroelectric system

The Cávado- Rabagão- Homem hydroelectric system (HS) – one of the most important systems in mainland Portugal, managed by EDP – is schematically presented in Figure 14, in which the representation of the main structures included in this system, as well as, the interconnection between them (the operational flow transfers and flow discharges locations) are marked. More specifically, it can be noted, through Figure 14, that the Cávado-Rabagão-Homem HS incorporates six main HS (whose year of entry into the first operation – as in some power reinforcements occurred later – are mentioned in brackets): i) Alto Rabagão HS (1964), ii) Venda Nova HS (1951), iii) Paradela HS (1956), iv) Salamonde HS (1953), v) Caniçada HS (1955), and vi) Vilarinho das Furnas HS (1972 – for the 1st group, 1987 – for the 2nd group, with pumping capacity). It can also be noted, in Figure 14, the existence of some weirs in the Venda Nova, Paradela and Vilarinho das Furnas Hydroelectric Systems: i) Cabreira (Venda Nova HS), ii) Toco, Cabril, Penedo, Castanheiro, and Abelheira (Paradela HS), iii) Brufe, Gemesura, Campo do Gerês and Freitas (Vilarinho das Furnas HS). The various power stations included in the Cávado-Rabagão-Homem HS are also presented in Figure 14. It should be noted that Venda Nova II (2005), Venda Nova III (2017) and Salamonde II (2015) power stations are, respectively, power reinforcements of the Venda Nova and Paradela Hydroelectric Systems. Table 8 presents a summary of some of the main information of the dams that integrate the Cávado- Rabagão- Homem HS.

More detailed information on each system and their interconnection is given in the following sub-sections.

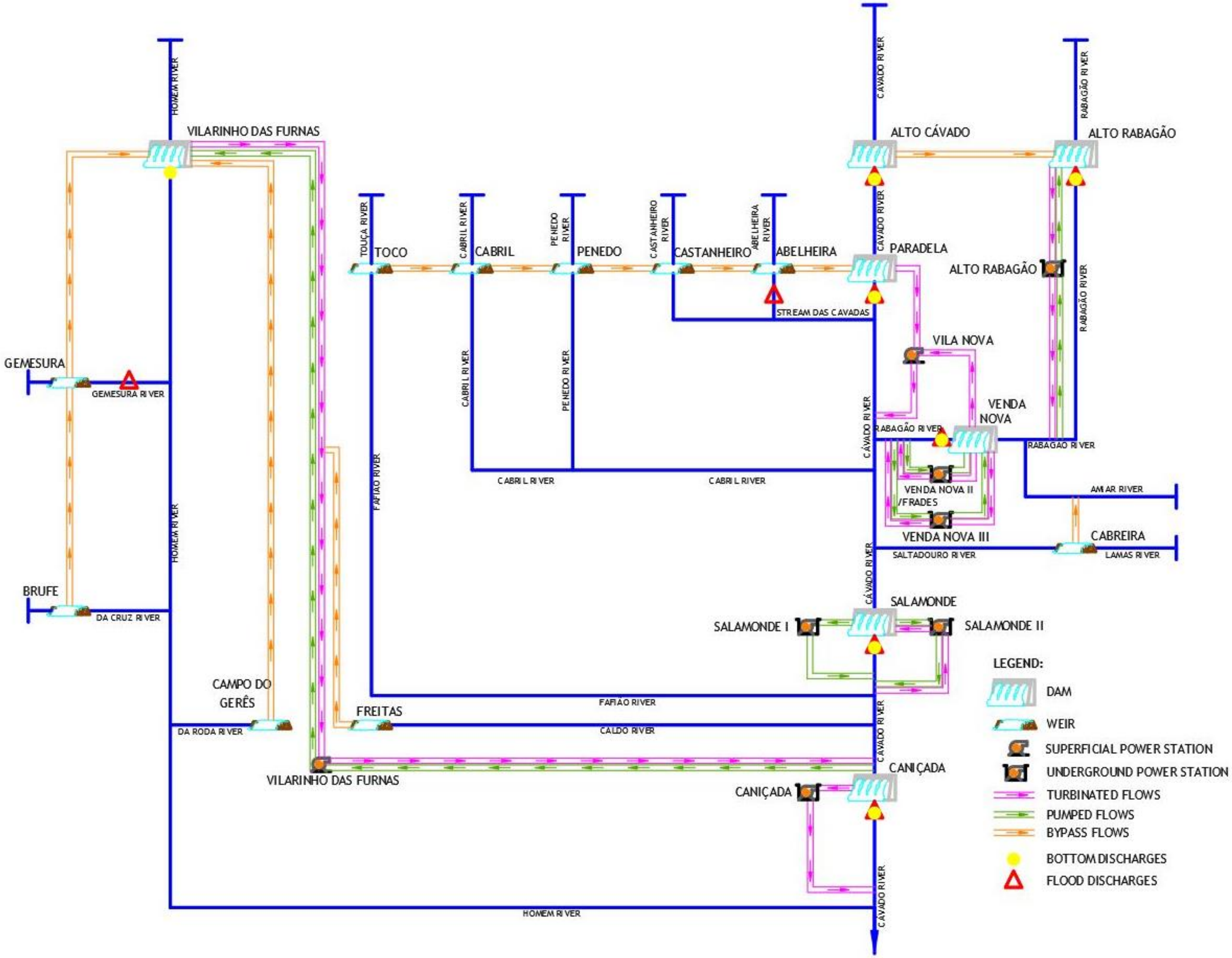


Figure 14 – Schematic representation of the Cávado-Rabagão-Homem HS.

Table 8 – Some of the main information of the dams that incorporate Cávado-Rabagão-Homem HS.

Characteristics	**Alto Rabagão**	**Venda Nova**	**Alto Cávado**	**Paradela**	**Salamonde**	**Caniçada**	**Vilarinho das Furnas**
Geographic coordinates a)	41º 43’ 57” (N) 7º51’38’’ (W)	41º 40’ 46” (N) 7º58’56’’ (W)	41º 48’ 10” (N) 7º52’34’’ (W)	41º 45’ 39” (N) 7º57’24’’ (W)	41º 41’ 20” (N) 8º5’40’’ (W)	41º 39’ 8” (N) 8º14’5’’ (W)	41º 45’ 33” (N) 8º13’00’’ (W)
County b)	Montalegre				Vieira do Minho	Terras do Bouro	
District b)	Vila Real				Braga		
River b)	Rabagão		Cávado				Homem
Year of construction c)	1964	1951	1964	1956	1953	1955	1972
Type of dam b)	Concrete (arch and gravity)	Concrete (arch)	Concrete (gravity)	Embankment (rockfill with upstream curtain)	Concrete (dome and arch)	Concrete (arch)	Concrete (arch)
Full reservoir level – FRL (m) b)	880	700	901.5	740	280	162	569.5
Highest Flood Level - HFL (m) b)	880.1	d)	905	741.6	280.5	d)	570
Minimum Draw-Down Level – MDDL (m) b)	829	645	d)	d)	d)	d)	d)
Flooded area at the MCL (hm^2)	2212	400	50	380	242	689	346
Total storage(hm^3)	568.69	94.5	3.3	164.4	65	170.6	117.69
Useful storage (hm^3)	557.92	93	2.0	159	56.3	159.3	116.08
Dead storage (hm^3)	10.77	d)	1.3	d)	d)	d)	d)

a) EDP 2016; b) CNPGB 2016; c) AQUALOGUS 2010; d) These values are not presented since any information was found about this.

3.3.1 Alto Rabagão HS

The Alto Rabagão HS was the first system built in Portugal with the main goal of interannual flow control. The system includes: i) two dams, the Alto Rabagão dam (the main structure of the HS, located in the Rabagão river) (Figure 15) and the Alto Cávado dam in the Cávado river (Figure 16), ii) one underground power station and iii) the hydraulic circuits associated. Alto Cávado dam creates a storage reservoir which water is diverted to the Alto Rabagão through a tunnel with 4.9 km of extension. Alto Rabagão dam has a spillway discharging flood flows immediately downstream, as well is the case of the bottom outlet of the dam. Regarding the turbined flows they are released through the hydraulic circuit in the storage reservoir of Venda Nova dam (located downstream Alto Rabagão dam). It is important to highlight that this system also works as water intake for the Alto Rabagão power station which also has the capacity of pumping water (EDP 2016).

Figure 15 – Alto Rabagão dam (CNPGB 2016, EDP 2016).

Figure 16 – Alto Cávado dam (CNPGB 2016).

3.3.2 Vila Nova/Venda Nova HS and Vila Nova/Paradela HS

The Vila Nova/Venda Nova HS is the oldest HS of the study area. This HS includes: i) the Venda Nova dam (the main infrastructure of this system, located in the Rabagão river) (Figure 17), ii) one power station named Vila Nova (Figure 18), iii) one weir located in Cabreira river (which water is diverted to the Borralha river – which is a small tributary of the Rabagão river discharging in the Venda Nova storage reservoir), and iv) the hydraulic circuits associated. The flows discharged (as flood and bottom flows) by the Venda Nova dam are immediately released downstream of the dam. The hydraulic circuit runs along the right bank of the Rabagão River and ends in a forced, open-air pipe, which is divided to three pipes in Vila Nova power station (one for each group). It could be highlighted that the Vila Nova power station is located along the left bank of the Cávado River, near its confluence with the Rabagão River. Vila Nova is located downstream Venda Nova dam and upstream of the Salamonde storage reservoir. Furthermore, it could be highlighted that this power station also integrates the called Vila Nova/Paradela HS. In fact, the Vila Nova power station has four groups, being three of them supplied by the Venda Nova dam, and one group supplied by Paradela dam, in the Cávado river (Figure 19). The turbined flows in this central are released just downstream of it.

Figure 17 – Venda Nova dam (CNPGB 2016).

Figure 18 – Vila Nova power station (EDP 2016).

Figure 19 – Paradela dam (CNPGB 2016).

The Paradela dam is the main infrastructure of the Vila Nova/Paradela HS. Besides, this HS comprises the existence of several weirs, as presented on Figure 14 (which diverted water from several tributaries of the right bank of the Cávado River to the Paradela storage reservoir) and the whole associated hydraulic circuits. Paradela dam has two types of flood spillways. One of the spillways releases the flows downstream the dam in the Cávado river at a distance of 120m of the bottom of the dam. The other one, releases the flows in the Sela river (one tributary of the Cávado river in right river bank).

3.3.3 Power reinforcements of the power of Venda Nova HS: Venda Nova II and Venda Nova III

The first reinforcement of the power of Venda Nova HS, named Venda Nova II/Frades has as a main structure an underground power station (Figure 20) located about 350 m deep, on the left bank of the Rabagão River. This power station has pumping capacity (which was not the case of Vila Nova power station). The flows that are turbined in this station are released on the left bank of the Rabagão River (about 150 m from its confluence with the Cávado River), immediately upstream of Salamonde storage reservoir. The water is pumped from this water storage, back to the Venda Nova storage reservoir.

Figure 20 – Venda Nova II or Frades power station (EDP 2016).

The second reinforcement of the power of Venda Nova HS, named Venda Nova III, has also as a main structure an underground power station with pumping capacity. This power station is very important as it is the first power station, in Portugal, with reversible groups of variable speed. This allows a faster response to fluctuations in existing power consumptions (Ribeiro 2016). The water intake of this power station is close to the Venda Nova II power station. The turbined flows of Venda Nova III are released upstream of the location where Venda Nova II release this same type of flows.

Figure 21 – Venda Nova III (EDP 2016).

3.3.4 Reinforcement of the power of Paradela HS: Paradela II

The reinforcement of the power of Vila Nova/Paradela HS, named Paradela II, in the phase of preliminary draft of the project, presents as a main structure an underground power station. This will be equipped with a reversible group to generate energy.

3.3.5 Salamonde HS and its power reinforcement, Salamonde II

The Salamonde HS includes: i) the Salamonde dam (the main structure of the HS) (Figure 22), ii) one underground power station and iii) the hydraulic circuits associated. The Salamonde dam is located on the Cávado River (near 5 km downstream from the confluence with the Rabagão River). The flood flows, as well as, the bottom flows are released immediately downstream the dam. The turbined flows in the central are released in the storage reservoir of Caniçada.

Figure 22 – Salamonde dam (CNPGB 2016).

The reinforcement of the power of Salamonde HS, named Salamonde II has as a main structure an underground power station (Figure 23). This power station has one reversible group.

Figure 23 – Salamonde II power station (CNPGB 2016).

3.3.6 Caniçada HS

The Caniçada HS includes: i) the Caniçada dam (the main structure of the HS) (Figure 24), ii) one underground power station and iii) the hydraulic circuits associated. The flood and bottom flows are immediately released downstream the dam. The turbined flows are released at around 7 km downstream the dam, in the Cávado river.

Figure 24 – Caniçada dam (CNPGB 2016).

3.3.7 Vilarinho das Furnas HS

The Vilarinho das Furnas HS includes: i) the Vilarinho das Furnas dam (the main structure of the HS) (Figure 25), ii) one underground power station iii) four weirs and iv) whole the hydraulic circuits associated.

The Vilarinho das Furnas dam, located in the Homem River, has a spillway that release flood flows in the Gemesura River (a tributary in the right bank of the Homem River). The flows turbined by the power station are released in the Caniçada storage reservoir, in the Cávado river. This is also the water intake to pump water for Vilarinho das Furnas (this was only possible after 1987, when the power station started to have the capacity to pump flows). Concerning the weirs incorporated in the Vilarinho das Furnas HS, it should be highlighted that three of them diverted flows from the Brufe, Gemesura and Campo do Gerês streams to the Vilarinho das Furnas storage reservoir. The fourth weir diverted flows from the Caldo River directly into the hydraulic circuit that leads storage water from the Vilarinho das Furnas to the power station.

Figure 25 – Vilarinho das Furnas dam (EDP 2016).

3.4 Environmental flows in the study region

As referred in Sub-chapter 2.6, in 2008, EDP Produção has signed up new concession contracts (with the Portuguese National Water Authority) for the use of surface water abstractions to produce hydroelectric energy. These contracts refer some constraints to the operational water resources management, namely the need to define and implement environmental flows to be released by each one of the dams included in the HS. Furthermore, the obligation to implement a monitoring program to assess the effectiveness of the implemented environmental flows is required (Padrão 2013, AQUALOGUS 2010). The environmental flows values established in these Concession Contracts (CC) are presented in Table 9. These were defined by the National Water Authority using hydrological methods.

Nevertheless, the National Water Authority gave EDP Produção the chance to propose alternative environmental flows to be released, which should however be accepted and approved by the National Water Authority. With this purpose, AQUALOGUS company was assigned by EDP Produção to perform an in-depth study that enabled the definition of alternative environmental flows. Based on this study (AQUALOGUS 2010), alternative environmental flows were proposed gathering the knowledge obtained through the application of several types of methods in the study area: the Wetted Perimeter method, the Incremental Flow Instream Methodology (IFIM) and Expert Evaluation. Furthermore, environmental flows for drought years were also defined, through the application of a monthly factor – estimated through the relation between the annual runoff for a drought year and the one for an average year – to the environmental flows established for an average year. The environmental flows for average and drought years, defined and proposed to APA, by EDP Produção, are also presented in Table 9.

Table 9 – Environmental flows established in the Concession Contracts (CC) for each dam of the Cávado-Rabagão-Homem HS (EDP 2016, EDP 2018) and alternative environmental flows for average years (AY) and drought years (DY) (AQUALOGUS 2010).

Dams		**Environmental flows (m^3/s)**											
		Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**Mai**	**Jun**	**Jul**	**Aug**	**Sep**
Alto Rabagão	**CC**	0.21	0.29	0.75	1.14	0.91	0.69	0.66	0.47	0.30	0.19	0.17	0.27
	AY	0.09	0.12	0.27	0.34	0.33	0.28	0.21	0.18	0.08	0.03	0.03	0.03
	DY	0.06	0.08	0.18	0.22	0.21	0.18	0.14	0.12	0.05	0.02	0.02	0.02
Venda Nova	**CC**	0.49	0.76	1.57	2.77	2.25	1.73	1.56	1.12	0.67	0.35	0.21	0.49
	AY	0.27	0.39	0.85	1.06	1.01	0.83	0.62	0.53	0.24	0.20	0.20	0.20
	DY	0.18	0.25	0.55	0.69	0.65	0.54	0.40	0.34	0.16	0.13	0.13	0.13
Alto Cávado	**CC**	0.14	0.29	0.76	1.10	0.95	0.79	0.69	0.55	0.30	0.18	0.14	0.18
	AY	0.14	0.14	0.28	0.35	0.31	0.24	0.17	0.14	0.14	0.14	0.14	0.14
	DY	0.09	0.09	0.18	0.22	0.20	0.16	0.11	0.09	0.09	0.09	0.09	0.09
Paradela	**CC**	0.40	0.67	1.47	2.50	2.07	1.65	1.47	1.06	0.58	0.31	0.21	0.50
	AY	0.22	0.31	0.67	0.84	0.81	0.67	0.51	0.43	0.21	0.21	0.21	0.21
	DY	0.14	0.20	0.43	0.54	0.51	0.43	0.32	0.27	0.13	0.13	0.13	0.13
Salamonde	**CC**	0.71	1.75	3.23	4.13	5.03	4.54	4.04	2.94	1.38	0.63	0.31	0.63
	AY	0.38	0.51	1.15	1.44	1.41	1.21	0.91	0.78	0.34	0.15	0.15	0.15
	DY	0.24	0.32	0.73	0.92	0.89	0.76	0.58	0.49	0.21	0.10	0.10	0.10
Caniçada	**CC**	1.38	3.02	5.32	7.11	8.90	8.68	6.97	5.02	2.42	1.04	0.37	1.35
	AY	0.91	1.29	2.82	3.51	3.35	2.80	2.10	1.77	0.80	0.37	0.37	0.37
	DY	0.58	0.82	1.80	2.25	2.14	1.79	1.34	1.13	0.51	0.24	0.24	0.24
Vilarinho das Furnas	**CC**	0.62	1.18	1.49	1.68	1.86	1.63	1.53	1.12	0.72	0.41	0.29	0.28
	AY	0.28	0.41	0.89	1.11	1.04	0.86	0.64	0.54	0.25	0.11	0.05	0.07
	DY	0.19	0.28	0.60	0.75	0.70	0.58	0.43	0.36	0.17	0.07	0.03	0.04

The National Water Authority agreed with the environmental flows proposed by EDP Produção (based on AQUALOGUS 2010). Hence, the presented (in Table 9) alternative environmental flows are the ones that should be implemented by EDP in each one of the dams. Nevertheless, before its implementation in each dam, EDP Produção had to establish the necessary conditions for environmental flows implementation, namely the design and construction of environmental flow devices. In fact, none of the seven dams were built considering this type of devices. Table 10 presents relevant information regarding these devices. Then, after the construction of the devices the environmental flows began to be progressively implemented along the HS. Table 11 presents photos of the environmental flow devices currently implemented (all except Alto Cávado). In terms of the current status of environmental flows implementation this is presented in Table 12 . It should be noted that EDP and APA have agreed not to release environmental flows in the Alto Cávado dam, due to eutrophication and water quality problems in the storage reservoir which may have consequences for the downstream sections of this dam. Moreover, it should be highlighted that Paradela dam has some losses of water through the dam, which are estimated as being even higher that the environmental flows defined for that dam. Also, it should be perceived that even though, as expressed on Table 9, there are environmental flows defined for drought years, EDP always has released environmental flows as defined for normal years.

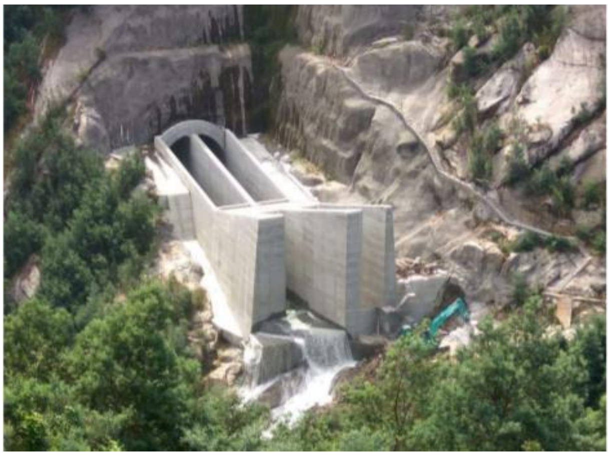
Table 10 – Information related with environmental flows devices (based on Oliveira 2018).

Dams	**Environmental flows devices**				
	Status			**Main characteristics**	**Capacity (m^3/s)**
	Already constructed	**Design phase**	**Year of conclusion**		
Alto Rabagão	x		2012	4 conduits DN 200 installed at the bottom of the dam (2 bottom outlets, 1 sand cleaning circuit and 1 draining circuit) equipped with valves and Venturi flowmeter	0.17 to 1.14
Venda Nova	x		2018	1 conduit carbon steel DN 600/DN 700 installed at the bottom outlet of the dam, equipped with valves	0.2 to 2.77
Alto Cávado		x			
Paradela	x		2016	A stainless-steel pipe DN 600 was connected to the bottom-outlet, equipped with one isolation gate type valve, one needle type control valve, one ultrasonic flowmeter and water quality monitoring system that comprehends a probe that measures water temperature and dissolved O_2	2.5
Salamonde	x		2016	Located in a new flood discharge spillway block, it shares both the superficial intake and the river institution (tunnel and downstream stairs). Made of a carbon steel pipe, is equipped with protection grid, lock gate, isolation valve butterfly type DN 900, and regulation valve, needle type and aerated with DN 800.	0.1 to 2.77
Caniçada	x		2018	Two parallel carbon steel circuits, installed in the spillway right wall intake, each one equipped with protection grid, lock gate, isolation valve (butterfly type), and regulation valve (needle type). The largest one has a first part of the conduit with 7 m extension and diameter 1.2 m (valves of this circuits are also	0.2 to 8.9

				DN 1200) and the downstream part is 15 m long. The thinner circuit’s upstream part is DN 800 (same as its valves) and 7 m long, while the downstream part is 13 m long and DN 1000. Both circuits are aerated in the needle valve section and release the e-flow inside the spillway tunnel.	
Vilarinho das Furnas	x		2014	2 conduits DN 350 installed at the bottom of the dam, equipped with valves	0.28 to 1.86

Table 11 – Photos of environmental flows devices (based on EDP Labelec 2018b, Oliveira 2018).

Dams	**Environmental flows devices**
Alto Rabagão	
Venda Nova	

Paradela	
Salamonde	
Caniçada	

Vilarinho das Furnas	

Table 12 – Starting date of environmental flows release in each one of the main dams in the HS in study.

Dams	Environmental flows release – starting date
Alto Rabagão	September 2012 (Autumn 2012)
Venda Nova	March 2018 (Spring 2018)
Alto Cávado	-
Paradela	February 2017 (Winter 2016/17)
Salamonde	March 2016 (Spring 2016)
Caniçada	June 2018 (Summer 2018)
Vilarinho das Furnas	October 2014 (Autumn 2014)

3.5 Sites selected for the assessment of environmental flows and for the evaluation of flow-ecology relationships

The sites selected by EDP- Produção to monitor ecological conditions (namely the effects of environmental flows) in the study region were the same selected herein in this study to look for the key step of this study, the establishment of flow – ecology relations. Figure 26 presents the locations of these sites. Some photos of those sites are presented on Figure 27 to Figure 33. Furthermore, in this study, is important to understand the location of each site within the Cávado-Rabagão-Homem HS (Figure 34), to perceive if, for example, the turbined flows are released upstream or downstream each selected site (which is important, for instance, to perceive if it would be hydropeaking effects on these sites). Moreover, relevant information about these sites (made available by EDP or assessed in this study, such as the altitudes) are presented in Table 13.

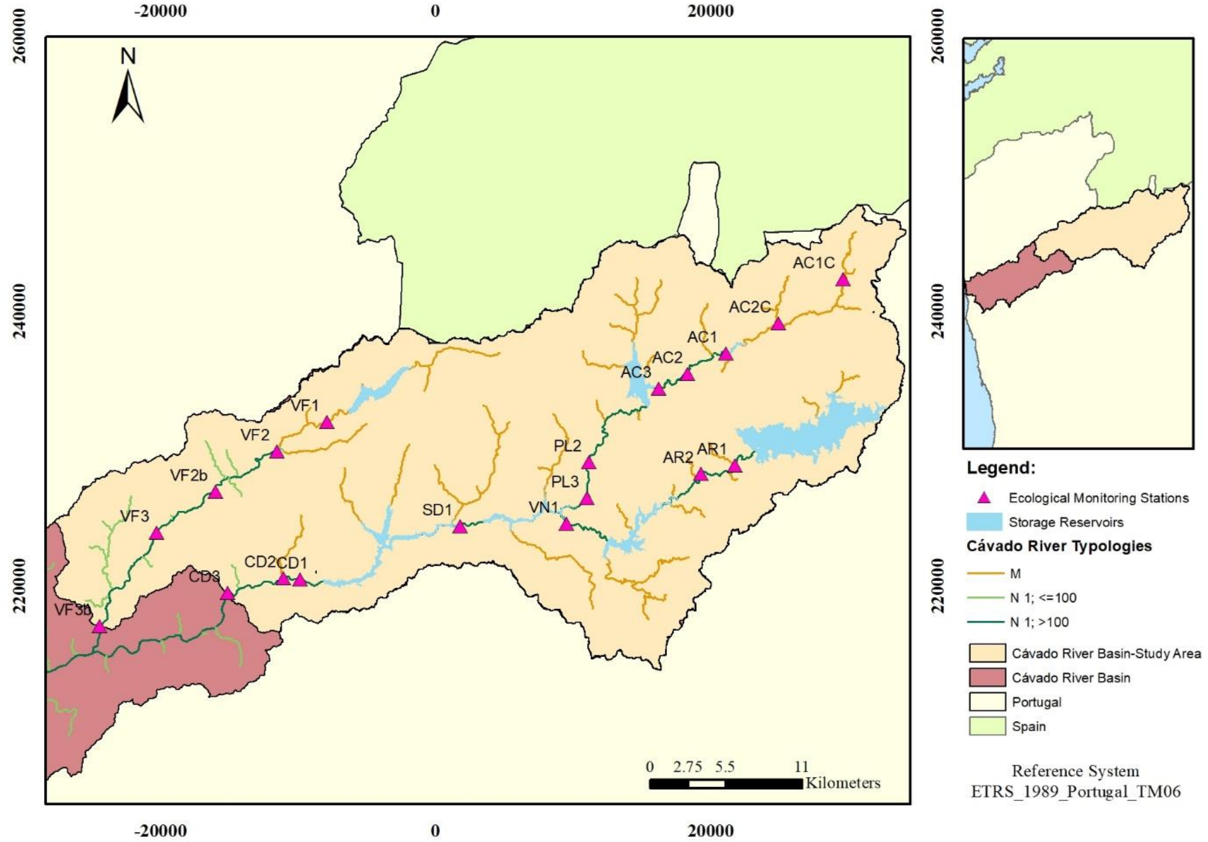


Figure 26 – Ecological monitoring stations – sites selected in this study.

a) b)

Figure 27 – Photos of the ecological monitoring stations downstream Alto Rabagão dam: a) AR1, b) AR2 (EDP Labelec 2018a).

Figure 28 – Photos of the ecological monitoring stations downstream Venda Nova dam: VN1 (EDP Labelec 2011d).

a) b)

c)

Figure 29 – Photos of the ecological monitoring stations downstream Alto Cávado dam: a) AC1, b) AC2, c) AC3 (EDP Labelec 2017).

a) b)

Figure 30 – Photos of the ecological monitoring stations downstream Paradela dam: a) PL2, b) PL3 (EDP Labelec 2011c).

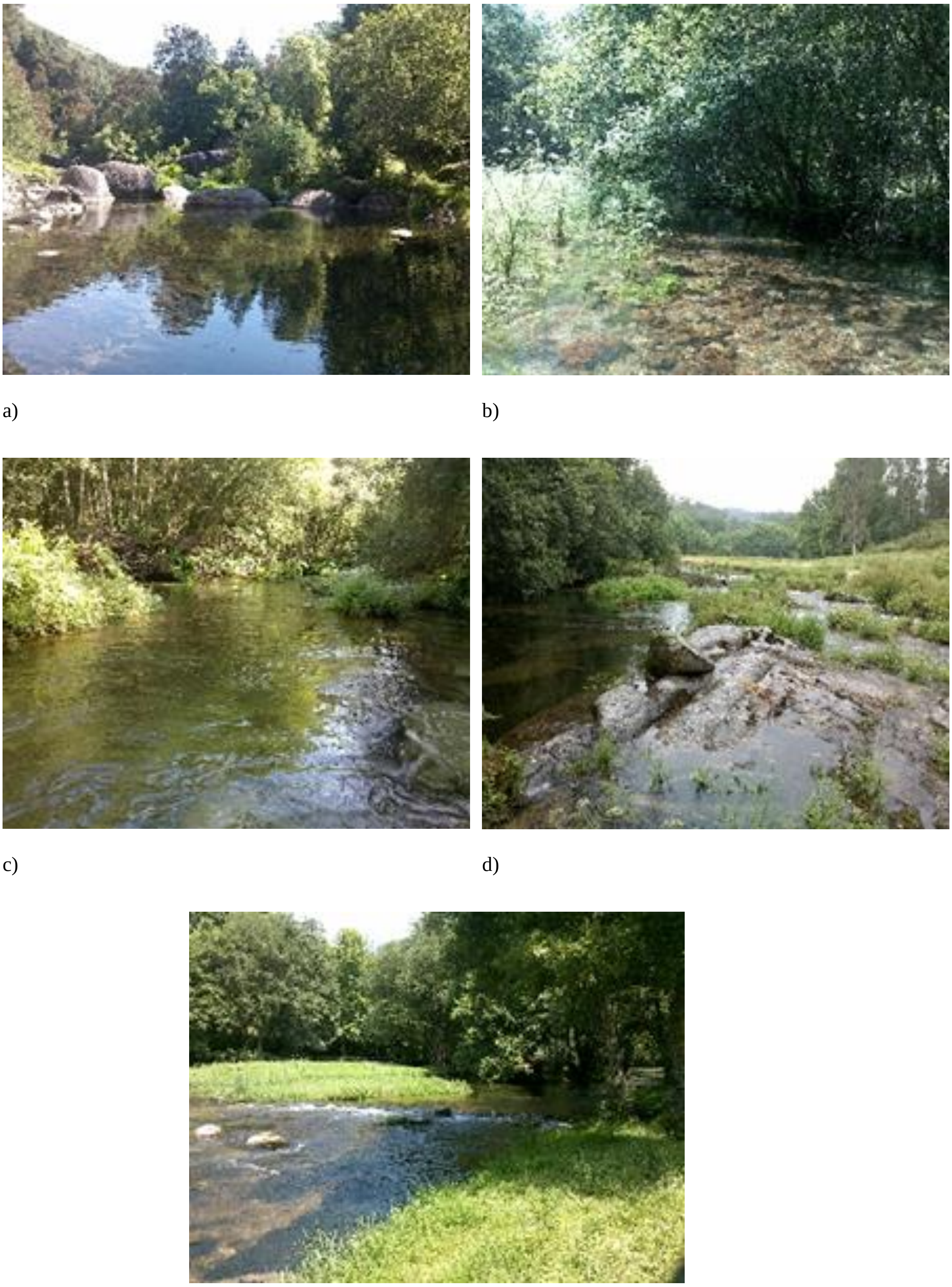
Figure 31 – Photos of the ecological monitoring stations downstream Salamonde dam: SD1 (EDP Labelec 2011a).

a)

b)

c)

Figure 32 – Photos of the ecological monitoring stations downstream Caniçada dam: a) CD1, b) CD2, c) CD3 (EDP Labelec 2011b).



a)

b)

c)

d)

e)

Figure 33 – Photos of the ecological monitoring stations downstream Vilarinho das Furnas dam: a) VF1, b) VF2, c) VF2b, d) VF3, e) VF3b (EDP Labelec 2018b).

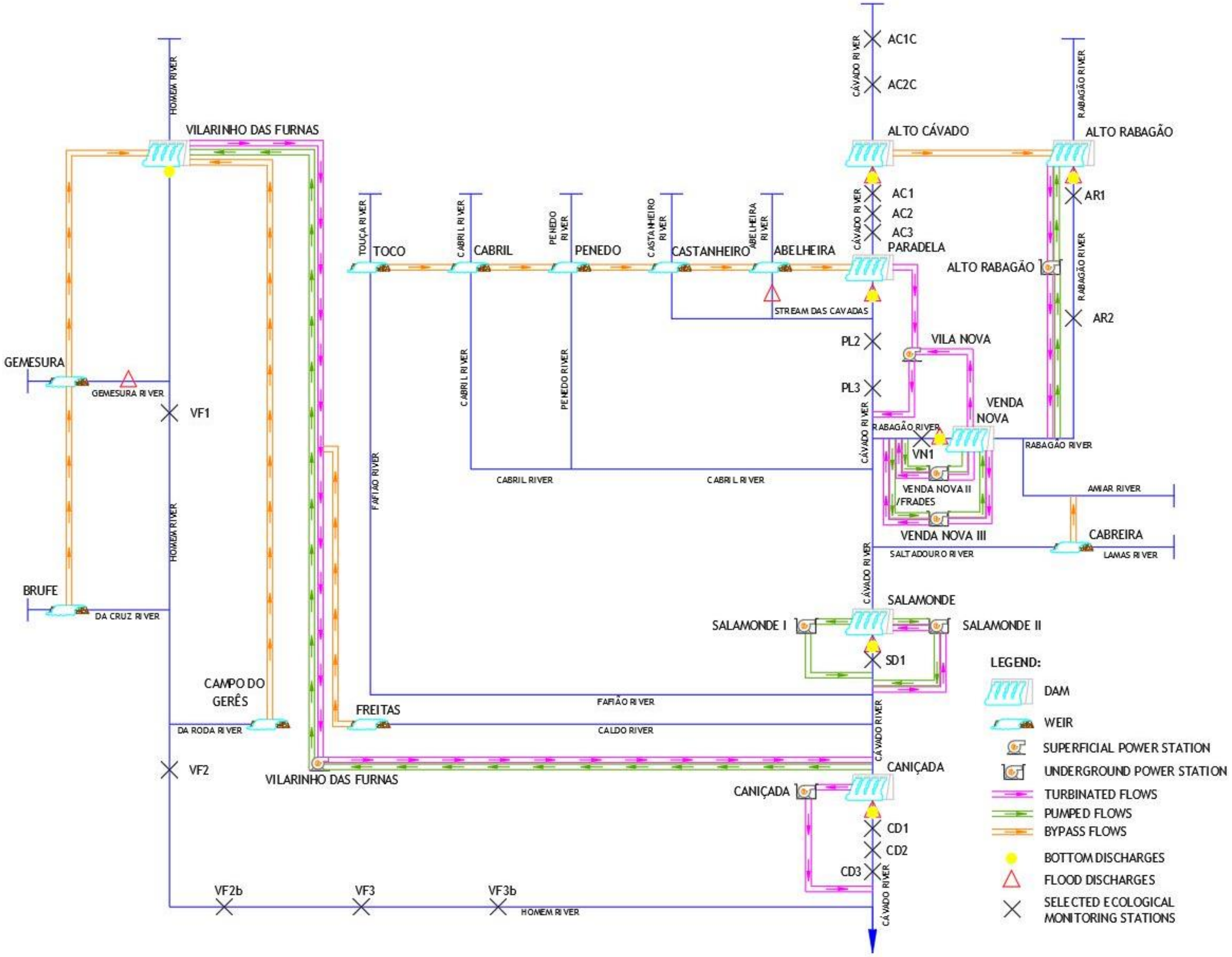


Figure 34 – Schematic representation of the Cávado-Rabagão-Homem HS with the representation of the EDP monitoring stations.

Table 13a – Information related with EDP ecological monitoring stations – sites selected in this study.

Dams	**Site**	**Coordinates (WGS84)**		**Altitude (m)**	**River**		**Location relative to the dam**	
		Lat.	**Long.**		**Name**	**Typology***	**U/D**	**Distance (m)**
Alto Rabagão	**AR1**	41° 43' 42" N	07° 52' 16" W	740	Rabagão	Northern Rivers with Medium-Large Dimensions N1>100 km^2	D	2500
	AR2	41° 43' 23" N	07° 54' 03" W	700				6300
Venda Nova	**VN1**	41° 41' 26" N	08° 01' 06" W	304	Cávado			4450
Alto Cávado	**AC1C**	41°50' 60" N	07°46'34 " W	960		Mountainous Northern Rivers (M)	U	-
	AC2C	41°49' 17" N	07°49'57 " W	909				-
	AC1	41°48' 07" N	07°52'44 " W	882		N1>100 km^2	D	250
	AC2	41°47' 18" N	07°54'45 " W	839				4500
	AC3	41°46' 43"N	07°56'15 "W	782				7100
Paradela	**PL2**	41° 43' 51" N	07° 59' 55" W	389				8300
	PL3	41° 42' 26" N	08° 00' 03" W	282				12000
Salamonde	**SD1**	41° 41' 19" N	08° 06' 41" W	158				1800

* As defined by INAG (2008). River typologies are groups of rivers with geographic and hydrological characteristics relatively homogeneous, considered relevant for the evaluation of ecological conditions.

Table 13b – Information related with EDP ecological monitoring stations – sites selected in this study.

Dams	**Site**	**Coordinates (WGS84)**		**Altitude (m)**	**River**		**Location relative to the dam**	
		Lat.	**Long.**		**Name**	**Typology***	**U/D**	**Distance (m)**
Caniçada	**CD1**	41˚ 39' 14" N	08˚ 15' 04" W	59	Cávado	N1>100 km^2	D	2000
	CD2	41˚ 39' 17" N	08˚ 15' 57" W	51				3500
	CD3	41˚ 38' 42" N	08˚ 18' 53" W	37				8700
Vilarinho das Furnas	**VF1**	41˚ 45' 26" N	08˚ 13' 40" W	434	Homem	M		2300
	VF2	41˚ 44' 16" N	08˚ 16' 18" W	129		N1>100 km^2		7300
	VF2b	41˚ 42' 41" N	08˚ 19' 32" W	61				14400
	VF3	41˚ 41' 03" N	08˚ 22' 37" W	44				20300
	VF3b	41˚ 37' 22" N	08˚ 25' 35" W	27				29600

* As defined by INAG (2008). River typologies are groups of rivers with geographic and hydrological characteristics relatively homogeneous, considered relevant for the evaluation of ecological conditions.

4.HYDROLOGICAL FOUNDATION AND ALTERATION

4.1 Introduction

To achieve the main goal of this study, the key step is the formulation of hydrologic alteration-ecological responses relationships. In order to attain this purpose, it was necessary to evaluate the hydrologic alterations on each selected location (Table 13). These alterations were evaluated based on the comparison between the natural and the modified flows at each site. This led to the need to develop a hydrological foundation for the study area. This involved the elaboration of a hydrological model of the study area that would allow the assessment of these different conditions. The development of this model, as well as, the estimation of natural flows and modified discharges, for each analysed section, it would be also relevant for the creation of a database which could be useful for further studies (for instance, those with the purpose to understand ecosystem responses to these changes).

At the beginning of this chapter (sub-chapter 4.2), a description about the selected software to develop the hydrological model for the study area is provided. Furthermore, a general overview about the model structure, the model parameters, the calibration objectives, as well as the measures provided by the model to evaluate its performance are provided. Then, the procedures performed for setting up the model, for its calibration (including a description about the objective functions and the measures to evaluate the performance of the model that were selected) and simulations are explained (in sub-chapter 4.3). Also, in sub-chapter 4.3, the methods performed for the estimation of the hydrological alteration on each selected site are described. After this, -sub-chapter 4.4 presents the results and the discussion of them. At the end of this chapter (in sub-chapter 4.5) the main conclusions achieved are pointed out.

4.2 Hydrological modelling framework

The purpose to build a model for the study area was to use it to obtain information related with the natural and current/modified flow conditions in the selected locations in this study (i.e., the ones chosen by EDP- Produção to assess ecological conditions downstream the dams). According with Graham (2014), it can be considered that the framework of a hydrological model is composed by: i) the flow system - the structure of the system – in which is important to include and understand the subsurface and the surface water flow system (such as, the topography, the geology, the hydraulic properties, the hydraulic structures in the area, the vegetation), ii) the external stresses, which are related with information related with climate conditions, river operations and groundwater pumping, for example, and, iii) the system response which is the response of the flow system influenced by the external stresses, resulting in information like surface and groundwater flows, reservoir levels and infiltration rates (Graham, 2014).

In order to accomplish the goals of this study, MIKE HYDRO – which is the common Graphical User Interface framework for some of the MIKE Water resources software products – was selected. MIKE HYDRO, developed by DHI (Danish Hydraulic Institute), as highlighted by DHI (2017a), "offers a state-of-art, map-centric user interface for intuitive model build, parameter definition and results presentation for water resources related applications". Mike HYDRO is a MIKE Zero component being accessible through it. It should be recognized that, as pointed out by DHI (2017b), MIKE Zero "is the common name of DHI's fully Windows integrated graphical user interface for setting up simulations, pre- and post- processing analysis, presentation and visualisation within a project-oriented environment."

In the following sub-chapters, a general overview about the model structure, the model parameters, the calibration objectives available in the model, as well as, the measures used to evaluate the performance of the model are described.

It should be highlighted that MIKE HYDRO enables the user to select different modules and sub-modules. In this study, the model type (or module) selected, was the "River module" due to its applicability for the purpose of this study. This model is called, as described by DHI (2017a), as MIKE HYDRO River model.

MIKE HYDRO River – the successor of the world-known MIKE 11 river modelling system – is the new generation DHI's river modelling framework/package for defining and executing one-dimensional river models to a large variety of river related project applications (such as: river hydraulics application, real time flood and drought forecasting, optimisation of reservoir and gate operations, ecology and water quality assessments in rivers and wetlands, water quality forecasting, sediment transport and long term assessment of river morphology changes).

MIKE HYDRO River offers a diversity of hydraulic and hydrological simulation engines, as well as, a wide range of sub-modules (add-on modules) (DHI 2019a). Within this study, two sub-modules were selected: i) the rainfall-runoff module, and ii) the hydrodynamic module. In the following chapters an overall description about this is provided.

4.2.1 Model description and structure

The rainfall-runoff module includes a variety of catchment runoff models, amongst others, the NAM (Nedbør-Afstrømnings-Model) (DHI 2019b). This was chosen, since as pointed out by DHI (2017c), “NAM model is a well-proven engineering tool that has been applied to a number of catchments around the world, representing many different hydrological regimes and climatic conditions”. NAM is a deterministic, lumped and conceptual rainfall-runoff model simulating the overland flow, interflow, and baseflow components as a function of water moisture contents in up to four different storages. Since NAM is a conceptual model it is based on physical structures and equations used together with semi-empirical ones. As a lumped model, each catchment is treated as a single unit. Therefore, the parameters and variables represent the average value within the entire catchment. NAM has the possibility to be applied independently or used to represent one or more contributing catchments that generate lateral inflows to a river network. By this way, within the same modelling framework it is possible to treat a single catchment or a large river basin containing numerous catchments and a complex network of rivers and channels. Furthermore, NAM model can be used for continuous hydrological modelling over a range of flows or for simulating single events (DHI 2017c).

NAM model, as previously referred, represents several components by continuously accounting for the water content in up to four different and mutually interrelated storages that represent different physical elements of the catchment. These storages (as depicted in Figure 35) are: i) snow storage, ii) surface storage, iii) lower or root zone storage, and, iv) groundwater storage.

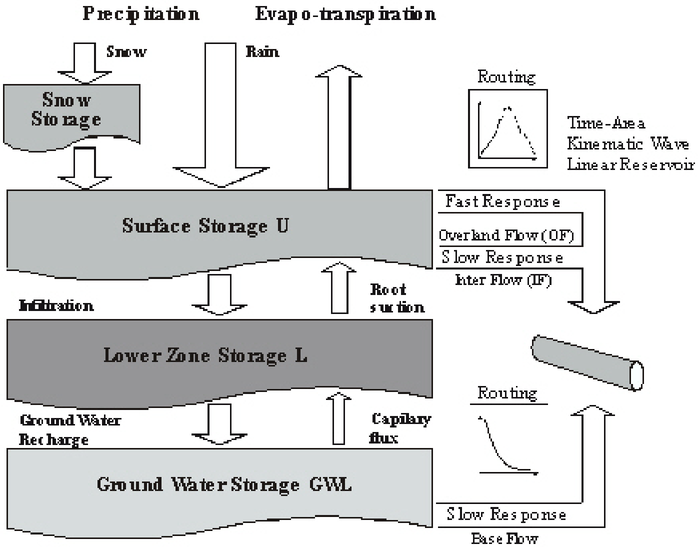


Figure 35 – Model structure of the NAM (DHI 2017c).

It should be noticed that this model also accounts the effects of man-made interventions in the hydrological cycle such as irrigation and groundwater pumping.

NAM model is characterised as having moderate input data requirements, being able to produce, based on them, catchment runoff (which is conceptually divided into overland flow, interflow and baseflow components), as well as information related with other elements of the land phase of the hydrological cycle (namely, temporal variation of the evapotranspiration, soil moisture content, groundwater recharge, groundwater levels).

4.2.2 Model parameters

The implemented conceptualisation of the physical processes treated by NAM model are presented in Figure 36. NAM is prepared, as a default, with nine parameters representing the surface zone, root zone and the groundwater storages (DHI 2017a). Following a description of the main parameters are described, based on the information provided by DHI (2017c).

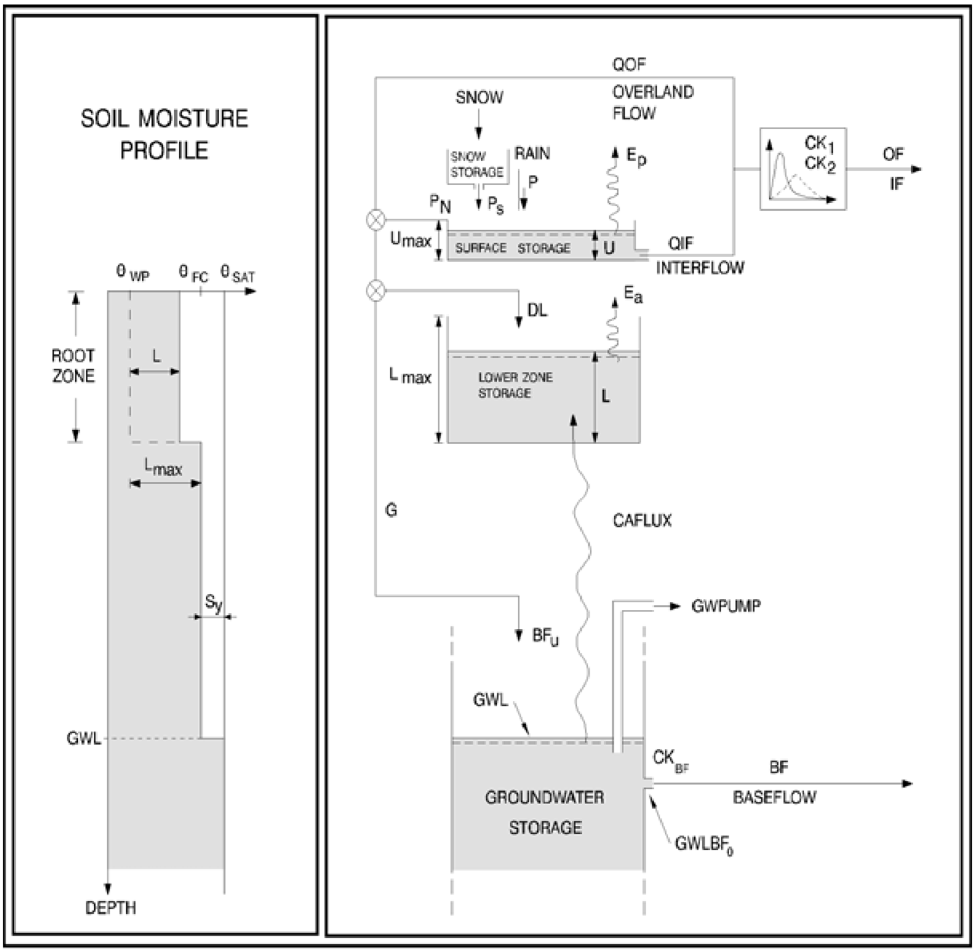


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Figure 36 – Conceptual model of NAM (DHI 2017c).

Surface storage is the amount of water in the surface (U) representing the moisture intercepted on the vegetation as well as water trapped in depressions and in the uppermost cultivated part of the ground. The value of the surface storage (U) decreases continuously through evaporative consumption, as well as, by horizontal leakage (interflow). The upper limit of the amount of water in the surface storage is the U_{max}, representing the maximum water content in the surface storage.

The lower zone or root zone is a soil layer below the surface from which the vegetation can draw water for transpiration. The soil moisture in the root zone is represented as lower zone storage (L). The upper limit of the amount of water in this zone is L_{max}. The moisture content in this zone is subject to consumptive loss from transpiration controlling the interflow, the overland flow and the amount of water that enters the groundwater storage.

Concerning the actual/real rate of evapotranspiration (E_a), it should be emphasized that this is proportional to the potential evapotranspiration (E_p) being considered to change in a linear manner with the relative soil moisture content (L/L_{max}) (Equation [1]). In fact, it is considered that, initially, the evapotranspiration demands are met at the potential rate from the surface storage. If the moisture content in the surface storage (U) is less than these requirements ($U < E_p$) the remaining fraction is assumed to be fulfilled by root activity from the lower zone storage.

$$E_a = \left(E_p - U\right)\frac{L}{L_{max}} \qquad [1]$$

When $U > U_{max}$ (i.e. when the surface storage spills), the excess of water (P_N) leads to overland flow as well as to infiltration. QOF reflects the portion of P_N that contributes to overland flow. It is considered that QOF is proportional to P_N and to linearly change with the relative soil moisture content, L/L_{max}, of the lower zone storage (Equation [2]).

$$QOF = \begin{cases} CQOF \times \dfrac{L/L_{max} - TOF}{1 - TOF} \times P_N & \text{for } L/L_{max} > TOF \\ 0 & \text{for } L/L_{max} \leq TOF \end{cases} \qquad [2]$$

$CQOF$ – overland flow runoff coefficient ($0 \leq \mathrm{CQOF} \leq 1$)

TOF – threshold value for overland flow ($0 \leq \mathrm{TOF} \leq 1$)

As referred the proportion of the excess water (P_N) that does not lead to overland flow infiltrates into the lower zone storage. A portion (ΔL, Equation [3]) of the water available for infiltration (P_N – QOF) is considered to increase the moisture content (L) in the lower zone storage. As highlighted by the DHI (2017c) the remaining amount of infiltrating moisture (G, Equation [4]) is assumed to percolate deeper and recharge the groundwater storage.

$$\Delta L = P_N - QOF - G \qquad [3]$$

$$G = \begin{cases} (P_N - QOF) \times \dfrac{L/L_{max} - TG}{1 - TG} & \text{for } L/L_{max} > TG \\ 0 & \text{for } L/L_{max} \leq TG \end{cases} \qquad [4]$$

TG – root zone threshold value for groundwater recharge ($0 \leq TG \leq 1$)

The interflow contribution is QIF (Equation [5]), considered to be proportional to U and to vary linearly with the relative moisture content of the lower zone storage.

$$QIF = \begin{cases} (CKIF)^{-1} \times \dfrac{L/L_{max} - TIF}{1 - TIF} \times U & \text{for } L/L_{max} > TIF \\ 0 & \text{for } L/L_{max} \leq TIF \end{cases} \qquad [5]$$

$CKIF$ – time constant for interflow

TIF – root zone threshold value for interflow ($0 \leq TIF \leq 1$)

It should be pointed out that, concerning the interflow and overland flow routing, the model considers that the interflow is routed over two linear reservoirs in series with equal time constant, $CK_{1,2}$ (Equation [6]). The overland flow routing is also based on the idea of linear reservoirs but with a variable time constant.

$$CK = \begin{cases} CK_{12} & \text{for } OF > OF_{min} \\ CK_{12} \times \left(\dfrac{OF}{OF_{min}}\right)^{-\beta} & \text{for } OF \leq OF_{min} \end{cases} \qquad [6]$$

Where:

OF – overland flow intensity (mm/hour)

OF_{min} – upper limit for linear routing (=0.4 mm/hour)

β =0.4

It should be noted that the baseflow, BF, from the groundwater storage is calculated as the outflow from a linear reservoir with time constant CK_{BF}.

4.2.3 General description of the calibration objectives and measures to evaluate the performance of the model

NAM model includes some default parameters (representing the surface zone, root zone and the groundwater storages), that were identified and described in the previous sub-chapter. The value of each parameter must be specified to use the model for estimating runoff values. Nevertheless, most of the parameters cannot be estimated by observation or measurement. The answer to set appropriate values for the parameters is calibration (whenever rainfall and streamflow observations are available. As referred by US Army Corps of Engineers (2016) "calibration uses observed hydrometeorological data in a systematic search for parameters that yield the best fit of the computed results to the observed runoff. This search is often referred to as optimization". In fact, it should be highlighted that initial/default estimates of the parameters are provided within NAM model, as well as, information related with the typical ranges of each parameter. With the purpose to get optimal parameter values, these parameters are fitted (automatically or manually), through the comparison between observed and simulated hydrographs. This comparison has the main goal to evaluate how well the model "fits" the real hydrologic system (US Army Corps of Engineers 2016).

For the subset of NAM parameters to be calibrated automatically the model provides default values for all the parameters, as well as, default lower and upper limits/bounds for each parameter. These values, based on physical and mathematical model constraints and experienced values for a range of different catchments, are presented on Table 14. The presented values are displayed within the software.

Table 14 – Default model parameters: default values and hypercube search space.

Parameter	Unit	Default value	Lower bound	Upper bound
U_{max}	[mm]	10	10	20
L_{max}	[mm]	100	100	300
$CQOF$	[-]	0.5	0.1	1
$CKIF$	[hours]	1000	200	1000
CK_{12}	[hours]	10	10	50
TOF	[-]	0	0	0.99
TIF	[-]	0	0	0.99
TG	[-]	0	0	0.99
CK_{BF}	[hours]	2000	1000	4000

The optimisation algorithm stops according with the so-called stopping criterion. This is the maximum number of model evaluations. As explained by DHI (2017c), “The appropriate number of model evaluations depends primarily on the number of calibration parameters and the complexity of the model (interaction between model parameters)”. Furthermore, “for a model calibration that includes all 9 parameters, a maximum number of model evaluations in the range 1000-2000 normally ensures an efficient calibration”.

It should be referred that the optimization algorithm also contains a parameter convergence criterion. In this situation, the algorithm stops if the entire population of parameter sets in an optimisation loop have converged into the same parameter values.

- Multi-objective calibration measures, optimization algorithm and the specifications for the NAM auto-calibration module

In the model calibration, it is possible to consider the following objectives: i) a good agreement between the average simulated and observed catchment runoff (i.e. a good water balance), ii) a good overall agreement of the shape of the hydrograph, iii) a good agreement of the peak flows with respect to timing, rate and volume; iv) a good agreement for low flows. It should be highlighted that peak flow events are defined as periods where the observed discharge is above a given (user-specified) threshold level. As is the case for the low flow events, defined as periods where the observed discharge is below a given (user-specified) threshold level.

Furthermore, the choice of the objective functions to include in the model simulation should reflect the objective of it.

As previously referred, the parameters can be calibrated, either automatically, either manually. Regarding the automatic calibration routine this is based on a multi-objective optimization strategy in which the four different calibration objectives, referred above, can be optimised simultaneously. As pointed out by DHI (2017c) "In automatic calibration, the calibration objectives have to be formulated as numerical goodness-of-fit measures that are optimised automatically." Furthermore, in terms of the four calibration objectives defined above "the numerical performance measures are used":

i) Overall volume error or overall water balance error – agreement between the average simulated and observed catchment runoff:

$$F_1(\theta) = \left| \frac{1}{N} \sum_{i=1}^{N} \left[Q_{obs,i} - Q_{sim,i}(\theta) \right] \right| \tag{7}$$

Where,

$Q_{obs,i}$ – is the observed discharge at time *i*

$Q_{sim,i}$ – is the simulated discharge at time *i*

θ – is the set of model parameters to be calibrated

N – is the number of time steps in the calibration period

ii) Overall root mean square error (RMSE) – overall agreement of the shape of the hydrograph:

$$F_2(\theta) = \left[\frac{1}{N} \sum_{i=1}^{N} \left[Q_{obs,i} - Q_{sim,i}(\theta) \right]^2 \right]^{1/2} \tag{8}$$

iii) Average RMSE of peak flow events – agreement of peak flows:

$$F_3(\theta) = \frac{1}{M_p} \sum_{j=1}^{M_p} \left[\frac{1}{n_j} \sum_{i=1}^{n_j} \left[Q_{obs,i} - Q_{sim,i}(\theta) \right]^2 \right]^{1/2} \tag{9}$$

Where,

M_p – is the number of peak flow events in the calibration period

n_j – is the number of time steps in event j

iv) Average RMSE of low flow events – agreement of low flows:

$$F_4(\theta) = \frac{1}{M_l}\sum_{j=1}^{M_l}\left[\frac{1}{n_j}\sum_{i=1}^{n_j}\left[Q_{obs,i} - Q_{sim,i}(\theta)\right]^2\right]^{1/2} \quad [10]$$

Where,

M_l – is the number of low flow events in the calibration period

The multi-objective problem can be framed as follows:

$$min\{F_1(\theta), F_2(\theta), F_3(\theta), F_4(\theta)\}, \theta \in \Theta \quad [11]$$

As explained in DHI (2017c), “the optimization problem is said to be constrained in the sense that θ is restricted to the feasible parameter space Θ. The parameter space is defined as a hypercube by specifying lower and upper limits on each parameter”. In general, the solution of the Equation [11], will not be, as highlighted by DHI (2017c), “a single unique set of parameters but will consist of the so-called Pareto set of solutions (non-dominated solutions), according to various trade-offs between the different objectives.”. More in-depth information about the optimization algorithm could be analysed in DHI (2017c).

- Evaluation of the performance of the model

As indicate in DHI (2017c), “Both graphical and numerical performance measures should be applied in the calibration process. The graphical evaluation includes comparison of the simulated and observed hydrograph, and comparison of the simulated and observed accumulated runoff”. There are a lot of numerical performance measures which can be used for evaluating modelling skills. These measures present several purposes, as pointed out by DHI (2017c): i) “at different stages in the modelling process performance criteria are used as an important element in the analysis of the model credibility, i.e. to evaluate if the model is sufficiently accurate for the purpose of the modelling being considered”, ii) “numerical performance measures are used in the calibration to evaluate the improvement in model performance as the parameter estimation process proceeds”. Moreover, in automatic calibration, numerical performance measures are used explicitly as objective functions to be optimised.

In order to evaluate the numerical performance of the model, some metrics are provided in the model, such as:

i) Coefficient of efficiency – Nash-Sutcliffe coefficient, NSE (Nash and Sutcliffe 1970):

$$NSE = 1 - \frac{\sum_{i=1}^{N}(OBS_i - SIM_i)^2}{\sum_{i=1}^{N}(OBS_i - \overline{OBS})^2} \quad [12]$$

ii) Index of agreement, d (Willmott et al 1985):

$$d = 1 - \frac{\sum_{i=1}^{N}(OBS_i - SIM_i)^2}{\sum_{i=1}^{N}(|SIM_i - \overline{OBS}| + |OBS_i - \overline{OBS}|)^2} \quad [13]$$

iii) Coefficient of determination, R^2:

$$R^2 = \frac{\left[\sum_{i=1}^{N}(OBS_i - \overline{OBS})(SIM_i - \overline{SIM})\right]^2}{\sum_{i=1}^{N}(OBS_i - \overline{OBS})^2 \sum_{i=1}^{N}(SIM_i - \overline{SIM})^2} \quad [14]$$

Where,

SIM_i – Simulated discharge at time *i*

OBS_i – Corresponding observed discharge

$\overline{OBS}$ – Average observed discharge

$\overline{SIM}$ – Average simulated discharge

It could be noted that all these measures are dimensionless, being useful when comparing model performance associated to different observed time series (i.e. different variables, locations, and periods).

4.3 Methodology

In this sub-chapter, firstly, a description about the main steps taken to build a model for the study area, as well as, the procedures followed for its calibration and simulation are detailed.

Subsequently, the actions that were carried out in order to assess the existing hydrological alteration at each one of the selected sites are mentioned.

4.3.1 Hydrological modelling

In order to build the model set up, as well as, to calibrate the model and obtain natural and current flows for each selected location, some procedures were pursued, being following described. As previously referred on sub-chapter 4.2, the software used for this purpose was the MIKE HYDRO River.

The procedures for the model construction and simulation were sequentially carried on, respectively, for: Alto Cávado, Alto Rabagão, Venda Nova, Salamonde, Paradela, Caniçada and Vilarinho das Furnas.

4.3.1.1 Data inputs

In this sub-chapter the tasks performed to gather and process inputs, to be used in the model, are described. Regarding the time series information (evapotranspiration, rainfall and flows) it should be noted that this information was gathered at a daily time step, since daily information is required for the calculation of the hydrological metrics selected in this study, which enable a more detailed description of the variability in flow regimes, that is important for ecosystem functioning. It should be highlighted that the selected period of analysis was October 1980 to September 2018.

A. Digital Elevation Model (DEM), Geospatial Data and catchment delineation

The Digital Elevation Model (DEM) has a resolution of 25 meters, being provided by EDP-Produção in txt file. ArcMap 10.3.1 was used to convert this file to ESRI ASCII, which could be introduced in the model. Furthermore, procedures were developed in ArcMap to process and convert the information for the same coordinate system used for all geographic information handle in this study (i.e. ETRS_1989_Portugal_TM06). Moreover, it should be highlighted that, when necessary, the acquired geospatial data information was downloaded at SNIAmb (Sistema Nacional de Informação de Ambiente), which is an information system at national level, of the Portuguese Environmental Agency (Agência Portuguesa do Ambiente – APA).

For catchment delineation it was chosen to apply the procedures reported in Merwade (2012a and 2012b). The catchments were delineated for each one of the: selected sites within this study, the dams and some weirs included in the hydroelectric system of Cávado-Ragabão-Homem. It should be pointed out that after this process, through the overlapping of the shapefiles (the one corresponding with the obtained catchments and the one related with the location of the storage reservoirs included in the Cávado River Basin – and downloaded in the SNIAmb) it was possible to perceive the need for some adjustments in the delineated catchments, and consequently, in the

DEM. This was performed using ArcMap. SNIAmb provides geographical information (in shapefiles) being a structuring project at national level, of the *Agência Portuguesa do Ambiente* (APA – the Portuguese Environmental Agency), and a benchmark in supporting the development and evaluation of environmental policies.

B. Reference/Potential evapotranspiration series

Firstly, in order to get reference evapotranspiration for the study area, the National Water Information System (*Sistema Nacional de Informação de Recursos Hídricos, SNIRH*) was accessed. It was possible to perceive that the information available is very scarce, even for monthly evapotranspiration. Based on this, two decisions were considered: i) to use, monthly evapotranspiration (instead of daily) and ii) to estimate reference evapotranspiration using a method based on air temperature records (with more existing records in the SNIRH when compared with reference evapotranspiration). To calculate monthly reference evapotranspiration, the Thornthwaite method was used (Thornthwaite 1948, Hipólito and Vaz 2012). This method is calculated based on the air temperature and the number of hours with sun (which is dependent of the location, i.e. the latitude). The steps required for its application are later described, being essential the obtention of air monthly temperature records.

Through the analysis of air monthly temperature records measured by the meteorological stations available in the SNIRH, as previously referred, it was possible to select fifteen stations with relevance for the study (stations with air monthly temperature records in the north region, at north of Douro River) (Figure 37).

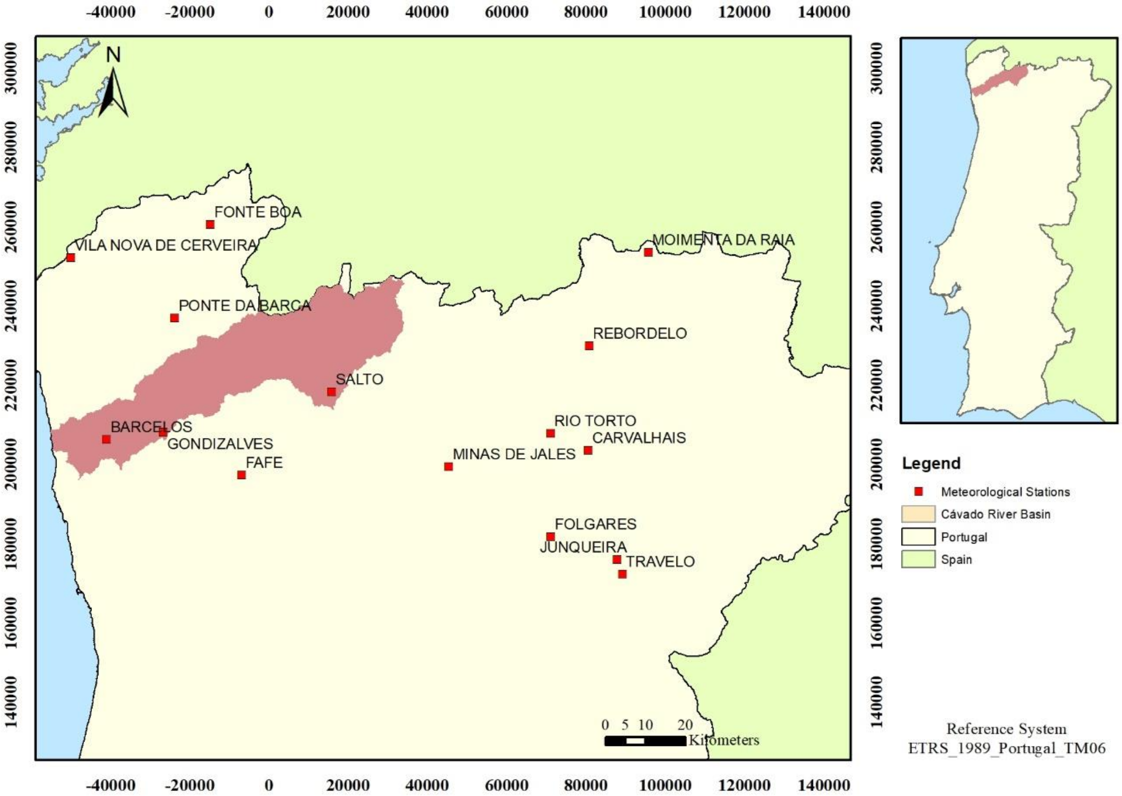


Figure 37 – Relevant meteorological stations with monthly air temperature records.

For each one of these stations: i) the number of monthly records, for each year (in order to identify those stations with temperature values comprising a full year), as well as, ii) the percentage of monthly values available since the start (October) of the water year 1980/81 were calculated. It was considered that the selection of those stations whose percentage of existing air temperature data (since October 1980 until the date of the analysis by that time, June 2018) were above 45% would be acceptable: Barcelos, Folgares, Gondizalves, Minas de Jales, Moimenta da Raia, Ponte da Barca e Rio Torto. For each station, mean, minimum and maximum temperature values were calculated for the period referred. This, as well as the distance between the meteorological stations were considered as relevant information to form groups of stations, that will used as a basis to fill the existent gaps. Based on this, Moimenta da Raia was removed from the study and two groups of stations were formed (mainly based on the distance between them). The linear regressions were established between the stations of each group, considering only the values of a given month/year that had values for the two stations under analysis. Table 15 presents the formed groups, as well as, the linear regressions obtained for the meteorological stations. Table 16, presents some characteristics of the meteorological stations.

Table 15 – Linear regression obtained for the meteorological stations.

Group	Station (x)	Station (y)	Linear regression	R^2
1	Barcelos	Gondizalves	T_y=1.0473 T_x -0.6529	0.9896
		Ponte da Barca	T_y =1.125 T_x -1.8124	0.977
	Gondizalves	Ponte da Barca	T_y =1.0661 T_x -1.0349	0.975
2	Minas de Jales	Folgares	T_y =1.0671 T_x +0.6144	0.9682
		Rio Torto	T_y =1.0865 T_x +1.7417	0.9712
	Folgares	Rio Torto	T_y =1.0159 T_x +1.3291	0.9680

Table 16 – Information related with those selected meteorological stations, for temperature calculations.

Station	Altitude (m)	Latitude (ºN)	Longitude (ºW)	District	Municipality
Barcelos	36	41.526	-8.624	Braga	Barcelos
Folgares	739	41.303	-7.283	Bragança	Vila Flor
Gondizalves	90	41.543	-8.454	Braga	Braga
Minas de Jales	853	41.464	-7.590	Vila Real	Vila Pouca de Aguiar
Ponte da Barca	39	41.803	-8.420	Viana do Castelo	Ponte da Barca
Rio Torto	322	41.538	-7.281	Vila Real	Valpaços

The process to fill the gaps, using the above referred regressions, was conducted starting with the stations of Barcelos and Minas de Jales (which are the stations with more information). To do this, some criteria have been established:

- If there was no information for Barcelos, the data were filled out based on the relationship between this station and Gondizalves. If this station also did not have data, the relation between Barcelos and Ponte da Barca was used. In the situation where Ponte da Barca also did not have information, another procedure was performed (which will be explained later);
- If there was no information for Minas de Jales, the data were filled out based on the relationship between this station and Rio Torto. If this station also did not have data, the relation between Minas de Jales and Folgares was used. In the situation where

Folgares also did not have information, another procedure was performed (which will be explained later);

To fill out the existing monthly air temperature records in the other stations, the linear regressions (Table 15) were used as referred: i) for Gondizalves station, first, based on the relation between Gondizalves – Barcelos and Gondizalves – Ponte da Barca, ii) for Ponte da Barca station, first, based on the relation between Ponte da Barca – Barcelos and Ponte da Barca – Gondizalves, iii) for Folgares station, first, based on the relation between Folgares – Minas de Jales and Folgares – Rio Torto, iv) for Rio Torto station, first, based on the relation between Rio Torto – Minas de Jales and Rio Torto – Folgares. Nevertheless, since there were still a significant number of missing data, a station from each of the groups formed was selected in order to establish relationships between them. For the first group, the Barcelos station was selected, and for the second group, the Minas de Jales station. The reason for these selections, were the higher values of R^2 obtained for the regressions in which these stations are included. Besides, the relationship between Barcelos (which is also located inside the Cávado River Basin) with any of the stations of the second group, revealed higher values of R^2. For similar reasons, as well as due to the existence of more information, Minas de Jales was selected as representing the second group. Based on this the relation between these two stations were assessed (Table 17) and some missing values filled out.

Table 17 – Linear regression between Minas de Jales and Barcelos.

Station (x)	**Station (y)**	**Linear regression**	**R^2**
Minas de Jales	Barcelos	$T_y = 0.745\ T_x + 6.0737$	0.9616

After this, however, there were still periods for which there was no information in any of the stations, hence the later regressions and procedures could not be used. For these situations, it was decided to fill these gaps through the mean monthly temperature values existing in each station.

All this process resulted in a set of monthly mean air temperatures for the six selected meteorological stations ranging the period of October 1980 to September 2018. With these, through the application of the Thornthwaite method, monthly potential evapotranspiration values were calculated for each meteorological station, in the period under analysis. This method mainly based on the values of monthly air temperatures has been widely used in regions where the mean monthly temperature is positive (Equation [15]).

$$ETP_m = \begin{cases} ETP_m = 16\, N_m \left(\dfrac{10\, \overline{T}_m}{I}\right)^a & , \overline{T}_m > 0 \\ 0 & , \overline{T}_m \leq 0 \end{cases} \qquad [15]$$

Where,

ETP_m – potential evapotranspiration in month m (mm);

N_m – an adjustment factor introduced to provide adjusted rates of potential evapotranspiration. Without the incorporation of this factor the evapotranspiration values obtained are unadjusted values for months of 30 days of 12 hours each (latitude 0 degrees). Hence, since the number of days in a month ranges from 28 to 31 and the number of hours in the day between sunrise and sunset, when evapotranspiration principally takes place, varies with the season and with latitude, it becomes necessary to reduce or increase the unadjusted rates of potential evapotranspiration by a factor that varies with the month and with the latitude (consequently, with the duration of sunlight). This adjustment factor must be the appropriate one for the latitude of the station. This factor is calculated considering the number of days in the month (D_m) and the daily mean possible duration of sunlight (hours) in that month (H_{0m}). The N_m adjustment factor can be calculated through the Equation [16]. A table with values of H_{0m} for each month and for different latitudes is provided in the Appendix A.

$$N_m = \frac{H_{0m}}{12} \times \frac{D_m}{30} \qquad [16]$$

$\overline{T}_m$ – monthly mean air temperature in month m (ºC);

I – annual heat index. Which is calculated based on summation of the 12 monthly values, Equation [17].

$$I = \sum_{m=1}^{12} i_m \qquad [17]$$

Where,

i_m – is the monthly heat index (i_m), of each one of the months of the year, estimated through Equation [18]:

$$i_m = \left(\frac{\overline{\mathrm{T}}_{\mathrm{m}}}{5}\right)^{1,514} \qquad [18]$$

a – a coefficient that varies with the annual heat index, calculated based on Equation [19[18]:

$$a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.792 \times 10^{-2} I + 0.49239 \qquad [19]$$

Based on the above referred equations, the values of monthly potential evapotranspiration, for each meteorological station, were estimated. It should be noticed that for the estimation of H_{0m}, the latitude values for each station (Table 16) were essential. Based on them, the H_{0m} values, for each station latitude, were obtained through linear interpolations of the values available at Appendix A.

Thereafter, the evapotranspiration was calculated for the watersheds of each ecological endpoint, through the delineation of the Thiessen polygons, which enabled the estimation of the area of influence of each station (Figure 38). Based on this, monthly potential evapotranspiration was calculated for each watershed.

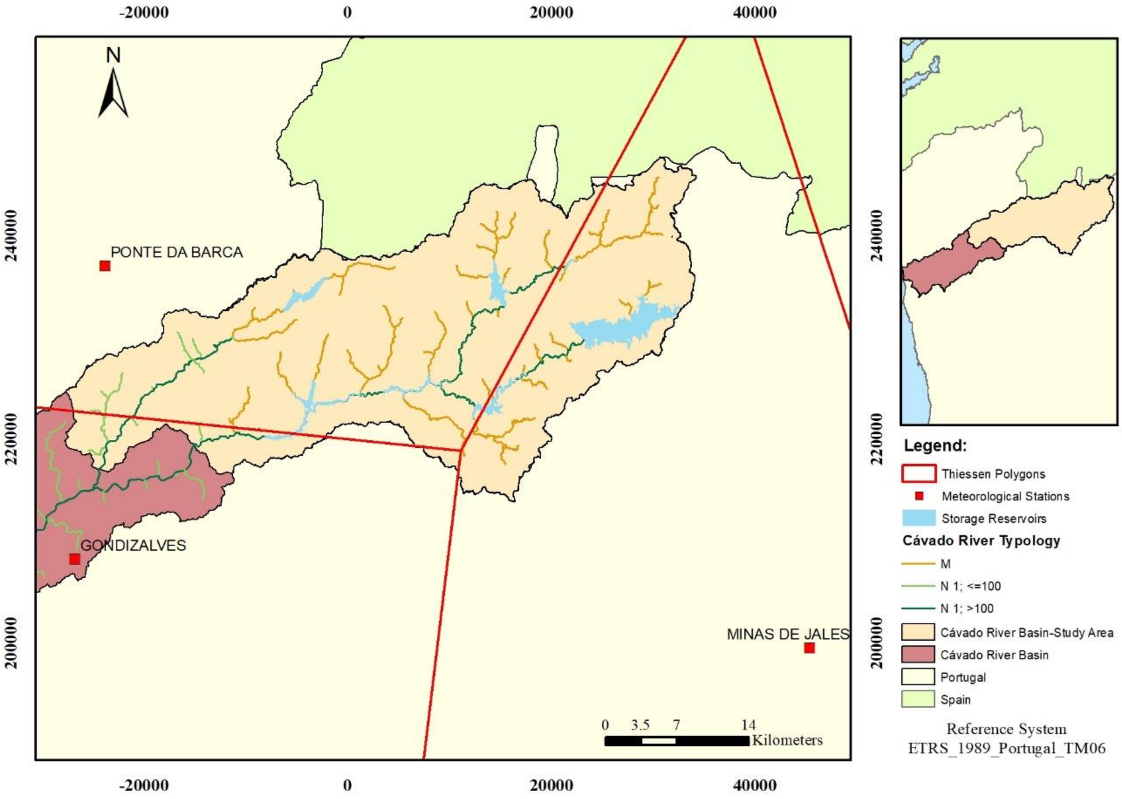


Figure 38 – Thiessen polygons of the selected meteorological stations (with monthly temperatures).

C. Rainfall/Precipitation records

In order to get precipitation records for the study area, the National Water Information System (*Sistema Nacional de Informação de Recursos Hídricos, SNIRH*) was accessed. Firstly, it was necessary to perceive which stations have influence in the Cávado River Basin. This was made through the delineation of Thiessen polygons. Through this, it was possible to perceive that 49 meteorological stations have influence in the Cávado River Basin, as represented on Figure 39. In Table 18, some information associated with the location of each meteorological station is represented.

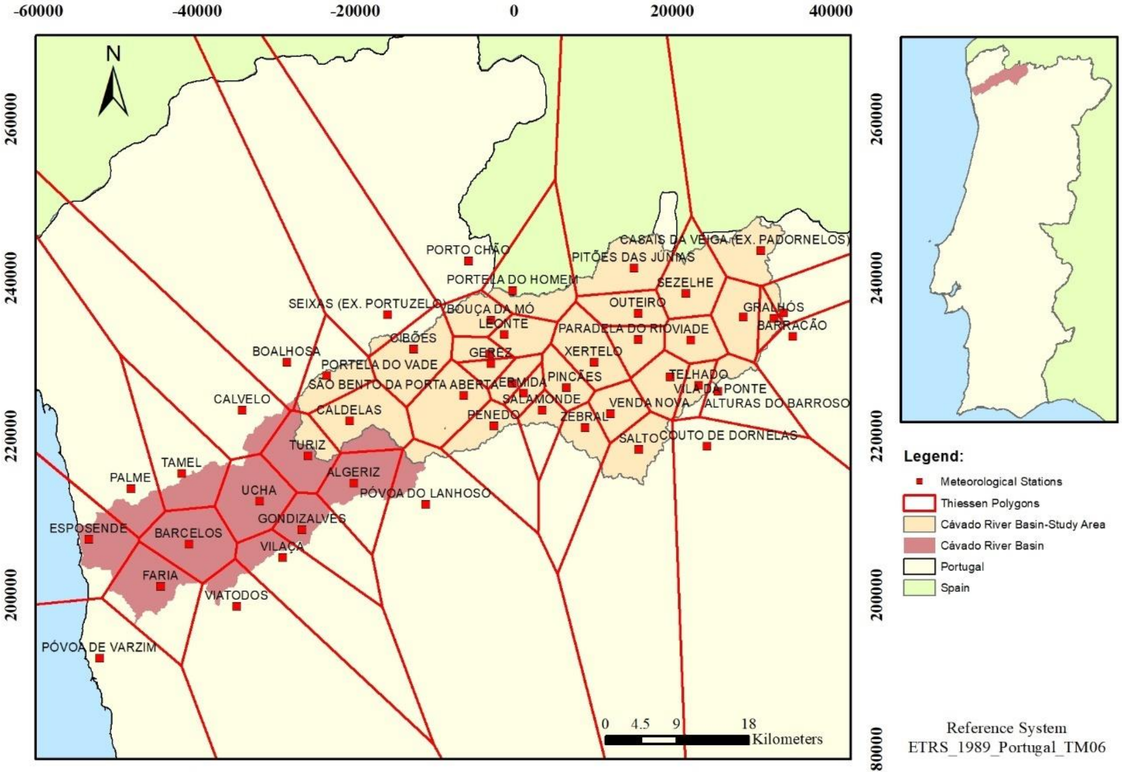


Figure 39 – Thiessen polygons of the meteorological stations with influence on the Cávado River Basin.

Table 18 – Information related with the location of the meteorological stations with influence in the Cávado River Basin.

Station	Altitude (m)	Latitude (ºN)	Longitude (ºW)	District	Municipality
Algeriz	146	41.596	-8.376	Braga	Braga
Alturas do Barroso	1068	41.700	-7.824	Vila Real	Boticas
Barcelos	36	41.526	-8.624	Braga	Barcelos
Barracão	801	41.763	-7.710	Vila Real	Montalegre
Boalhosa	567	41.734	-8.477	Viana do Castelo	Ponte de Lima
Bouça da Mó	551	41.782	-8.168	Braga	Terras de Bouro
Caldelas	93	41.667	-8.382	Braga	Amares
Calvelo	179	41.679	-8.545	Viana do Castelo	Ponte de Lima
Casais da Veiga (ex. Padornelos)	1065	41.860	-7.757	Vila Real	Montalegre
Cibões	531	41.749	-8.285	Braga	Terras de Bouro
Couto de Dornelas	679	41.638	-7.840	Vila Real	Boticas
Covide (ex. Junceda)	895	41.743	-8.170	Braga	Terras de Bouro
Ermida	337	41.699	-8.118	Braga	Terras de Bouro
Esposende	6	41.531	-8.776	Braga	Esposende
Faria	65	41.478	-8.667	Braga	Barcelos
Firvidas	935	41.789	-7.723	Vila Real	Montalegre

Gerez	664	41.732	-8.168	Braga	Terras de Bouro
Gondizalves	90	41.543	-8.454	Braga	Braga
Gralhós	910	41.784	-7.738	Vila Real	Montalegre
Leonte	874	41.765	-8.147	Braga	Terras de Bouro
Outeiro	845	41.790	-7.944	Vila Real	Montalegre
Palme	99	41.589	-8.713	Braga	Barcelos
Paradela do Rio	834	41.760	-7.945	Vila Real	Montalegre
Pedra Bela	714	41.710	-8.135	Braga	Terras de Bouro
Penedo	536	41.661	-8.163	Braga	Vieira do Minho
Pincães	479	41.705	-8.053	Vila Real	Montalegre
Pitões das Júnias	1077	41.840	-7.950	Vila Real	Montalegre
Portela do Homem	844	41.815	-8.135	Braga	Terras de Bouro
Portela do Vade	219	41.718	-8.417	Braga	Vila Verde
Porto Chão	798	41.849	-8.201	Viana do Castelo	Ponte da Barca
Póvoa de Varzim	18	41.396	-8.758	Porto	Póvoa de Varzim
Póvoa do Lanhoso	173	41.573	-8.266	Braga	Póvoa de Lanhoso
Salamonde	600	41.679	-8.09	Braga	Vieira do Minho
Salto	837	41.635	-7.943	Vila Real	Montalegre

São Bento da Porta Aberta	357	41.696	-8.209	Braga	Terras de Bouro
São Vicente de Chã	901	41.785	-7.784	Vila Real	Montalegre
Seixas (ex. Portuzelo)	364	41.788	-8.325	Viana do Castelo	Ponte da Barca
Sezelhe	969	41.812	-7.872	Vila Real	Montalegre
Tamel	164	41.606	-8.636	Braga	Barcelos
Telhado	1042	41.707	-7.853	Vila Real	Montalegre
Turiz	70	41.627	-8.445	Braga	Vila Verde
Ucha	52	41.575	-8.518	Braga	Barcelos
Venda Nova	707	41.675	-7.986	Braga	Vieira do Minho
Viade	919	41.759	-7.864	Vila Real	Montalegre
Viatodos	83	41.456	-8.551	Braga	Barcelos
Vila da Ponte	745	41.717	-7.896	Vila Real	Montalegre
Vilaça	140	41.512	-8.483	Braga	Braga
Xertelo	711	41.734	-8.011	Vila Real	Montalegre
Zebral	857	41.660	-8.025	Braga	Vieira do Minho

Following the analysis of the SNIRH records it was possible to perceive a substantial gaps of data for the period in analysis (October 1980 to September 2018). In this context, the search for other daily precipitation databases was essential. In fact, the analysis of two databases were, firstly, added to this study too. One of the databases, referred as Dataset PT02, was developed by the Portuguese Meteorological Service (*Instituto de Meteorologia, IM*), which is freely available by the Portuguese Institute of the Sea and Atmosphere (*Instituto Português do Mar e da Atmosfera, IPMA*), only for research and learning purposes. According with IPMA, “The dataset PT02 is a new high resolution (0.2°×0.2°) daily gridded precipitation dataset over mainland

Portugal. This dataset spans the period from 1950 to 2003 and is based on 806 stations, 188 meteorological stations from Portuguese Meteorological Service (IM) and 618 rain gauges from the National Water Institute (INAG). Most of these (726) stations have at least 10 years of data". The spatial distribution of the stations is presented on Figure 40. The interpolation method applied to create the PT02 dataset was the ordinary kriging, which was compared with simpler techniques, namely, inverse distance weighting methods. A more in-depth description about this dataset is provided in Belo-Pereira et al. (2011).

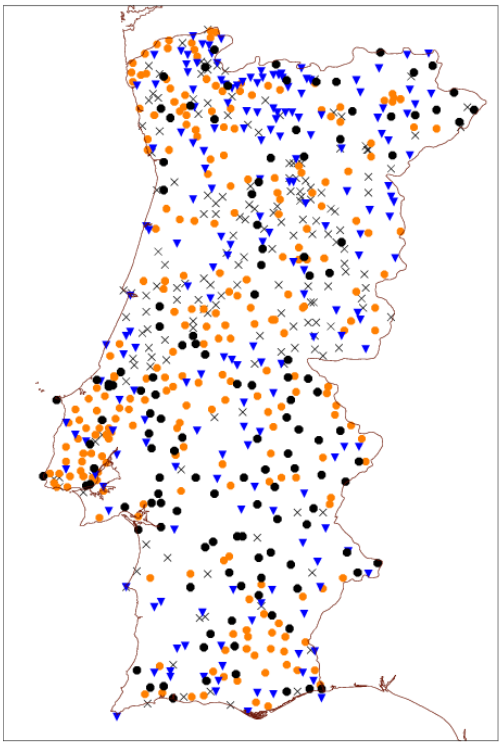


Figure 40 – Spatial distribution of the meteorological stations and rain gauges in mainland Portugal. The black circles pointed out those stations with more than fifty years of data. The blue triangles, the orange circles and the black crosses represent, respectively, those stations with information ranging: i) thirty one to fifty years, ii) twenty one to thirty years, and, iii) ten years to twenty years (IPMA 2018).

The other database, found useful for the purposes of this study, corresponds to NASA information – more specifically to the Tropical Rainfall Measuring Mission (TRMM) Level 3 Product –available to download in the Climate Data Library of the International Research Institute for Climate and Society of the Columbia University (IRI 2019). The available NASA dataset has daily precipitation information starting in the first day of March 2000 (01/03/2000), with a (0.25°×0.25°) resolution.

Having in consideration these two databases, the provided by IPMA and by the Columbia Institute (referent to NASA Products), a procedure was developed with the purpose of filling the gaps in the precipitation records of the 49 meteorological stations from SNIRH. The idea behind the procedures performed was to fill the missing values – at each meteorological station – by sequentially using information from neighbouring stations from SNIRH (local/ground information), then from IPMA (0.20°×0.20° resolution), and then from NASA (0.25°×0.25° resolution). Hence, if there was no precipitation value for a given day, of a certain meteorological station, the interpolation technique – inverse distance weighting – was applied considering the precipitation records for that day in the SNIRH neighbour stations, located at 10 km from the station to be fill out. Then, if still there was no information, the gaps were filled with information from IPMA. The idea was to fill the gaps considering information from IPMA, not farther than 15 km of the location of the SNIRH station. It should be perceived that to apply these criteria, a circle – centered in each SNIRH station – with 15 km of radius is delineated. Hence, IPMA cells are included in the calculation of the estimated precipitation of the meteorological station, only if the 15 km circle of the meteorological station intersects the center of the IPMA cell. Then, if still there was no information, the process described to use IPMA database was replicated for the utilisation of the NASA database, but in this case, it was assumed to use a 17.5 km circle.

After this, the precipitation series for each SNIRH station were completed, without any missing values, could be used to calculate daily precipitation records for each one of the watersheds selected in this study. Nevertheless, before this, within this study, an extra procedure was performed in order to perceive if the precipitation records obtained, through the process described above, are close to real/measured precipitation records. In fact, using the calibration parameters, obtained within Monteiro et al (2017), for the Alto Cávado watershed, the hydrological model was run with the new precipitation records developed. It should be highlighted that the selection of the Alto Cávado hydrological model to evaluate the precipitation records, was related with the fact that there are observed/real runoff values for this section (enabling the analysis of the effect of different precipitation records in the runoff). Hence, after the introduction of the developed precipitation records it was possible to perceive that the new estimated flow values are much smaller than the observed ones, especially after 2010. This happen because the SNIRH precipitation records for this period are mostly equal to zero. In fact, during this period SNIRH report some problems in the meteorological stations due to Portuguese economic problems. This, together with the discrepancy in the flow values obtained, bring a low confidence in the SNIRH precipitation records for that period.

Consequently, a different approach to obtain precipitation records for each studied watershed, for the study period (October 1980 to September 2018) was performed. As described in Alemi et al (in phase of submission), a comparison between SNIRH records and three different selected datasets were carried out, with the purpose to evaluate the similarity between the datasets and the available SNIRH precipitation records, providing insights about the suitability of its use. The selected datasets were the ones already described before (from IPMA and NASA), plus the dataset PERSIANN-CDR (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks – Climate Data Record) available from (the IRI Data Library https://iridl.ldeo.columbia.edu/). The PERSIANN-CDR dataset is daily gridded precipitation with 0.25°×0.25° resolution (the same resolution as the one from NASA dataset). Hence, firstly, the difference between the monthly precipitation SNIRH records (i.e., rain gauge data) and each one of the studied datasets, were investigated through the computation of some statistical parameters, such as: the correlation coefficient (r), the mean bias error (MBE), the bias and root mean square error (RMSE). Then, to minimize the obtained differences and improve the correlation among the SNIRH records and each one of the datasets, the assessment and computation of an adjustment factor, was performed, for each cell over the study region. By the referred study (Alemi et al in phase of submission), it could be perceived that the IPMA precipitation database (Dataset PT02), reveals a general strongest correlation with the SNIRH precipitation records, followed by the PERSIANN-CDR database and then, by the NASA dataset (TRMM Level 3 Product). Therefore, in this research work, to cover the whole study period, it was considered appropriate to use two periods, each with a different reference dataset. The precipitation data from the IPMA database (modified by the obtained adjustment factors, for each cell) was considered since the beginning of the study period (October 1980) until the latest day of the available information from IPMA (September 2000). For the period onward (September 2000), until the end of the period under study (September 2018), the PERSIANN-CDR (also modified by the cells adjustment factors) was used, It should be recognized, however, that NASA precipitation data was used only (in the few cases where some daily precipitation records were missing from the PERSIANN-CDR dataset).

After this process, the daily precipitation for each catchment (in total 36) was calculated through the intersection of the catchment areas and the grids of the different groups of datasets.

D. Flows records – measured and estimated

To establish a hydrologic foundation, i.e. a database with natural and modified/current flow conditions in the selected sites, an analysis of hydrological information available for the study area was, firstly, performed.

Most of the information of daily flows, related to the operation of the hydroelectric plants, was provided by EDP-Produção. This database comprises information of: i) total inflows to each dam, ii) turbined and pumped flows in each central of the hydroelectric system, iii) flood discharges, iv) environmental flows (already described in Chapter 3). It should be highlighted that, as referred by EDP, the value of flood discharges also includes the bottom discharges. Nevertheless, the release of this type of flows is rare (only occurring in order to check if the bottom discharge device is operational).

EDP also provide information related with water levels measurements on the main (seven) dams: Alto Rabagão, Venda Nova, Paradela, Salamonde, Caniçada and Vilarinho das Furnas.

Based on storage-elevation curve of each dam (made available by EDP), daily water storage volumes were calculated for each dam, enabling the evaluation of the variation of water volumes ($\pm\Delta V$) for each day.

It is important to notice that whole the information available was collected within the selected study period (01/10/1980 until 30/09/2018). Since the amount of information provided was very high (and organised differently), its use required the development of a script in the R programming language. This allowed to automatically process the large amount of data.

Also, the availability of river flows measured in stream gauge stations was analyzed. Thus, it was possible to gather some information (total inflows, and in some cases bypass flows) in some of the dams/weirs sections included in the study area: i) Alto Cávado, ii) Toco, iii) Cabreira, and, iv) Abelheira (Figure 41). EDP-Produção made available the information related to i) Alto Cávado, ii) Toco and iii) Cabreira. Regarding the information related with Abelheira this was acquired through SNIRH. It should be pointed out that the available flows datasets were not completed for the period from October 1980 to September 2018, hence these flows were estimated through modelling (thereafter described on the next section). Furthermore, there was also flow series information, in Covas stream gauge station (which has flow measurements even before the construction of Vilarinho das Furnas dam. Figure 41 presents the location of presents the location of all stream gauging stations, weirs and dams in the study area.

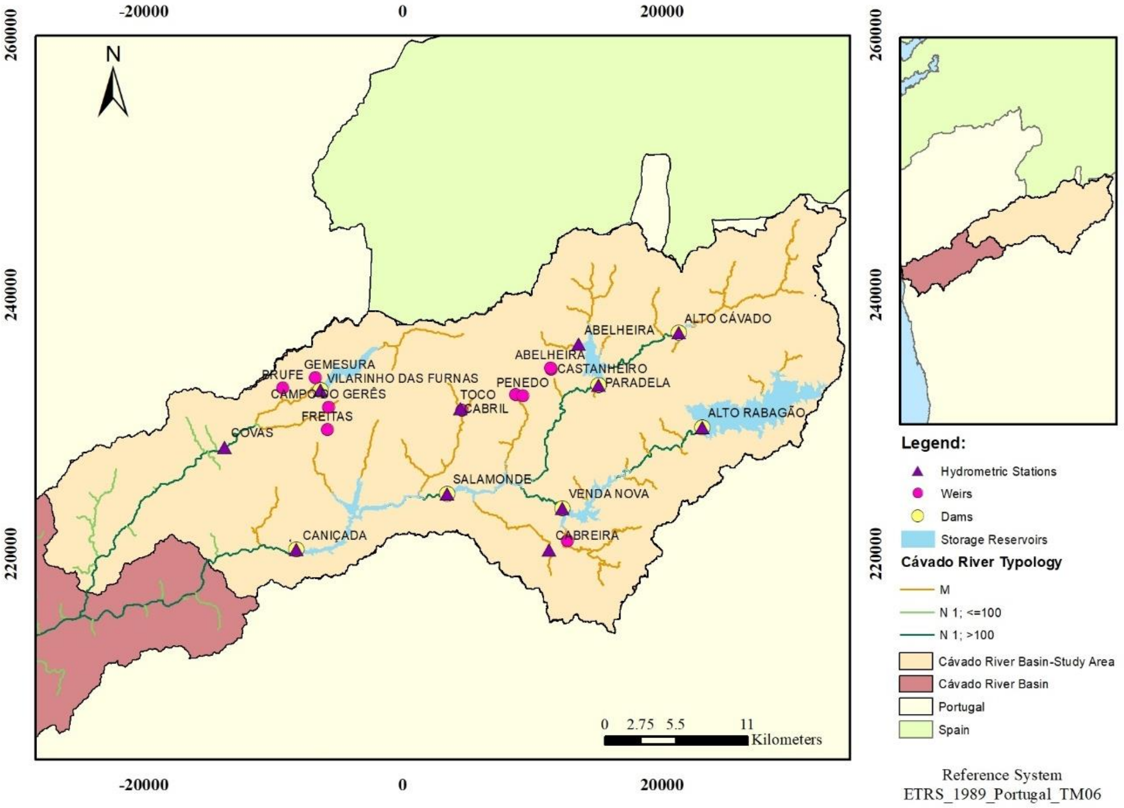


Figure 41 – Stream gauge stations in the study area.

Reconstruction of natural flows conditions in each dam

As previously referred, one of the main goals of this study is to define, for each selected site, the natural and current flow conditions. Due to the lack of natural flow data, which could be used to calibrate the model, it was decided to undertake a reconstruction of natural flow conditions based on dams' operations information. The basis to accomplish this purpose was to perform the water balance in each dam, through the Equation [20].

$$\pm \Delta Q = Q_{total\ inflows} - Q_{total\ outflows} \tag{20}$$

The Equation [20] was transposed for each one of the main dams: i) Alto Rabagão (AR) – Equation [21]; ii) Venda Nova (VN) – Equation [22]; iii) Paradela (PL) – Equation [23]; iv) Salamonde – Equation [24]; v) Caniçada – Equation [25]; and vi) Vilarinho das Furnas – Equation [26]. It should be highlighted that the presented equations only present equation terms that were directly measured or that could be justifiably estimated (considering other values measured in the system under study). Nevertheless, there are other parameters that could be incorporated in the balance, if more information was available. For instance, water evaporated on each storage reservoir, water supply consumptions, clandestine water abstractions, as well as, water losses through the soil. All these potential water volumes are included in the equations through the term Q_{other}. A general description of the Equation terms will be following provided, using as example the terms presented on Equation [21]: i) $Q_{natural\ flows\ AR}$ – natural flows in AR section; ii) $Q_{bypass\ AC \to AR}$ – bypass flows from AC dam to AR dam; iii) $Q_{pumped\ VN \to AR}$ – pumped flows from VN to AR; iv) $Q_{turbine\ AR}$ – turbine flows in the central of the AR hydroelectric system; v) $Q_{flood\ discharges\ AR}$ – flood discharges in the AR dam, v) $Q_{eflows\ AR}$ – environmental flows released in the AR, vi) $Q_{other_{AR}}$ – includes water evaporated on each storage reservoir, water supply consumptions, clandestine water abstractions, as well as, water losses through the soil (as previously referred). The meaning of some acronyms that appear in the following Equations should also be highlighted. The acronym TCPCA (in Equation [23]) is used to reflect the small set of weirs – Toco, Cabril, Penedo, Castanheiro, Abelheira – which are included in the hydroelectric system of Paradela. These weirs are interconnected providing flows (through bypass) to the Paradela dam. The acronym BG (in Equation [26]) is referred to the weirs of Brufe and Gemesura, which are included in the hydroelectric system of Vilarinho das Furnas and interconnected.

$$\begin{aligned}\pm\Delta Q_{AR} = {} & Q_{bypass\ AC\rightarrow AR} + Q_{natural\ flows\ AR} + Q_{pumped\ VN\rightarrow AR} - Q_{flood\ discharges} \\ & - Q_{turbined\ AR} - Q_{eflows\ AR} \pm Q_{other_{AR}}\end{aligned} \tag*{[21]}$$

$$\begin{aligned}\pm\Delta Q_{VN} = {} & Q_{bypass\ Cabreira\rightarrow VN} + Q_{natural\ flows\ VN} + Q_{turbined\ AR} \\ & + Q_{flood\ discharges\ AR} + Q_{eflows\ AR} + Q_{pumped\ SD\rightarrow VN} \\ & - Q_{flood\ discharges\ VN} - Q_{turbined\ VN} - Q_{eflows\ VN} \\ & - Q_{pumped\ VN\rightarrow AR} \pm Q_{other_{VN}}\end{aligned} \tag*{[22]}$$

$$\begin{aligned}\pm\Delta Q_{PL} = {} & Q_{bypass\ TCPCA\rightarrow PL} + Q_{natural\ flows\ PL} + Q_{flood\ discharges\ AC} \\ & + Q_{eflows\ AC} - Q_{flood\ discharges\ PL} - Q_{turbined\ PL} - Q_{eflows\ PL} \\ & \pm Q_{other_{PL}}\end{aligned} \tag*{[23]}$$

$$\begin{aligned}\pm\Delta Q_{SD} = {} & Q_{natural\ flows\ SD} + Q_{flood\ discharges\ PL} + Q_{turbined\ PL} + Q_{eflows\ PL} \\ & + Q_{flood\ discharges\ VN} + Q_{turbined\ VN} + Q_{eflows\ VN} \\ & + Q_{flood\ discharges\ CPCA} + Q_{flood\ discharges\ Cabreira} \\ & + Q_{pumped\ CD\rightarrow SD} - Q_{flood\ discharges\ SD} - Q_{turbined\ SD} \\ & - Q_{eflows\ SD} - Q_{pumped\ SD\rightarrow VN} \pm Q_{other_{SD}}\end{aligned} \tag*{[24]}$$

$$\begin{aligned}\pm\Delta Q_{CD} = {} & Q_{natural\ flows\ CD} + Q_{flood\ discharges\ SD} + Q_{turbined\ SD} + Q_{eflows\ SD} \\ & + Q_{flood\ discharges\ Freitas} + Q_{flood\ discharges\ Toco} + Q_{turbined\ VF} \\ & - Q_{flood\ discharges\ CD} - Q_{turbined\ CD} - Q_{eflows\ CD} \\ & - Q_{pumped\ CD\rightarrow VF} \pm Q_{other_{CD}}\end{aligned} \tag*{[25]}$$

$$\begin{aligned}\pm\Delta Q_{VF} = {} & Q_{bypass\ BG\rightarrow VF} + Q_{bypass\ Campo\ do\ Gerês\rightarrow VF} + Q_{natural\ flows\ VF} \\ & + Q_{pumped\ CD\rightarrow VF} - Q_{flood\ discharges\ VF} - Q_{turbined\ VF} \\ & - Q_{eflows\ VF} \pm Q_{other_{VF}}\end{aligned} \tag*{[26]}$$

Following, some considerations relevant to the application of the Equations will be presented.

All the terms related with $Q_{turbined}$, Q_{pumped} and Q_{eflows}, were measured (as previously referred). Notice that the term $Q_{eflows\ AC}$ is presented in the Equation [23], nevertheless this value is equal to zero for the period under study, since there are not environmental flows being released at AC dam.

Moreover, most of the terms associated with $Q_{flood\ discharges}$, were measured, with the exception of: $Q_{flood\ discharges\ AC}$, $Q_{flood\ discharges\ CPCA}$, $Q_{flood\ discharges\ Cabreira}$, and $Q_{flood\ discharges\ Freitas}$, $Q_{flood\ discharges\ Toco}$, $Q_{flood\ discharges\ BG}$, $Q_{flood\ discharges\ Campo\ do\ Gerês}$ which were estimated through some assumptions.

As regards $Q_{flood\ discharges\ AC}$ these were calculated considering:

$$Q_{flood\ discharges\ AC} = Q_{total\ inflows\ AC} - Q_{bypass\ AC\rightarrow AR} \qquad [27]$$

It should be noted, however, that since the available information for $Q_{total\ inflows\ AC}$ and $Q_{bypass\ AC\rightarrow AR}$, did not cover the whole period under study (October 1980 and September 2018), it was necessary to estimate these terms. The procedure carried out is following described. Hence, for the period without values, in order to define $Q_{flood\ discharges\ AC}$, firstly, it was necessary to estimate the total inflows (i.e. the natural flows in these cases), generated within the catchment of Alto Cávado through hydrological modelling. In the following sections, more details about the modelling and calibration process will be provided. After the estimation of $Q_{total\ inflows\ AC}$, it was necessary to estimate the maximum bypass flow (taking into consideration the characteristics of the pipeline that connects Alto Cávado to the Alto Rabagão dam). Then, the estimation of the $Q_{bypass\ AC\rightarrow AR}$ and $Q_{flood\ discharges\ AC}$ were calculated as following described.

If [28]

$$Q_{total\ inflows\ AC} \leq maximum(Q_{bypass\ AC\rightarrow AR})$$

then,

$Q_{bypass\ AC\rightarrow AR} = Q_{total\ inflows\ AC}$ and $Q_{flood\ discharges\ AC} = 0$

If not,

$$Q_{bypass\ AC\rightarrow AR} = maximum(Q_{bypass\ AC\rightarrow AR})$$

$$Q_{flood\ discharges\ AC} = Q_{total\ inflows\ AC} - Q_{bypass\ AC\rightarrow AR}$$

Where,

$maximum\left(Q_{bypass\ AC \rightarrow AR}\right) \cong 60\ m^3/s$ (maximum bypass flow value that could be deviated according to the hydraulic characteristics of the pipeline)

In relation to $Q_{flood\ discharges\ CPCA}$, a more description will be provided. The CPCA is system of the small set of weirs: Cabril, Penedo, Castanheiro, Abelheira (notice that the acronym – TCPCA – is used to include also the Toco weir, connected to this CPCA system). In terms of the flood discharges in each weir, it should be highlighted that, while Toco weir contribute with flood discharges to Caniçada dam, the other ones, expressed by the term $Q_{flood\ discharges\ CPCA}$, contribute to the existing flows in the storage reservoir of Salamonde. Since, for the small set of weirs, there are some flows measurements related with $Q_{bypass\ Toco \rightarrow Cabril}$ and some values for $Q_{bypass\ Abelheira \rightarrow Paradela}$ it was considered necessary, prior to the estimation of the flows discharged by the system, to evaluate the total inflows to the system CPCA. These total inflows were estimated through hydrological modelling of the system. After the estimation of $Q_{total\ inflows\ CPCA}$ the $Q_{flood\ discharges\ CPCA}$ where calculated by:

$$Q_{flood\ discharges\ CPCA} = Q_{bypass\ Toco \rightarrow Cabril} + Q_{total\ inflows\ CPCA} - Q_{bypass\ TCPCA \rightarrow PL} \qquad [29]$$

It should be highlighted that, due to the existence of some missing values of $Q_{bypass\ Toco \rightarrow Cabril}$, its estimation were necessary. As is the case of the flood discharged by this weir, $Q_{flood\ discharges\ Toco}$. The process to estimate these terms, when there is no information, was like the one explained for Alto Cávado. The main difference was the estimation of the maximum bypass flow, which was determined based on the estimation of the maximum bypass flow value recorded by the Toco stream gauge station, instead of through the study of the hydraulic characteristics of the pipeline. The estimation was carried out based on the following equations.

If [30]

$$Q_{total\ inflows\ Toco} \leq maximum\left(Q_{bypass\ Toco \rightarrow Cabril}\right)$$

then,

$Q_{bypass\ _{Toco\rightarrow Cabril}} = Q_{total\ inflows\ _{Toco}}$ and $Q_{flood\ discharges\ _{Toco}} = 0$

If not,

$$Q_{bypass\ _{Toco\rightarrow Cabril}} = maximum\left(Q_{bypass\ _{Toco\rightarrow Cabril}}\right)$$

$$Q_{flood\ discharges\ _{Toco}} = Q_{total\ inflows\ _{Toco}} - Q_{bypass\ _{Toco\rightarrow Cabril}}$$

Where,

$maximum\left(Q_{bypass\ _{Toco\rightarrow Cabril}}\right) = 16.5\ m^3/s$ (maximum bypass flow value recorded by the Toco stream gauge station)

It was considered that, for those days with flow values of $Q_{bypass\ _{Abelheira\rightarrow Paradela}}$, the term $Q_{bypass\ _{TCPCA\rightarrow PL}}$:

$$Q_{bypass\ _{TCPCA\rightarrow PL}} = Q_{bypass\ _{Abelheira\rightarrow Paradela}} \qquad [31]$$

If no measured values exist (for $Q_{bypass\ _{Abelheira\rightarrow Paradela}}$) than the $Q_{bypass\ _{TCPCA\rightarrow PL}}$ and the $Q_{flood\ discharges\ _{CPCA}}$ are calculated through:

If [32]

$$Q_{total\ inflows\ _{CPCA}} + Q_{bypass\ _{Toco\rightarrow Cabril}} \leq maximum\left(Q_{bypass\ _{Abelheira\rightarrow Paradela}}\right)$$

then,

$Q_{bypass\ _{TCPCA\rightarrow PL}} = Q_{total\ inflows\ _{CPCA}} + Q_{bypass\ _{Toco\rightarrow Cabril}}$ and

$$Q_{flood\ discharges\ _{CPCA}} = 0$$

If not,

$$Q_{bypass\ _{TCPCA\rightarrow PL}} = maximum\left(Q_{bypass\ _{Abelheira\rightarrow Paradela}}\right)$$

$$Q_{flood\ discharges\ _{CPCA}} = Q_{total\ inflows\ _{CPCA}} + Q_{bypass\ _{Toco\rightarrow Cabril}} - maximum\left(Q_{bypass\ _{Abelheira\rightarrow Paradela}}\right)$$

Where,

$maximum(Q_{bypass\ _{Abelheira \to Paradela}}) = 36\ m^3/s$ (maximum bypass flow value recorded by the Abelheira stream gauge station)

In terms of the flood discharges and bypass flows from Cabreira, the same approach described for the Toco gauging station was performed to estimate these terms.

Regarding the terms $Q_{bypass\ _{BG \to VF}}$ and $Q_{bypass\ _{Campo\ do\ Gerês \to VF}}$ they were also estimated, since they are not measured. For this, firstly, the total inflows generated within the catchment of Brufe, Gemesura and Campo Gerês were estimated through hydrological modelling (more details about the modelling process will be provided). Hence, after the estimation of $Q_{total\ inflows\ _{BG}}$ and $Q_{total\ inflows\ _{Campo\ do\ Gerês}}$, the bypass and flood discharges were calculated as following described.

If [*33*]

$$Q_{total\ inflows\ _{BG}} \leq maximum(Q_{bypass\ _{BG \to VF}})$$

then,

$Q_{bypass\ _{BG \to VF}} = Q_{total\ inflows\ _{BG}}$ and $Q_{flood\ discharges\ _{BG}} = 0$

If not,

$$Q_{bypass\ _{BG \to VF}} = maximum(Q_{bypass\ _{BG \to VF}})$$

$$Q_{flood\ discharges\ _{BG}} = Q_{total\ inflows\ _{BG}} - maximum(Q_{bypass\ _{BG \to VF}})$$

Where,

$maximum(Q_{bypass\ _{GB \to VF}}) = 14\ m^3/s$ (maximum bypass flow value that could be deviated according to the characteristics of the pipelines of Brufe and Gemesura, provided by EDP)

For the estimation of the parameters for the weir of Campo do Gerês the following process was used.

If [*34*]

$$Q_{total\,inflows\ _{Campo\ do\ Gerês}} \leq maximum\left(Q_{bypass\ _{Campo\ do\ Gerês \to VF}}\right)$$

then,

$$Q_{bypass\ _{Campo\ do\ Gerês \to VF}} = Q_{total\,inflows\ _{Campo\ do\ Gerês}} \text{ and}$$

$$Q_{flood\ discharges\ _{Campo\ do\ Gerês}} = 0$$

If not,

$$Q_{bypass\ _{Campo\ do\ Gerês \to VF}} = maximum\left(Q_{bypass\ _{Campo\ do\ Gerês \to VF}}\right)$$

$$\begin{aligned} Q_{flood\ discharges\ _{Campo\ do\ Gerês}} \\ &= Q_{total\,inflows\ _{Campo\ do\ Gerês}} \\ &- maximum\left(Q_{bypass\ _{Campo\ do\ Gerês \to VF}}\right) \end{aligned}$$

Where,

$maximum\left(Q_{bypass\ _{Campo\ do\ Gerês \to VF}}\right) = 12\ m^3/s$ (maximum bypass flow value that could be deviated according to the characteristics of the pipelines of Campo do Gerês, provided by EDP)

Finally, in terms of the $Q_{flood\ discharges\ _{Freitas}}$ since any type of information was available, and also due to its characteristics, the evaluation was carried out as if this weir had no effect on flows.

After this process the only terms that were missing were the ones referred as $Q_{natural\,flows}$ and Q_{other}. It should be emphasized that concerning the terms presented as $Q_{natural\,flows}$ these represent the natural flows (i.e., the flow generated due to the precipitation and the feedback between it and the water cycle components).

Firstly, the $Q_{natural\,flows}$ were estimated based on the Equations [21] to [26] as if the Q_{other} are not included on those Equations. If the $Q_{natural\,flows}$ obtained are smaller than 0, then the value estimated for the Q_{other} term is the modulus of the negative number obtained for the $Q_{natural\,flows}$. However, in this study, it was considered relevant to define a limit (maximum allowable) value for term Q_{other} , which would help in the detection of possible major errors in the base data. This means that if the estimation of Q_{other} , is higher than the maximum allowable value considered acceptable, then an evaluation and revision of the measured water levels (and consequently the variation of water volumes in each dam) was carried out. Before a demonstration of one of the main examples, of the application of assumptions and calculations referred, it should be highlighted that the maximum Q_{other} assumed acceptable for each dam was 30% of the maximum flow value that can be discharged by the bottom discharge. These values are presented at Table 19.

Table 19 – Maximum flow value assumed acceptable for the Q_{other} .

Dams	**Maximum assumed acceptable value for the Q_{other} m^3/s**
Alto Rabagão	8.1
Venda Nova	108.0
Alto Cávado	42.60
Paradela	54.0
Salamonde	19.50
Caniçada	39.0
Vilarinho das Furnas	40.5

One of the main examples of the process for each day could be highlighted. Therefore, for the day 31/07/81, the Equation [21] was applied in order to calculate the $Q_{natural\,flows\,AR}$. The procedures were carried out as described:

$$\pm \Delta Q_{AR} = Q_{bypass\,AC\rightarrow AR} + Q_{natural\,flows\,AR} + Q_{pumped\,VN\rightarrow AR} - Q_{flood\,discharges\,AR} - Q_{turbinated\,AR} - Q_{eflows\,AR} \pm Q_{other_{AR}} \quad [21]$$

$$\Leftrightarrow$$

<u>1st</u>

$$\Leftrightarrow -681.86 = 0 + Q_{natural\,flows\,AR} + 7.92 - 0 - 3.35 - 0 + 0 \Leftrightarrow$$

$$\Leftrightarrow Q_{natural\ flows\ AR} = -686.43\ m^3/s$$ KO

$$Q_{other_{AR}} = |Q_{natural\ flows\ AR}| \Leftrightarrow Q_{other_{AR}} = 686.43\ m^3/s$$

Since,

$$686.43\ m^3/s\,(Q_{other_{AR}}) \gg 8.1\,m^3/s\,(maximum\ value\ of\ Q_{other_{AR}})$$ KO

Because of this, as explained before, it was considered that a mistake might be occurred by the time the water level was registered. Hence, through iteration of the values the water levels were corrected, as well as, the associated $\pm \Delta Q_{AR}$. As can be noticed (Table 20), the correction of the water level value in the day 31/07/81 influences the value of the consecutive day.

Table 20 – Example of correction.

	Original		**Used**	
Date	$Water\ level_{AR}$	ΔQ_{AR}	$Water\ level_{AR}$	ΔQ_{AR}
30/07/81	876.92	-7.24	876.92	-7.24
31/07/81	873.93	-681.86	**876.93**	**2.41**
01/08/81	876.97	693.93	876.97	**9.66**

<u>2nd</u>

$$\Leftrightarrow 2.41 = 0 + Q_{natural\ flows\ AR} + 7.92 - 0 - 3.35 - 0 + 0 \Leftrightarrow$$

$$\Leftrightarrow Q_{natural\ flows\ AR} = -2.16\ m^3/s$$ KO

$$Q_{other_{AR}} = |Q_{natural\ flows\ AR}| \Leftrightarrow Q_{other_{AR}} = 2.16\ m^3/s$$

Since,

$$2.16\ m^3/s\left(Q_{other_{AR}}\right) < 8.1\,m^3/s\left(maximum\ value\ of\ Q_{other_{AR}}\right)$$ OK

Then,

$$Q_{natural\ flows\ AR} = 0\,m^3/s$$ and $$Q_{other_{AR}} = 2.16\,m^3/s$$

4.3.1.2 Model calibration

As previously described, there are 9 parameters, as default, for the calibration of the NAM model. In this study, these parameters were calibrated based on an automatic optimization routine, available within MIKE HYDRO River/NAM, with the purpose to get optimal parameter values, through the comparison between observed/reconstructed and simulated hydrographs.

As previously mentioned, the procedures for the hydrological modelling were sequentially carried on, respectively, considering the hydroelectric systems of: Alto Rabagão (in which Alto Cávado is included), Venda Nova, Salamonde, Paradela, Caniçada and Vilarinho das Furnas.

Furthermore, it should be also noted that the calibration periods selected were at least 3 years, and, at most, 6 years. (Table 27).

Table 21 – Period of calibration of each calibrated section.

Sections	Period of calibration
Alto Cávado	01/10/1983-01/10/1988
Alto Rabagão	01/10/1987-01/10/1990
Venda Nova	01/10/1987-01/10/1991
Salamonde	01/10/1988-01/10/1991
Paradela	01/10/1997-30/09/2000
Caniçada	01/10/1990-01/10/1994
Vilarinho das Furnas	01/10/1997-01/10/2000
Toco	01/11/1997-01/11/2000
Covas	01/10/1967-30/09/1970
Cabreira	01/10/1987-01/10/1992

Due to the objectives of the present study, the selection of the four calibration objectives, referred in the sub-chapter 4.2.3 were considered relevant for all the calibrated catchments.

In terms of the evaluation of the model performance, both graphical and numerical performance measures were applied in the calibration process. The numerical performance of the model was assessed through the: i) Nash-Sutcliffe coefficient (Equation [12]), ii) index of agreement (Equation [13]), and iii) coefficient of determination (Equation [14]). It should be highlighted that, to assess the performance of the model, within the objectives of this study, the Nash-Sutcliffe coefficient was considered as the one with greater importance in the analysis and evaluation of performance. That followed by the coefficient of determination, and last, by the index of agreement.

In the literature, there are several classifications (for each one of the selected performance measures) to help in the process of evaluating the performance of the models. Table 23 presents the classification defined: i) for the Nash-Sutcliffe coefficient (by Molnar, 2011), ii) for the coefficient of determination (by Moussa et al., 2007), and for iii) for the index of agreement (by Moriasi et al. 2015). These classifications were used within this study to evaluate the performance of the model. The choice of Molnar (2011) and Moussa et al. (2007) was made since they are considered the most appropriate ones due to the high complexity of the system under study. In fact, within the work developed by Moriasi et al. (2015), classification ranges are presented for all the coefficients selected for assessing the performance of the model developed in this study. However, it should be emphasized that, the Moriasi et al. (2015) rating scale could lead to worse evaluations of the model's performance when compared with the one provided by Molnar (2011) and Moussa et al. (2007). This happens because the former presents a much severe classification range.

Table 22 – Classification of the selected evaluation measures to assess the goodness-of-fit of the model.

Performance evaluation criteria	**Nash and Sutcliffe (NSE)**	**Coefficient of Determination (R^2)**	**Index of Agreement (d)**
Excellent	$NSE > 0.80$	**-**	**-**
Very good	$0.60 < NSE \leq 0.80$	$R^2 > 0.90$	$d > 0.90$
Good	$0.40 < NSE \leq 0.60$	$0.72 < R^2 \leq 0.90$	$0.85 < d \leq 0.90$
Satisfactory	$0.20 < NSE \leq 0.40$	$0.56 < R^2 \leq 0.72$	$0.75 < d \leq 0.85$
Not satisfactory	$NSE \leq 0.20$	$R^2 \leq 0.56$	$d \leq 0.75$

Alto Rabagão (in which Alto Cávado is included) and Venda Nova

The first calibration procedure was performed in the catchment of Alto Cávado. As previously referred, in the Alto Cávado dam there is a stream gauge measuring the natural flows, which were used for calibration of this watershed. Firstly, the process of calibration was applied through the selection of the four previously referred objective functions. As regards with the objective functions related with the peak and low flows, the introduction of a threshold level was used. For the assessment of these limits, peak and low flow values were iteratively placed to evaluate the effect into the Nash- Sutcliffe coefficient. From a certain limit value, it was found that the obtained coefficients instead of increasing (showing a better performance of the model) started to decrease. Hence, this limit value was selected to carry out the calibration process of the Alto Cávado watershed.

Then, a similar approach was applied for the Alto Rabagão catchment, using the reconstructed natural flows described in sub-chapter 4.3.1.1 (in section D). Nevertheless, in this case, in order to establish the peak and low flow limit value more quickly, it was decided to start the calibrations with a starting value, obtained based on the frequency distribution of the natural flows for Alto Rabagão section. The starting value selected, i.e. the threshold of the peak flows, was the one corresponding to the 90% of the cumulative frequency, while for the low flows were 30%. Besides to this, a comparative analysis of this value was made with the one obtained iteratively, having been verified that both were of the same order of magnitude. Thus, it was considered convenient to evaluate the peak and low flows threshold for the remaining dams, considering the frequency distribution.

The procedure implemented for Venda Nova calibration, was very similar to the one specified for the Alto Rabagão.

Salamonde, Paradela and Caniçada

The calibration of Salamonde was very similar to the one performed in Alto Rabagão and Venda Nova. The calibration was performed based on the reconstructed flows at Salamonde section (Equation [24]), although in a first step, the term $Q_{flood\ discharges_{CPCA}}$ was not considered. In fact, after the evaluation of the flood discharges it was possible to perceive that floods discharges in this system barely happen throughout the period under study. Hence, after the calibration of Salamonde, based on the referred assumption, the calibration parameters were used to simulate the $Q_{natural\ flows_{CPCA}}$ and, consequently, the $Q_{by-pass\ flows_{CPCA}}$ and

$Q_{flood\ discharges_{CPCA}}$. With the modification of these values, the calibration in Salamonde was repeated. In fact, this process was repeated iteratively until the calibration parameters are similar.

The methods performed for the calibration of Paradela and Caniçada were very similar to the ones applied for Salamonde.

Vilarinho das Furnas

As previously referred, downstream Vilarinho das Furnas dam, there was a stream gauge station measuring flow values before the construction of this dam. Therefore, firstly, a model was constructed and calibrated for the section of Covas. Since the catchments of Brufe, Gemesura and Campo do Gerês are included in the catchment of Covas, it was considered, at first, that the calibration parameters of these watersheds are the same to the ones obtained in Covas. This helped the estimation of natural flows in the section of these weirs (Brufe, Gemesura, Campo do Gerês), as well as the bypass and floods discharges. As for the case of the CPCA system, this process was repeated until calibration parameters were similar in VF and the other systems.

4.3.1.3 Model simulation

After the calibration procedures the model was run to obtain natural flows and modified flows. The simulations were conducted for: i) a simulation period ranging from the 1st of October 1980 to the 30th of September of 2018, and ii) a daily time step length (as previously referred).

Due to the inexistence and unfeasibility to reconstruct/estimate flows in some sections over the study area (and consequently, the inability to calibrate the model at these strategic sites), some assumptions were necessary, in order to obtain natural and modified flows for those sections. For this purpose, it was considered relevant and essential to simulate flows over the catchments of these sites using the model parameters obtained through the calibration of nearby catchments considered before (Table 21). Table 23 presents the interconnections between calibrated and simulated catchments used. It should be emphasized that the association of each site, to one of the catchments calibrated (and consequently to the model parameters), was performed considering the location of each site.

Table 23 – Relationships/interconnection between calibrated and simulated catchments used for model simulation.

Calibrated catchments	**Simulated catchments**	**Location of the simulated catchments in relation to calibrated catchments**
Catchments whose calibration parameters were also used for hydrologic simulations of other (nearby) catchments	Nearby Catchments	
AC	AC1C	Upstream
	AC2C	
	AC	
AR	AR	
VN	AR1	
	AR2	
	VN	
Cabreira	Cabreira	
PL	AC1C	
	AC2C	
	AC3	
	PL	
SD	Cabril	
	Penedo	
	Castanheiro	
	Abelheira	
	PL2	
	PL3	
	VN1	
	SD	
Toco	Toco (*)	
CD	Toco	
	SD1	
	Freitas	
	CD	
	CD1	Downstream
	CD2	
	CD3	
VF	VF	
Covas	Brufe	Upstream
	Gemesura	
	Campo do Gerês	
	VF1	
	VF2	
	VF2b	Downstream
	VF3	
	VF3b	

(*) It should be noted that even though Toco catchment was calibrated using its values, the performance of the model was not satisfactory, for that reason, in order to obtain simulated flows the model was run using the calibration parameters of CD.

4.3.2 Hydrologic alteration

Firstly, it was chosen to evaluate the existing hydrological alteration considering the hydrological metrics referred as ecologically relevant (chapter 2). That is, the flow metrics – usually calculated using the Indicators of Hydrologic Alteration (IHA) tool – reflecting the main components of the flow regime (Richter et al. 1996; Poff et al. 1997): i) magnitude, ii) frequency, iii) duration, iv) timing, and v) rate of change. However, another (more global) approach was chosen, as the high quantity and variability of results obtained makes their transposition into feasible environmental flows difficult to implement. In addition, usually, in the context of the search for relations between hydrological alteration - ecological condition relationships, it was found that the hydrologic alteration results, frequently, present a narrower hydrologic change gradient which makes very difficult the establishment of relationships. Therefore, in view of the purpose of this study, it was chosen to assess the global mean hydrological change (AH). Thus, for each strategic site selected, based on the natural and modified daily flows, the mean flows for each month of the hydrological year were calculated. The hydrological alteration (HA) was calculated as follows on Equation [35]:

$$HA = \frac{Current\ conditions - Natural\ conditions}{Natural\ conditions} \times 100 \qquad [35]$$

It should be noted that to have an overall idea of the hydrologic alteration before and after the beginning of environmental flows release, the hydrologic alterations considering those two periods were calculated. For example, in the case of Alto Rabagão, the quantification of the hydrologic alteration was carried out for a period defined as "period before environmental flows release" covering the period 1980/81 to 2010/2011, considering the information presented in Table 12 (i.e. environmental flows started to be released in 2012). Regarding the period defined as "total period (before and after environmental flows release)", it should be noted that this covers the period 1980/81 to 2017/18. It should be highlighted that the whole period was covered, rather than only a portion of the period 2012/13 to 2017/18 (i.e. after the release of environmental flows). In fact, if this was done, a very short period of time would be taken into consideration in relation to the "period before environmental flows release". Moreover, in order to try to capture the natural range of variation of the existing flows (i.e. of different types of years classification – such as, drought years) it would be pertinent to analyse a long period. As highlighted in the literature (namely by Richter et al 1997, which highlights the need to use at least a 20-year period). The periods assessed to calculate the hydrological alteration to each selected site are described in Table 24.

Table 24 – Periods selected for the analysis of hydrological alteration.

Sites	**Period referred as “period before environmental flows release”**	**Period referred as “total period (before and after environmental flows release)”**
AR1, AR2	01/10/1980 – 30/09/2011	01/10/1980 – 30/09/2018
VN1	01/10/1980 – 30/09/2017	01/10/1980 – 30/09/2018
AC1, AC2, AC3	-	-
PL2, PL3	01/10/1980 – 30/09/2015	01/10/1980 – 30/09/2018
SD1	01/10/1980 – 30/09/2015	01/10/1980 – 30/09/2018
CD1, CD2, CD3	01/10/1980 – 30/09/2017	01/10/1980 – 30/09/2018
VF1, VF2, VF2b, VF3, VF3b	01/10/1980 – 30/09/2013	01/10/1980 – 30/09/2018

4.4 Results

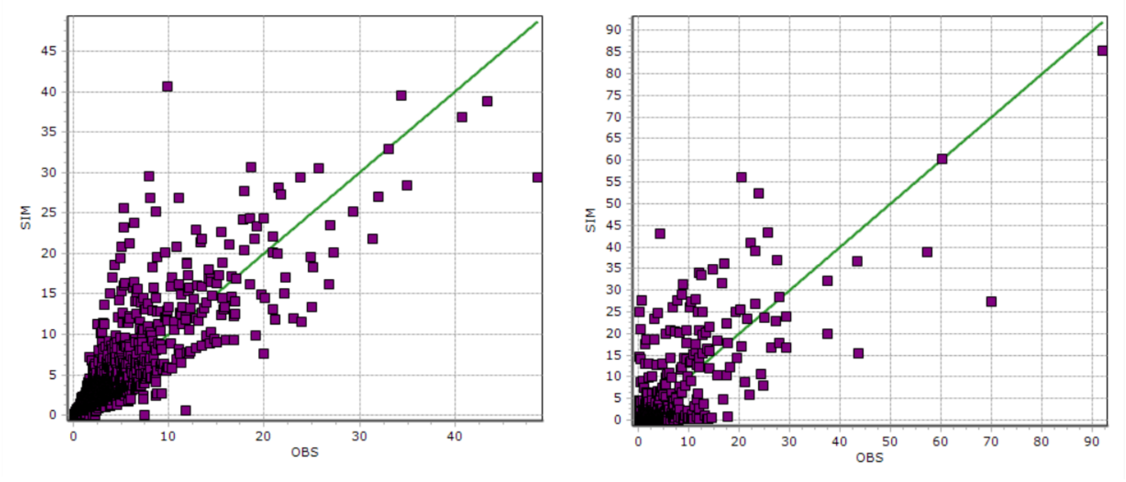
4.4.1 Analysis of the model calibration and performance

In this section the main results of the model are described. Initially, the model parameters obtained through the process of autocalibration are provided in Table 25.

Table 25 – Calibrated model parameters, for the calibrated catchments in this study.

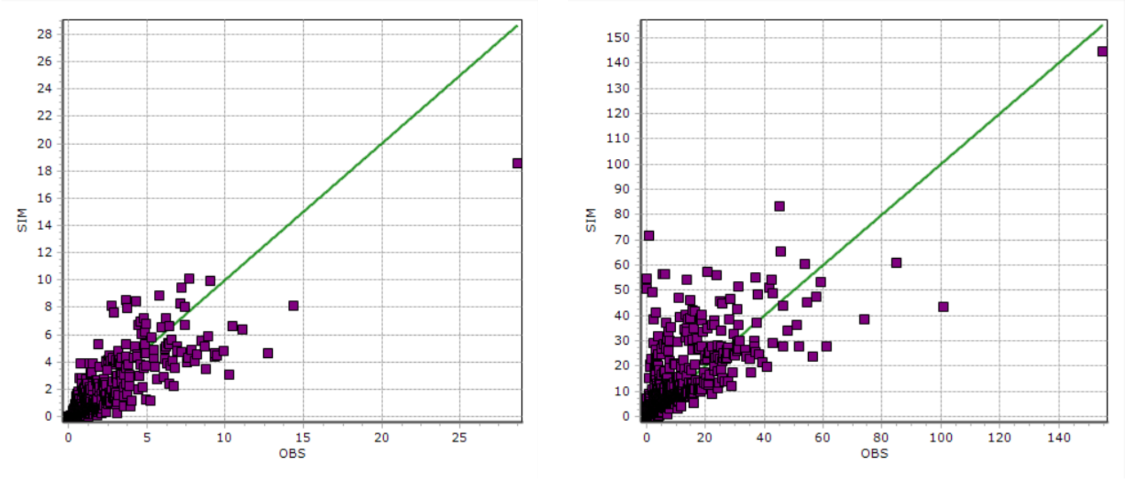
Parameter	**Unit**	**Default value**	**Lower bound**	**Upper bound**	**AC**	**AR**	**Cabreira**	**VN**	**SD**	**Toco**	**PL**	**CD**	**Covas**	**VF**
U_{max}	[mm]	10	10	20	10.87	19.48	14.03	19.11	10.83	10.59	18.67	10.88	11.14	10.51
L_{max}	[mm]	100	100	300	155.61	149.68	100.22	109.73	101.22	102.99	100.53	127.09	101.20	101.41
$CQOF$	[-]	0.5	0.1	1	0.70	1.00	1.00	0.62	1.00	1.00	1.00	1.00	1.00	0.99
$CKIF$	[hours]	1000	200	1000	240.52	646.50	978.63	216.85	958.05	836.15	286.70	657.65	465.61	601.81
$CK_{1,2}$	[hours]	10	10	50	12.58	10.34	10.01	11.64	10.03	10.11	12.15	14.48	10.12	10.11
TOF	[-]	0	0	0.99	0.99	0.97	0.60	0.64	0.37	0.96	0.06	0.86	0.99	0.48
TIF	[-]	0	0	0.99	0.44	0.53	0.80	0.58	0.96	0.68	0.78	0.43	0.92	0.13
TG	[-]	0	0	0.99	0.85	0.97	0.99	0.88	0.99	0.99	0.95	0.87	0.88	0.98
CK_{BF}	[hours]	2000	1000	4000	1010.73	2495.26	2495.33	1017.86	3183.85	2342.84	1499.90	1919.14	3438.53	2125.82

The dispersion diagrams and observed and simulated hydrographs were examined to visually evaluate the deviation between the observed/reconstructed and simulated flows are presented below. Figure 42 (a and b) presents the dispersion diagrams and the Figure 43 (a to e) the hydrographs.



a) AC

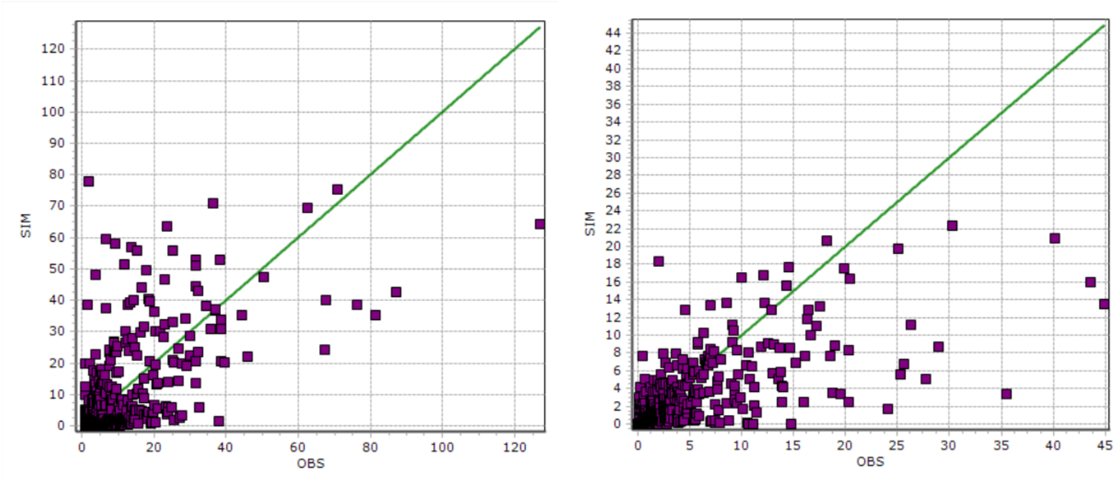
b) AR



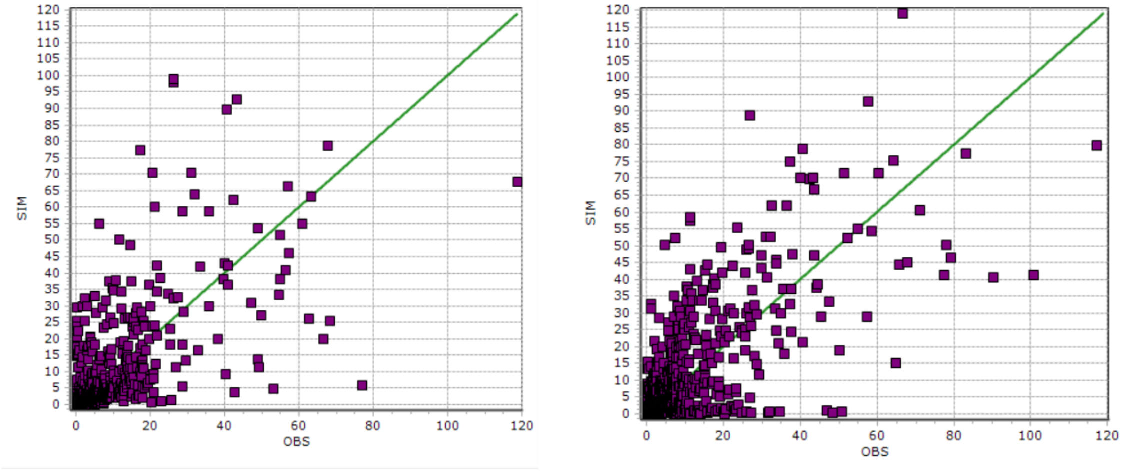
c) Cabreira

d) VN

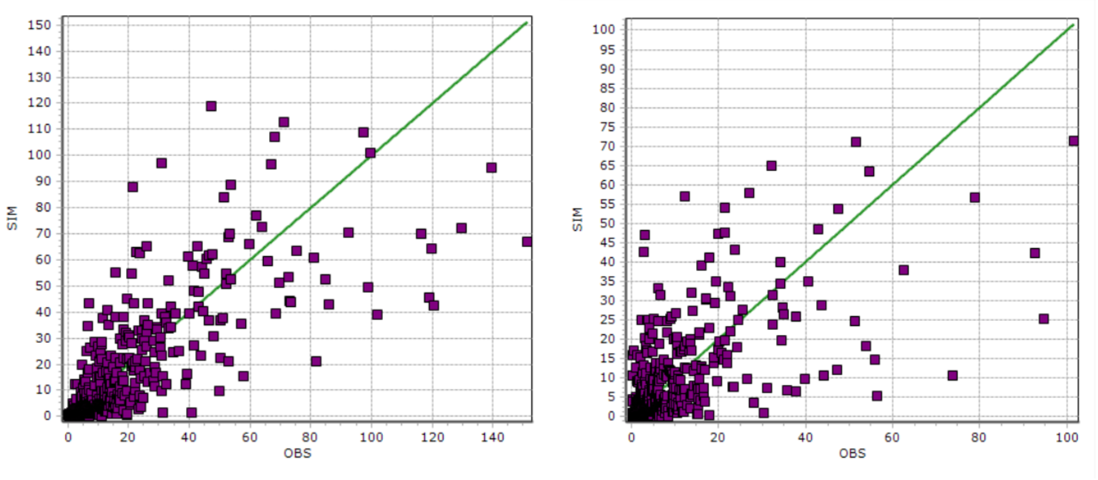
Figure 42a – Dispersion diagrams between the input (observed or reconstructed) flow discharges and the simulated flows discharges, for the correspondent calibration periods.



e) SD **f) Toco**

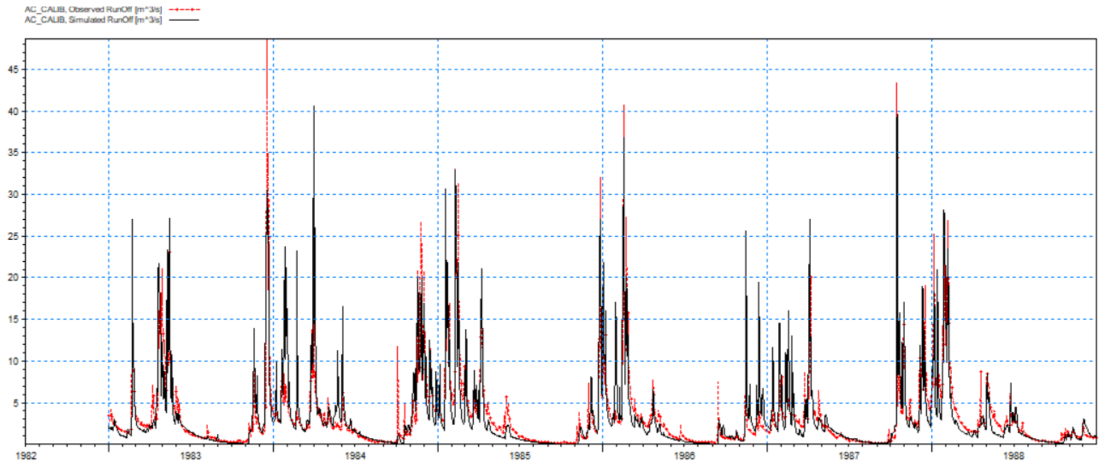


g) PL **h) CD**

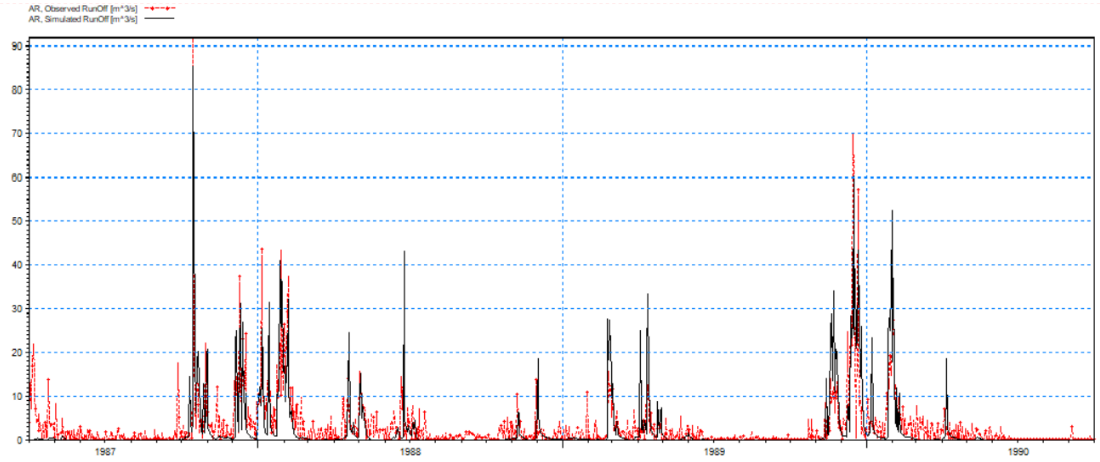


i) Covas **j) VF**

Figure 42b – Dispersion diagrams between the input (observed or reconstructed) flow discharges and the simulated flows discharges, for the correspondent calibration periods.

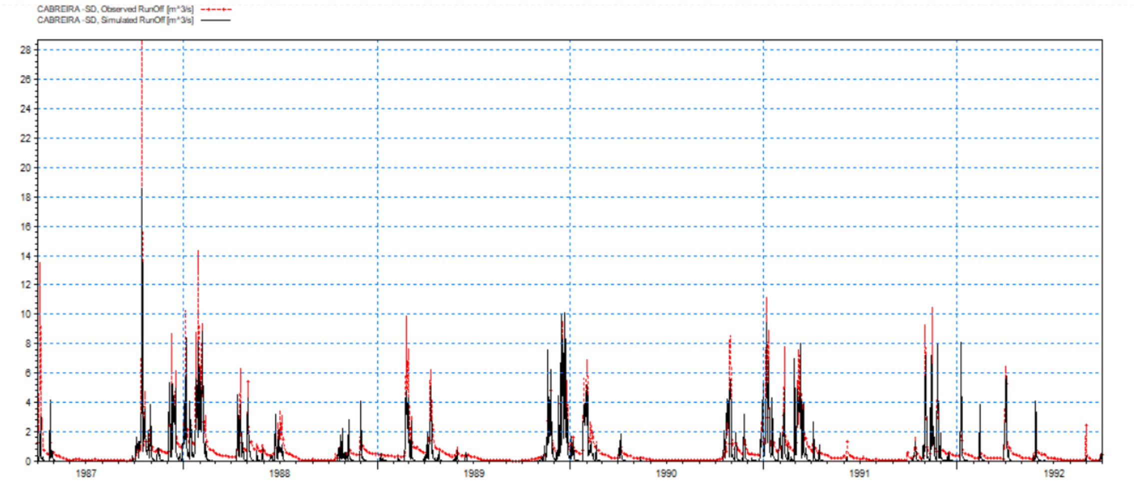


a) AC

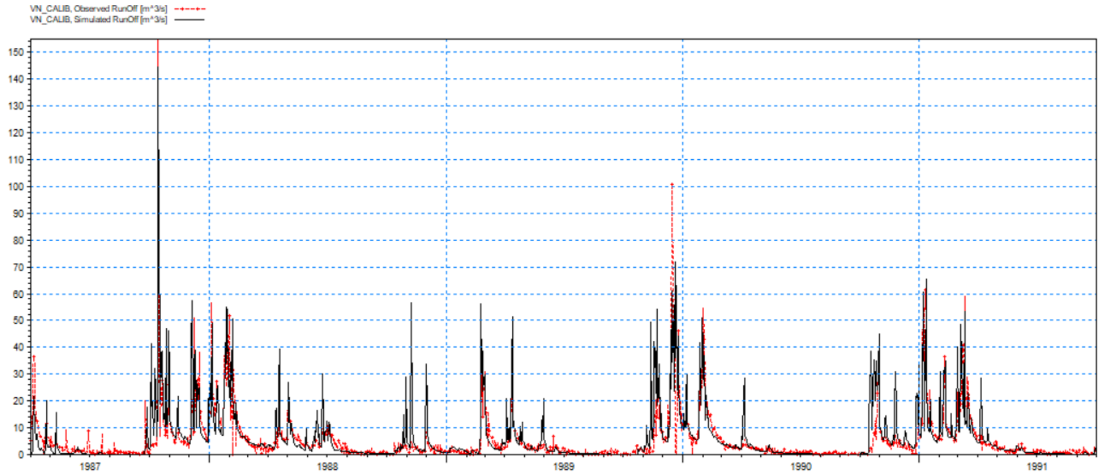


b) AR

Figure 43a – Graphical comparison between the hydrographs obtained for the input (observed or reconstructed) flow discharges and simulation flows discharges, for the correspondent calibration periods.

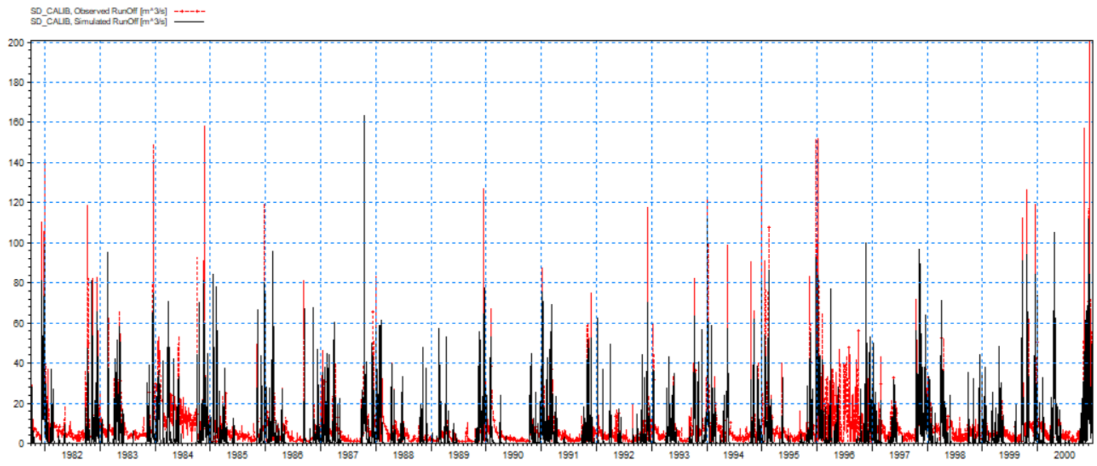


a) Cabreira

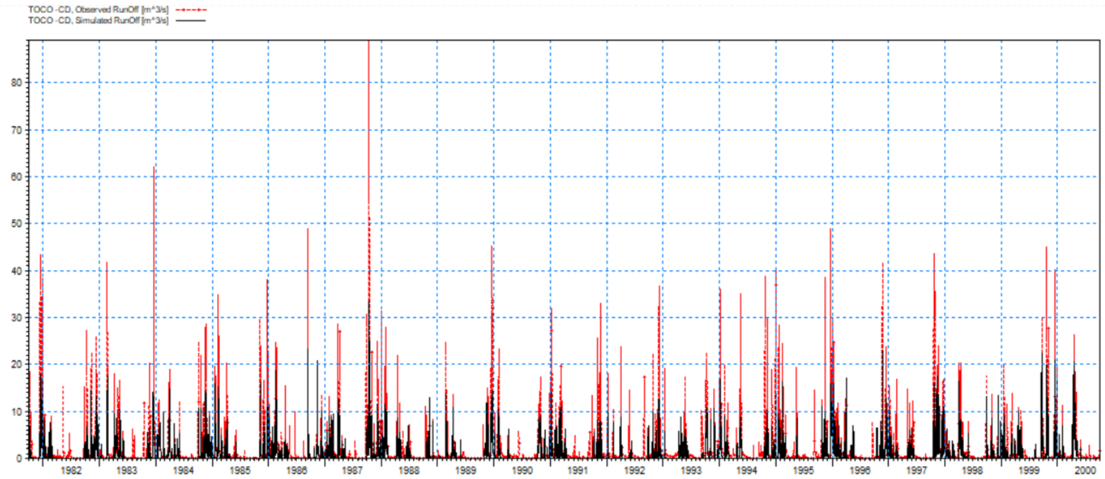


b) VN

Figure 43b – Graphical comparison between the hydrographs obtained for the input (observed or reconstructed) flow discharges and simulation flows discharges, for the correspondent calibration periods.

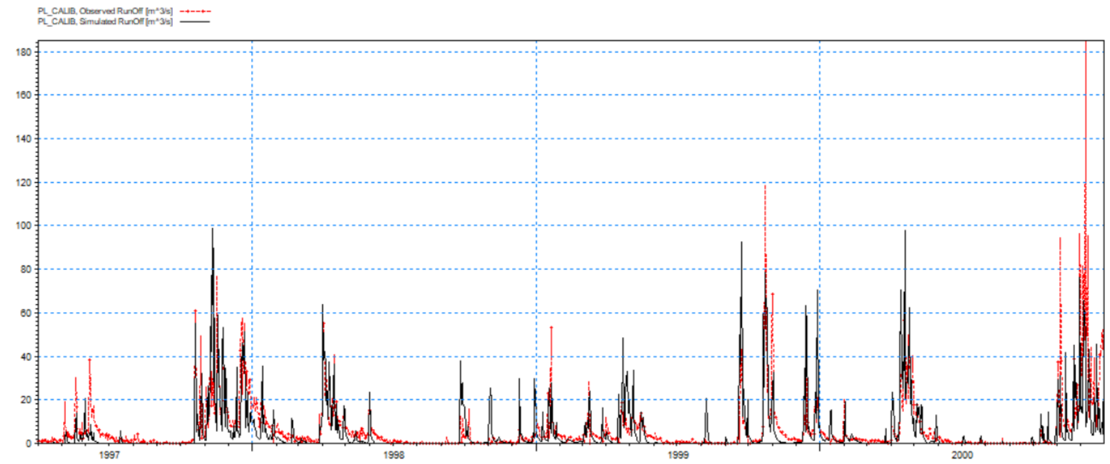


a) SD

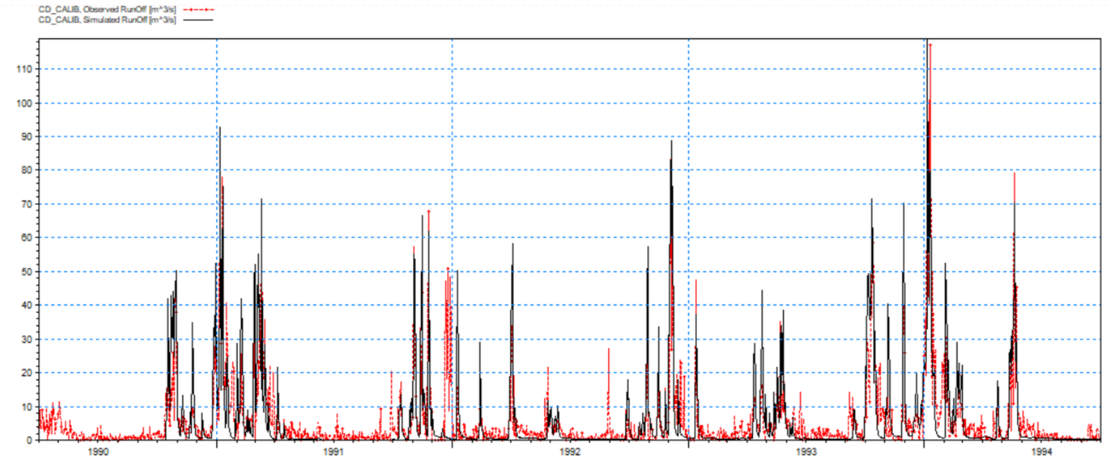


b) Toco

Figure 43c – Graphical comparison between the hydrographs obtained for the input (observed or reconstructed) flow discharges and simulation flows discharges, for the correspondent calibration periods.

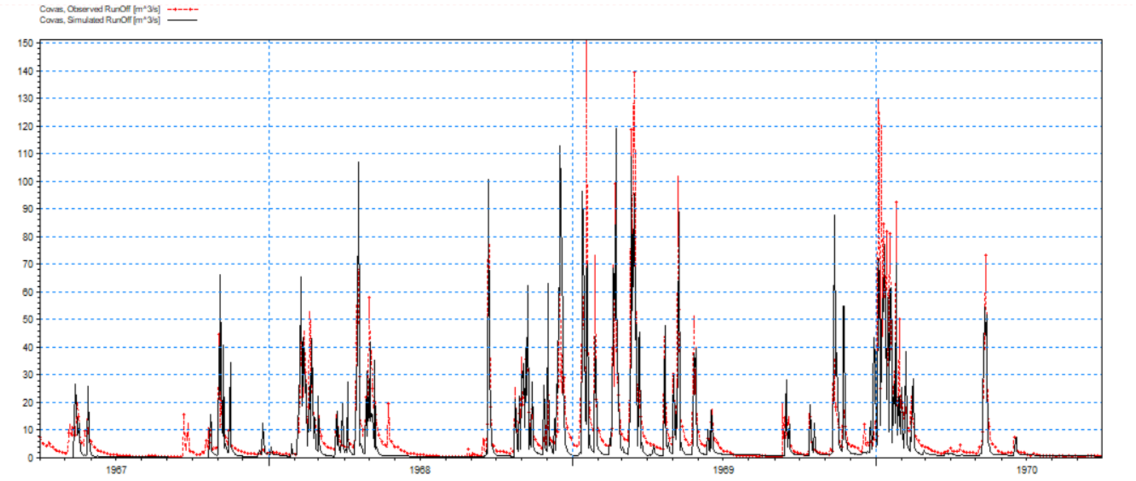


a) PL

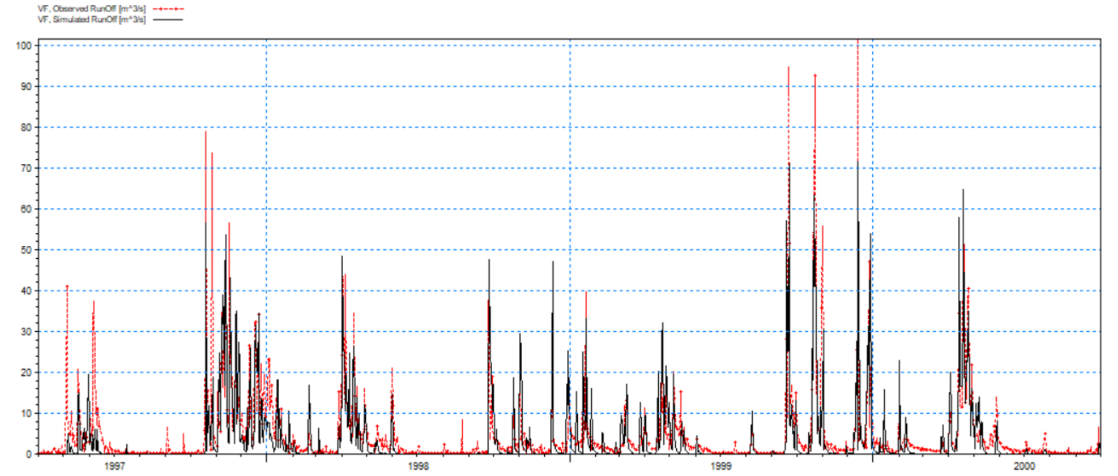


b) CD

Figure 43d – Graphical comparison between the hydrographs obtained for the input (observed or reconstructed) flow discharges and simulation flows discharges, for the correspondent calibration periods.



a) Covas



b) VF

Figure 43e – Graphical comparison between the hydrographs obtained for the input (observed or reconstructed) flow discharges and simulation flows discharges, for the correspondent calibration periods.

Through the visual analysis of the dispersion graphs and hydrographs it was possible to verify that the observed and simulated flow values are more similar with respect to the lower flow values. As far as the higher flow values are concerned, the simulated flows obtained are generally underestimated.

The values obtained for the metrics chosen to assess the numerical performance of the model calibration are presented in Table 26. Based on these results, it was possible to perceive the numerical performance of the model, through the comparison of the obtained values and the performance evaluation criteria presented in Table 22.

Table 26a – Results of the metrics used to evaluate the performance of the model, for the calibrated catchments in this study.

Metric		**Unit**	**AC**	**AR**	**Cabreira**	**VN**	**SD**
Coefficient of efficiency	NSE	[-]	0.71 (“Very good”)	0.56 (“Good”)	0.56 (“Good”)	0.58 (“Good”)	0.35 (“Satisfactory”)
Coefficient of determination	R^2	[-]	0.72 (“Good”)	0.58 (“Satisfactory”)	0.74 (“Good”)	0.60 (“Satisfactory”)	0.45 (“Not satisfactory”)
Index of agreement	d	[-]	0.92 (“Very good”)	0.86 (“Good”)	0.90 (“Good”)	0.87 (“Good”)	0.80 (“Satisfactory”)

Table 26b – Results of the metrics used to evaluate the performance of the model, for the calibrated catchments in this study.

Metric		**Unit**	**Toco**	**PL**	**CD**	**Covas**	**VF**
Coefficient of efficiency	NSE	[-]	-0.25 (“Not satisfactory”)	0.44 (“Good”)	0.39 (“Satisfactory”)	0.54 (“Good”)	0.35 (“Satisfactory”)
Coefficient of determination	R^2	[-]	0.56 (“Satisfactory”)	0.47 (“Not satisfactory”)	0.41 (“Not satisfactory”)	0.56 (“Satisfactory”)	0.49 (“Not satisfactory”)
Index of agreement	d	[-]	0.80 (“Satisfactory”)	0.81 (“Satisfactory”)	0.78 (“Satisfactory”)	0.85 (“Good”)	0.82 (“Satisfactory”)

Most of the obtained classifications vary between “Satisfactory” and “Good”. Even if the system under study is highly complex and there is a lack of hydrometeorological observations, those results enabled us to use the developed hydrological foundation with confidence for the assessment of hydrological alteration.

4.4.2 Hydrologic alteration results

In terms of the hydrologic alteration the obtained values are presented on the following Figures, each showing a radar graph for each of the selected sites. Each graph presents information regarding the analysis of the hydrological alteration of two periods, as referred before (section 4.3): a period immediately before the release of environmental flows (referred as “Period before environmental flows release”) and a period that includes that release (referred as “Total period (before and after environmental flows release)”). That is, for example, for Alto Rabagão, where the environmental flows were released from 2012 onwards: the selected “Period before environmental flows release” covers the years 1980 to 2011; the “Total period (before and after environmental flows release)” covers the years 1980 to 2018. Furthermore, it should be highlighted that the more distant from zero the greater the hydrological alteration. Moreover, the hydrological alterations, associated to each month, may be positive (marked with a filled circle) or negative (marked with an open circle). The sign (positive or negative) of the hydrological alteration reflects different situations. That is, negative hydrological alterations mean that the modified hydrological conditions are lower than the natural hydrological conditions. On the other hand, positive hydrological alterations correspond to hydrological conditions where the modified flows are higher than natural flows.

Legend

— **Total period (before and after environmental flows release)**

— **Period before environmental flows release**

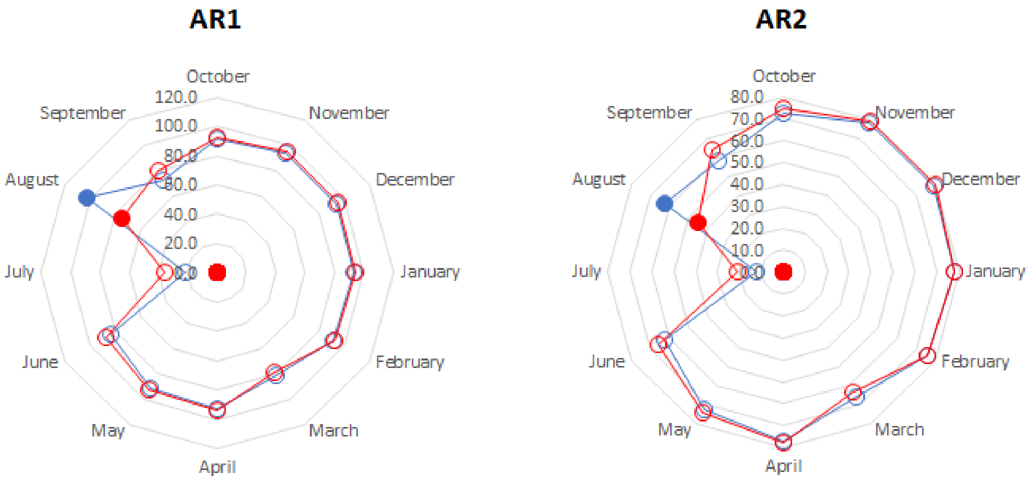


Figure 44 – Hydrologic alterations obtained downstream Alto Rabagão dam (sites AR1 and AR2).

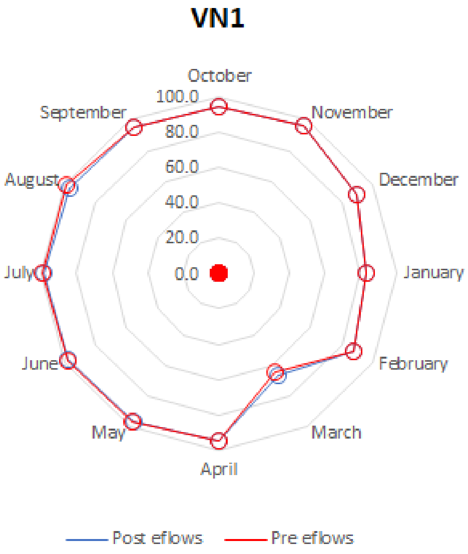


Figure 45 – Hydrologic alterations obtained downstream Venda Nova dam (site VN1).

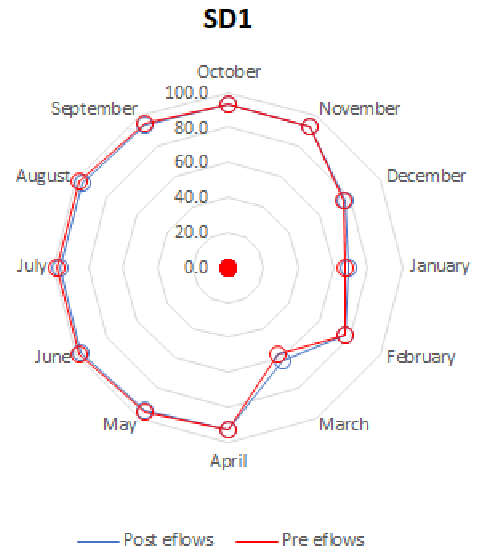


Figure 46 – Hydrologic alterations obtained downstream Salamonde dam (site SD1).

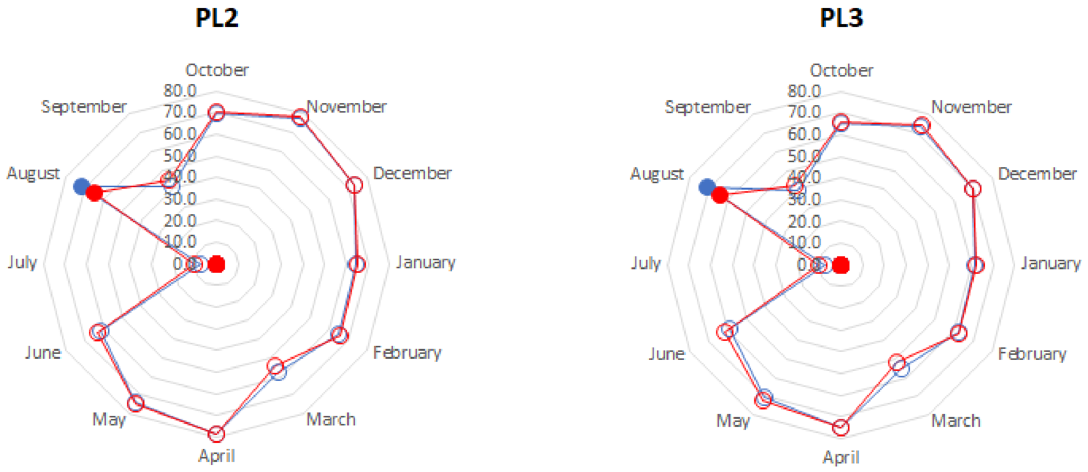


Figure 47 – Hydrologic alterations obtained downstream Paradela dam (sites PL2 and PL3).

Figure 48 – Hydrologic alterations obtained downstream Caniçada dam (sites CD1, CD2 and CD3).

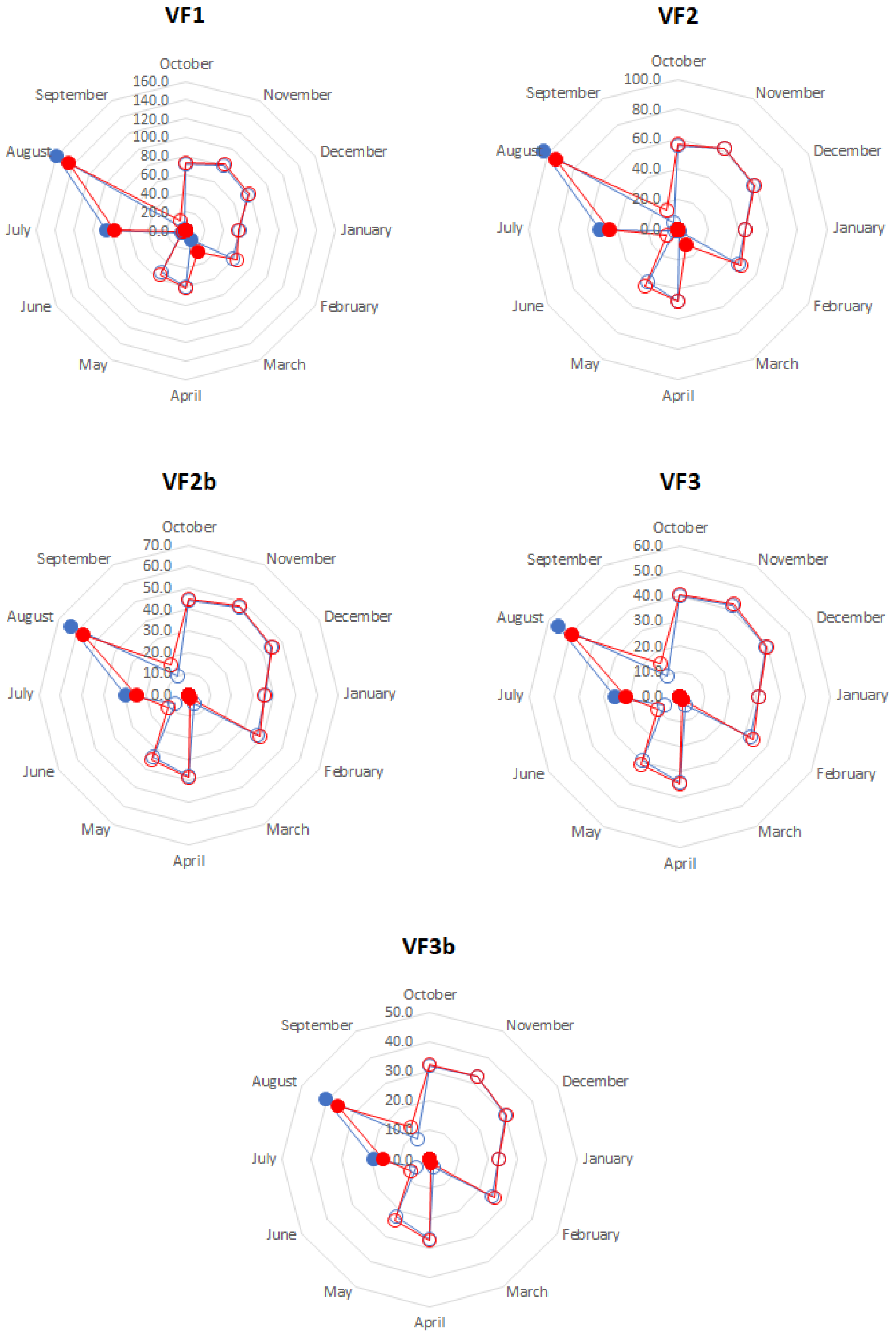


Figure 49 – Hydrologic alterations obtained downstream Vilarinho das Furnas dam (sites VF1, VF2, VF2b, VF3 and VF3b).

Due to the hydrologic alteration patterns obtained, it was decided to evaluate the results in four groups: 1) sites associated to Alto Rabagão and Paradela dams, 2) sites associated to Salamonde dam, 3) sites associated to Vilarinho das Furnas dam, 4) sites associated to Venda Nova and Caniçada dams.

Alto Rabagão and Paradela

In general, it was possible to verify that the sites just downstream the Alto Rabagão and Paradela dams, reveal hydrological alterations with similar patterns. That is, values of hydrological alterations, mostly negative (both periods under study). This shows that the modified conditions presented mean flows below the estimated natural conditions. This trend did only not occur for the month of August, when values of positive hydrological alteration (for the sites of Alto Rabagão and Paradela) were recorded. This indicates precisely the opposite, i.e. that, on average, for August the flow released by these dams is higher than the mean flows that would exist if these dams did not exist (natural flow). In fact, this is even more striking for the total period (before and after environmental flows release) and may lead to the conclusion that for the month of August, normally one of the driest months of the hydrologic year, the conditions imposed by the dam are typical higher than the natural conditions. Thus, in hydrological terms, the environmental flows may be changing the natural conditions of the sections of river in question. In terms of the magnitude of the hydrological alteration, it is possible to verify significant hydrological changes (mostly, more than 60%). In this context, it is also worth mentioning the fact that the month of July is the one with the lowest hydrological alterations, always lower than 20%.

Salamonde

Regarding the values of hydrological alterations obtained just downstream of Salamonde, the existence of significant hydrological changes can be highlighted, and there is a great similarity between the values obtained, for both periods analyzed. That shall most possibly be because the environmental flows only have an influence on the last three hydrological years of the period under analysis.

Vilarinho das Furnas

Concerning the hydrological alteration values obtained for the different sites downstream of Vilarinho das Furnas dam, it was possible to verify hydrological change magnitudes generally smaller than those obtained for the other sites (with the exception of the values associated with point VF1), showing closer modified and natural conditions. As in the strategic sites described above (AR and PL), the hydrological alterations associated with the months of August are positive. The same trend is evident for the values associated with the month of July. This reveals that for these months the existing flows have been higher than if the dam had not been built.

Venda Nova and Caniçada

As regards, the sites downstream of these two dams, it was possible to perceive significant degrees of hydrological alteration. Concerning the effect of environmental flows on these changes, this was not noticeable. Indeed, this behavior was expected as the environmental flows only started to be released in the last year of the study period.

5.ECOLOGICAL CHARACTERIZATION

5.1 Introduction

The main goal of this chapter is to provide information regarding the ecological characterization of the study region. This is one of the key steps of this study, and consequently, a step of crucial relevance to reach the main goal of this study: the definition of flow-ecology relationships.

Therefore, the following sub-chapter (5.2.1), provides information regarding the compilation of the available ecological information. In the first section of the referred sub-chapter (5.2.1), an overview of the main ecological elements used in this study is provided. Then (5.2.2), relevant details concerning the monitoring programs, as well as the criteria to establish groups of analysis are given.

After this, in sub-chapter (5.3), information respecting of the methods used to calculate each one of the ecological indicators, available, and used to assess water bodies ecological status are described. Then (in sub-chapter 5.4), the results gathered and calculated for each ecological element are provided. At the end of this chapter (sub-chapter 5.5), a quantitative analysis and the discussion of the results is presented.

5.2 Ecological data

5.2.1 Ecological elements

This study presents a compilation and evaluation of those ecological quality elements, collected in the study area, used to assess water bodies ecological status. As previously referred, for the evaluation of these elements, there are normative Portuguese indices that should be evaluated, accordingly to the river typology where the sampling took place. Table 27 presents those ecological elements and the associated indices adopted by APA, the Portuguese Environmental Agency (and National Water Authority) for surface water bodies, more specifically, used for the assessment of the ecological status of rivers. It is important to emphasize that since, by the date of this study, no specific indicators and classifications are known for assessing the ecological potential of heavily modified water bodies (which are included in the study area), it was decided to use the indicators and respective classifications of the ecological status of water bodies (as carried out by EDP within their monitoring campaigns). Therefore, the classification criteria used in order to classify the obtained results, ends up being even more demanding supporting the conservation of freshwater ecosystems.

Table 27 – Ecological elements and associated indices used to assess ecological status in the study region (adapted from APA 2016).

Ecological status elements		**Indices**
Biological quality elements	**Benthic invertebrates**	Portuguese Northern Invertebrate Index (*Índice Português de Invertebrados Norte* – IPtI$_N$)
	Phytobenthos	Specific Polluosensitivity Index (*Índice de Poluossensibilidae Específica* – IPS)
	Macrophytes	Biological Macrophyte Index for Rivers (*Índice Biológico de Macrófitos de Rio* – IBMR)
	Fish	Biotic Index of Fish Integrity ((*Índice Piscícola de Integridade Biótica para rios Vadeáveis de Portugal Continental* – F-IBIP)
Chemical & physicochemical quality elements	**General**	Dissolved oxygen (mg O$_2$. L^{-1})
		Dissolved oxygen saturation rate (%)
		BOD (mg O$_2$. L^{-1})
		pH
		Ammoniacal nitrogen (mg NH$_4$. L^{-1})
		Nitrate (mg NO$_3$. L^{-1})
		Total phosphorus (mg P. L^{-1})
	Specific Pollutants	Such as copper and chromium.
Hydromorphological quality elements		Habitat Quality Assessment – HQA (*Índice de Qualidade do Habitat*)
		Habitat Modification Score – HMS (*Índice de Modificação do Habitat*)

5.2.2 Monitoring programs

In this study, as previously referred, with the purpose to define flow – ecology relationships, an estimation of flow conditions (natural and modified/current) and evaluation of ecological conditions was carried out for some sites/locations along the Cávado-Rabagão-Homem rivers. The sites selected were those that integrate the ecological monitoring network defined by EDP-Produção to monitor environmental flows effects along the study region, throughout the years.

In this context, firstly, an analysis of all monitoring programs conducted and/or supported by EDP – Produção, in the Cávado Region, was carried out, namely: i) the ones related with environmental flows definition, implementation and monitoring, as well as, ii) those related with the construction of relevant infrastructures – the power reinforcement of Venda Nova (Venda Nova III) and Salamonde (Salamonde II), and the complementary spillway in Caniçada – in the Cávado-Rabagão-Homem HS. In fact, in order to look for the definition of flow-ecology relationships it is essential to compile all the ecological data measurements in these locations throughout the years. The understanding of flow-ecology relationships should be enhanced as more ecological data is available. Hence, besides the analysis of EDP- Produção studies, with the goal to gather as much ecological information as possible, an analysis of other studies performed in the region (where ecological elements were evaluated) was carried out. It was possible to get information related with the: i) field programs conducted through orientation of the Portuguese National Water Authority to define reference conditions of water bodies in Portugal (as required for WFD implementation), ii) field programs conducted within the elaboration of the 1st RBMPs in the region (as required for WFD implementation), and, iii) field program elaborated within the AQUARIPORT Project (Oliveira et al. 2007). The information related with the first two referred field programs were made available by the experts responsible for the field programs in the study region (nevertheless, permission for its use was granted by a representative of Portuguese National Water Authority). The information of AQUARIPORT Project was made available through representatives of ICNF (*Instituto da Conservação da Natureza e das Florestas).*

All the monitoring programs, provide ecological information for several sampling points throughout the study area (Figure 50) and for different time periods. Even though, some of these sampling points coincide with those sites currently included in EDP's ecological monitoring network, there are other points whose ecological sampling has been carried out at different locations. Thus, an assessment of the spatial proximity between the selected sites (presented in Table 13) and the points sampled during the referred field programs was performed. The idea was to check the possibility to combine sampling points in order to get an overall picture of ecological condition throughout the time (for each selected location). It was possible to perceive that there are some sampling points that could be aggregated due to their spatial proximity, enabling to enlarge the ecological observations per location, which is essential to a more in-depth assessment of the evolution of the ecological conditions. Therefore, to aggregate as much ecological data as possible, monitoring groups were defined for each location. This was conducted for all the sites located in the main rivers – Cávado, Rabagão and Homem. Each group was named accordingly with the name of the EDP monitoring station included in each group. Appendix B presents the monitoring groups formed.

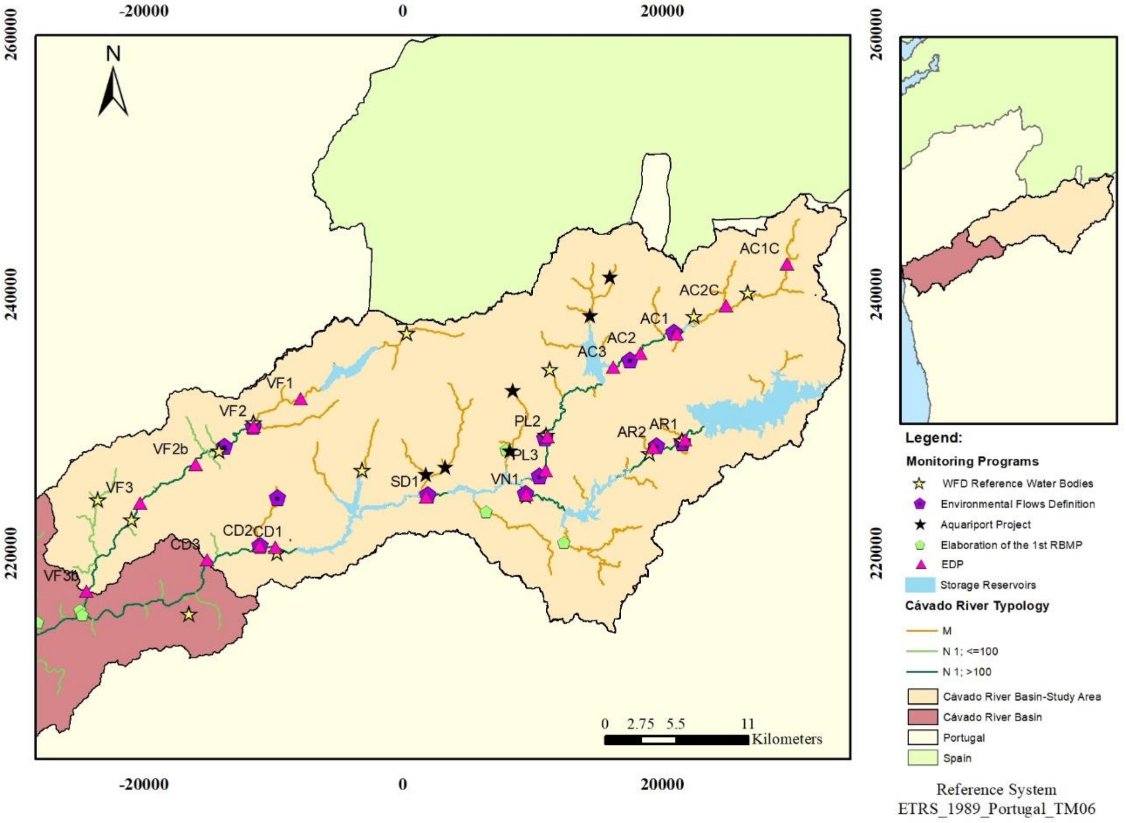


Figure 50 – Sampling points location of the overall studies evaluated within this study.

The information compiled (i.e. the ecological metrics gathered and the respectively period of sampling), for each group was analysed and evaluated. An overall evaluation of the available information showed that the information was very scarce (with punctual and disparate samplings) for phytobenthos and specific pollutants. Furthermore, also the current and future EDP monitoring programs do not foresee the monitoring of these elements, and their consideration within the scope of their monitoring goals is not seen as relevant. Having this in consideration, these elements were not considered within this study.

Within this study, it was necessary to elaborate an important systematization of the sampling information, analysing the different dates for which information was available, and compiling and organizing ecological data per season, and per ecological element measured. Hence, Table 28a to Table 28e present the time period of all the monitoring programs available and gathered in this study, for each ecological element, and for the sites associated to each dam. It should be emphasized that a season is marked if, at least, one sample was collected in one of the site locations associated to each dam. Furthermore, it will be important to highlight that the temporal period pointed out in these Tables start in 2004 (where the WFD monitoring programs started), with a gap between 2005 to 2009 (since no information was found for this period), ending in 2019 (even though the current study is carried out until 2018, due to the available ecological information). Finally, it should be emphasized that these Tables also indicate the seasons in which environmental flows releases have started (marked with an “x”).

Table 28a – Invertebrates monitoring programs – throughout the years and seasons (Wi- Winter, Sp- Spring, Su-Summer, Au-Autumn) in each dam (D): Alto Rabagão (AR), Venda Nova (VN), Alto Cávado (AC), Paradela (PL), Salamonde (SD), Caniçada (CD), Vilarinho das Furnas (VF) – related with: i) environmental flows definition (in "blue colour"), ii) evaluation before environmental flows release, i.e. the so-called reference condition (in "grey colour"), iii) evaluation of environmental flows effectiveness (in "green colour"), iv) construction of infrastructures (in "light blue colour"), v) definition of WFD reference water bodies (in "toasted yellow colour"), vi) elaboration of the 1st *RBMPs (marked with an "o"), and, vii) elaborated within the AQUARIPORT project (marked with an "Δ"). The seasons marked with an "x" are the ones in which environmental flows release have been started. It should be emphasized that a season is marked if, at least, one sample was collected in one of the site locations of each dam.*

	2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AR		🟨														▨										x		🟩				🟩				🟩				🟩				🟩				🟩							
VN																▨								🟦				🟦				🟦				🟦												x							
AC						🟨										▨																												▨											
PL		🟨														▨																🟦				🟦					🟦		x	🟩				🟩							
SD																▨ o				🟦				🟦				🟦				🟦				🟦				🟩 x				🟩				🟩							
CD		🟨														▨																				🟦				🟦									x						
VF		🟨				🟨										▨ o																		x		🟩				🟩				🟩				🟩							

Table 28b – Fish monitoring programs – throughout the years and seasons (Wi- Winter, Sp- Spring, Su-Summer, Au-Autumn) in each dam (D): Alto Rabagão (AR), Venda Nova (VN), Alto Cávado (AC), Paradela (PL), Salamonde (SD), Caniçada (CD), Vilarinho das Furnas (VF) – related with: i) environmental flows definition (in "blue colour"), ii) evaluation before environmental flows release, i.e. the so-called reference condition (in "grey colour"), iii) evaluation of environmental flows effectiveness (in "green colour"), iv) construction of infrastructures (in "light blue colour"), v) definition of WFD reference water bodies (in "toasted yellow colour"), vi) elaboration of the 1st RBMPs (marked with an "o"), and, vii) elaborated within the AQUARIPORT project (marked with an "Δ"). The seasons marked with an "x" are the ones in which environmental flows release have been started. It should be emphasized that a season is marked if, at least, one sample was collected in one of the site locations of each dam.

	2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AR		🟨										🟦 Δ														x		🟩				🟩				🟩				🟩				🟩				🟩							
VN												🟦 Δ												▨				▨				▨				▨												x							
AC						🟨						🟦 Δ																																▒											
PL		🟨										🟦																				▨				▨					▨		x	🟩				🟩							
SD												🟦				o				▨				▨				▨				▨				▨				🟩 x				🟩				🟩							
CD		🟨										🟦																								▨				▨									x						
VF		🟨				🟨						🟦 Δ																						x		🟩				🟩				🟩				🟩							

Table 28c – Macrophytes monitoring programs – throughout the years and seasons (Wi- Winter, Sp- Spring, Su-Summer, Au-Autumn) in each dam (D): Alto Rabagão (AR), Venda Nova (VN), Alto Cávado (AC), Paradela (PL), Salamonde (SD), Caniçada (CD), Vilarinho das Furnas (VF) – related with: i) environmental flows definition (in "blue colour"), ii) evaluation before environmental flows release, i.e. the so-called reference condition (in "grey colour"), iii) evaluation of environmental flows effectiveness (in "green colour"), iv) construction of infrastructures (in "light blue colour"), v) definition of WFD reference water bodies (in "toasted yellow colour"), vi) elaboration of the 1st RBMPs (marked with an "o"), and, vii) elaborated within the AQUARIPORT project (marked with an "Δ"). The seasons marked with an "x" are the ones in which environmental flows release have been started. It should be emphasized that a season is marked if, at least, one sample was collected in one of the site locations of each dam.

	2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AR			🟨									🟦														x		🟩																											
VN												🟦												🔷								🔷																x							
AC							🟨					🟦																																											
PL			🟨									🟦																				🔷											x					🟩							
SD												🟦								🔷								🔷								🔷				🟩 x															
CD			🟨									🟦																																					x						
VF			🟨				🟨					🟦																						x		🟩																			

Table 28d – General chemical and physicochemical monitoring programs – throughout the years and seasons (Wi- Winter, Sp- Spring, Su-Summer, Au-Autumn) in each dam (D): Alto Rabagão (AR), Venda Nova (VN), Alto Cávado (AC), Paradela (PL), Salamonde (SD), Caniçada (CD), Vilarinho das Furnas (VF) – related with: i) environmental flows definition (in "blue colour"), ii) evaluation before environmental flows release, i.e. the so-called reference condition (in "grey colour"), iii) evaluation of environmental flows effectiveness (in "green colour"), iv) construction of infrastructures (in "light blue colour"), v) definition of WFD reference water bodies (in "toasted yellow colour"), vi) elaboration of the 1st RBMPs (marked with an "o"), and, vii) elaborated within the AQUARIPORT project (marked with an "Δ"). The seasons marked with an "x" are the ones in which environmental flows release have been started. It should be emphasized that a season is marked if, at least, one sample was collected in one of the site locations of each dam.

	2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AR		🟨														▨	▨	▨	▨							x		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩					
VN																▨	▨	▨	▨				🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦										x							
AC						🟨										▨	▨	▨	▨																						▨	▨	▨	▨											
PL		🟨														▨	▨	▨	▨													🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟩 x	🟩	🟩	🟩	🟩								
SD																▨ o	▨ o	▨ o	▨ o	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟩 x	🟩	🟩	🟩	🟩	🟩	🟩	🟩								
CD		🟨														▨	▨	▨	▨															🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					x					
VF		🟨				🟨									o	▨ o	▨ o	▨ o	▨															x	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩							

Table 28e – Hydromorphological monitoring programs – throughout the years and seasons (Wi- Winter, Sp- Spring, Su-Summer, Au-Autumn) in each dam (D): Alto Rabagão (AR), Venda Nova (VN), Alto Cávado (AC), Paradela (PL), Salamonde (SD), Caniçada (CD), Vilarinho das Furnas (VF) – related with: i) environmental flows definition (in "blue colour"), ii) evaluation before environmental flows release, i.e. the so-called reference condition (in "grey colour"), iii) evaluation of environmental flows effectiveness (in "green colour"), iv) construction of infrastructures (in "light blue colour"), v) definition of WFD reference water bodies (in "toasted yellow colour"), vi) elaboration of the 1st RBMPs (marked with an "o"), and, vii) elaborated within the AQUARIPORT project (marked with an "Δ"). The seasons marked with an "x" are the ones in which environmental flows release have been started. It should be emphasized that a season is marked if, at least, one sample was collected in one of the site locations of each dam.

	2004				**2005**					**…**	**2009**				**2010**				**2011**				**2012**				**2013**				**2014**				**2015**				**2016**				**2017**				**2018**				**2019**				
	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AR		🟨										🟦				▒										x		🟩																											
VN												🟦				▒								▧								▧																x							
AC						🟨						🟦				▒																																							
PL		🟨										🟦				▒																▧											x												
SD												🟦				▒ o				▧				▧				▧				▧				▧				x															
CD		🟨										🟦				▒																																	x						
VF		🟨				🟨						🟦				▒																		x		🟩																			

5.3 Methods to calculate ecological indicators used to assess water bodies ecological status

Based on the ecological information collected, as described in the sub-chapter 5.2, the next step was the calculation, for each selected site and time period, of the normative ecological indicators adopted to assess water bodies ecological status and included in this study. Herein, a description about the methods used for their calculation is provided.

5.3.1 Benthic Invertebrates

The Portuguese Northern Invertebrate Index – *Índice Português de Invertebrados do Norte*, IPtIN – in used to evaluate the benthic invertebrates (macroinvertebrates) community. According to APA (2014 and 2016) this index is calculated based on the sum of several weighted metrics, which globally allowed to assess the level of degradation of a water body (which results from organic pollution, specific pollutants and hydromorphological pressures). The used metrics express information related with the quantification of taxa sensitive to degradation or the quantification of the diversity level of benthic invertebrate communities. The index is calculated based on the following equation (INAG 2009):

$$IPtI_N = N° \, Taxa \times 0.25 + EPT \times 0.15 + Evenness \times 0.1 + (IASPT - 2) \times 0.3 + \log(Sel.ETD + 1) \times 0.2 \quad [36]$$

Where,

$N° \, Taxa$ – Number of existent taxa; EPT – Number of families included in the Order Ephemeroptera, Plecoptera, Trichoptera; $Evenness$ – Pielou’s index, which is calculated as $Evenness = H/\ln S$ (where, H – Number derived from the Shannon-Wiener index, $\ln S$ – neperian logarithm of the total number of species; the Shannon-Wiener índex is calculated based on $H = -\sum p_i ln p_i$ where $p_i = \frac{n_i}{N}$, which is the proportion of individuals belonging to the *i*th species in the dataset of interest (in other words, the number of individuals of each taxon i (n_i) divided by the number of the total individuals (N) presented in the sample) ; $IASPT$ – Iberic ASPT Ibérico, calculated based on the Iberic BMWP divided by the number of families included in the calculation of the Iberic BMWP; $\log(Sel.ETD + 1)$ – calculated through: log_{10} (1 + sum of the abundances of the individuals included in the families Heptageniidae, Ephemeridae, Brachycentridae, Goeridae, Odontoceridae, Limnephilidae, Polycentropodidae, Ephemeridae, Brachycentridae, Goeridae, Odontoceridae, Limnephilidae, Polycentropodidae, Athericidae, Dixidae, Dolichopodidae, Empididae, Stratiomyidae.

In order to calculate the index and metrics presented on Equation [36] – when necessary – an excel file was prepared (see Appendix C).

5.3.2 Fish

As previously referred, in order to evaluate the fish community and express their water quality status in Portuguese water bodies, the Fish-based Index of Biotic Integrity for Portuguese Wadeable Streams – *Índice Piscícola de Integridade Biótica para rios Vadeáveis de Portugal Continental*, F-IBIP – is the official index used. According to APA (2014 and 2016), this Index in composed by several metrics reflecting the basic structural and functional characteristics of fish community. These metrics express the response of fish communities to a wide range of pressures. One of the limitations of this Index is that it does not incorporate the age structure of fish population, which is considered one of the components necessary to be included in the evaluation of fish communities' conditions under the WFD implementation. It should be noted that unlike the other indices presented (for the other ecological elements) the thresholds of classification are the same for all national river typologies and are applicable as long the rivers are wadeable. The metrics used to calculate the index value, for a certain site, are dependent on the type of fish groups associated to each stream, according with the work developed by INAG and AFN (2012). In this work, developed at a national level, six types of fish groups were defined, each one, with a certain set of characteristics. Table 29, present the types of fish groups for the sites selected in this study.

Table 29 – Types of fish groups in the EDP monitoring stations (the information presented in this Table was made available by EDP-Produção).

Dams	**Station**	**Types of fish groups**	
		N.	**Name**
Alto Rabagão	**AR1**	2	Salmonid-Cyprinid Transition of the North Region
	AR2	2	Salmonid-Cyprinid Transition of the North Region
Venda Nova	**VN1**	2	Salmonid-Cyprinid Transition of the North Region
Alto Cávado	**AC1C**	1	Salmonid of the North Region
	AC2C	1	Salmonid of the North Region
	AC1	1	Salmonid of the North Region
	AC2	2	Salmonid-Cyprinid Transition of the North Region
	AC3	2	Salmonid-Cyprinid Transition of the North Region
Paradela	**PL2**	2	Salmonid-Cyprinid Transition of the North Region
	PL3	2	Salmonid-Cyprinid Transition of the North Region
Salamonde	**SD1**	2	Salmonid-Cyprinid Transition of the North Region
Caniçada	**CD1**	3	Cyprinid medium-sized of the North Region
	CD2	3	Cyprinid medium-sized of the North Region
	CD3	3	Cyprinid medium-sized of the North Region
Vilarinho das Furnas	**VF1**	2	Salmonid-Cyprinid Transition of the North Region
	VF2	2	Salmonid-Cyprinid Transition of the North Region
	VF2b	2	Salmonid-Cyprinid Transition of the North Region
	VF3	3	Cyprinid medium-sized of the North Region
	VF3b	3	Cyprinid medium-sized of the North Region

It should be highlighted that each type of fish group corresponds to a set of metrics that must be calculated in order to estimate the overall index. The metrics used to evaluate the Index for each type of fish groups are presented on Table 30. It should be highlighted that this information was obtained in INAG and AFN (2012).

Table 30 – Metrics used for each type of fish groups for the F-IBIP calculation (adapted from INAG and AFN 2012).

Types of fish groups		**Metric**	**Type of metric**	**With an increase of the anthropogenic degradation, the metric express a:**
N.	**Name**			
1	**Salmonid of the North Region**	% intolerants	Tolerance	Decrease
		% exotics	Composition	Increase
		% omnivores	Trophic	Increase
2	**Salmonid-Cyprinid Transition of the North Region**	% exotics	Composition	Increase
		% intolerants + % intermediates	Tolerance	Decrease
		% invertivores (excluding tolerant species)	Trophic	Decrease
		% potamodromous	Migration	Decrease
3	**Cyprinid medium-sized of the North Region**	% native species	Composition	Decrease
		% exotics	Composition	Increase
		% intolerants + % intermediates	Tolerance	Decrease

Hence, for the calculation of the metrics presented in Table 30, first, it is essential to develop a characterization of the fish communities based on their status (native or exotic species) and according to the concept of ecological/functional guild, in terms of the following ecological aspects: tolerance to degradation, food habits, reproductive habits, habitat uses and migratory behavior.

According to INAG and AFN (2012), the value of F-IBIP is obtained through the arithmetic mean of the overall metrics associated to each type of fish group (Table 30), where the individual value of each metric, varies on a continuous scale ranging between 0 and 1.

It should be pointed out that, when necessary, the F-IBIP was calculated using a web-tool (http://www.isa.ulisboa.pt/proj/fibip/), since that more specific details related with the calculation of this official index are not public available.

5.3.3 Macrophytes

The Biological Macrophyte Index for Rivers – *Índice Biológico de Macrófitos de Rio*, IBMR– is used to evaluate macrophyte communities. As stated by APA (2014 and 2016) this Index is based on the occurrence and abundance of indicator species (not including terrestrial and woody species, even if hygrophytes are presented in the river bed) in the aquatic environment, and in nearby zones of it. The indicator species are sensitive to pollution existence, mostly to the presence of nutrients. The IBMR index is calculated through (Aguiar et al 2014, Haury et al 2006):

$$IBMR = \frac{\sum_{i=1}^{N}(CS_i \times E_i \times K_i)}{\sum_{i=1}^{N}(E_i \times K_i)} \qquad [37]$$

Where,

CS_i – trophic value, indicator value of taxon *i*, ranging from 0 (heavy organic pollution and heterotrophic taxa) to 20 (oligotrophy)*;* E_i – coefficient of ecological amplitude of taxon *i*, ranging from 1 to 3; K_i – scale of cover, going from 1 to 5 (the scale of cover is evaluated based on the percentage cover, which is estimated in the field for all the macrophyte taxa *i*, and classed according to a scale of cover (K_i), considering the following classification (Haury et al 2006): i) $K_i = 1$ if percentage of cover <0.1%; ii) $K_i = 2$ if percentage of cover is between 0.1 – <1%; iii) $K_i = 3$ if percentage of cover is between 1 - <10%; iv) $K_i = 4$ if percentage of cover is between 10 - <50%; v) $K_i = 5$ if percentage of cover ≥50%.

The absolute values of IBMR range from 0 to 20, with the highest values corresponding to oligotrophic situations (more than 14) and the lowest values (less than 8) corresponding to highly eutrophicated waters (Aguiar et al 2014). Then, in order to obtain the IBMR index for the location, this absolute value is divided by the IBMR reference value. Although, there is also a web-tool for the calculation of IBMR values, http://www.isa.ulisboa.pt/proj/ibmr/, it was chosen to build an excel file to calculate this index (see Appendix D).

5.3.4 General chemical and physicochemical

As previously referred, for the ecological status classification for rivers is also necessary to evaluate the general chemical and physico-chemical quality elements supporting the biological elements. The parameters included in these elements express the oxygenation, acidification and nutrient conditions. Within this study the parameters selected are the ones already indicated, the general chemical and physico-chemical parameters: dissolved oxygen (mg O_2. L^{-1}), dissolved oxygen saturation rate (%), biochemical oxygen demand - BOD (mg O_2. L^{-1}), pH, ammoniacal nitrogen (mg NH_4. L^{-1}), nitrate (mg NO_3. L^{-1}), and total phosphorus (mg P. L^{-1}). The specific pollutants were not assessed within this study.

5.3.5 Hydromorphological support elements

The evaluation of the supporting hydromorphological elements could be conducted based on the information gathered through the application of the River Habitat Survey (RHS) – a system for assessing the character and habitat quality of rivers based on their physical structure (Raven et al 1997, 1998). The RHS includes four main components (Riverdene Consultancy 2018a): i) a standard field survey method, ii) a computer database in order to enter results from survey sites and comparing them with information from other sites; iii) a collection of methods for assessing habitat quality and iv) a system for describing the extent of artificial channel modification. Thus, based on the RHS data, an assessment of habitat quality and extent of channel modification can be derived to two main indices used as a basis for setting hydromorphological quality of water bodies, the Habitat Quality Assessment (HQA) and the Habitat Modification Score (HMS). As referred in (Riverdene Consultancy 2018b):

i) HQA "is a broad indication of overall habitat diversity provided by natural features in the channel and river corridor. Points are scored for the presence of features such as point, side and mid-channel bars, eroding cliffs, large woody debris, waterfalls, backwaters and floodplain wetlands. Additional points reflect the variety of channel substrata, flow-types, in-channel vegetation, and also the distribution of bank-side trees and the extent of near natural land-use adjacent to the river. Points are added together to provide HQA score". "Higher HQA scores represent more diverse sites".

ii) HMS "is an indication of artificial modification to river channel morphology. To calculate the HMS for a site, points are allocated for the presence and extent of artificial features such as culverts and weirs and also modifications caused by re-profiling and reinforcement of banks. Greater and more severe modification result in a high score. The cumulative points total provides the HMS. A Habitat Modification Class (HMC) protocol has been developed which allocated the condition of the channel in a site to one of five modification classes, based on the total score (1 = near natural; 5 = severely modified). In contrast to HQA, higher HMS scores reflect more artificial intervention and modification of the river channel within a site ".

In short, the HQA translates the quality of habitats in the sampled section (the higher its value the higher the quality of the site) and the HMS reflects the degree of hydromorphological modification (a higher value express a higher degree of disturbance) (APA 2012).

Furthermore, it should be highlighted that the hydromorphological elements are only used to distinguish those water bodies that are in an excellent status from the other ones (Table 31).

5.3.6 Classification thresholds for the ecological indicators used to assess surface (more specifically, rivers) water bodies ecological status/potential

After calculating each indicator (by means of the corresponding methodology previously described), with the purpose of evaluate and classify the ecological condition, the WFD classification system was used in order to assess the status of each ecological element (APA 2016).

Table 31 – Classification thresholds for the ecological indicators used to assess ecological water bodies status, for each WFD river typology included in the study area (APA 2016).

Ecological elements			**River Typology**	**Reference**	**High**	**Good**	**Moderate**	**Poor**	**Bad**
Biological quality elements	**Benthic invertebrates**	**IPtI$_N$**	M	0.98	≥ 0.86	[0.60-0.86[	[0.40-0.60[	[0.20-0.40[	[0-0.20[
			N1 < 100 km^2	1.02	≥ 0.87	[0.68-0.87[	[0.44-0.68[	[0.22-0.44[	[0-0.22[
			N1 > 100 km^2	1.00	≥ 0.88	[0.68-0.88[	[0.44-0.68[	[0.22-0.44[	[0-0.22[
	Fish	**F-IBIP**	All river typologies (as long they are wadeable streams)		≥ 0.85	[0.675-0.850[	[0.450-0.675[	[0.225-0.450[	[0-0.225[
	Macrophytes	**IBMR**	M	12.68	≥ 0.92	[0.69-0.92[	[0.46-0.69[	[0.23-0.46[	[0-0.23[
			N1 < 100 km^2	12.68	≥ 0.92	[0.69-0.92[	[0.46-0.69[	[0.23-0.46[	[0-0.23[
			N1 > 100 km^2	12.68	≥ 0.92	[0.69-0.92[	[0.46-0.69[	[0.23-0.46[	[0-0.23[
General chemical	**Dissolved oxygen (mg O$_2$. L^{-1})** **a)**		M, N1 < 100 km^2,	-	-	≥ 5	-	-	-

and physico-chemical quality elements	**Dissolved oxygen saturation rate (%) a)**	N1 > 100 km^2	-	-	Between 60% and 120%	-	-	-
	Biochemical oxygen demand (mg O_2. L^{-1}) a)		-	-	≤ 6	-	-	-
	pH a)		-	-	Between 6 and 9 c)	-	-	-
	Ammoniacal nitrogen (mg NH_4. L^{-1}) a)		-	-	≤ 1	-	-	-
	Nitrate (mg NO_3. L^{-1}) b)		-	-	≤ 25	-	-	-
	Total phosphorus (mg P. L^{-1}) b)		-	-	≤ 0.10	-	-	-
Hydromorphological elements	**HQA**	M	-	≥ 42	-	-	-	-
		N1 < 100 km^2, N1 > 100 km^2	-	≥ 46	-	-	-	-
	HMS	M, N1 < 100 km^2, N1 > 100 km^2	-	≤16	-	-	-	-

a) 80% of the samples should respect the established limit if the sampling frequency is monthly or higher, in other situations, 100% of the samples must respect the established limit; b) Annual average. For the calculation of the annual average, and when in a sample the values are lower than the established limit, the value corresponding to half of the limit of quantification should be used (as in accordance with the Decree Law nº 83/2011); c) The indicated limits may be exceeded if they occur naturally.

5.4 Ecological indicators results

In this sub-chapter, in order to demonstrate the results of each ecological element and, subsequently, evaluate the interaction between them, it was considered relevant, firstly, to present the overall results associated with each dam. After this, at the end of this sub-chapter, a compilation of the ecological elements, considering all the results obtained within the study area, will be presented. The selection of the ecological elements will be done considering those: i) with more information, ii) that reveal significant changes throughout the time, and iii) that are likely to express a meaningful answer to flow alterations. These, ecological elements will be used to look for flow alterations and ecological conditions relationships.

In this section, results of the official indicators used to evaluate water bodies ecological status are shown, considering all the elements evaluated and measured in the selected locations.

Alto Rabagão

Table 32 – Results of biological indicators used to assess ecological water status/potential, for AR1 and AR2.

		2004				**2005**					**…**	**2009**				**2010**				**2011**				**2012**				**2013**				**2014**				**2015**				**2016**				**2017**				**2018**				**2019**				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AR1	**IPtI$_N$**		1.186														0.98										x		1.290				1.248				1.27				1.29				1.535				1.453							
	F-IBIP		0.848										0.854														x		0.818				0.840				0.896				0.973				0.898				0.896							
	IBMR			1.10									1.12														x		0.99																											
AR2	**IPtI$_N$**		1.060														1.05										x		1.163				1.256				1.3				1.2				1.432				1.271							
	F-IBIP		0.00*										0.173														x		0.025				0.070				0.127				0.015				0.012				0.081							
	IBMR			1.21									1.19														x		1.05																											

* This value should be perceived with careful since the percentage of Gobio Lozanoi (exotic) was 95.7% of the total number of species captured.

Table 33 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for AR1. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

			2004				2005				…		2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019			
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
	DO		11.29														9.4	7.7	9	10.1							x		8.4	10.0	10.7	10.5	11.2	9.2	9.5	11.8	10.7	9.8	9.6	12.0	9.5	8.1	9.9	11.5	10.0	8.7	10.9	15.6	10.5	10.1	10.4					
	DOSR		115.6														98	89.8	87.3	95.6							x		78.2	113.5	103.3	97.6	112	105.0	85.0	104.0	107	108.0	96.3	113	103	87.1	95.2	97	105	97	105	133	104	106	100					
	BOD		10														1.2	0.5	0.7	1.5							x		< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.0	1.0	< 1.0	< 1.0	1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.2	< 1.0	< 1.0	1.1	< 1.0	< 1.0	< 1.0					
	pH		5.8														6.9	6.9	6.7	6.5							x		6.7	6.8	6.5	6.7	6.2	6.6	6.6	6.9	6.8	6.6	6.4	6.7	7.1	6.4	6.7	6.6	6.8	6.3	6.4	6.7	6.9	6.7	7.1					
AR1	**NH3-N**		0.20														< 0.05	< 0.05	< 0.05	< 0.05							x		< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.1	0.06	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.06	< 0.05	< 0.05					
	NO_3^-		0.6														0.3	0.5	0.8	1.5							x		0.5	0.6	1.2	1.3	0.6	0.6	0.8	0.6	0.6	1.2	0.7	1.0	0.5	0.5	1.1	1.5	0.9	0.6	0.8	0.5	0.8	0.5	0.9					
			a)														0.8												0.9				0.7				0.9				0.9				0.7				a)							
	TP		0.10														0.0111	0.0137	0.0140	< 0.0098							x		< 0.010	0.010	< 0.010	< 0.010	< 0.010	0.010	0.010	< 0.010	0.008	0.011	0.011	0.011	0.009	0.009	0.011	0.006	0.007	0.010	0.011	0.009	0.012	0.010	0.012					
			a)														< 0.012												< 0.010				< 0.010				0.010				0.009				0.009				a)							

a) The mean annual value (and consequently classification) were not calculated since there were only one value (for 2004) and three values (for 2018).

Table 34 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for AR2. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

			2004				**2005**				…		**2009**				**2010**				**2011**				**2012**				**2013**				**2014**				**2015**				**2016**				**2017**				**2018**				**2019**			
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AR2	**DO**		11.4														9.9	7.5	10.7	10.4							x		9.2	8.9	10.3	10.6	10.3	8.5	9.4	11.5	11.2	8.6	9.8	11.8	9.5	7.8	9.2	10.9	9.3	9.3	10.4	13.2	11.7	7.9	9.7					
	DOSR		120														96.7	88.4	102	98.5							x		86.9	99.5	99.2	97.1	107	96.0	84.0	101	111	94.9	98.4	109	101	85.8	88.0	91.5	99	104	98	111	120	82	92					
	BOD		10														0.8	0.6	0.7	1.5							x		< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.5	< 1.0	1.2	< 1.0	< 1.0	< 1.0	< 1.0	1.1	< 1.0	< 1.0	1.1	< 1.0	< 1.0	< 1.0					
	pH		5.0														6.9	6.8	6.7	6.6							x		6.7	6.7	6.7	6.6	6.2	6.4	6.6	6.8	6.8	6.5	6.4	6.7	6.9	6.4	6.6	6.5	6.8	6.1	6.3	6.6	7.0	6.5	7.0					
	NH3-N		0.20														< 0.05	0.05	< 0.05	< 0.05							x		< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.06	0.24	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.06	< 0.05	< 0.05	0.06	< 0.05	< 0.05					
	NO_3^-		0.6														0.4	0.6	0.5	0.8							x		0.5	0.6	0.7	0.8	0.5	0.6	0.5	0.5	0.5	0.5	0.4	0.8	< 0.3	0.4	0.5	1.0	0.6	0.6	0.5	0.5	0.3	0.6	1.4					
			a)														0.6												0.7				0.5				0.6				< 0.6				0.6				a)							
	TP		0.10														< 0.0098	0.01435	< 0.0097	0.0153							x		< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	0.010	0.010	< 0.010	0.008	0.009	0.009	0.009	0.011	0.007	0.008	0.007	0.008	0.013	0.007	0.006	0.010	0.017	0.017					
			a)														< 0.012												< 0.010				< 0.010				0.009				0.008				0.009				a)							

[a] The mean annual value (and consequently classification) were not calculated since there were only one value (for 2004) and three values (for 2018).

Venda Nova

Table 35 – Results of biological indicators used to assess ecological water status/potential, for VN1.

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
VN1	**IPtI$_N$**																1.04								0.979				0.792				0.966				0.992												x							
	F-IBIP												0.781*												0.641				0.798				0.772				0.775												x							
	IBMR												1.30												0.95								0.92																x							

*This value was calculated based on the information collected within the study of AQUALOGUS (2010). In fact, for the same period it was possible to calculate F-IBIP using the information provided by ICNF (regarding the Aquariport study), being possible to obtain a F-IBIP of 0.805. Nevertheless, since for the same period (Sp 2009) the information provided for the macrophytes (expressed by the IBMR) is from AQUALOGUS (2010), it was considered appropriate to use both values obtained from the same study.

Table 36 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for VN1. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
VN1	**DO**																10.6	7.8	10.0	10.8				12.7	10.9	9.6	10.6	11.6	10.4	9.4	10.2	11.8	10.1	9.6	10.1	12	9.5	9.6	11.3										x							
	DOSR																101	90.4	93.5	102				105.0	110	107.0	100.0	104	105	106.3	97.5	111	95	108	98.0	103	95	104	107										x							
	BOD																0.9	0.9	1.0	1.3				2.8	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	1.1	<1.0	<1.0	<1.0	1.1	<1.0	<1.0	<1.0	<1.0										x							
	pH																7.1	7.3	6.8	6.7				6.5	6.7	7.5	6.9	6.8	6.8	7.2	7.1	6.6	7.6	6.9	6.8	6.6	7.3	7.2	6.4										x							
	NH3-N																< 0.05	< 0.05	< 0.05	< 0.05				0.8	0.1	< 0.05	< 0.05	< 0.05	< 0.05	0.1	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05										x							
	NO_3^-																0.4	0.3	1.5	1.3				29.2	11.1	10.9	5.1	6.0	4.2	3.4	6.3	1.9	1.6	2.7	1.9	1.8	1.6	1.8	1.7										x							
																	0.9							14.1				5.0				2.0				1.7																				
	TP																< 0.00978	0.01435	< 0.00978	0.0127				< 0.01	< 0.01	0.02	< 0.01	0.02	0.02	0.02	< 0.01	< 0.01	0.022	0.020	0.009	0.008	0.007	0.009	0.008										x							
																	< 0.012							< 0.013				< 0.018				< 0.015				< 0.008																				

Alto Cávado

Table 37 – Results of biological indicators used to assess ecological water status/potential, for AC1C and AC2C.

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AC1C	**IPtI$_N$**						0.440																																						1.274											
	F-IBIP						0.333*																																						1.000											
	IBMR							0.99																																																
AC2C	**IPtI$_N$**						0.663																																						1.206											
	F-IBIP						0.644																																						0.456											
	IBMR							1.18																																																

* This value should be perceived with careful since the total number of species captured is small. In fact, there were 3 individuals of Pseudochondrostoma polylepis

Table 38 – Results of biological indicators used to assess ecological water status/potential, for AC1 and AC2.

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AC1	IPtI$_N$																1.16																												1.321											
	F-IBIP												1.000[b]																																1.000[a]											
	IBMR												1.19																																											
AC2	IPtI$_N$																1.29																												1.536											
	F-IBIP												0.871																																0.824											
	IBMR												1.26																																											

[a] This value should be perceived with careful since the total number of species captured (and also, identified until the level of species) is small. In fact, there were 5 individuals of Salmo trutta and n=1 Cyprinidae N.I.

[b] This value was calculated based on the information collected within the study of AQUALOGUS (2010). In fact, for the same period it was possible to calculate F-IBIP using the information provided by ICNF (regarding the Aquariport study), being possible to obtain the same value of the represented F-IBIP. As explained before, since for the same period (Sp 2009) the information provided for the macrophytes (expressed by the IBMR) is from AQUALOGUS (2010), it was considered appropriate to use both values obtained from the same study.

Table 39 – Results of biological indicators used to assess ecological water status/potential, for AC3.

		2004				**2005**					**…**	**2009**				**2010**				**2011**				**2012**				**2013**				**2014**				**2015**				**2016**				**2017**				**2018**				**2019**				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AC3	**IPtI$_N$**																																												1.439											
	F-IBIP																																												0.750*											
	IBMR																																																							

* This value should be perceived with careful since the total number of species captured is small. In fact, there were 2 individuals of Pseudochondrostoma duriense. The EDP reported that this might happen since the sampling efficiency of fishes (electric fishing) was very low due to the characteristics of this fluvial section (in terms of hydromorphology and conductivity).

Table 40 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for AC1C. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AC1C	**DO**						9.87																																			10.0	10.0	11.3	9.5											
	DOSR						110																																			98.4	94.5	86	99											
	BOD						4.00																																			< 1.0	< 1.0	1.0	< 1.0											
	pH						6.5																																			7.0	6.7	6.5	6.8											
	NH3-N						0.96																																			< 0.05	< 0.05	< 0.05	< 0.05											
	NO_3^-						1.7																																			1.3	0.6	0.9	0.7											
							a)																																			0.9														
	TP						0.09																																			0.012	0.010	0.003	0.016											
							a)																																			0.010														

a) The mean annual value (and consequently classification) were not calculated since there were only one value (for 2005).

Table 41 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for AC2C. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AC2C	DO						8.82																																			8.3	10.8	13.4	9.1											
	DOSR						94.5																																			87.7	99.1	101	96											
	BOD						2.00																																			1.0	1.0	1.4	< 1.0											
	pH						6.6																																			7.0	6.8	6.6	6.9											
	NH3-N						0.047																																			< 0.05	< 0.05	< 0.05	< 0.05											
	NO_3^-						0.74																																			0.3	1.7	2.0	1.1											
							[a]																																			1.3														
	TP						0.004																																			0.07	0.09	0.012	0.06											
							[a]																																			0.058														

[a] The mean annual value (and consequently classification) were not calculated since there were only one value (for 2005).

Table 42 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for AC1. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AC1	DO																8.9	8.6	9.7	10.6																						10.3	9.6	11.1	9.6											
	DOSR																94.9	87.5	91.5	98.3																						96.3	91.4	88	98											
	BOD																0.9	0.6	0.7	1.3																						< 1.0	< 1.0	< 1.0	1.1											
	pH																6.8	6.9	6.8	6.5																						6.7	6.7	6.6	6.5											
	NH3-N																< 0.05	< 0.05	< 0.05	< 0.05																						< 0.05	< 0.05	< 0.05	< 0.05											
	NO_3^-																< 0.3	0.4	< 0.3	< 0.3																						< 0.3	< 0.3	0.3	0.5											
																	< 0.3																									< 0.3														
	TP																< 0.0098	< 0.0098	< 0.0098	< 0.0098																						0.011	0.013	< 0.003	0.007											
																	< 0.010																									< 0.010														

Table 43 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for AC2. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				**2005**					…	**2009**				**2010**				**2011**				**2012**				**2013**				**2014**				**2015**				**2016**				**2017**				**2018**				**2019**				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AC2	**DO**																9.2	7.7	10.2	10.6																					8.9	10.8	13.0	9.6											
	DOSR																94.2	86.0	92.8	98.6																					90.1	99	94	89											
	BOD																1.0	0.8	0.8	1.2																					< 1.0	< 1.0	< 1.0	1.0											
	pH																7.0	6.9	6.8	6.6																					6.9	6.8	6.5	6.7											
	NH3-N																< 0.05	< 0.05	0.06	< 0.05																					< 0.05	< 0.05	< 0.05	< 0.05											
	NO_3^-																0.4	0.5	0.6	0.6																					0.5	< 0.3	0.9	0.7											
																	0.5																								< 0.7														
	TP																< 0.0098	0.0114	< 0.0098	< 0.0098																					0.010	0.008	< 0.003	0.005											
																	< 0.010																								< 0.006														

Table 44 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for AC3. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
AC3	**DO**																																									10.3	11.0	12.0	11.0											
	DOSR																																									105	102	96	111											
	BOD																																									< 1.0	1.0	< 1.0	1.3											
	pH																																									7.0	6.9	6.5	6.8											
	NH3-N																																									< 0.05	< 0.05	< 0.05	< 0.05											
	NO_3^-																																									1.0	0.6	1.0	0.8											
																																										0.9														
	TP																																									0.014	0.008	< 0.003	0.010											
																																										< 0.008														

Paradela

Table 45 – Results of biological indicators used to assess ecological water status/potential, for PL2 and PL3.

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
PL2	**IPtI$_N$**		1.04														1.00																1.063				1.338					1.111		x	1.00				0.96							
	F-IBIP		*										0.739																				0.900				0.970					1.000		x	0.991				1.00							
	IBMR			1.20									1.30																				1.20											x					1.12							
PL3	**IPtI$_N$**																1.07																1.217				1.35					1.18		x	1.03				0.69							
	F-IBIP												0.683																				0.975				0.855					0.592		x	0.514				0.604							
	IBMR												1.06																				1.17											x					1.20							

*Even though, this point was evaluated no individual were captured.

Table 46 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for PL2. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

			2004				2005				…		2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019			
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
PL2	**DO**		11.40														9.3	8.6	9.9	11.0													10.5	11.6	10.6	11.6	10.9	10.3	10.6	12.2	10.6	10.7	9.6	11.1 (x)	11.2	10.5	12.2	11.4								
	DOSR		123.0														95.6	96.1	96.3	102													102	122	96	103	106	111	106	109	96.2	109	91.5	94 (x)	116	107	113	104								
	BOD		10.0														0.9	0.9	0.8	1.6													< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.0	1.0	< 1.0	< 1.0	< 1.0 (x)	< 1.0	< 1.0	< 1.0	< 1.0								
	pH		6.30														7.0	7.0	6.6	6.7													7.0	6.8	6.9	6.6	6.9	6.8	6.7	6.7	6.8	6.8	6.9	6.5 (x)	7.2	6.2	6.8	6.3								
	NH3-N		0.200														< 0.05	< 0.05	< 0.05	< 0.05													< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.05	< 0.05	< 0.05	0.06	< 0.05	0.05 (x)	< 0.05	< 0.05	< 0.05	< 0.05								
	NO_3^-		0.6														0.4	0.3	2.0	0.6													0.4	0.5	0.5	0.4	0.3	0.6	0.5	0.7	0.3	0.5	0.7	1 (x)	0.9	0.7	0.9	0.7								
			a)														0.8																0.5				0.5				0.6				0.8											
	TP		0.10														< 0.00978	< 0.00978	0.0157	< 0.00978													0.005	0.01	0.02	0.004	< 0.003	0.004	0.005	0.006	0.004	0.008	0.006	< 0.003 (x)	0.007	< 0.003	0.005	0.007								
			a)														< 0.011																0.010				< 0.005				< 0.005				< 0.006											

a) The mean annual value (and consequently classification) were not calculated since there were only one value (for 2004).

Table 47 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for PL3. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				**2005**					…	**2009**				**2010**				**2011**				**2012**				**2013**				**2014**				**2015**				**2016**				**2017**				**2018**				**2019**				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
PL3	**DO**																9.7	8.6	10.3	10.8													9.8	8.5	9.9	12.0	11.1	9.7	10.7	12.0	11.1	10.5	9.9	14.7 (x)	10.2	10.5	11.1	12.3								
	DOSR																98.7	95.7	97.8	99.5													95	96	90	106	108	106	106	109	101	110	93.6	123 (x)	106	106	102	104								
	BOD																1.3	1.4	0.9	1.2													< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0 (x)	< 1.0	< 1.0	< 1.0	< 1.0								
	pH																6.9	7.0	6.7	6.7													7.0	6.8	6.9	6.5	6.9	6.8	6.8	6.8	6.8	6.9	6.9	6.5	7.1	6.2	6.8	6.4								
	NH3-N																< 0.05	< 0.05	< 0.05	< 0.05													< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.06	< 0.05	< 0.05	0.05	< 0.05	0.05 (x)	< 0.05	< 0.05	< 0.05	< 0.05								
	NO_3^-																0.6	1.0	2.0	0.6													0.6	0.6	0.6	0.5	0.5	0.9	0.5	0.9	0.4	0.5	0.8	1 (x)	0.8	1.0	0.9	0.8								
																	1.1																0.6				0.7				0.7				0.9											
	TP																< 0.00978	< 0.00978	0.0160	< 0.00978													0.006	< 0.01	0.01	0.003	< 0.003	< 0.003	0.006	0.005	< 0.003	< 0.005	< 0.005	< 0.003 (x)	0.007	< 0.003	0.006	0.007								
																	< 0.011																< 0.007				< 0.004				< 0.004				< 0.006											

Salamonde

Table 48 – Results of biological indicators used to assess ecological water status/potential, for SD1.

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
SD1	IPtI$_N$																0.53[b]				0.683				0.698				0.390				0.640				0.497				0.806 (x)				0.705				0.722							
	F-IBIP												0.119[a]				0.700				0.594				0.831				0.724				0.705				0.635				0.512 (x)				0.605				0.398							
	IBMR												1.13								0.87								0.87								0.93				0.92 (x)															

[a] This value should be perceived with careful since the total number of species captured is small. In fact, there were 4 individuals (one of Luciobarbus bocagei and three of Cobitis Paludica – this one, a translocated species).

[b] This value was obtained based on the database from EDP (related with the monitoring and evaluation of the reference conditions, in the sites selected by EDP). Nevertheless, it should be highlighted that, for the same year, there is also information from the 1st RBMPs. Based on the available database of this study, the value calculated of IPtI$_N$ was 0.426 (mediocre). Since most of the information is based on EDP monitoring programs, the value selected for IPtI$_N$ was the calculated based on their database. Nevertheless, it should be highlighted that the other information presented for fishes (F-IBIP) were obtained based on the one from the 1st RBMPs, since for that years, EDP did not monitored these organisms.

Table 49 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for SD1. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
SD1	**DO**																10.2	7.1	10	11.4	9.3	8.5	9.7	11.8	13.2	9.0	11.2	12.1	9.8	10.1	10.7	10.9	10.2	9.5	10.5	12.5	10	9.9	11.8	11.4	11.2 (x)	9.7	10.3	12.3	9.8	9.1	10.3	12.4								
	DOSR																95.8	87.8	91.6	102	107	88.5	93.6	97.6	132	104	104	109	102	121.6	97.8	103	101	117	100	107	105	111	111	101	109 (x)	111	101	105	103	95	100	107								
	BOD																0.6	0.8	1.1	1.4	0.9	0.8	< 0.5	1.2	< 1.0	< 1.0	< 1.0	1.4	< 1.0	< 1.0	1.6	1.0	< 1.0	< 1.0	1.3	< 1.0	< 1.0	1.0	< 1.0	< 1.0	< 1.0 (x)	< 1.0	< 1.0	1.2	< 1.0	< 1.0	< 1.0	1.0								
	pH																7.1	7.1	6.7	6.6	7.6	6.6	6.9	6.7	6.7	7.3	6.6	6.6	6.9	7.0	7.0	6.9	7.4	7.0	7.3	6.8	7.4	7.1	6.3	6.8	6.8 (x)	7.3	6.9	6.9	7.1	6.5	6.5	6.9								
	NH3-N																< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.2	< 0.05	< 0.05	< 0.05	0.1	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.07	< 0.05	< 0.05	< 0.05	0.06	< 0.05	0.07								
	NO_3^-																1.7	1.4	2.1	0.8	2.0	1.5	16.7	2.9	8.4	7.2	31.7	9.2	4.2	4.3	3.5	3.2	3.0	3.3	3.0	3.4	2.6	1.6	3.6	2.2	0.9	0.7	0.7	1.1	1.2	0.8	0.7	1.1								
																	1.5				5.8				14.1				3.8				3.2				2.5				0.9				1.0											
	TP																< 0.00978	< 0.00978	0.0183	0.0104	< 0.01	< 0.01	0.05	0.01	< 0.01	< 0.01	0.01	< 0.01	0.030	< 0.01	0.008	< 0.01	0.018	0.012	0.005	0.006	0.007	0.00554	0.007	0.003	0.005 (x)	< 0.003	0.005	0.004	0.008	0.005	< 0.003	0.007								
																	< 0.012				< 0.02				< 0.01				< 0.015				0.010				0.006				< 0.004				< 0.006											

Caniçada

Table 50 – Results of biological indicators used to assess ecological water status/potential, for CD1 and CD2.

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
CD1	IPtI$_N$		0.64														0.73																				1.10				0.84									x						
	F-IBIP		0.444																																		0.573				0.674									x						
	IBMR			1.28																																														x						
CD2	IPtI$_N$																0.92																				1.01				1.15									x						
	F-IBIP												0.947																								0.389				0.389									x						
	IBMR												1.23																																					x						

Table 51 – Results of biological indicators used to assess ecological water status/potential, for CD3.

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
CD3	**IPtI$_N$**																0.77																				0.91				0.84									x						
	F-IBIP																																				0.278				0.389									x						
	IBMR																																																	x						

Table 52 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for CD1. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
CD1	DO		10.9														10	8.5	9.9	10.9															11.1	11.1	9.9	9.3	11.4	12.2	9.6	9.9	10.7	12.2	10.0					x						
	DOSR		121.1														111	104	92.5	98.8															99.0	95.1	101	112	102.0	112	99.6	119	98.3	101	105					x						
	BOD		10														0.5	0.9	0.8	1.1															1.1	< 1.0	< 1.0	< 1.0	< 1.0	1.0	< 1.0	< 1.0	1.1	1.2	< 1.0					x						
	pH		6.3														6.6	7.0	6.6	6.5															6.6	6.7	6.8	7.0	6.7	6.5	6.7	7.7	7.1	6.7	6.9					x						
	NH3-		0.20														< 0.05	< 0.05	< 0.05	< 0.05															< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.07	< 0.05	< 0.05	< 0.05					x						
	NO_3^-		2.8														2.2	1.5	2.0	1.6															1.4	3.3	2.3	5.8	4.4	3.6	2.0	3.5	< 0.3	4.3	3.0					x						
			a)														1.8																		3.2				3.4				a)													
	TP		0.100														0.00978	0.0127	0.0157	< 0.0978															0.012	0.008	0.007	0.009	0.009	0.009	0.006	0.012	< 0.003	0.005	0.011					x						
			a)														< 0.012																		0.009				0.009				a)													

a) The mean annual value (and consequently classification) were not calculated since there were only one value (for 2004) and three values (for 2016/2017).

Table 53 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for CD2. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
CD2	DO																9.9	9.4	10.3	10.9															11.5	12.8	10.5	9.0	10.9	11.7	11.0	9.4	10.5	12.3	10.2					x						
	DOSR																103	106	94.9	97															101.0	109	100	100	100	107	107	105	97.4	104	104					x						
	BOD																0.9	2.2	0.9	1.1															1.3	< 1.0	< 1.0	1.3	< 1.0	1.0	< 1.0	1.3	1.3	1.4	< 1.0					x						
	pH																6.7	6.9	6.7	6.5															6.6	6.3	6.8	6.9	6.6	6.5	6.6	6.9	6.8	6.7	6.9					x						
	NH3-N																< 0.05	0.18	< 0.05	< 0.05															0.06	< 0.05	< 0.05	0.18	< 0.05	< 0.05	< 0.05	0.33	< 0.05	0.06	< 0.05					x						
	NO_3^-																2.2	3.4	2.0	2.1															1.0	2.2	1.9	4.4	1.8	2.2	1.3	3.6	2.5	3.2	2.1					x						
																	2.4																		2.4				2.2				a)													
	TP																0.0205	0.0613	0.0160	< 0.0098															0.013	0.007	0.009	0.040	0.005	0.007	0.011	0.06	0.023	0.017	0.013					x						
																	< 0.027																		0.017				0.021				a)													

[a] The mean annual value (and consequently classification) were not calculated since there were only three values (for 2016/2017).

Table 54 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for CD3. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
CD3	**DO**																9.4	9.4	9.7	10.8															11.7	12.6	10.0	8.1	12.5	11.3	10.4	9.1	11.5	12.4	9.5					x						
	DOSR																104	112	90.2	98.6															104	109	104	98.0	110	106	106	110	105	103	102					x						
	BOD																1.1	2.0	0.9	0.8															1.2	< 1.0	1.2	1.0	< 1.0	< 1.0	< 1.0	1.0	1.4	1.3	< 1.0					x						
	pH																6.7	7.0	6.7	6.5															6.6	6.6	6.8	7.1	6.5	6.5	6.5	7.0	6.6	6.7	6.9					x						
	NH3-N																0.07	0.07	< 0.05	< 0.05															< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.06	< 0.05	0.05	< 0.05					x						
	NO_3^-																2.8	0.9	2.8	2.5															1.6	3.7	2.7	2.4	3.6	3.7	2.2	2.2	3.3	4.0	2.4					x						
																	2.3																		2.6				2.9				a)													
	TP																0.0170	0.0222	0.0212	<															0.013	0.008	0.007	0.010	0.010	0.011	0.011	0.013	0.008	0.015	0.014					x						
																	< 0.018																		0.010				0.011				a)													

a) The mean annual value (and consequently classification) were not calculated since there were only three values (for 2016/2017).

Vilarinho das Furnas

Table 55 – Results of biological indicators used to assess ecological water status/potential, for VF1 and VF2.

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
VF1	IPtI$_N$																0.99																		x		1.16				1.18				1.221				1.046							
	F-IBIP																																		x		0.958				1.000				0.837				1.000[b]							
	IBMR																																		x			1.15																		
VF2	IPtI$_N$						1.02										1.12																		x		1.58				1.33				1.413				1.325							
	F-IBIP						0.979						0.996[a]																						x		1.000				1.000				1.000				1.000							
	IBMR							1.16					1.14																						x			1.05																		

[a] This value was calculated based on the information collected within the study of AQUALOGUS (2010). In fact, for the same period it was possible to calculate F-IBIP using the information provided by ICNF (regarding the Aquariport study), being possible to obtain a very similar value of the represented F-IBIP (0.993). As explained before, since for the same period (Sp 2009) the information provided for the macrophytes (expressed by the IBMR) is from AQUALOGUS (2010), it was considered appropriate to use both values obtained from the same study.

[b] This value should be perceived with careful since the total number of species captured is small. In fact, there were 6 individuals of Salmo trutta.

Table 56 – Results of biological indicators used to assess ecological water status/potential, for VF2b and VF3.

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
VF2b	**IPtI$_N$**		1.21																																x		1.02				1.22				0.886				0.930							
	F-IBIP		0.724										0.905																						x		0.380				0.402				0.197				0.193							
	IBMR			1.16									1.21																						x			0.84																		
VF3	**IPtI$_N$**		0.89														0.98																		x		1.16				1.21				1.153				1.059							
	F-IBIP		0.000																																x		0.390				0.464				0.397				0.667							
	IBMR			1.29																															x			0.94																		

Table 57 – Results of biological indicators used to assess ecological water status/potential, for VF3b.

		2004				**2005**					**…**	**2009**				**2010**				**2011**				**2012**				**2013**				**2014**				**2015**				**2016**				**2017**				**2018**				**2019**				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
VF3b	**IPtI$_N$**																																		x		0.85				0.88				1.036				0.859							
	F-IBIP																																		x		0.670				0.389				0.667				0.430							
	IBMR																																		x			0.96																		

Table 58 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for VF1. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
VF1	DO																10.1	8.9	10.3	10.8															x	11.8	10.9	10.8	10.9	12.6	11.6	10.9	12.2	12.5	10.9	10.7	12.9	11.8	10.9							
	DOSR																101	97.9	98.2	101															x	109	106	112	106	109	108	114	110	116	121	104	115	107	105							
	BOD																0.6	< 0.5	1.1	1.3															x	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.1	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0							
	pH																6.5	6.8	6.5	6.2															x	6.4	6.3	6.0	6.2	6.2	6.3	6.6	6	6.2	6.8	6.9	6.7	6.4	5.4							
	NH3-N																< 0.05	< 0.05	< 0.05	< 0.05															x	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.05	< 0.05	0.08	< 0.05	< 0.05							
	NO_3^-																0.3	0.5	< 0.3	1.6															x	0.5	0.4	0.6	0.6	0.7	0.4	0.4	0.7	0.8	0.9	1.2	0.6	0.8	0.7							
																	< 0.7																			0.5				0.6				0.9				a)								
	TP																< 0.0098	< 0.0098	< 0.0098	< 0.0098															x	< 0.003	0.005	< 0.003	0.010	0.006	0.005	< 0.003	0.006	< 0.003	0.006	0.006	0.007	< 0.003	< 0.003							
																	< 0.010																			< 0.005				< 0.005				< 0.006				a)								

Table 59 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for VF2. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
VF2	DO						9.89										10.3	8.5	9.8	10.7															x	12.6	9.2	10.5	10.7	12.3	11	10.4	11.7	11.6	9.8	9.8	11.4	11.8	11.1							
	DOSR						97.1										106	94.8	93.6	98.5															x	116	93	113.0	103	110	105	113	107	109	104	98	100	108	108							
	BOD						5.0										0.9	0.8	1.1	1.6															x	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.2	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0							
	pH						6.9										6.9	6.8	6.6	6.5															x	6.7	6.5	6.1	6.5	6.3	6.4	6.7	6.5	6.7	6.7	6.8	6.8	6.8	5.9							
	NH3-N						0.005										< 0.05	< 0.05	< 0.05	< 0.05															x	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.06	< 0.05	< 0.05	< 0.05	< 0.05							
	NO_3^-						0.88										1.2	1.2	1.8	1.5															x	1.0	1.0	1.0	1.3	1.5	0.8	1	1.1	1.3	1.7	1.7	1.1	1.5	1.1							
							a)										1.4																			1.1				1.1				1.5				a)								
	TP						0.0044										0.0238	< 0.0098	0.0130	< 0.0098															x	0.005	0.006	0.005	0.013	0.008	0.004	0.009	0.007	0.007	0.009	0.007	0.007	0.005	0.005							
							a)										< 0.014																			0.007				0.007				0.008				a)								

Table 60 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for V2b. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
VF2b	**DO**		11.98																																x	11.7	10.5	8.9	11.5	12.4	12	9.9	10.9	12.0	9.1	9.5	11.8	11.9	11.5							
	DOSR		127.9																																x	108	104	98	110	112	108	109	98.7	113	99	98	100	109	113							
	BOD		10																																x	1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.2	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0							
	pH		5.7																																x	6.7	6.4	6.3	6.5	6.4	6.7	6.8	6.6	6.8	6.8	6.7	6.8	6.8	5.9							
	NH3-N		0.200																																x	< 0.05	< 0.05	0.07	0.1	< 0.05	< 0.05	0.06	< 0.05	< 0.05	0.07	< 0.05	< 0.05	< 0.05	< 0.05							
	NO_3^-		1.6																																x	1.7	1.6	2.0	1.9	2.2	1.4	1.9	2.0	1.9	2.4	2.0	1.8	1.9	1.7							
			a)																																	1.8				1.9				2.0				a)								
	TP		0.100																																x	0.010	0.008	0.016	0.017	0.008	0.009	0.017	0.014	0.009	0.016	0.010	0.024	0.005	0.007							
			a)																																	0.013				0.012				0.015				a)								

Table 61 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for VF3. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
VF3	**DO**		9.23														9.5	7.6	10	10.4															x	11.8	10.9	9.0	11.5	11.6	11.5	9.9	10.8	11.8	9.5	9.2	11.9	11.7	11.9							
	DOSR		92.8														97.6	87.9	94.2	94.5															x	109	112	102	110	106	113	112	98.4	110	107	98	99	109	117							
	BOD		10														0.6	0.8	0.5	1.0															x	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.4	< 1.0	1.1	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0							
	pH		6.2														6.9	6.7	6.7	6.6															x	6.7	6.4	6.3	6.4	6.4	6.6	6.8	6.6	6.8	6.8	6.7	6.8	7.0	6.9							
	NH3-N		0.200														< 0.05	< 0.05	< 0.05	< 0.05															x	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.05	< 0.05	0.06	< 0.05	< 0.05	< 0.05	< 0.05							
	NO_3^-		2.3														2.3	2.2	2.4	3.1															x	2.3	2.1	2.6	2.5	3.3	2.2	2.4	2.5	2.6	2.8	2.5	2.1	2.6	2.5							
			a)														2.5																			2.4				2.6				2.5				a)								
	TP		0.100														0.0254	0.0183	0.0212	< 0.0098															x	0.008	0.008	0.013	0.022	0.009	0.006	0.013	0.011	0.007	0.014	0.012	0.018	0.008	0.007							
			a)														< 0.019																			0.013				0.010				0.013				a)								

Table 62 – Results of chemical and physicochemical indicators used to assess ecological water status/potential, for VF3b. Where: DO- dissolved oxygen (mg/L); DOSR- dissolved oxygen saturation rate (%); BOD – biological oxygen demand (mg O_2/L); pH; NH3-N – ammoniacal nitrogen (mg NH_4/L); NO_3^- – nitrate (mg NO_3/L); TP– total phosphorus (mg P/L).

		2004				2005					…	2009				2010				2011				2012				2013				2014				2015				2016				2017				2018				2019				
		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi		Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi	Sp	Su	Au	Wi
VF3b	DO																																		x	11.4	9.9	8.6	11.6	11.9	12.2	9.2	10.6	11.1	8.6	8.2	11.3	11.7	11.3							
	DOS																																		x	107	107	100	112	110	113	110	98.7	107	101	90	95	110	113							
	BOD																																		x	1.2	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.1	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0							
	pH																																		x	6.8	6.6	6.4	6.5	6.4	6.6	6.8	6.7	6.8	6.7	6.7	6.9	6.7	6.2							
	NH3-N																																		x	0.1	0.11	0.26	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.06	< 0.05	< 0.05	< 0.05	< 0.05							
	NO_3^-																																		x	4.8	4.4	4.5	4.2	5.5	4.3	4.2	4.5	4.6	4.5	3.3	3.4	4.3	4.3							
																																				4.5				4.6				4.0				a)								
	TP																																		x	0.028	0.033	0.070	0.04	0.009	0.011	0.018	0.012	0.009	0.016	0.017	0.013	0.011	0.011							
																																				0.043				0.013				0.014				a)								

5.5 Qualitative analysis and discussion of the ecological indicators results

In this sub-chapter, an overall analysis – in terms of the qualitative status of the ecological indicators – will be provided. This analysis was performed, mainly to answer the following research questions:

1) Are significant changes in the evolution of water bodies status (in terms of biological and physicochemical parameters) throughout the time?
2) Is there a modification of those status after the release of environmental flows?
3) Are similarities, throughout the time, in the values obtained for the selected sites located downstream each dam?
4) For a certain period, is it possible to perceive a spatial pattern of modification as we go downstream the river?

Firstly, the analysis of the variations of the biological indicators will be provided and discussed, then, for the other elements used to assess ecological status/potential. It should be highlighted that, a quantitative analysis and discussion of the ecological results will be conducted in the next chapter, together with the evaluation of a cause-effect relationship of these values with flow conditions.

Macroinvertebrates

Through a qualitative analysis of the results, as a result of an overall analysis, regarding the macroinvertebrates indicator (the $IPtI_N$), it was possible to verify that there was no significant variability in the quality conditions over time. In fact, for some locations (with more than three values), such as AR1, AR2, PL2, CD2, VF1, VF2, VF2b, VF3, the indicator always expressed an “Excellent” condition, throughout the time. This was also the case for the sites evaluated downstream Alto Cávado (AC1, AC2 and AC3), although for these locations, the macroinvertebrate samplings were less than three (and, therefore, these results should be viewed with caution). The sites VN1, PL3, CD3 and VF3b, have a considerable majority of indicators with the classification equal to “Excellent”, existing some values whose classification is “Good”. The site with worse conditions, ranging from “Poor“ to “Good”, and a greater variability on the results throughout the time is the SD1, followed by CD1 (with values varying between “Moderate to “Excellent”).

In relation to the research question number 2, firstly, it should be highlighted that there was ecological information before and after environmental flows release only for the sites downstream Alto Rabagão (AR1, AR2), Paradela (PL2, PL3), Salamonde (SD1) and Vilarinho das Furnas (VF1, VF2, VF2b, VF3 and VF3b). Moreover, only for the sites located downstream Alto Rabagão and Vilarinho das Furnas, there were more than three values since the release of environmental flows started earlier for these locations. As previously referred, for both sites located downstream Alto Rabagão dam (AR1, AR2), also for PL2, and, for most of the sites downstream the Vilarinho das Furnas dam (VF1, VF2, VF2b, VF3), the macroinvertebrate indicators were always equal to "Excellent", either before and after environmental flows release. For the site VF3b, since this site was sampled only after the environmental flows release, it was not possible to assess the differences between and after environmental flows implementation. Relating to the PL3 (the most downstream point of the Salamonde dam), it was possible to verify that after the release of the environmental flows, the biological quality class remained "Excellent" (in fact, this status was always the one obtained before the release of environmental flows), however, in the third year of sampling the biological quality class decreased to the "Good" status. In fact, if the latest value of $IPtI_N$ is evaluated in quantitative terms, it is possible to perceive that there is a decrease in this value, as for PL2 (however, in this case, despite the decrease in quantitative terms, the obtained $IPtI_N$ value remained in the category of "Excellent"). This may lead to ask if this decrease, in the year 2018, is related to the environmental flows release (which was not expected) or was linked with other type of modification occurring in the freshwater system. Regarding the SD1, the site being pointed out as with more diverse and worst conditions (ranging from "Poor" to "Good" as previously referred), and also as the site with the most frequent macroinvertebrate sampling over time, it was possible to recognize that after the release of environmental flows there was an overall improvement of the quality condition, being all the values equal to "Good" (which was not the case before the release of environmental flows, where there were $IPtI_N$ values associated with "Poor" and "Moderate" conditions). As for the case of the behavior in the PL2, in order to perceive this, more information of the next sampling monitoring programs should be assessed. Based on the overall information, it was not possible to recognize a clear effect of environmental flows in the water quality values provided by macroinvertebrates.

Concerning the research question number 3 it was possible to perceive similar conditions between the sites of the same group, more evident for the sites related with the Alto Rabagão (AR1 and AR2) and Alto Cávado (AC1, AC2 and AC3). Also, it was possible to verify, in spatial terms, an overall similarity between the values obtained for Paradela (PL2 and PL3) and the values obtained for Vilarinho das Furnas (VF1, VF2, VF2b, VF3 and VF3b), being possible to observe by comparing the quality classes obtained, slightly worse quality classes for the most downstream points of each group (i.e. PL3, in the case of Paradela, and VF3b, in the case of Vilarinho das Furnas). Moreover, it should be pointed out that, comparing the results obtained in the upstream and downstream sites of the Alto Cávado dam, there were some differences in the quality classes obtained, reaching, in some cases, worse classifications in the upstream sites (which would not be expected). However, it should be noted that the amount of information, per point, is inferior to three values, reason why those results should be, therefore, analysed with caution.

In terms of the research question 4, related with the perception of a spatial pattern of modification as we go downstream the river, it was possible to perceive that, in a general way, more values linked with inferior quality classes are identified as we go downstream, being the situation in Salamonde and Caniçada the ones that present inferior quality classes.

Fish

Through the analysis of the results, it is possible to verify that the F-IBIP presents a variability of quality classes much higher than those presented for $IPtI_N$, showing quality values between “Bad” and “Excellent”. In general, through the indicators used, the fish quality of the river is worse than the quality of the macroinvertebrate community. This may be related to the presence of exotic species, which lower the value of the index.

By analysing the results of AR1, AC1, AC2, PL2, VF1 and VF2 over time (research question 1), the overall F-IBIP values obtained mainly reflect quality classes of “Excellent”, being the sites with overall better quality conditions. It may seem that better conditions, at least for these sites, are closer to the dam.

Regarding the sites VN1, AC3, PL2, all the values present quality values higher or equal to “Moderate” conditions.

On the other hand, there is another set of sites (AR2, AC2C, CD1, CD3, VF3, VF3b) where the F-IBIP values always express quality values below or equal to the “Moderate” condition. Within this set, the site with worst conditions is AR2 (presenting over time quality classes always equal to “Bad”). This may be related to the fact that, in this place, the percentage of exotic species is very high. Recall that the percentage of exotic species is considered for the calculation of the overall indicator, impacting the overall value of this indicator.

It was also possible to verify that the SD1 and VF2b sites are those ranging a greater variability in the quality classes obtained, showing, respectively, variation from “Bad” to “Good” status and from “Bad” to “Excellent”. In the case of the site CD2, throughout the time there was a decrease on the quality class of “Excellent” to “Poor”.

Finally, it should be highlighted that for those sites with a very small number of values the analysis of the results should be considered with caution (as such for the sites associated with the Alto Cávado dam).

Concerning the effects of environmental flows on the quality classes obtained, it was not possible to identify a cause-effect relationship between the release of environmental flows and a potential improvement on the quality classes (research question 2). In fact, as mentioned above, there was a significant variability on the quality classes obtained with no trend over time clearly observed, or even a trend related to the release of environmental flows. In fact, different behaviors can be highlighted, such as: i) no modification of quality classes over time (and thus maintenance of quality classes either before or after the release of environmental flows) – AR1 and VF2; ii) a worsening of the quality classes obtained over time, with even lower quality classes of F-IBIP, during or after environmental flows releases – PL3 and VF2b.

In relation to research questions 3 and 4, it can be noted that, overall, as already mentioned, there is a great variability in the quality classes obtained, with no predominantly evidence of similarity between the sites located downstream of each dam, or even a consistent pattern of modification along the river.

Macrophytes

Regarding the values obtained for IBMR, a significant consistency can be highlighted in the quality classes obtained, existing many values in the ecological quality "Excellent" and only a few values with a "Good" condition – sites SD1 and VF2b. Furthermore, it can be noted that in relation to SD1 there is no trend in the quality classes obtained, and for point VF2 there is a decrease in the quality class (from "Excellent" to "Good"). However, it should be perceived that these results should be analyzed with caution, since the quantity of existing values is quite scarce, being in most cases less than or equal to three).

General chemical and physicochemical elements

Through the analysis of the chemical and physico-chemical parameters supporting the biological elements, it was possible to verify that most of the parameters suggest a "Good" chemical and physicochemical status. Only a few values express a lower quality class, however, these are extremely close to the threshold of "Good" status. As such, these scarce values are not considered significant.

6. FORMULATION OF HYDROLOGIC ALTERATION-ECOLOGICAL RESPONSES RELATIONSHIPS

6.1 Introduction

In the following sub-chapter (6.2) the methods applied to try to define relationships between hydrologic alteration and ecological responses are described. Then, in sub-chapter 6.3 the results obtained, as well as, an analysis and discussion of the results are presented.

6.2 Methods for the assessment of hydrologic alteration – ecological responses

In order to assess the existence of a cause-effect relationship between the hydrological alteration and the ecological condition, several steps were carried out.

The first step was to evaluate the hydrological alteration and the ecological conditions for a certain period. The procedures carried out to define the natural and modified hydrological conditions, for each of the selected sites, have already been described previously in chapter 4. In that chapter, the existing hydrological alteration for the period before and after the release of environmental flows has also been presented. It should be noted, however, that in order to establish a cause-effect relationship between the hydrological change and the ecological condition, it was recognized suitable to consider the mean values of the hydrological change for the year immediately before the date of the ecological sampling. That is, for example, if ecological sampling took place in May 2015, then the hydrological alteration from May 2014 until April 2015 was considered. This was done in order to describe the existing hydrological variability, and the possible ecological response to this variability. In terms of the representation of ecological responses (i.e. the ecological conditions), it was considered relevant to assess these responses using the official/normative indicators normally used for the assessment of the biological status of water bodies. It was therefore considered appropriate to look for links between the hydrological alteration and each one of the biological indicators assessed ($IPtI_N$, F-IBIP and IBMR). Thus, graphs were drawn of mean annual hydrological change vs. ecological indicator, for each one of the selected sites. These graphs were used to check whether there is a cause-effect relationship between the hydrological change and the biological indicators, that is, whether there are any quantitative relationships between the evaluated variables. It should be pointed out, that in this chapter the information related with the general chemical and physicochemical indicators, as well as, the hydromorphological indicators, were not considered.

It should also be noted that, after evaluating the cause-effect relationships per selected site, an attempt was made to aggregate, for each indicator, the available biological information considering the river typology to which the sampling point belongs. In fact, according to the work developed within the scope of the WFD implementation, river typologies (i.e. rivers with relatively homogeneous geographical and hydrological characteristics, considered relevant for the definition of ecological conditions) were developed in order to establish an ecological reference condition enabling the classification of water bodies status.

In the following sub-chapter 6.3, the results obtained are presented, as well as, an analysis and discussion of them. It should be noted that it has been established as a criterion that those graphs whose points sampled are less than three will not be presented, since the number of values is not significant enough to draw conclusions.

6.3 Hydrological alteration – ecological responses

In this sub-chapter, as mentioned before, the results obtained concerning the attempt to define cause-effect relationships between the hydrological alteration and the ecological response (expressed through the biological indicators) is presented. The results and relationships obtained (and corresponding analysis and discussion) will be specified, first in terms of the macroinvertebrates ($IPtI_N$), then, of fish communities (F-IBIP), and, finally, of the macrophytes (IBMR).

Before the presentation of the results, their analysis and discussion, some research hypotheses or considerations that might be expected regarding the results should be emphasized. These are the following:

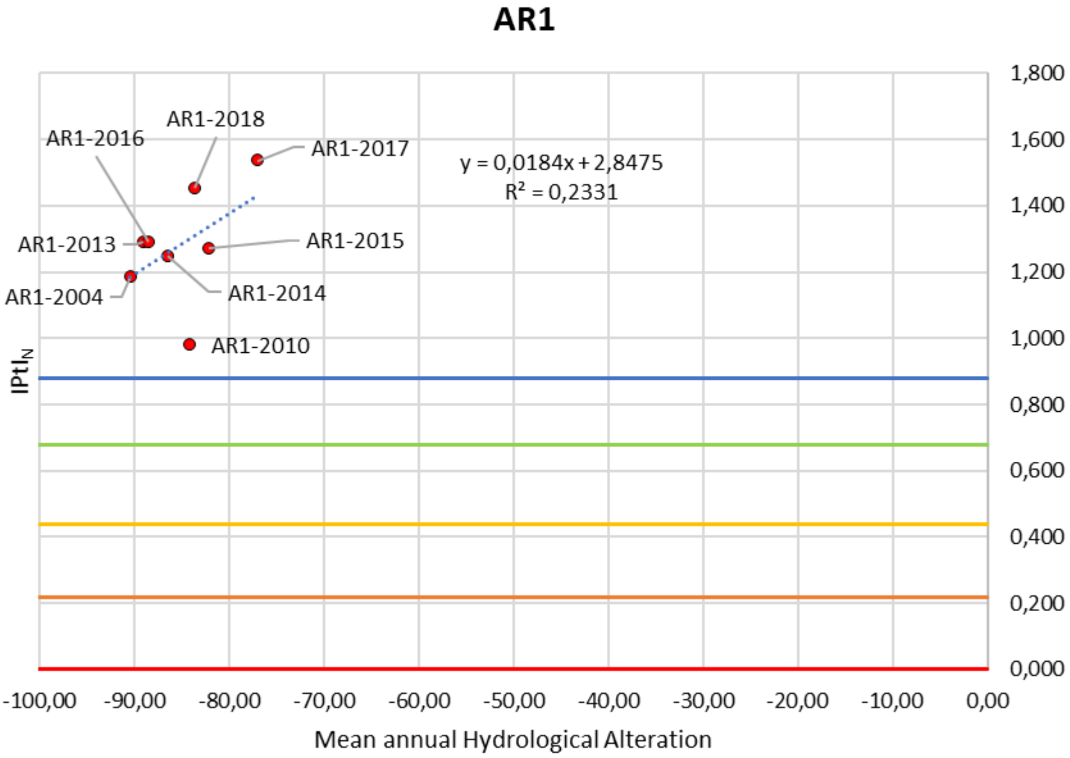
1) It would be expected that after the release of environmental flows the values of the biological indicators would improve compared to the indicators evaluated in periods before environmental flows releases.
2) The greater the hydrological alteration (i.e. the greater the difference between the current flow regimes and the ones that would exist if there are natural conditions) the greater the likely impact on freshwater ecosystems, i.e., biological indicators with values associated to worse ecological conditions would be expected. In other words, as the hydrological alteration values increases, biological indicators values are expected to decrease.

Hydrological alteration vs. Macroinvertebrates ($IPtI_N$)

Hereinafter (Figure to Figure 56), the graphs and relationships obtained considering the hydrological alteration and the macroinvertebrates are presented. Figure 57, reveal the results obtained based on the aggregation of information of the sampling points included in the river typology N1>100. It should be highlighted that, in those Figures, the minimum threshold associated with the $IPtI_N$ biological quality classification (accordingly with the valued presented on Table 31) are indicated.

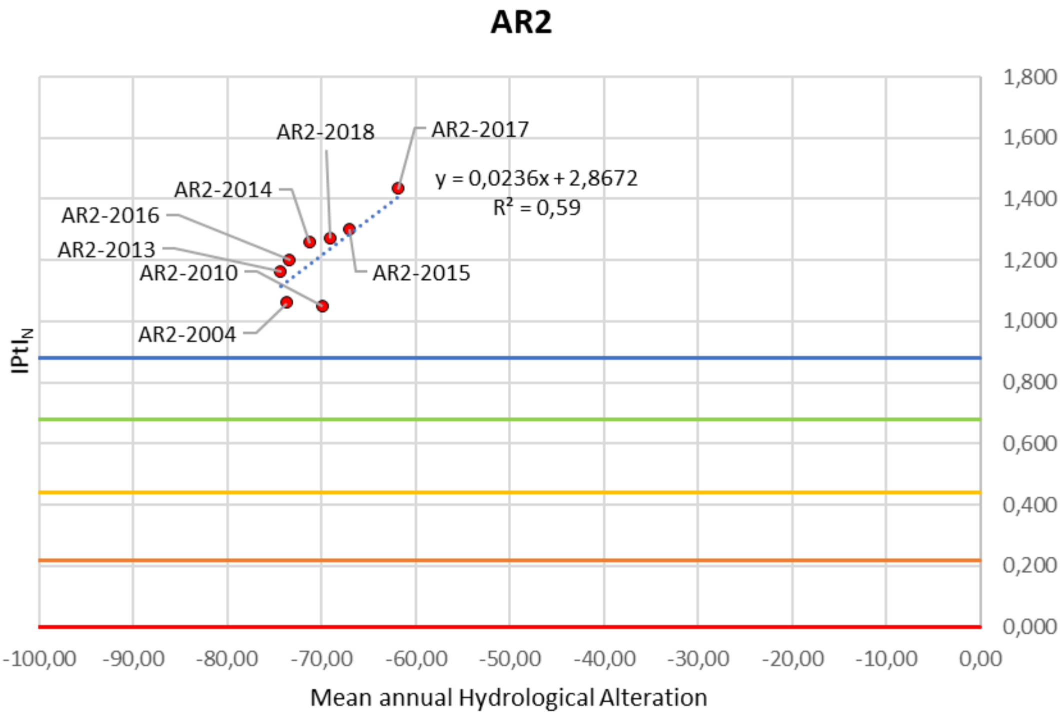
Legend:

●	Information for the selected sites
🟦	High status
🟩	Good status
🟨	Moderate status
🟧	Poor status
🟥	Bad status



a)

Figure 51a – Hydrological alteration vs. $IPtI_N$ for sites downstream Alto Rabagão dam: a) AR1, b) AR2.



b)

Figure 51b – Hydrological alteration vs. IPtI$_N$ for sites downstream Alto Rabagão dam: a) AR1, b) AR2

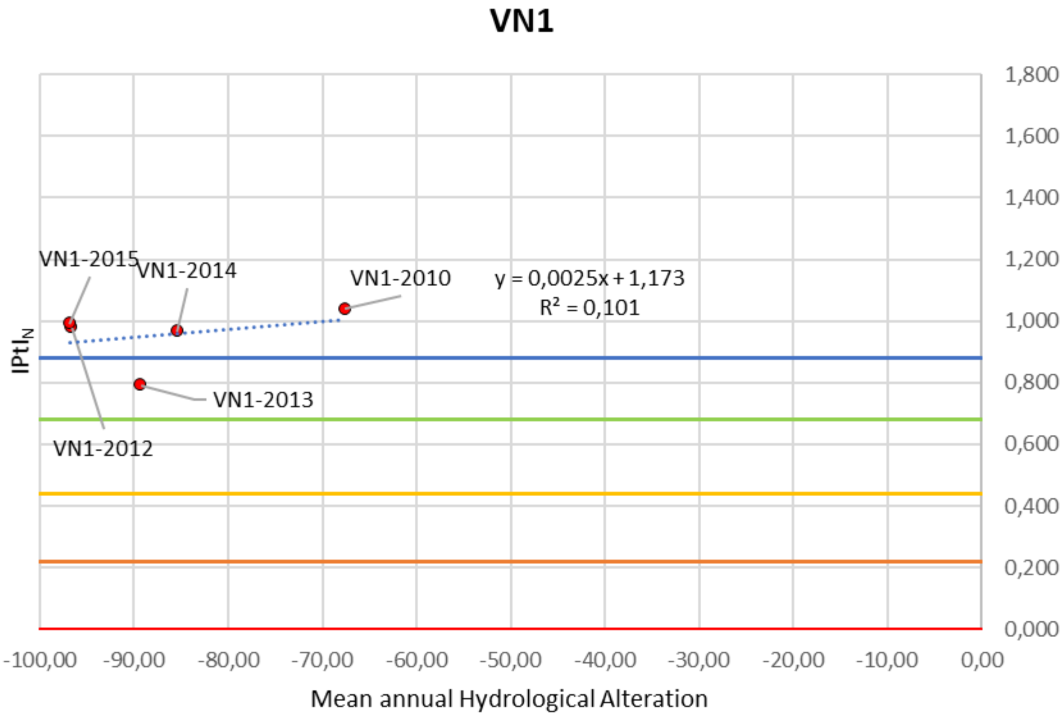
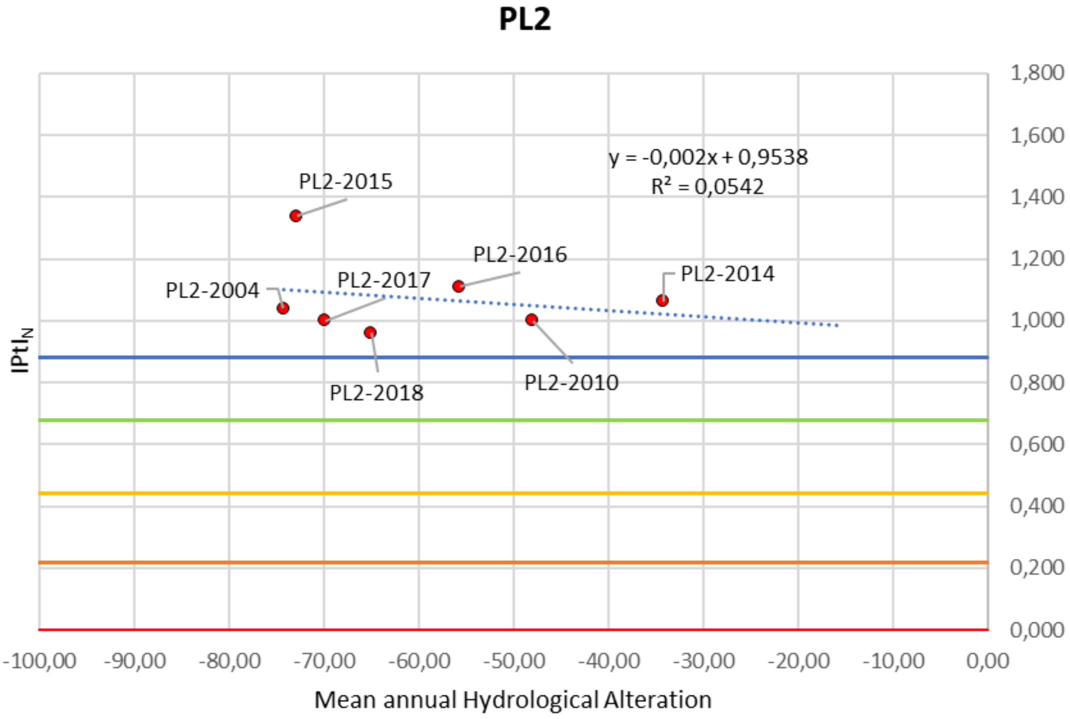
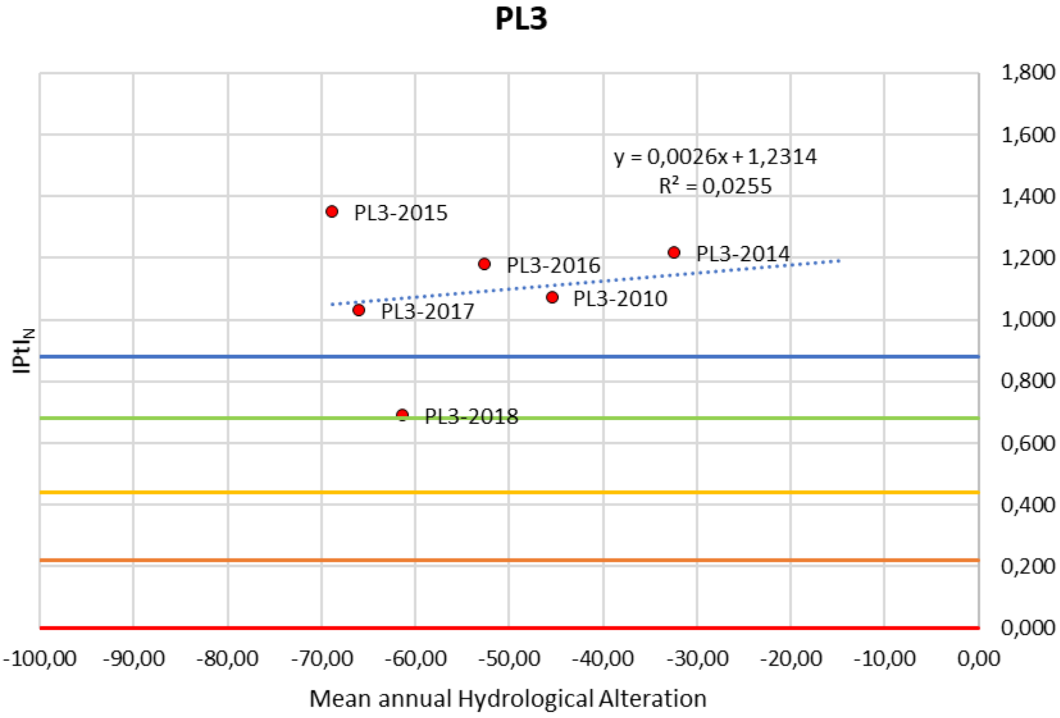


Figure 52 – Hydrological alteration vs. IPtI$_N$ for site downstream Venda Nova dam: VN1



a)



b)

Figure 53 – Hydrological alteration vs. IPtI$_N$ for sites downstream Paradela dam: a) PL2, b) PL3.

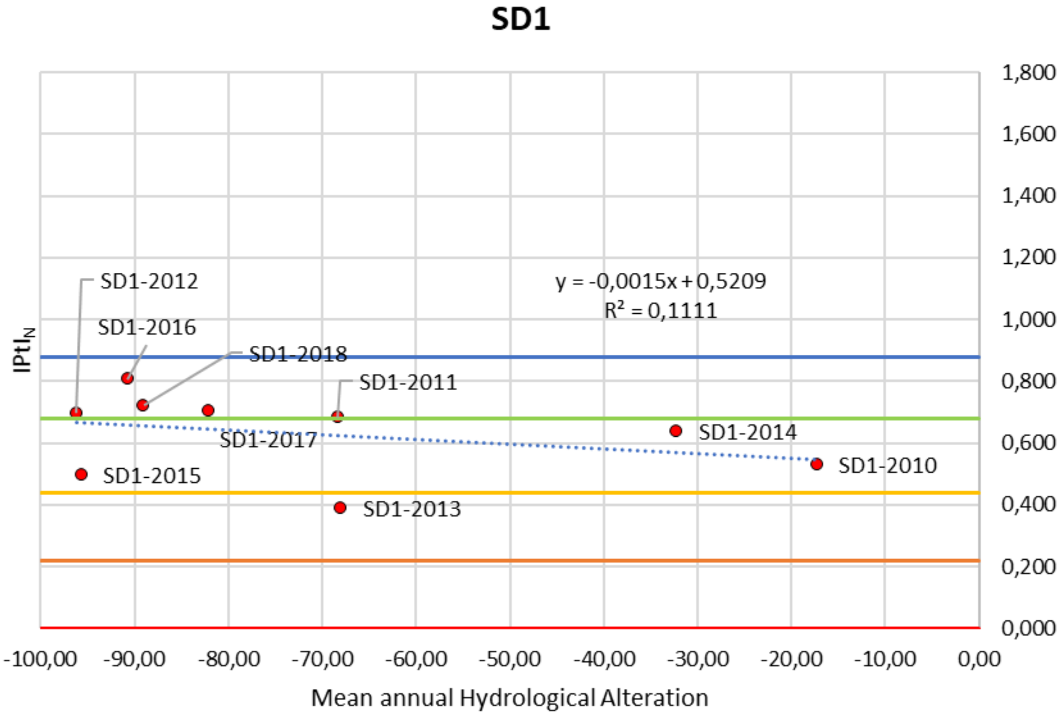
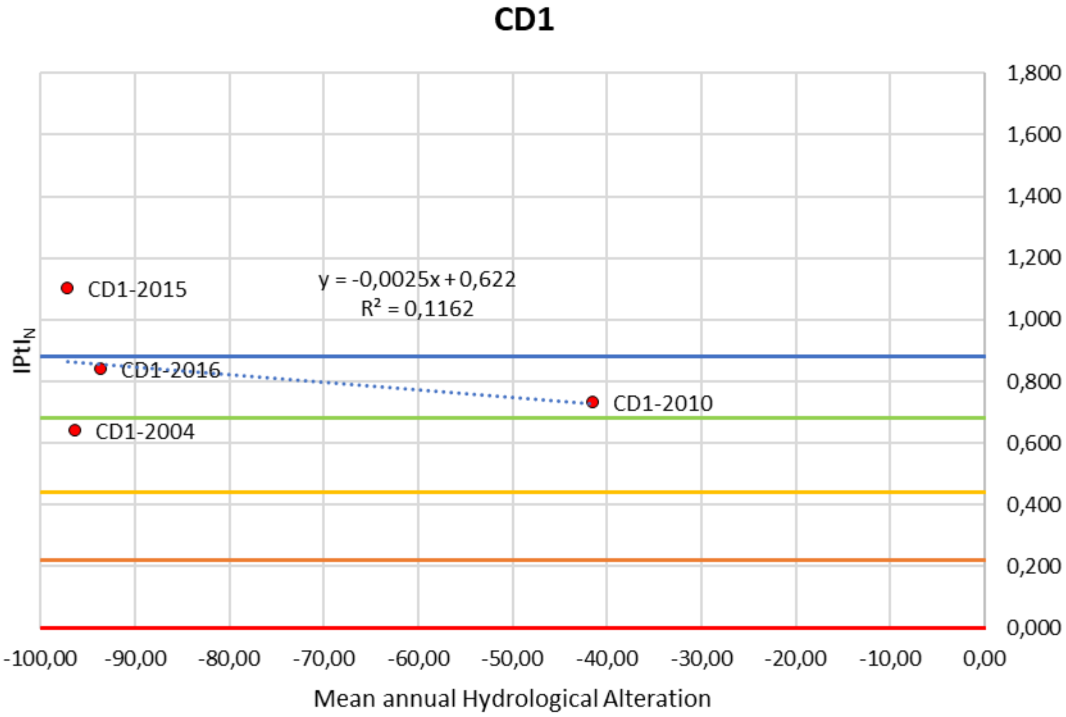
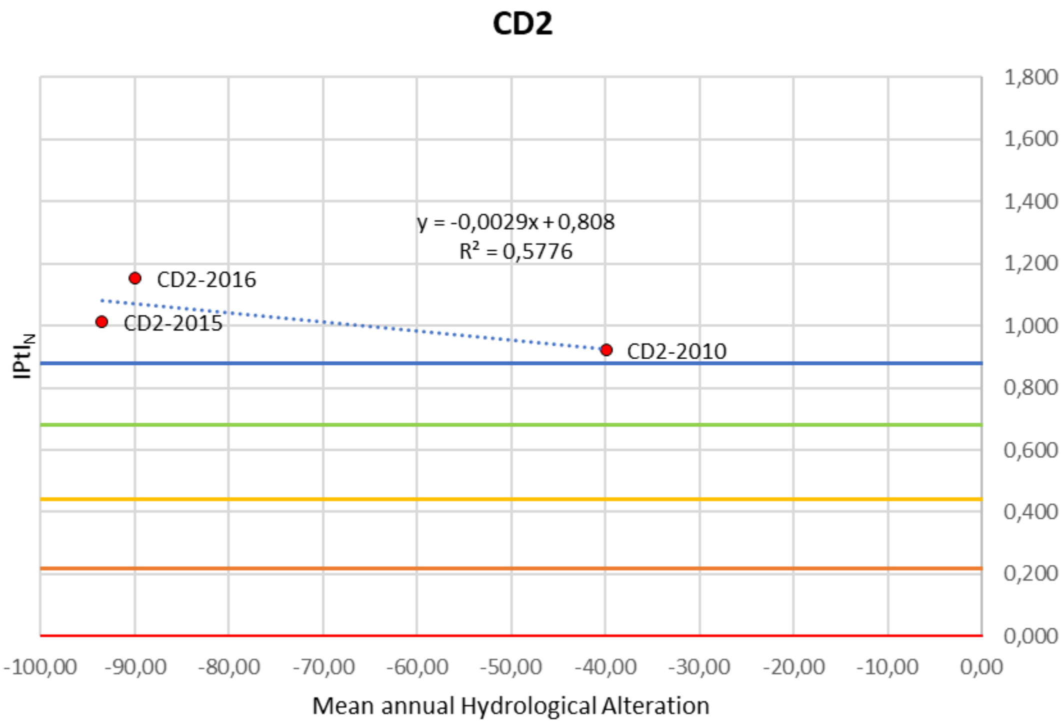


Figure 54 – Hydrological alteration vs. IPtI$_N$ for site downstream Salamonde dam: SD1

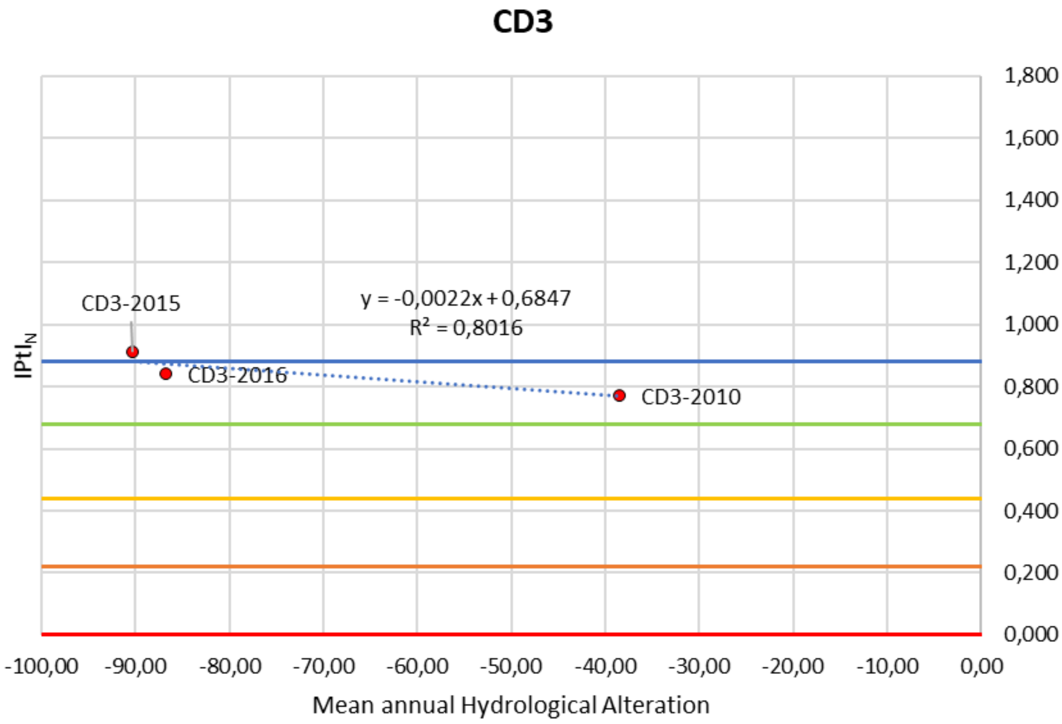


a)

Figure 55a – Hydrological alteration vs. IPtI$_N$ for sites downstream Caniçada dam: a) CD1, b) CD2, c) CD3.

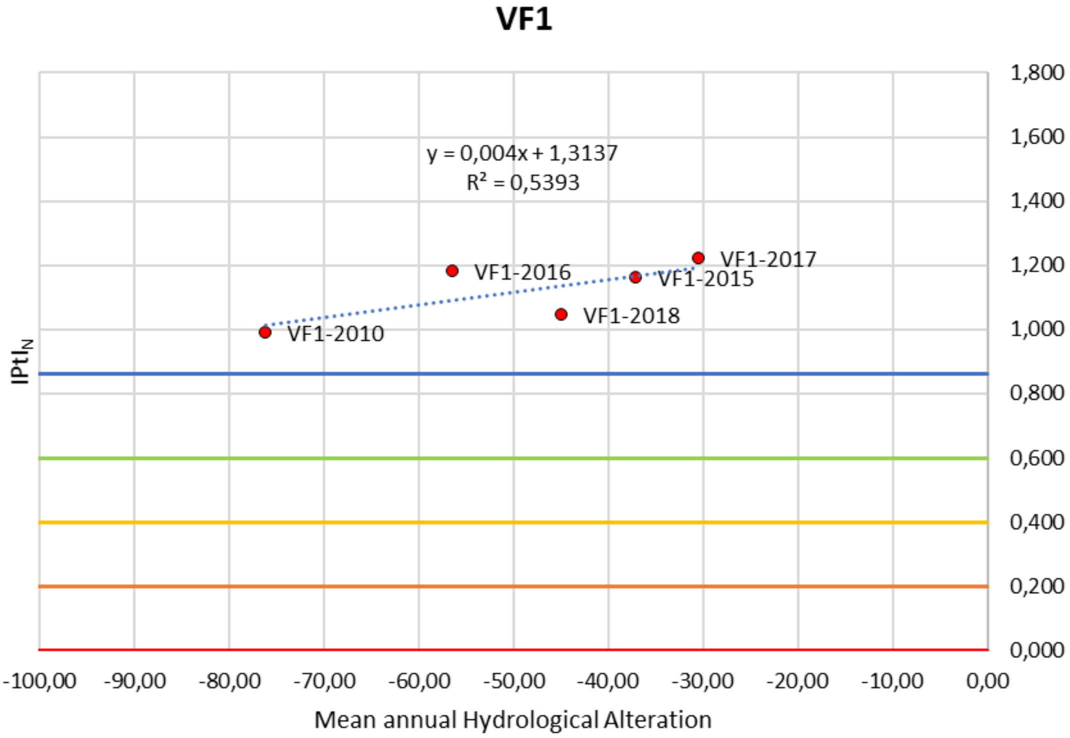


b)

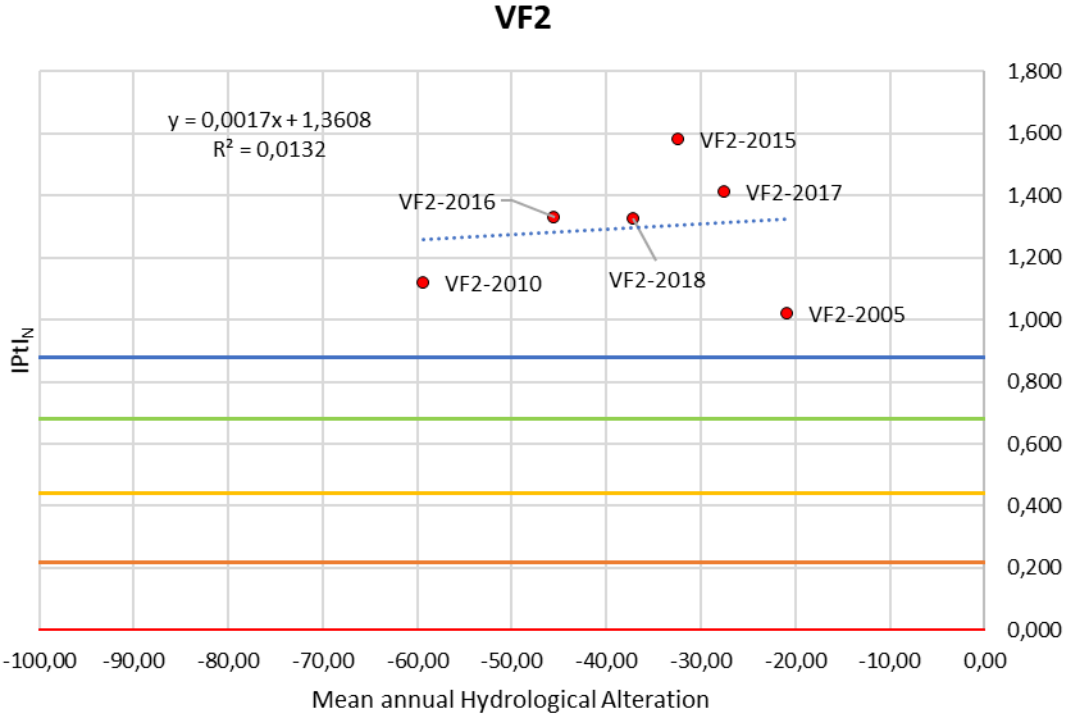


c)

Figure 55b – Hydrological alteration vs. IPtI$_N$ for sites downstream Caniçada dam: a) CD1, b) CD2, c) CD3.

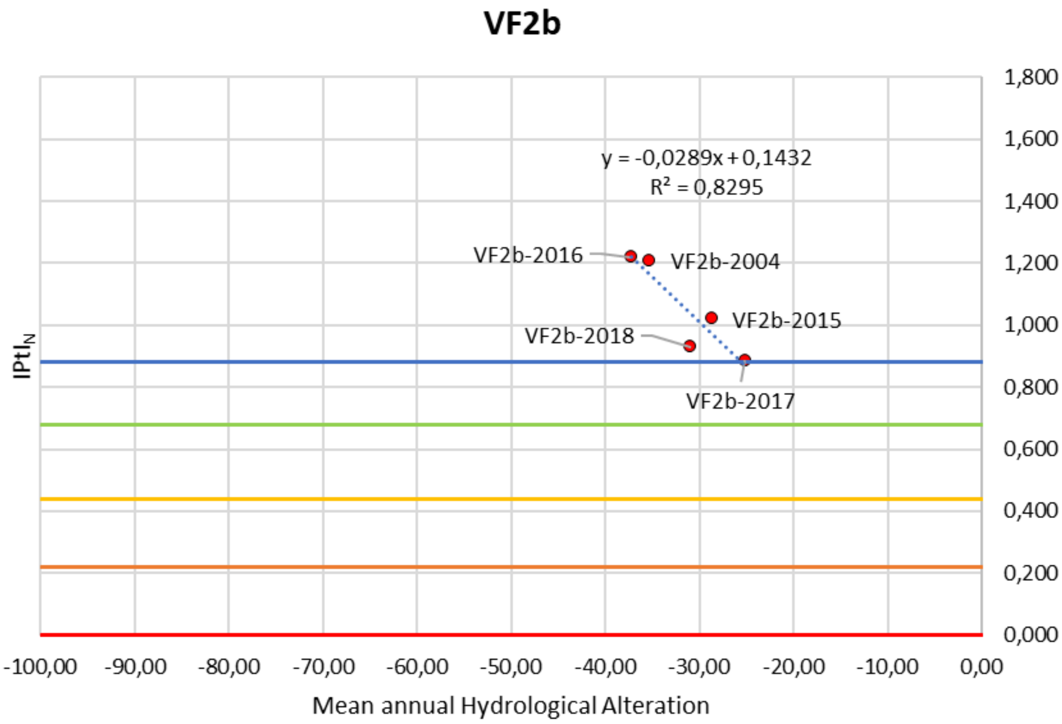


a)

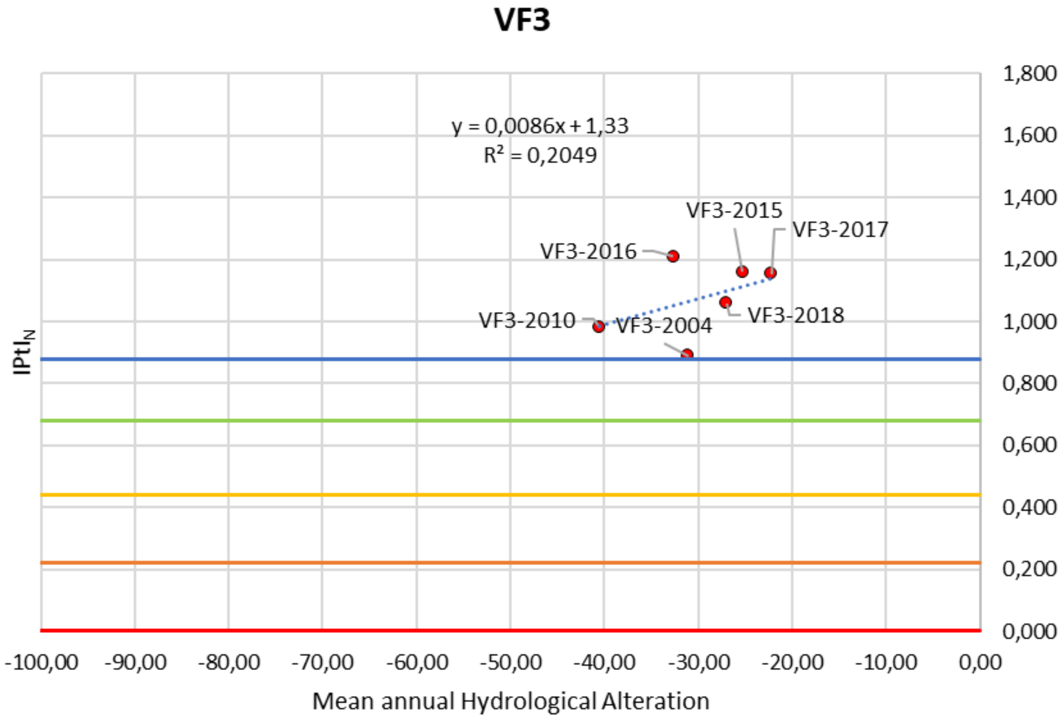


b)

Figure 56a – Hydrological alteration vs. IPtI$_N$ for sites downstream Vilarinho das Furnas dam: a) VF1, b) VF2, c) VF2b, d) VF3, e) VF3b.

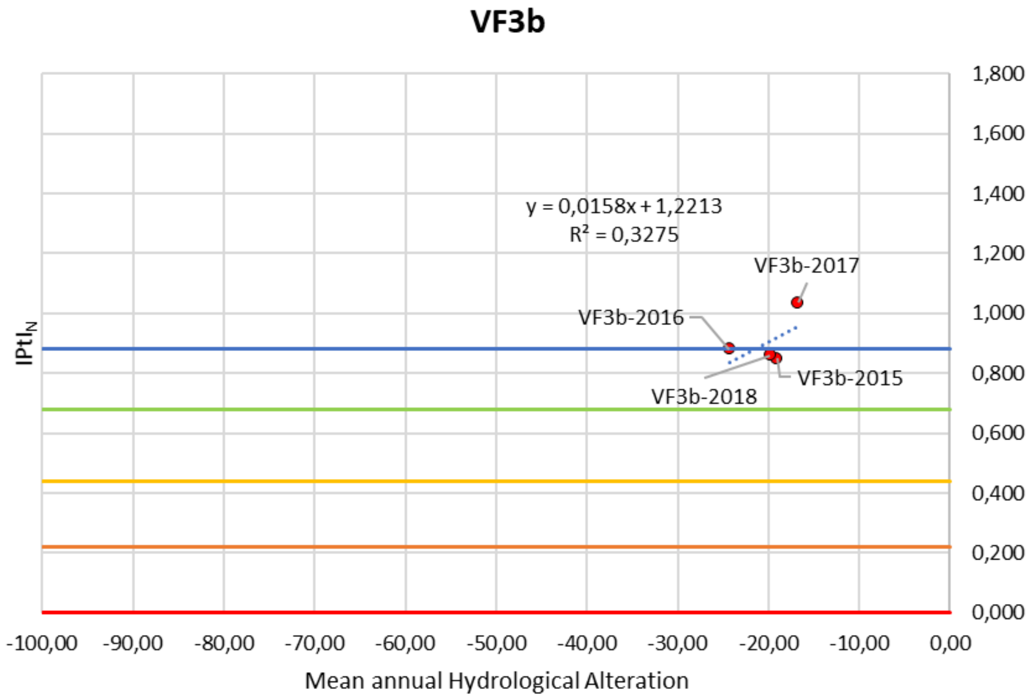


c)



d)

Figure 56b – Hydrological alteration vs. IPtI$_N$ for sites downstream Vilarinho das Furnas dam: a) VF1, b) VF2, c) VF2b, d) VF3, e) VF3b.



e)

Figure 56c – Hydrological alteration vs. IPtI$_N$ for sites downstream Vilarinho das Furnas dam: a) VF1, b) VF2, c) VF2b, d) VF3, e) VF3b.

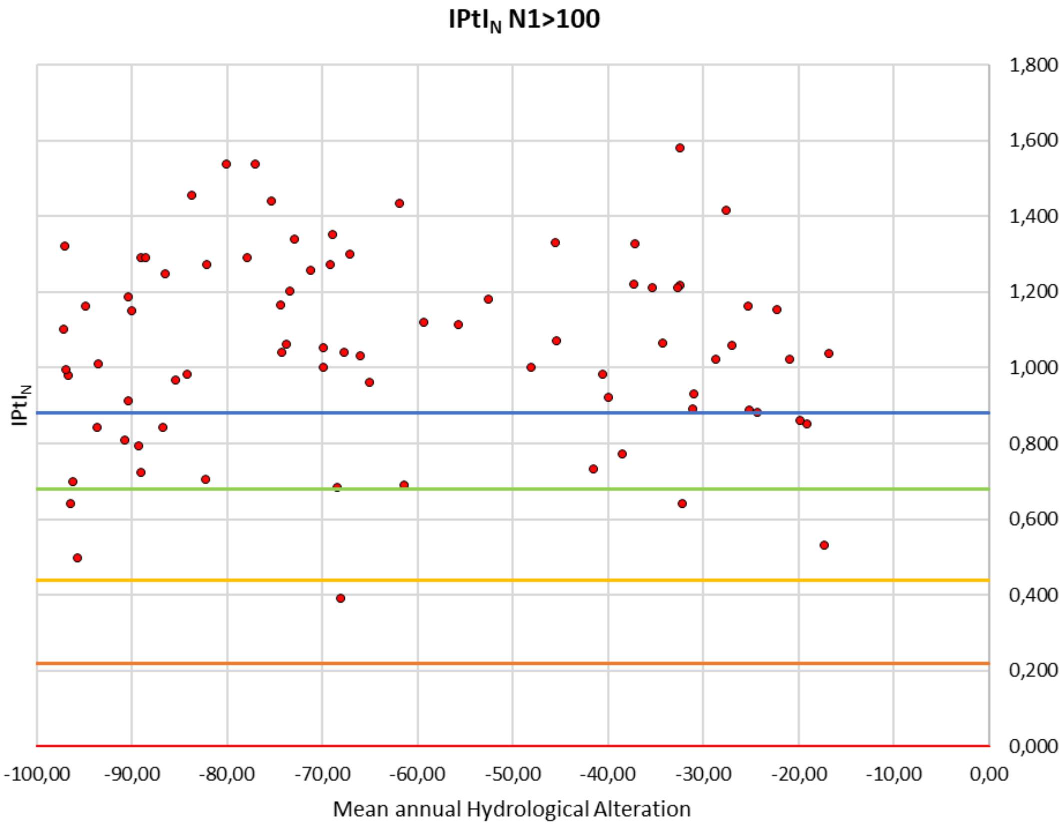


Figure 57 – Hydrological alteration vs. IPtI$_N$ for selected sites within the same WFD river typology (N1 > 100 km^2).

It should be referred that in relation to the research hypothesis 1 (i.e. the expectation that after the release of environmental flows the values of the biological indicators would improve compared to the indicators evaluated in periods before environmental flows releases), the sites associated with the Venda Nova, Caniçada and Alto Cávado dams were not considered. This happened because there are not $IPtI_N$ values after the release of environmental flows in these dams. Regarding the sites associated with Alto Cávado dam, these points were also not affected by environmental flows since Alto Cávado dam is not releasing this type of flows. Regarding the VF3b site there were only values after environmental flows releases, which made unfeasible to study this research hypothesis.

Furthermore – through the observation of Figure 51 to Figure 56 – regarding the research hypothesis 1, it can be noted that in the vast majority of the sites investigated (i.e. AR1, AR2, SD1, VF1, VF2, and VF3), the $IPtI_N$ values obtained before the release of environmental flows are lower (in quantitative terms) than those associated with periods after environmental flows releases.

Concerning the sites downstream of the Paradela dam (Figure 53), it can be noted that there was a slight decrease in values after the release of environmental flows. In PL2, this decrease did not lead to a drop in the ecological quality class (which was always equal to "Excellent"). However, in the case of PL3, there was a decrease in the quality level from “Excellent” to “Good”. This might occur because in the last few years there has been a decrease in terms of water losses due to infiltration through the dam structure. In fact, prior to the signaled release of environmental flows, in February 2017, the values of water losses by the body of the dam were even higher than the environmental flows established in terms of the concession contract. Thus, even in the absence of an official release of environmental flows, the water losses acted as an "environmental flow" in terms of water volume.

As regards the research hypothesis 2 (i.e. the expectation that the greater the hydrological alteration, the greater the likely impact on freshwater ecosystems) – through the analysis of Figure 51 to Figure 56 – in general, through the analysis of the graphs (Figure 51 to Figure 56), it was possible to perceive that the values shown a scattered behavior, being difficult to perceive an evident trend or relationship with the hydrological alteration. Nevertheless, some considerations could be stated. Regarding the sites AR1, AR2, VF1, VF2, and VF3, it was possible to perceived that greater hydrological alteration leads (with some exceptions) to lower $IPtI_N$ values (i.e. worse ecological conditions). On the other hand, for the VF2b, this was not the case, being possible to perceive an opposite trend (i.e. the higher the hydrological alteration, the higher the value of the $IPtI_N$ indicator). In fact, for most of the sites (for example, for: PL2, PL3, SD1, CD1, CD2 and CD3), there was a great variability, as mentioned above, being possible to verify sites with higher hydrological alterations and higher IPtI$_N$ values, as well as, sites whose samples show very different IPtI$_N$ vaues despite similar hydrological alteration values.

As previously mentioned, in order to have a global view of all sites evaluated, Figure 57 reserves the values for all the sites (included in the same river typology, N1>100) showing all the values of hydrological change vs. IPtI$_N$. Through the observation of this graph it is possible to confirm, in an integrated way, the great variability and dispersion of the results. In fact, it was possible to verify a larger number of points between hydrological changes -60% to -100%, and -20% to -40%, but in a very diverse way, that is, without a specific hydrological alteration gradient. Furthermore, within these ranges of hydrological alteration variability, the largest amount of IPtI$_N$ values is in the ecological quality class "Excellent" and "Good". This may lead us to conclude that, although a cause-effect relationship between the values is not evident, in operational terms, i.e. in terms of WFD objectives agreement, the overall ecological condition reflected conditions above “Good”.

Another conclusion that can be drawn, is that the IPtI$_N$ indicator, the normative and global indicator used under the WFD to assess different types of anthropogenic pressures, is not sufficiently sensitive to hydrological alteration.

<u>Hydrological alteration vs. Fish (F-IBIP)</u>

Following (Figure 58 to Figure 63), the graphs and relationships obtained considering the hydrological alteration and fishes are presented. Figure 64, reveal the results obtained based on the aggregation of information of the sampling points included in the river typology N1>100. It should be highlighted that, in those Figures, the minimum threshold associated with the F-IBIP biological quality classification (accordingly with the valued presented on Table 31) are indicated.

Legend:

● Information for the selected sites

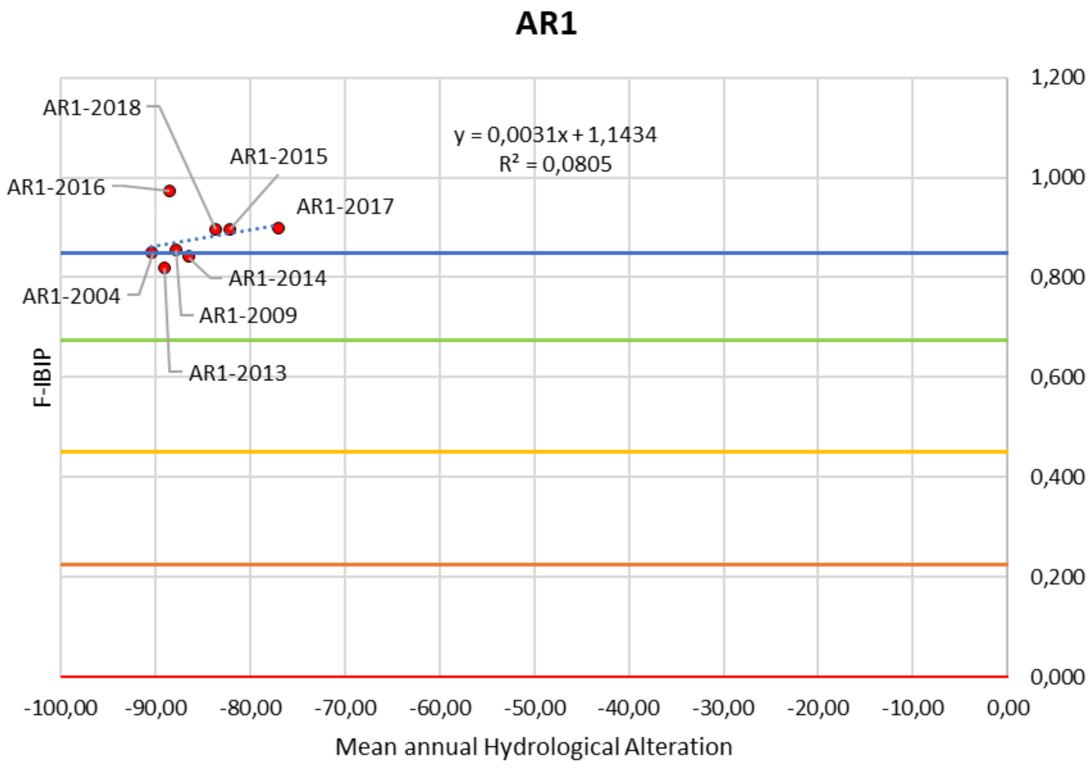
— High status

— Good status

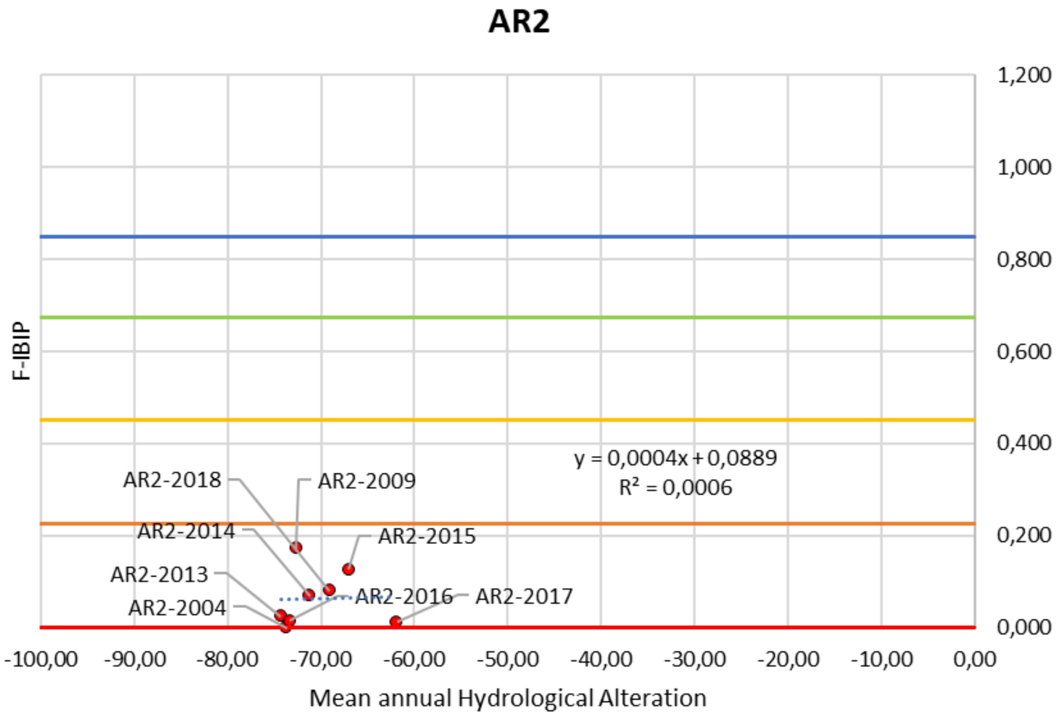
— Moderate status

— Poor status

— Bad status



a)



b)

Figure 58 – Hydrological alteration vs. F-IBIP for sites downstream Alto Rabagão dam: a) AR1, b) AR2

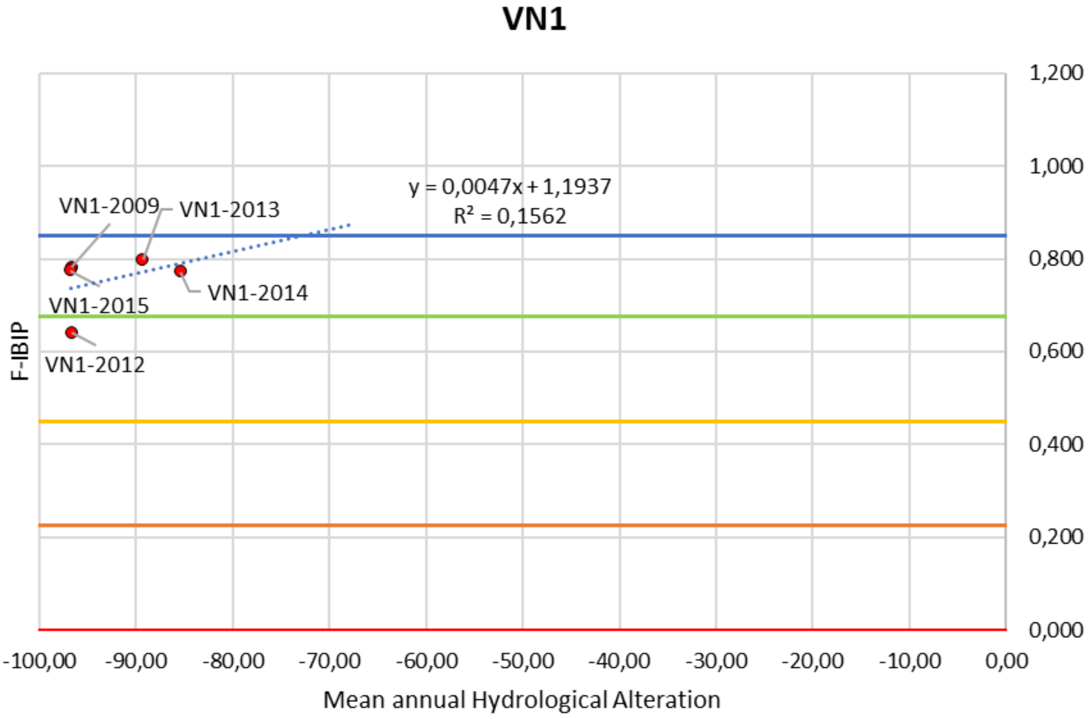
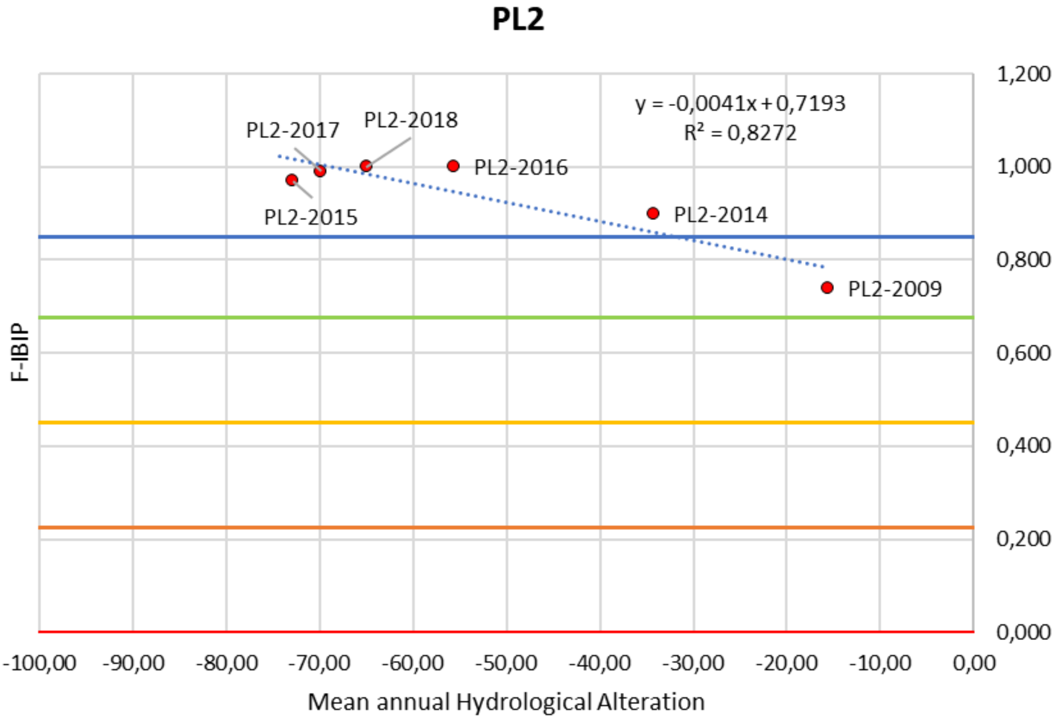
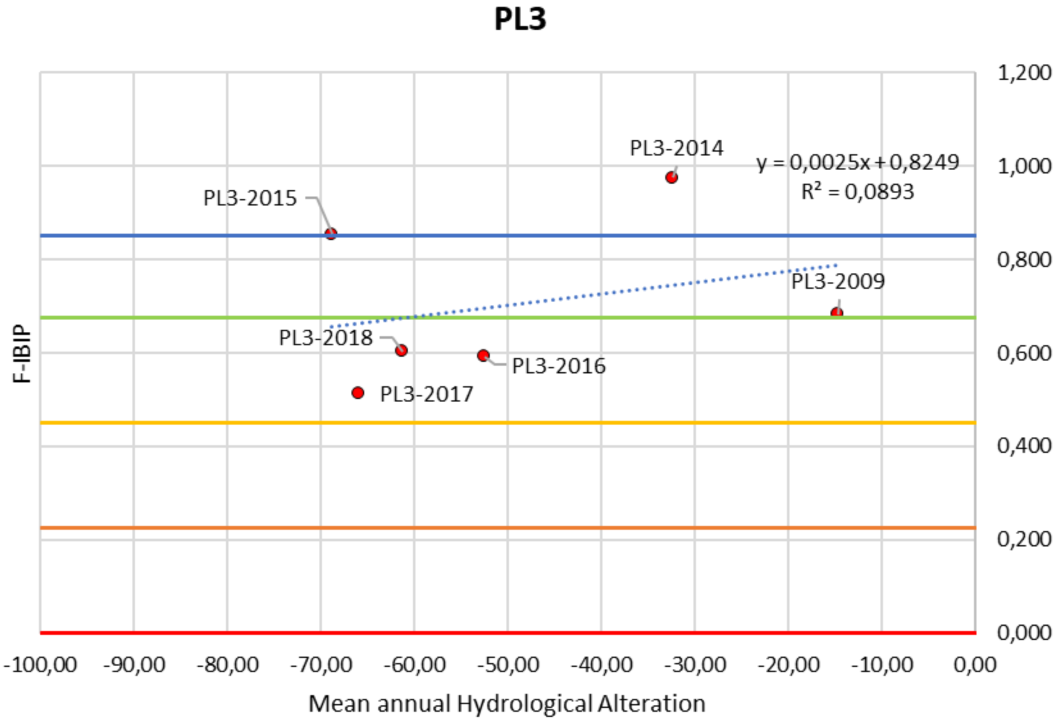


Figure 59 – Hydrological alteration vs. F-IBIP for site downstream Venda Nova dam: VN1



a)

Figure 60a – Hydrological alteration vs. F-IBIP for sites downstream Paradela dam: a) PL2, b) PL3



b)

Figure 60b – Hydrological alteration vs. F-IBIP for sites downstream Paradela dam: a) PL2, b) PL3

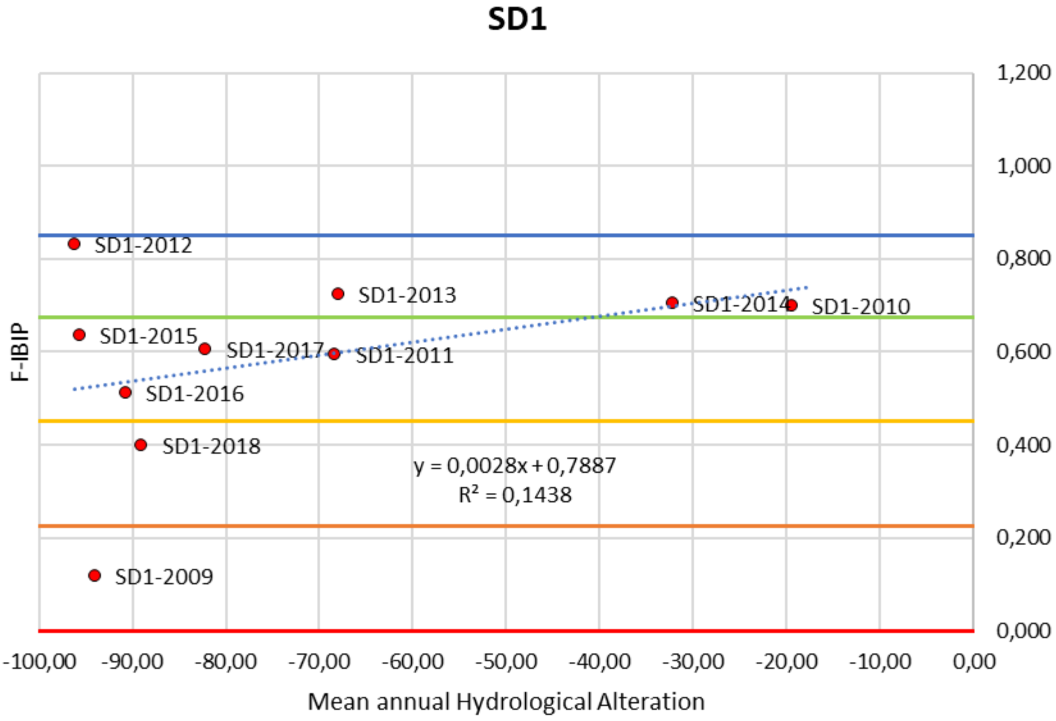
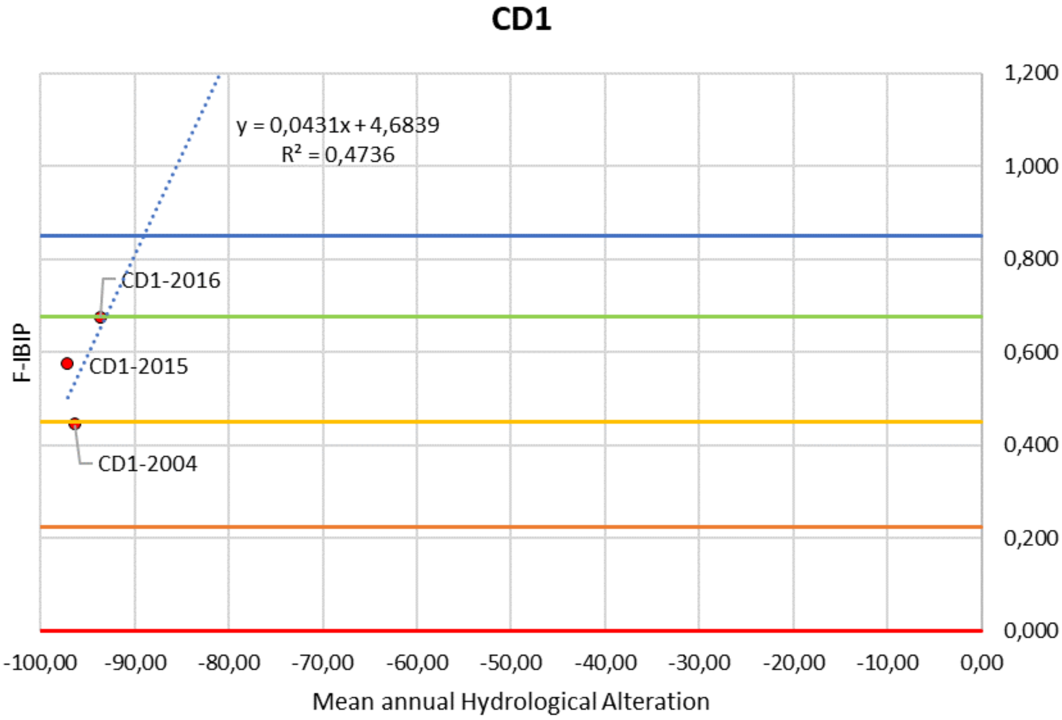
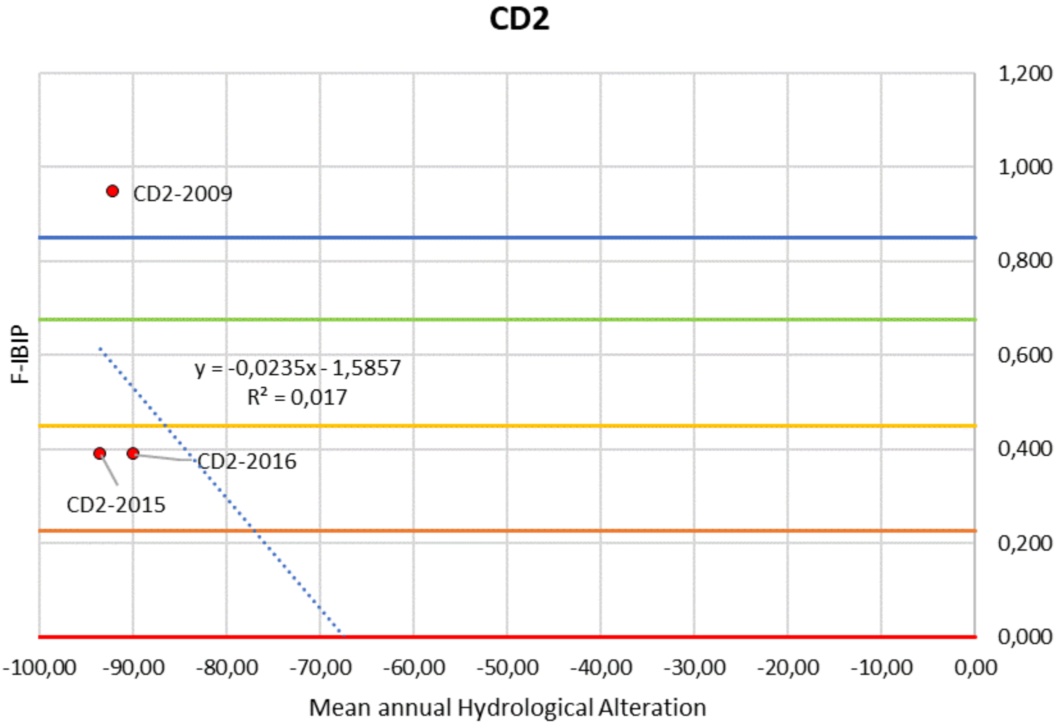


Figure 61 – Hydrological alteration vs. F-IBIP for site downstream Salamonde dam: SD1

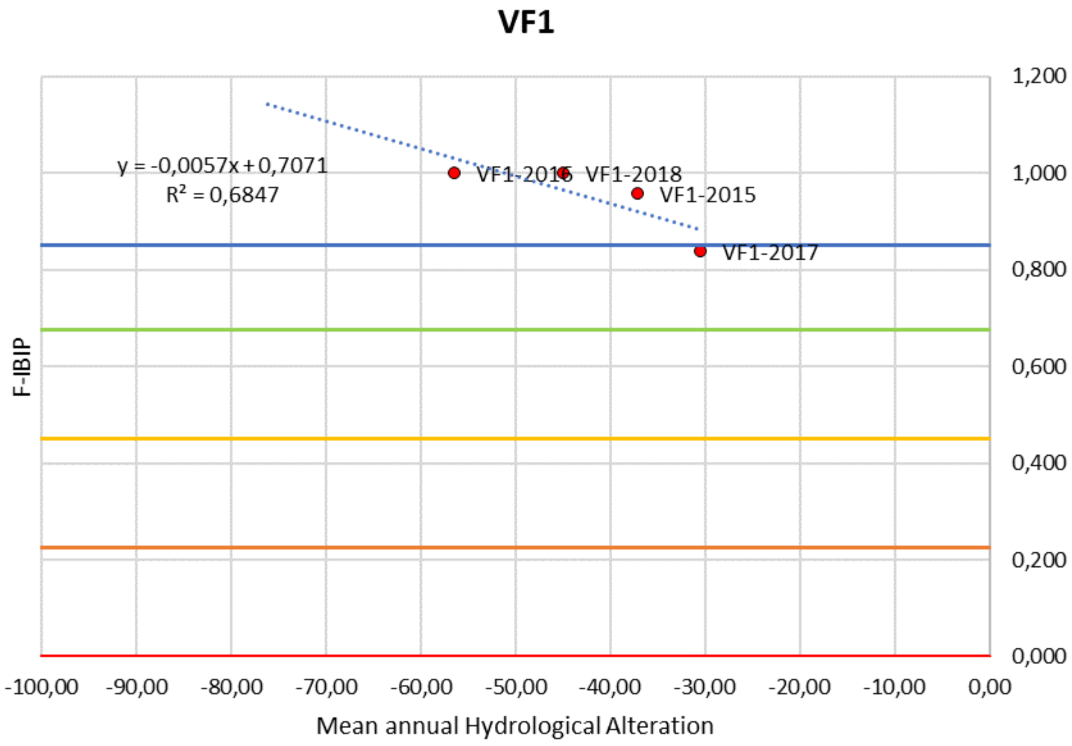


a)

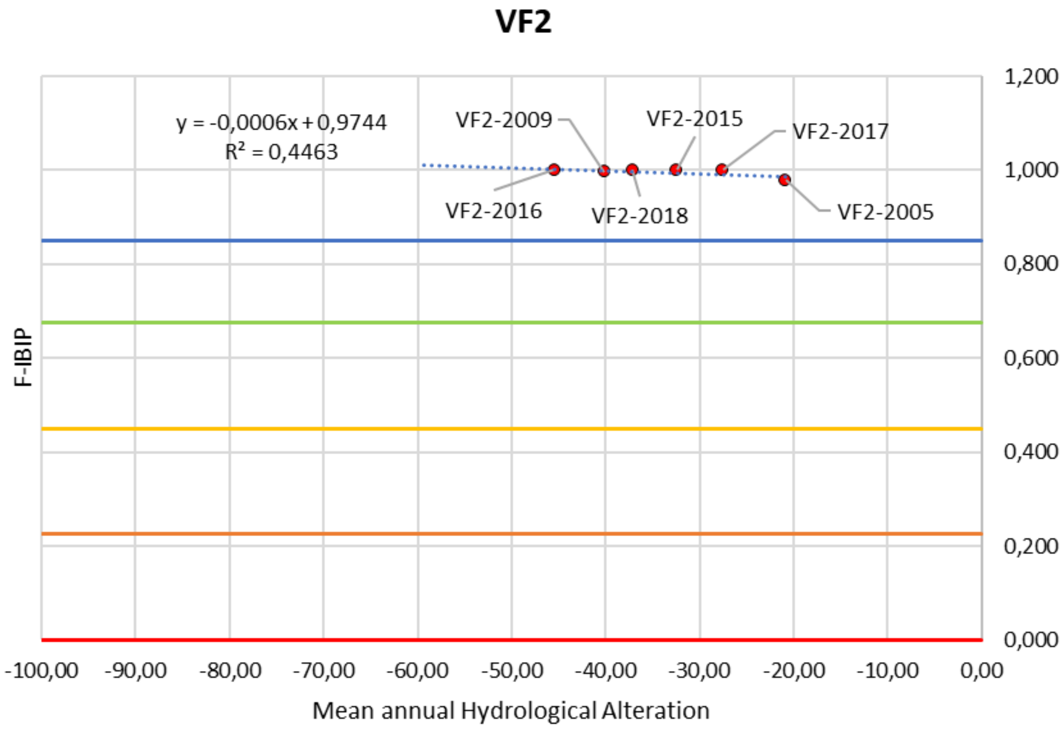


b)

Figure 62 – Hydrological alteration vs. F-IBIP for sites downstream Caniçada dam: a) CD1, b) CD2 and c) CD3.

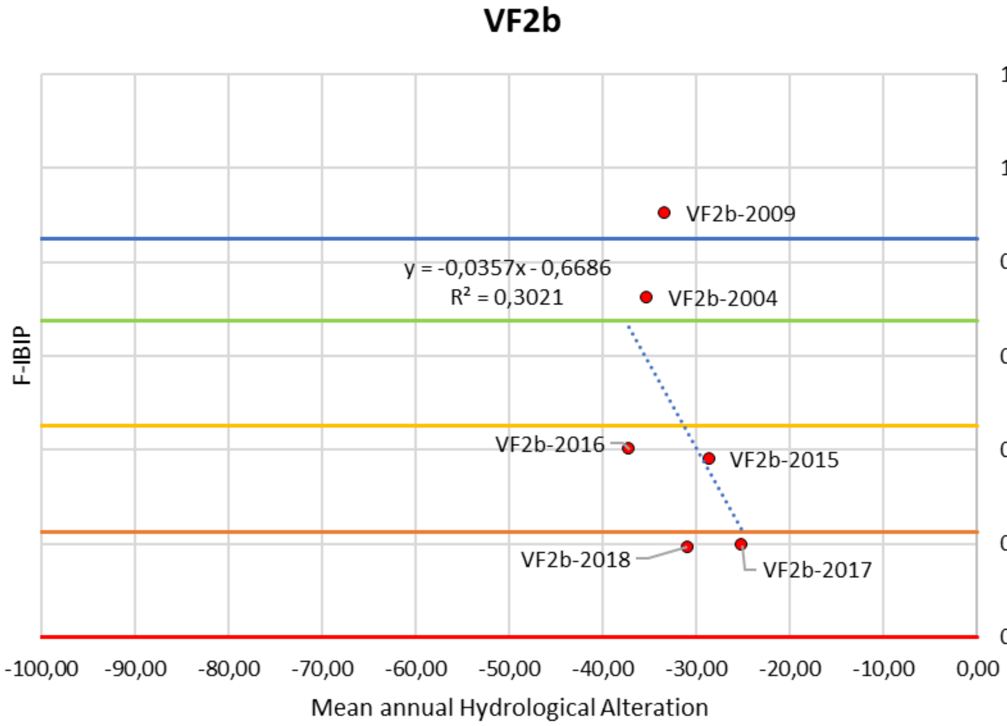


a)

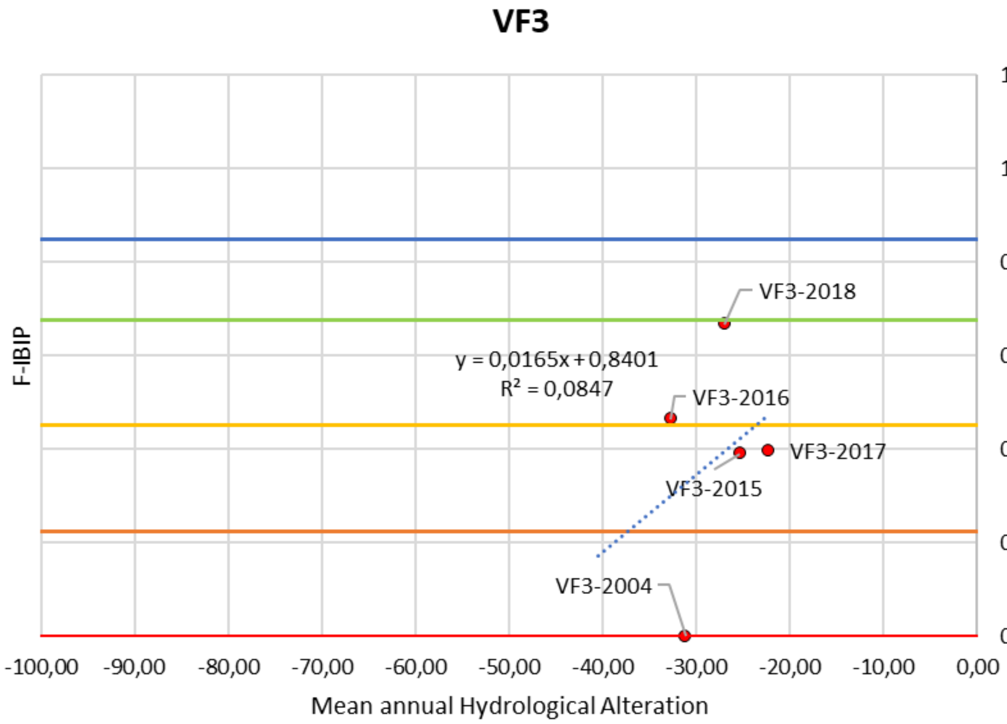


b)

Figure 63a – Hydrological alteration vs. F-IBIP for sites downstream Vilarinho das Furnas dam: a) VF1, b) VF2 c) VF2b, d) VF3, e) VF3b.

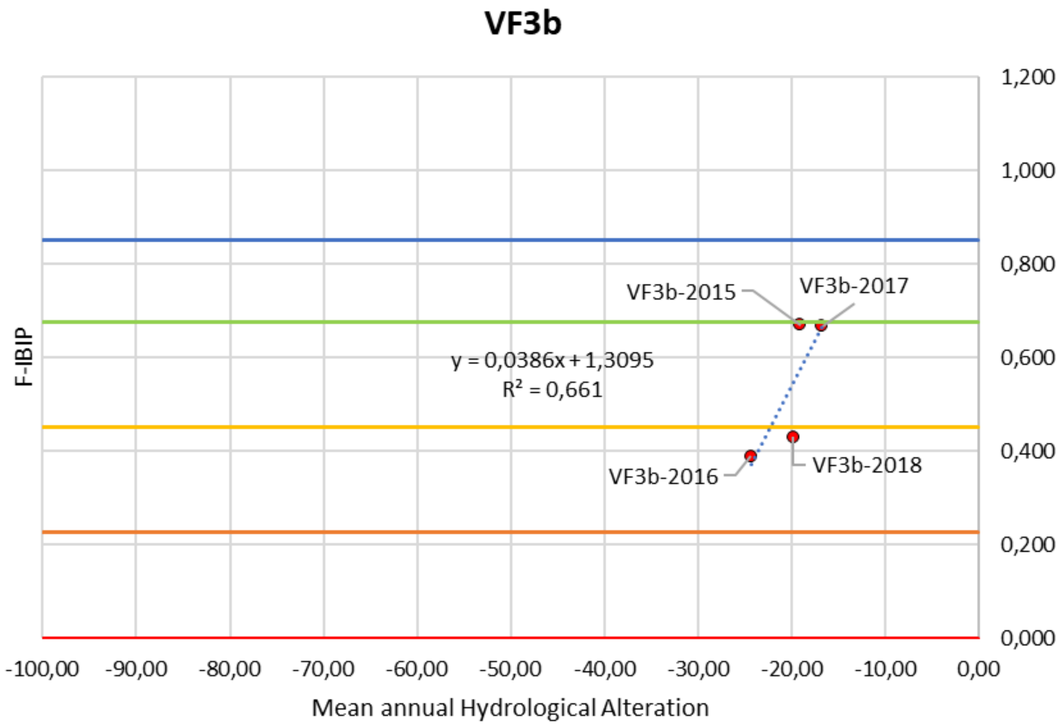


c)



d)

Figure 63b – Hydrological alteration vs. F-IBIP for sites downstream Vilarinho das Furnas dam: a) VF1, b) VF2 c) VF2b, d) VF3, e) VF3b.



e)

Figure 63c – Hydrological alteration vs. F-IBIP for sites downstream Vilarinho das Furnas dam: a) VF1, b) VF2 c) VF2b, d) VF3, e) VF3b.

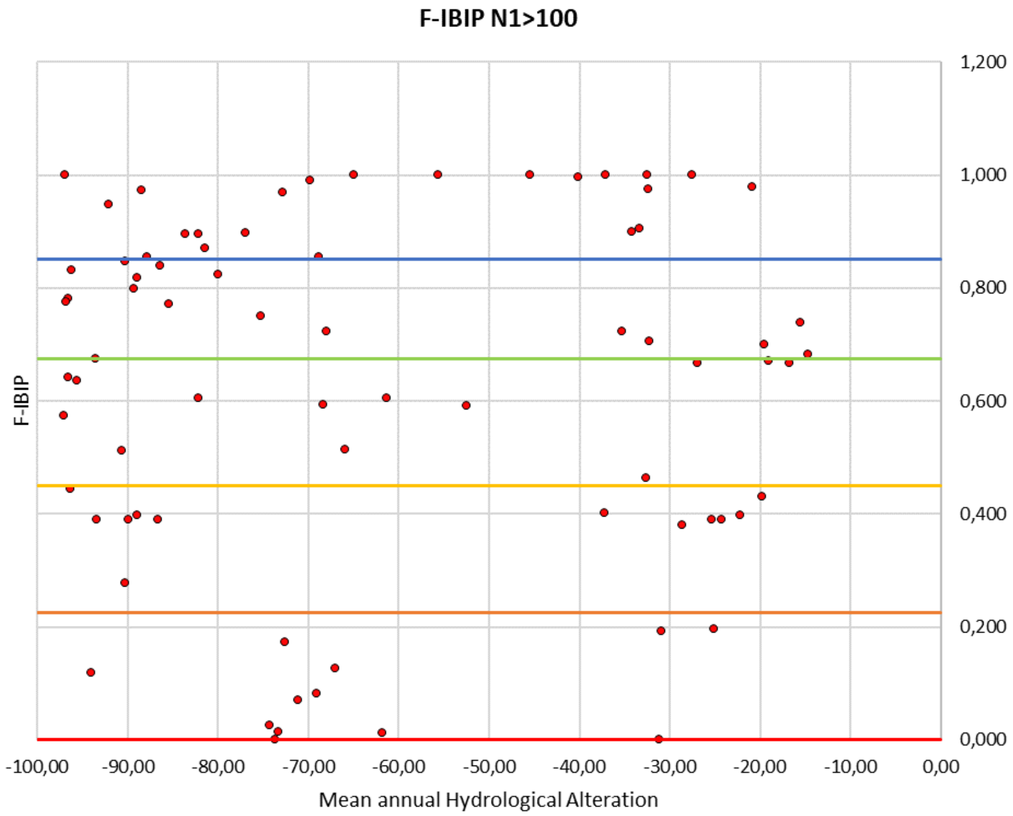


Figure 64 – Hydrological alteration vs. F-IBIP for selected sites within the same WFD river typology (N1 > 100 km^2).

For the fish community – through the observation of Figure 58 to Figure 63– as regards research hypothesis 1 (i.e. the expectation that after the release of environmental flows the values of the biological indicators would improve compared to the indicators evaluated in periods before environmental flows releases), a high disparity was observed in the F-IBIP values obtained, before and after the release of environmental flows. Thus, in general, it was not possible to show consistency in the values obtained. In fact, it was possible to verify various types of behaviors.

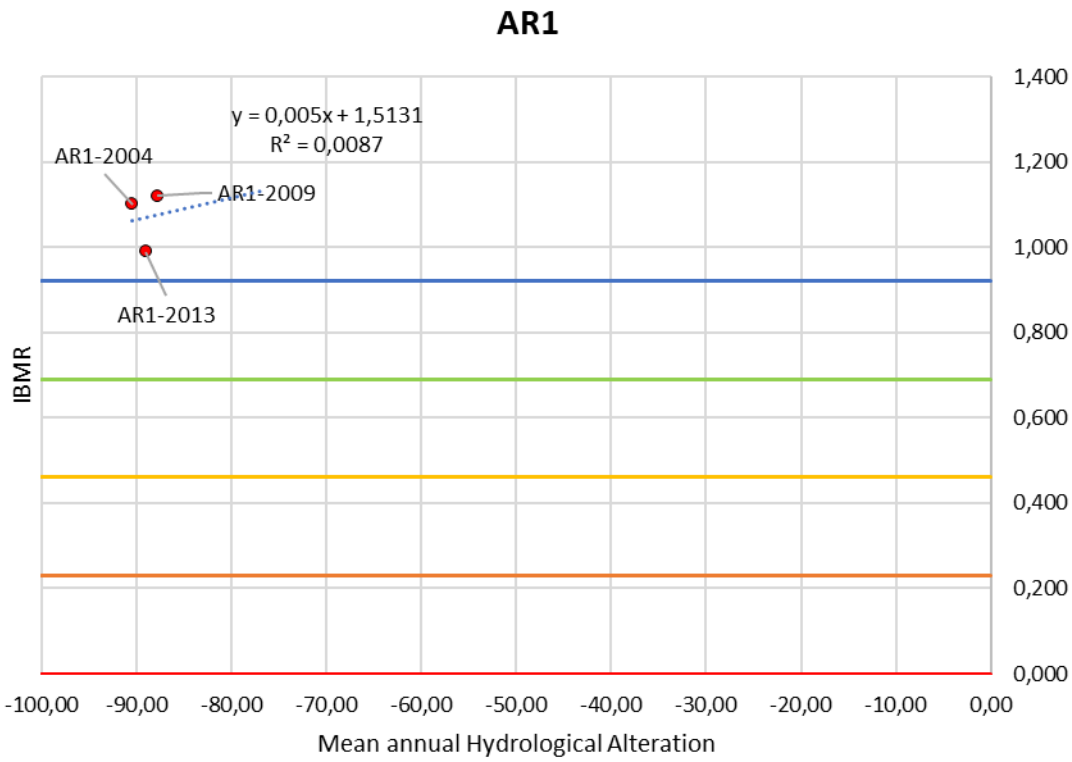
In general, as far as the verification of the research hypothesis 2 (i.e. the expectation that the greater the hydrological alteration, the greater the likely impact on freshwater ecosystems) is concerned, it was possible to verify the existence of a wide range variability in the obtained results, being difficult and not feasible to provide an overall answer to the research hypothesis. It was, however, possible to analyse and highlight the different patterns of results that were achieved.

In fact, in most of the sampled points (namely, for AR1, AR2, CD1, CD2, VF2b, VF3) it was not noticeable that the highest hydrological alteration corresponded to a lower value of the F-IBIP indicator (i.e. a worse ecological condition). It was also found that for similar hydrological alterations (e.g. for VN1, PL3, SD1 and VF3b), quite different values of F-IBIP are evident. On the other hand, at VF2, it was possible to observe that despite the existence of different hydrological alterations, the F-IBIP values remain practically unchanged. It should be highlighted that for PL2, a particular behavior of the obtained results were perceived. In fact, for PL2, higher values of F-IBIP are linked with higher hydrological alterations.

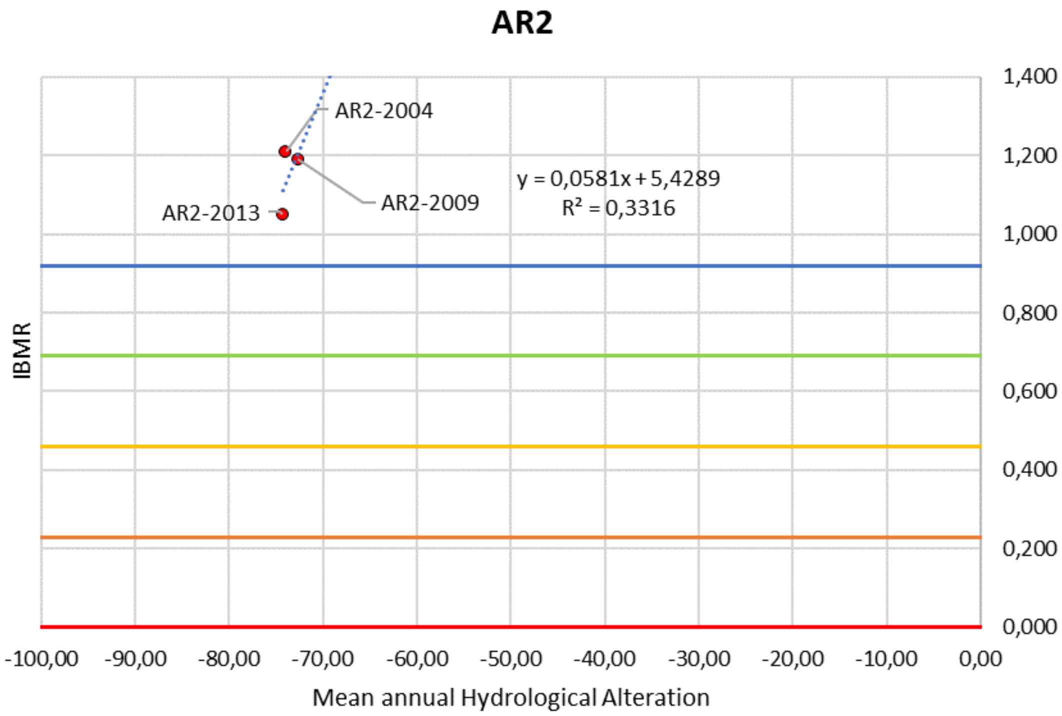
Through the results obtained, this indicator (F-IBIP), despite being used to assess the water bodies status, because it responds to several types of pressures, does not seem to have a cause-effect relationship with the different hydrological alteration. In fact, the F-IBIP indicator is strongly influenced by the percentage of exotic species in the sample, being found that, in general, when low values of F-IBIP are obtained, these values can be associated with a high percentage of exotic species.

Hydrological alteration vs. Macrophytes (IBMR)

Below (Figure 65 to Figure 69), the graphs and relationships obtained considering the hydrological alteration and macrophytes are presented. Figure 70, reveal the results obtained based on the aggregation of information of the sampling points included in the river typology N1>100. It should be highlighted that, in those Figures, the minimum threshold associated with the IBMR biological quality classification (accordingly with the valued presented on Table 31) are indicated.



a)



b)

Figure 65 – Hydrological alteration vs. IBMR for sites downstream Alto Rabagão dam: a) AR1, b) AR2.

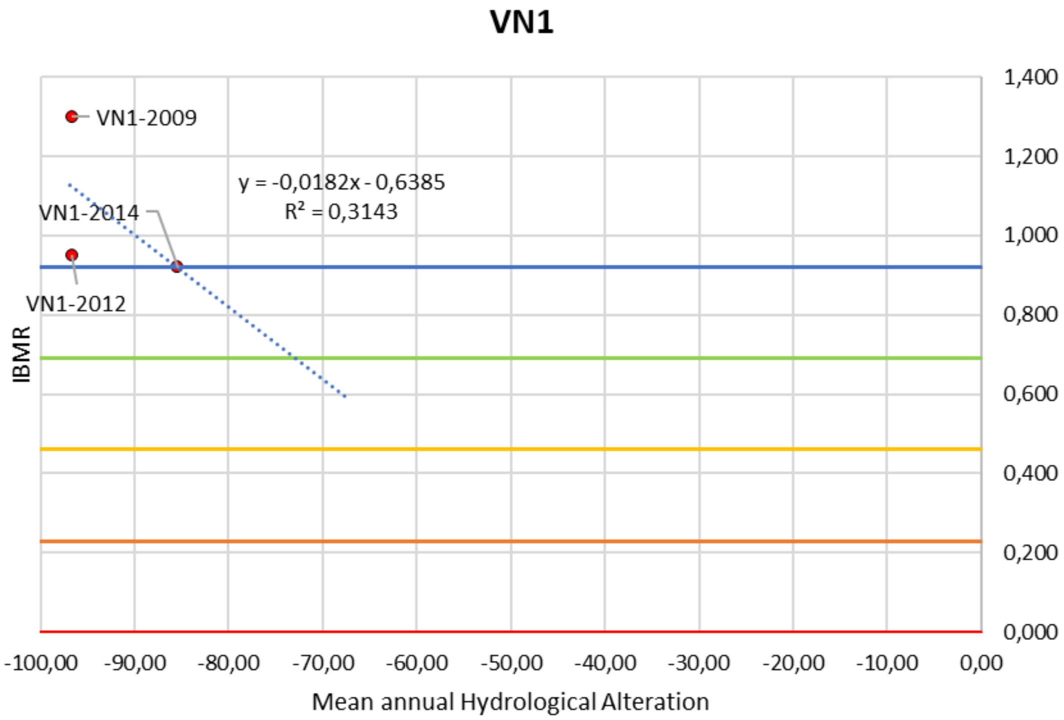
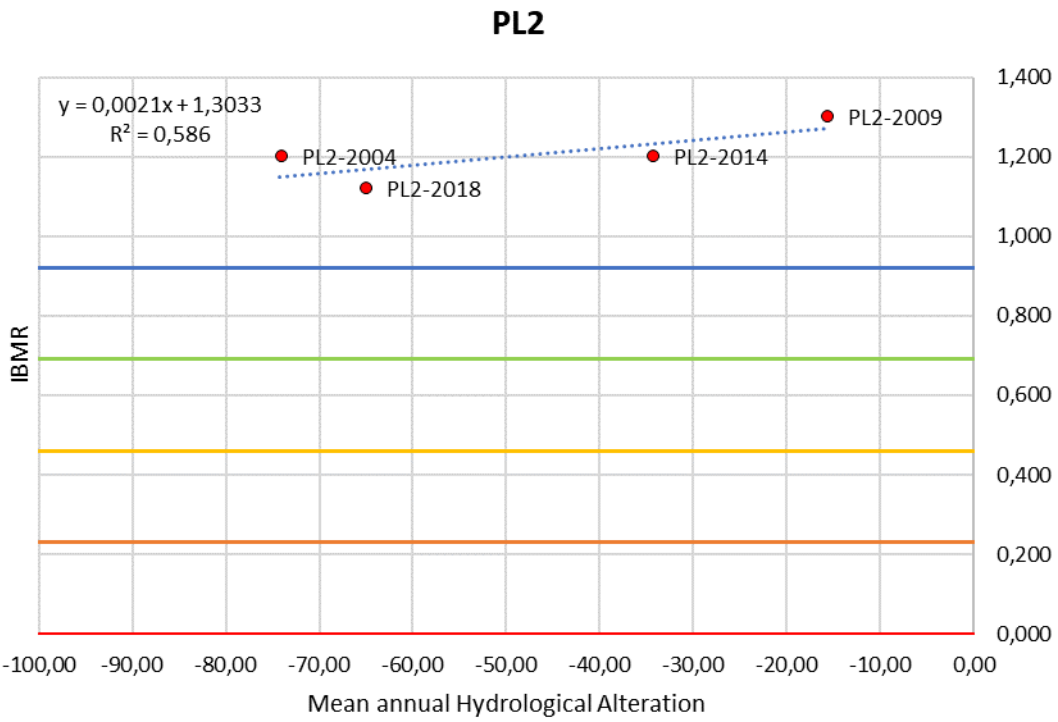
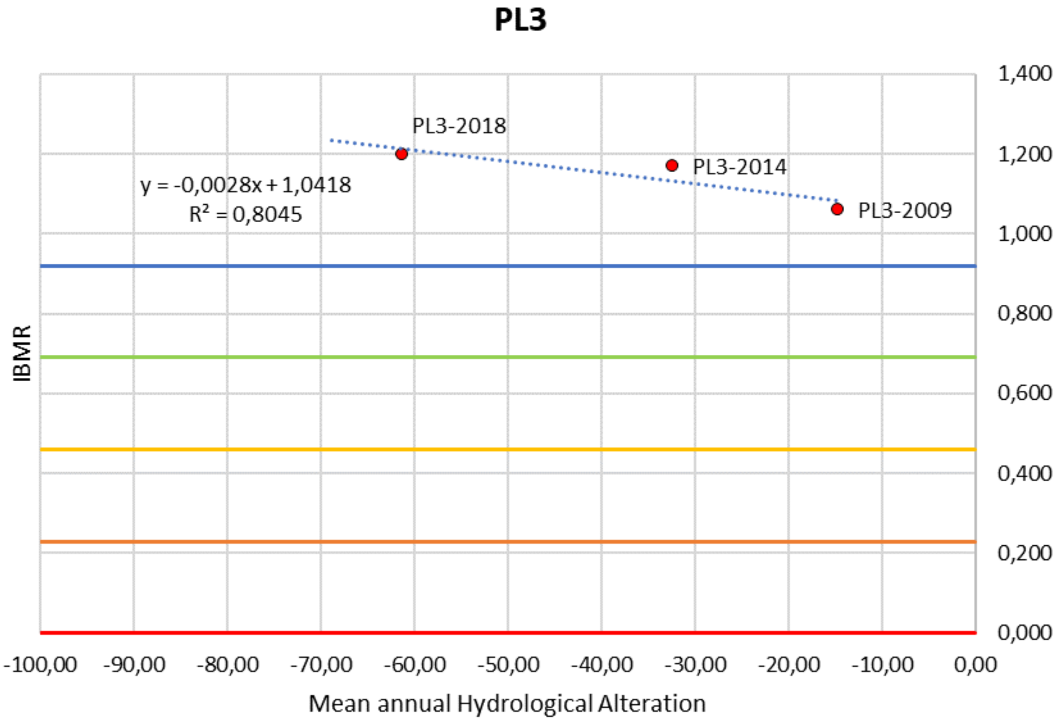


Figure 66 – Hydrological alteration vs. IBMR for site downstream Venda Nova dam: VN1.



a)

Figure 67a – Hydrological alteration vs. IBMR for sites downstream Paradela dam: a) PL2, b) PL3.



b)

Figure 67b – Hydrological alteration vs. IBMR for sites downstream Paradela dam: a) PL2, b) PL3.

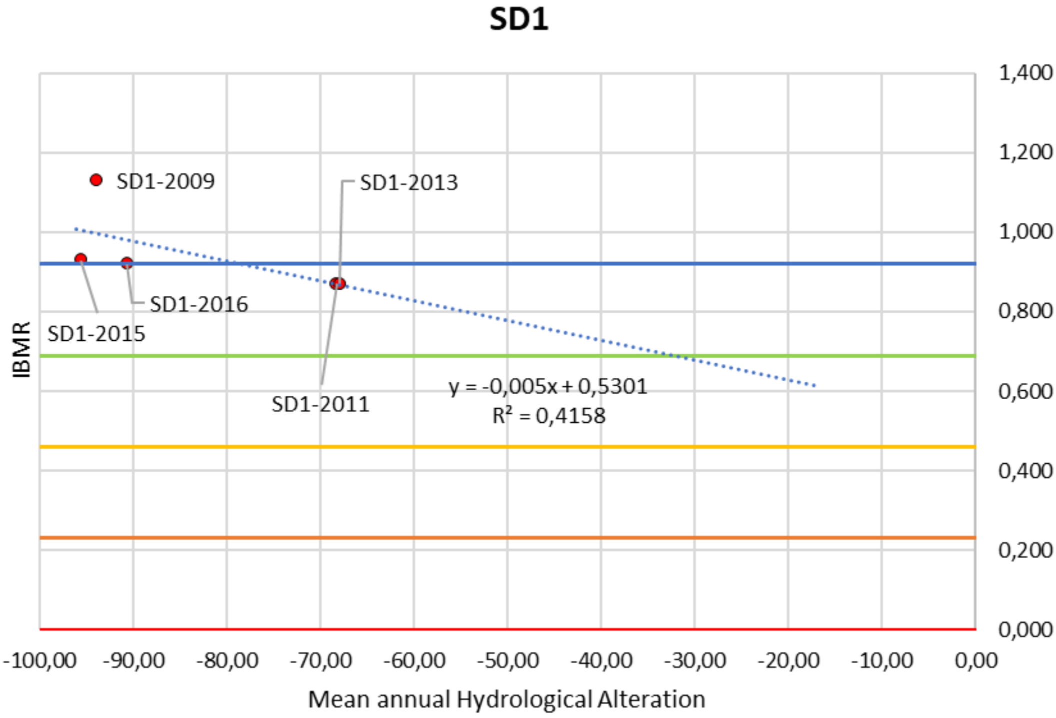
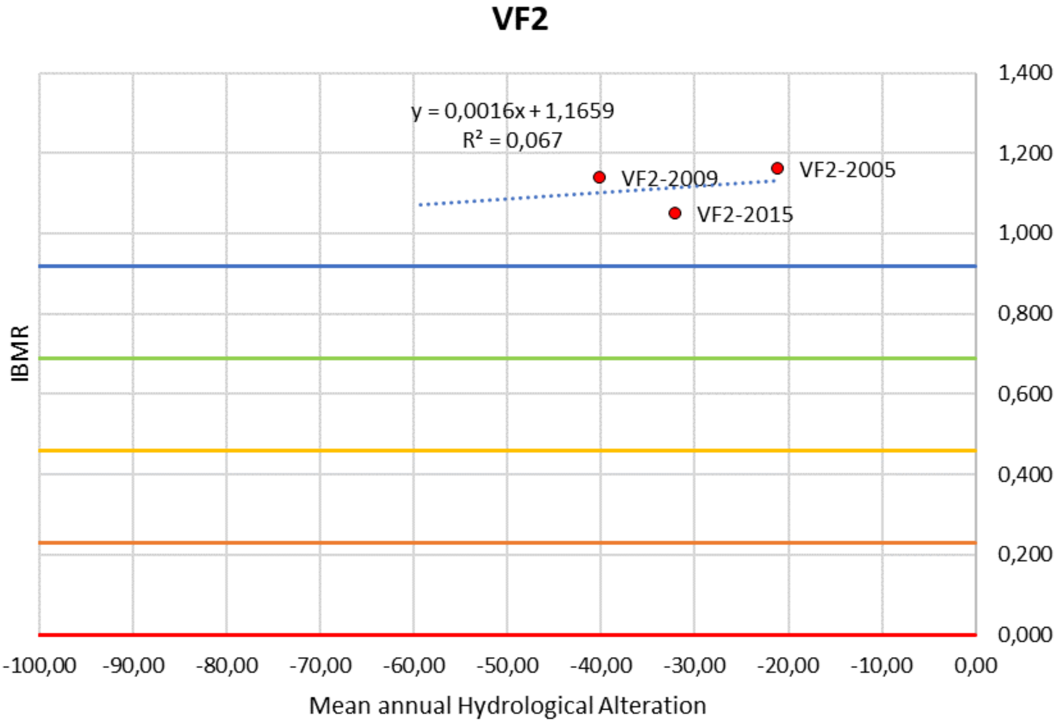
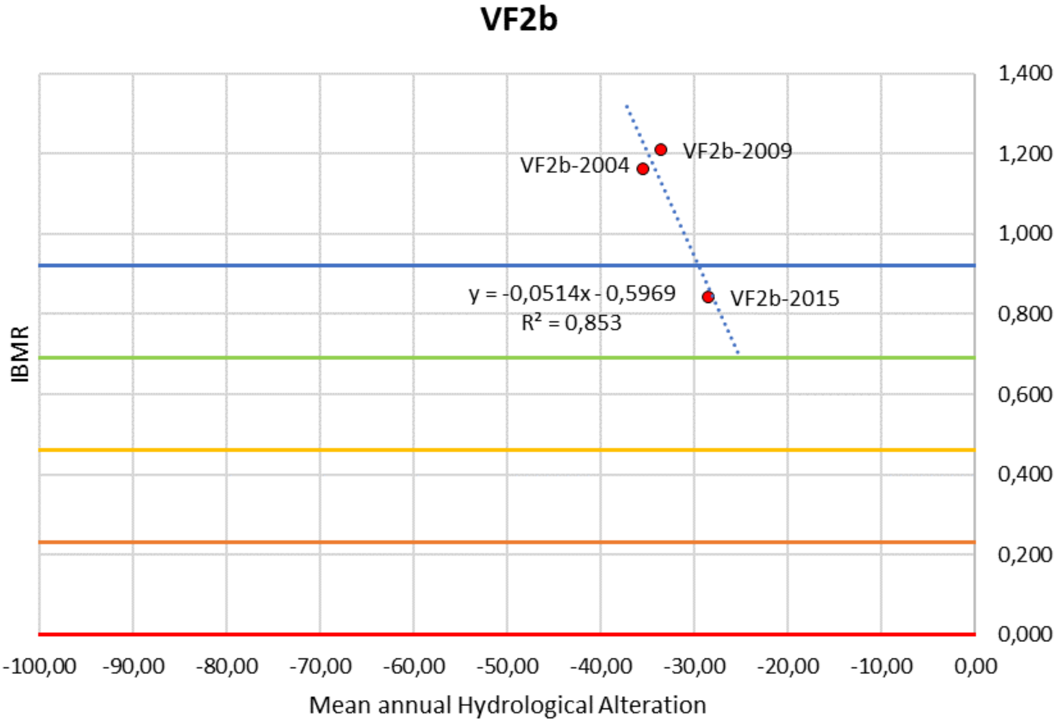


Figure 68 – Hydrological alteration vs. IBMR for site downstream Salamonde dam: SD1.



a)



b)

Figure 69 – Hydrological alteration vs. IBMR for sites downstream Vilarinho das Furnas dam: a) VF2, b) VF2b.

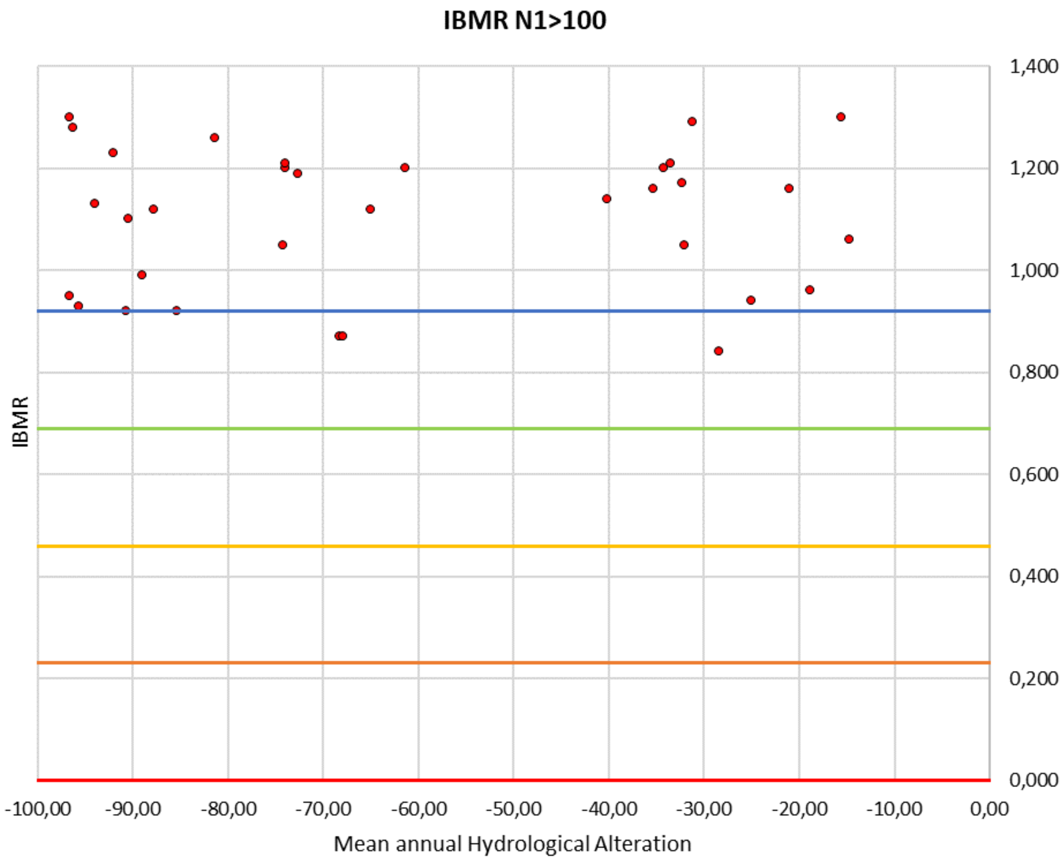


Figure 70 – Hydrological alteration vs. IBMR for selected sites within the same WFD river typology (N1 > 100km^2).

First of all, it should be referred that research hypothesis 1 (i.e. the expectation that after the release of environmental flows the values of the biological indicators would improve compared to the indicators evaluated in periods before environmental flows releases), had not been considered for VN1 and SD1, since the existing data only concern samples taken before environmental flows releases.

In fact, through the observation of Figure 65 to Figure 69, as regards research hypothesis 1, it was possible to perceive that the IBMR values are very similar before and after the release of the environmental flows. Most of the sites (AR1, AR2, PL2, VF2 and VF2b) show a slight decrease of the IBMR values after environmental flows, however, this decrease is not significant. The PL3 presents a slightly increase of the values after environmental flows. It should be noted, however, that the number of macrophytes samples carried out over time was very scarce, and even lower than the existing data for the other biological elements evaluated.

Concerning the research hypothesis 2 (i.e. the expectation that the greater the hydrological alteration, the greater the likely impact on freshwater ecosystems) – based on Figure 65 to Figure

69 – some considerations are outlined below. There were sites (notably AR1, AR2, VN1, SD1 and VF2b) where there was no trend, being possible to verify slight differences in IBMR values in the face of similar hydrological alterations. The results obtained in PL3 reveal that the higher the hydrological alteration, the higher the IBMR values (which were not expected). On the other hand, the PL2 and VF2 points mostly demonstrate that the higher the hydrological alteration, the lower the value of the IBMR.

7. CONCLUSIONS, CONSIDERATIONS AND SUGGESTIONS FOR FUTURE WORK

7.1 Conclusions and considerations

In this section, the main conclusions of this study are presented.

Concerning the hydrological alteration, it was found that for each one of the selected sites the hydrological alterations are quite significant. This is particularly noticeable for the month of August. In fact, for this dry month, the natural flow regime that would naturally exist in the river was presented as having a very small value. Thus, any increase in the flow (resulting from the existence of the dam, and consequently the modified condition) leads to a major hydrological change.

Another evident aspect was expressed by the different values of hydrological alteration obtained for the different strategic sites associated with Vilarinho das Furnas. At these sites, it was possible to note that as the distance of the strategic site from the dam increases, the smaller the hydrological alteration.

It was also found that environmental flows contribute to the decrease of the magnitude of the existing hydrological changes, although for the moment, due to the short period of environmental flow regimes implementation, still in a non-significant way.

In fact, the implementation of the environmental flows is relatively recent in Portugal (having started, in the area under study, less than a decade ago), as such, the existing environmental flows regimes do not seem to have resulted on much effect on the hydrological alteration of this system. It is therefore expected that studies similar to this one, covering a longer period, will be developed.

Nevertheless, the value of hydrological alteration was quite high before the release of environmental flows. Although these reduced the value of hydrological alteration, it still is quite high, compared to natural conditions.

Regarding the ecological conditions obtained, in qualitative terms, it was found that most IPTIN results expressed conditions superior to "Good" (with most classifications being equal to "Excellent"). Similar behavior was observed with respect to macrophytes.

Concerning the conditions expressed by the F-IBIP indicator, it was possible to observe a great variability, with a greater dispersion in the quality classes obtained (from “Bad” to “Excellent”). Through the results obtained it was possible to conclude that the F-IBIP, is an indicator strongly influenced by the presence of exotic species and is therefore an indicator whose use as a response to hydrological alteration is, in itself, limited.

Globally, after the implementation of the environmental flows, the quality level of the lotic system has not changed significantly over time. In quantitative terms, it was also possible to conclude that in most of the sampled points IPtIN showed slight improvements in its values after environmental flows release. However, very slight improvements. Nevertheless, of all the biological indicators, the macroinvertebrates seem to be the most influenced by environmental flows.

In terms of the ecological quality classifications obtained, it should also be perceived that even before the release of environmental flows, in most of the sites, the objectives set under the WFD were already achieved, with quality status mostly higher than "Good", as mentioned above.

This raises several questions and may potentially lead us to wonder whether the global (and official and normative) biological indicators used within the WFD implementation are capable to reflect the hydrological alteration obtained. On the basis of the study here, it seems that the biological indicators used might be useful for assessing other anthropogenic pressures (such as, the pressures associated with diffuse pollution, the effect of exotic species on the community), but are not suitable for assessing hydrological alteration. In fact, the existence of pressures of other types is barely considered (since the land cover of the study area are mainly forest and semi-natural areas, being only possible to report some existing subsistence and pastoral agriculture, as well as, the presence of low values of population, scattered throughout the study area). It should also be noted that the sites sampled over time are not impacted by hydropeaking phenomena.

Hence, through the results of this study, the results can also be perceived from another perspective. That is, the overall good results of the ecological indicators obtained, can be indicators of a lotic system, potentially adapted to the current conditions. In fact, the major hydrological alterations were imposed by the construction of dams in the study area, since the 1950s.

The results obtained in terms of hydrologic alteration vs. biological condition, allowed the verification of values scattered in different ranges of hydrological alteration and biological condition. Thus, not being clear a coherent relationship between the hydrological change vs. ecological condition. The lack of a consistent cause-effect relationship between the hydrological alteration and the ecological condition precluded estimation of any potential threshold. Which in turn, prevent the definition of a hydrological alteration threshold, which hampered the establishment of environmental flows based on a cause-effect relationship between flows and ecology.

Finally, it can also be mentioned that in terms of operational water resources management, the results obtained (especially the ecological ones, and consequent ecological quality classes obtained), may lead us to question the role of environmental flows in the "recovery" of this particular system. This is because if, according to the biological indicators, most of the elements sampled are already meeting the objectives imposed under the WFD, then what should be the criterion for the evaluation of effectiveness of environmental flows releases in the "recovery" of these ecosystems. For example, control measures for exotic species should be prioritized in view of their high percentage in some sites, which has led to rather low F-IBIP values (and consequently quality classes).

It will therefore be essential to continue with the monitoring of the selected sites, in order to enhance the assessment of the effects of environmental flows on the ecological status of water bodies, thus increasing the possibility of understand the ecological responses to the alterations imposed by environmental flows. This will enable an adaptative management of environmental flows.

Summarizing what was referred in the previous paragraphs, the major conclusions of this work are:

- The dams in this system were built more than five decades ago. For more than fifty years, the system adapted itself to the new flow conditions, both from the hydrological and the ecological points of view. This fact can explain most of the good ecological classification results obtained previously to the release of ecological flows. If we take this into consideration, releasing ecological flows of a higher magnitude than those presently in place, could eventually act as a disturbing factor.
- The monitoring of the water quality, both before and after the release of environmental flows, presented inconsistencies, both in time and space, as well as concerning the different parameters that were analysed. This prevented a more robust analysis of the data gathered, namely for the establishment of flow-ecology relationships. Nevertheless, given the high number of “Good” and “Excelent” results that were obtained, the hypothesis that the system adapted to the after-dam situation is reinforced.

- The use of the fish community as a biological indicator, specifically the F-IBIP, although obligatory according to the WFD, is quite problematic. The widespread presence of exotic species often leads to low quality values, although the presence of these species is not causing such a deep reduction in water quality.
- The fact that there is no hydropeaking also helps to justify the adaptation of the system.

7.2 Suggestions for future work

In this section, some suggestions for future work will be provided.

A persisting challenge for environmental flows is to develop robust and, if possible, transferrable flow-ecology relationships. In fact, flow variables and ecological variables can be defined in many ways, which is (and have been) a challenge to get generalized and transferable flow-ecology relationships (Poff and Zimmerman 2010, Stewardson and Webb 2010, Webb et al 2013, Stewart-Koster et al 2014, Webb et al 2017).

Regarding the hydrological study itself, some suggestions for future work can be highlighted. One of them is related to the development of more methods and techniques (or even software) that allow to point out and correct the existence of data inconsistencies in the precipitation records measured in the gauging stations. Furthermore, it should be highlighted that one of the major difficulties in establishing natural and/or modified flow regimes was the lack of flow records measured over the hydroelectric system under study, which made it difficult to calibrate the model developed. In fact, if possible, it will be essential to introduce more stream gauging stations to improve the model performance, thus, reducing the existing uncertainty. Within the area study in here, the inclusion of, at least, two stream gauge stations (in Vilarinho das Furnas and Salamonde) is considered important. Furthermore, other sources of uncertainty, consequently affecting the performance of the model, could be quantified, and/or mitigated. For instance, the introduction of monitoring systems in the main dams under study, which allow the quantification of evaporation rate in the storage reservoirs over time. Another issue, is related with the need to update the volume-area-capacity curves of each main dam, which were developed some years ago, and which could introduce some errors in the existing transpositions (measured water level in the dam to water volume storage capacity), due to the accumulation of sediments in the storage reservoir.

In the present study – concerning the ecological variables analyzed – it was decided to study the response of some of the global ecological indicators (the official in terms of WFD implementation in Portugal), which are used to evaluate water bodies ecological status/potential. It will be essential to compile more ecological information. In fact, this task will be feasible over time, as EDP continues to implement the monitoring programs carried out to evaluate the effectiveness of environmental flows. The possibility of increasing the existing ecological database could help to support the conclusions drawn in this study or indicate other trends in the ecological response. In addition, more ecological information can boost robustness in the application of statistical methods and the development of ecological models.

Another issue that can be further assessed is the expansion of the environmental flows domain to include other key drivers of ecological process. In fact, environmental flows have primarily focused on flow management, mainly because the regulation of the flow regime below a dam is much easier when compared to other types of environmental modification such as altered thermal and sediment regimes. Indeed, to get a broader perspective of riverine ecology it will be important to take into consideration key partially independent variables, such as, temperature, sediment and species interactions (Olden and Naiman 2010, Wohl et al. 2015, Shenton et al. 2012).

The importance of considering sediment dynamics and channel structure is a major issue that has been recognized over the years. In fact, in regulated rivers where sediment dynamics are out of balance due to the storage of sediment by a dam, the hydraulics of habitat can change dramatically (Wohl et al. 2015). Thus, to understand habitat dynamics and ecological response it will be important to incorporate hydraulic and hydrologic models into environmental flows assessments and applications. In this context, the biggest challenge is related to the fact that hydraulic models need a considerable amount of data and are applied, mainly, at local scales. Indeed, more research work should be done to hydraulic regionalization models that can be combined with hydrological models to bring insight into structure and dynamics of the habitat, in many locations (Wilding et al. 2014, Poff et al. 2017).

Summarizing what was referred in the previous paragraphs:

- The number of gauging stations and meteorological stations in the system studied was not enough to produce hydrological models with a very robust calibration. The inclusion of, at least, two stream gauge stations (in Vilarinho das Furnas and Salamonde) is considered important.

- The lack of direct measures of the evaporation rate is another situation that affected the calibration of the hydrological models. It would be important to measure it and deeply evaluate its effects, in future works.

- The monitoring of water quality should continue in the short and medium term, with the guarantee that sampling is coherent in time, space, and the type of parameters included. This should help to build the basis for a better calibration of models, thus allowing to obtain better flow-ecology results.

- In systems like the one studied in this work, with a very low number of stressing factors (no chemical pollution, no intensive agriculture, no large human settlements, etc.) compensatory measures should be more holistic. Besides the fact, already mentioned, that the system is adapted to the presence of dams, and so the release of ecological flows can, eventually, act as an additional stress factor, other hypothsis should be considered. For instance, a flexible management of the ecological flows released, according to the climatic circumstances (particularly relevant in a context of climatic change); a better management of the water level in the different dams; the implementation of ecological restoration programs to help consolidate banks and river bottom; etc.

References

Acreman M (2001) Ethical aspects of water and ecosystems. Water Policy; Volume 3: 257-265.

Acreman M, Dunbar MJ (2004) Defining environmental river flow requirements – a review. Hydrology and Earth System Sciences, 8(5), 861-876.

Acreman M, Arthington AH, Colloff MJ, Couch C, Crossman ND, Dyer F, Overton I, Pollino CA, Stewardson MJ, Young W (2014a) Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world. Frontiers in Ecology and the Environment. doi: 10.1890/130134.

Acreman M, Overton I, King J, Wood P, Dunbar M, Kendy E, Young W (2014b) The changing role of ecohydrological science in guiding environmental flows. Hydrological Sciences Journal, Volume 59(3-4): 433-450. doi: 10.1080/02626667.2014.886019

Aguiar FC, Fernandes MR, Ferreira MT (2014) Manual para Aplicação do IBMR (Índice Biológico de Macrófitos de Rio) no âmbito da Monitorização para a Diretiva Quadro da Água. Contrato 193879-201312/APA. Instituto Superior de Agronomia. Universidade de Lisboa.

Alves MH, Bernardo JM (2002) Caudais Ecológicos em Portugal. INAG, Ministério das Cidades, Ordenamento do Território e Ambiente, Lisboa, Portugal.

Anderson KE, Paul AJ, McCauley E, Jackson LJ, Post JR, Nisbet RM (2006) Instream flow needs in streams and rivers: the importance of understanding ecological dynamics. Frontiers in Ecology and the Environment, Volume 4: 309-318.

Annear T, Chisholm I, Beecher H, Locke A, Aarrestad P, Coomer C, Estes C, Hunt J, Jacobson R, Jobsis G, Kauffman J, Marshall J, Mayes K, Smith G, Wentworth R, Stalkner C (2004) Instream Flows for Riverine Resource Stewardship, Revised Edition. Instream Flow Council, Cheyenne, Wyoming. 268 pp.

APA – Agência Portuguesa do Ambiente (2012) Plano de Gestão da Região Hidrográfica do Cávado, Ave e Leça. Relatório Técnico – Comissão Europeia.

APA (2014) Relatório de Caracterização (art. 5º da DQA). Região Hidrográfica do Cávado, Ave e Leça (RH2). Plano de Gestão de Região Hidrográfica 2016/2021.

APA (2016) Plano de Gestão da Região Hidrográfica. Parte 2 – Caracterização e Diagnóstico. Região Hidrográfica do Cávado, Ave e Leça (RH2).

AQUALOGUS (2010) Estudos Ambientais para a Determinação de Regime de Caudais Ecológicos das Barragens de Alto Rabagão, Venda Nova, Alto Cávado, Paradela, Salamonde, Caniçada e Vilarinho das Furnas (Lote A). Relatório Final. Volume 1 – Memória Geral.

Arthington AH, King JM, O'Keeffe JH, Bunn SE, Day JA, Pusey BJ, Blühdorn DR and Tharme R (1992). Development of an holistic approach for assessing environmental flow requirements of riverine ecosystems. In Proceedings of an International Seminar and Workshop on Water Allocation for the Environment, Pigrim JJ, Hooper BP (Eds.), 69-76. Armidale, Australia: Centre for Water Policy Research.

Arthington AH (1998) Comparative evaluation of environmental flow assessment techniques: review of holistic methodologies. LWRRDC Occasional Paper 26/98. LWRRDC, Canberra, Australia.

Arthington AH, Rall JL, Kennard MJ, Pusey BJ (2003) Environmental flow requirements of fish in Lesotho Rivers using the DRIFT methodology. River Reser, Appl. 19 (5-6), 641-666.

Arthington AH, Bunn S, Poff NL, Naiman RJ (2006) The challenge of providing environmental flow rules to sustain river ecosystems. Ecological Applications; 16: 1311-1318.

Arthington AH, Baran E, Brown CA, Dugan P, Halls AS, King JM, Minte-Vera CV, Tharme RE, Welcomme RL (2007) Water requirements of floodplain rivers and fisheries: existing decision support tools and pathways for development. Comprehensive Assessment of Water Management in Agriculture Research Report 17. International Water Management Institute, Colombo, Sri Lanka.

Arthington AH, Naiman RJ, McClain ME, Nilsson C (2010) Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. Fresh Biol, Volume 55: 1-16.

Arthington AH, Mackay SJ, James CS, Rolls RJ, Sternberg D, Barnes A, Capon SJ (2012) Ecological limits of hydrologic alteration: a test of the ELOHA framework in south-east Queensland. National Water Commission Waterlines Report 75. Canberra, Australia.

Arthington AH (2012) Environmental Flows – Saving Rivers in the Third Millennium. Freshwater Ecology Series. ISBN 978-0-520-27369-6.

Arthington AH, Bhaduri A, Bunn SE, Jackson SE, Tharme RE, Tickner D, Young B, Acreman M, Baker N, Capon S, Horne AC, Kendy E, McClain ME, Poff NL, Richter BD, Ward S (2018) The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018). Front. Environ. Sci.; 6:45. doi: 10.3389/fenvs.2018.00045.

Baron JS, Poff NL, Angermeier PL, Dahm CN, Gleick PH, Hairston NG, Jackson RB, Johnston CA, Richter BD, Steinman AD (2002) Meeting ecological and societal needs for freshwater. Ecological Applications; Volume 12 (5): 1247-1260.

Beames P, Lehner B, Anand M (2019) Global Reservoir and Dam (GRanD) database. Technical documentation. Version 1.3.

Belo-Pereira M, Dutra E, Viterbo P (2011). Evaluation of global precipitation data sets over the Iberian Peninsula. Journal of Geophysical Research; 116, 16 pp. doi: 10.1029/2010JD015481

Bernhardt E, Bunn SE, Hart DD, Malmqvist B, Muotka T, Naiman RJ, Pringle C, Reuss M, van Wilgen B (2006) Perspective the challenge of ecologically sustainable water management. Water Policy, Volume 8: 475-479.

Blake DJH, Sunthornratana U, Promphakping B, Buaphuan S, Sarkkula J, Kummu M, Ta-oun M, Waleetorncheepsawat P, Boonyothayan S, Tharme R, Osbeck M, Janprasart S (2011) E-flows in the Nam Songkhram River Basin. Final Report. M-POWER Mekong Program on Water, Environmental and Resilience, IUCN, IWMI, CGIAR, Challenge Program on Water and Food, and Aalto University, Finland.

Boeuf B, Frisch O (2016) Studying the implementation of the Water Framework Directive in Europe: a meta-analysis of 89 journal articles. Ecology and Society, 21(2): 19. doi: 10.5751/ES-08411-210219.

Bovee KD (1982) A guide to stream habitat analysis using the Instream Flow Incremental Methodology. Instream Flow Information Paper 12. U.S.D.I. Fish and Wildfire Service, Office of Biological Services FWS/OBS-82/26.

Brizga SO, Arthington AH, Pusey BJ, Kennard MJ, Mackay SJ, Werren GL, Craigie NM, Satish C (2002) Benchmarking, a “top-down” methodology for assessing environmental flows in Australian rivers. Environmental Flows for River Systems. An International Working Conference on Assessment and Implementation, incorporating the 4th International Ecohydraulics Symposium. Southern Waters, Cape Town, South Africa.

Buchanan, C., Moltz, H. L. N., Haywood, H. C., Palmer, J. B., and Griggs, A. N. (2013). A test of the ecological limits of hydrologic alteration (ELOHA) method for determining environmental flows in the Potomac River basin, USA. *Freshw. Biol.* 58, 2632–2647. doi: 10.1111/fwb.12240

Bunn SE, Arthington AH (2002) Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management; 30: 492-507.

Carlisle DM, Wolock DM, Meador MR (2011) Alteration of streamflow magnitudes and potential ecological consequences: a multiregional assessment. Frontiers in Ecology and the Environment; Volume 9: 264-270.

CNPGB – Comissão Nacional Portuguesa das Grandes Barragens (2016) Barragens de Portugal. http://cnpgb.apambiente.pt/gr_barragens/gbportugal/index.htm. Acedido em junho de 2016.

Decree-Law nº 45/94 of February 22. https://dre.pt/pesquisa/-/search/515808/details/maximized. Last accessed at January 2020.

Decree-Law nº 46/94 of February 22. https://dre.pt/pesquisa/-/search/515806/details/maximized. Last accessed at January 2020.

Decree-Law nº 77/2006 of March 30. https://dre.pt/pesquisa/-/search/672144/details/maximized. Last accessed at January 2020.

Decree-Law nº 226-A/2007 of May 31. https://dre.pt/web/guest/pesquisa-avancada/-/asearch/340237/details/normal?types=SERIEI&numero=226-A%2F2007&tipo=%22Decreto-Lei%22. Last accessed at January 2020.

Decree-Law nº 103/2010 of September 24. https://dre.pt/pesquisa/-/search/342131/details/normal. Last accessed at January 2020.

Decree-Law nº 83/2011 of June 20. https://dre.pt/pesquisa/-/search/670030/details/normal. Last accessed at January 2020.

Decree-Law nº 130/2012 of June 22. https://dre.pt/pesquisa/-/search/178512/details/maximized?q=Lei+n.%C2%BA%2010%2F97/en. Last accessed at January 2020.

DHI (2017a) MIKE HYDRO River User Guide. MIKE Powered by DHI. The expert in Water Environments.

DHI (2017b) MIKE Zero – The Common DHI User Interface for Project Oriented Water Modelling – User Guide. MIKE Powered by DHI. The expert in Water Environments.

DHI (2017c) MIKE 1D – DHI Simulation Engine for 1D river and urban modelling – Reference Manual. MIKE Powered by DHI. The expert in Water Environments.

DHI (2019a) MIKE HYDRO River. Comprehensive river network modelling. https://www.mikepoweredbydhi.com/products/mike-hydro-river. Last accessed at July 2019.

DHI (2019b) Hydrology. Modelling of catchment runoff for river applications. https://www.mikepoweredbydhi.com/products/mike-hydro-river/hydrology. Last accessed at July 2019.

Dickens C, O'Brien GC, Stassen J, Kleynhans M, Rossouw N, Rowntree K, et al. (2015) Specialist consultants to undertake baseline studies (flow, water quality and geomorphology) and Instream Flow Requirement (IFR) Assessment for phase 2: instream flow requirements for the Senqu River: final report. Prepared by the Institute of Natural Resources NPC NPC on behalf of the Lesotho Highlands Development Authority (LHDA). Maseru, Lesotho.

Dudgeon D, Arthinghton AH, Gessner MO, Kawabata Z, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard A, Soto D, Stiassny MLJ, Sullivan CA (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. Biological Reviews; 81: 163-182.

Dyson M, Bergkamp M, Scanlon J (2003) Flow: The Essentials of Environmental Flows. Gland, Switzerland, and Cambridge, UK: IUCN.

EC – European Commission (2000) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (Water Framework Directive). Official Journal of the European Communities L327 1-72.

EC (2015). Ecological Flows in the Implementation of the WFD. CIS Guidance Document no. 31. Technical Report 2015-086. Brussels.

EC (2017a) The EU water framework directive – integrated river basin management for Europe. http://ec.europa.eu/environment/water/water-framework/index_en.html. Last accessed at December 2017.

EC (2017b) Status of implementation of the WFD in the Member States. http://ec.europa.eu/environment/water/participation/map_mc/map.htm. Last accessed at December 2017.

EDP (2016) Declaração Ambiental 2016. Aproveitamentos Hidroelétricos da EDP – Gestão da Produção de Energia, S. A. Referente ao período de 2016-01-01 a 2016-12-31.

EDP Labelec (2011a) Avaliação da qualidade ecológica do troço fluvial a jusante da barragem de Salamonde. Relatório de 2010/2011. 112/11-AB. LAB-MA – Laboratório de Ambiente.

EDP Labelec (2011b) Avaliação da qualidade ecológica do troço fluvial a jusante da barragem da Caniçada. Relatório de 2010/2011. 113/11-AB. LAB-MA – Laboratório de Ambiente.

EDP Labelec (2011c) Avaliação da qualidade ecológica do troço fluvial a jusante da barragem da Paradela. Relatório de 2010/2011. 114/11-AB. LAB-MA – Laboratório de Ambiente.

EDP Labelec (2011d) Avaliação da qualidade ecológica do troço fluvial a jusante da barragem de Venda Nova. Relatório de 2010/2011. 115/11-AB. LAB-MA – Laboratório de Ambiente.

EDP Labelec (2017) Aproveitamento hidroelétrico do Alto Rabagão. Programa de monitorização para avaliação da qualidade do rio Cávado na zona envolvente da barragem do Alto Cávado. Relatório de monitorização de 2016/2017. 1251/17-AB. LAB-MA – Laboratório de Ambiente.

EDP Labelec (2018a) Aproveitamento hidroelétrico do Alto Rabagão. Programa de monitorização para avaliação da eficácia do regime de caudais ecológicos da barragem do Alto Rabagão. Relatório Anual de 2017/2018. 835/18-AB. LAB-MA – Laboratório de Ambiente.

EDP Labelec (2018b) Aproveitamento hidroelétrico de Vilarinho das Furnas. Programa de monitorização para avaliação da eficácia do regime de caudais ecológicos da barragem de Vilarinho das Furnas. Relatório Anual de 2017. 734/18-AB. LAB-MA – Laboratório de Ambiente.

EEA – European Environment Agency (2017) Copernicus Land Service – Pan-European Component: CORINE Land Cover. European Commission.

Eheart JW (2004) No river left behind: A call for regulation in a deregulating and misregulating era. J. Water Resour. Plann. Manage – ASCE, Volume 130: 357-358.

Folke C, Carpenter S, Walker BH, Scheffer M, Elmqvist T, Gunderson LH, Holling CS (2004) Regime shifts, resilience, and biodiversity in ecosystem management. Annual Review in Ecology, Evolution and Systematics 35; 557-581.

Gao YX, Vogel RM, Kroll CN, Poff NL, Olden JD (2009) Development of representative indicators of hydrologic alteration. J Hydrology, Volume 374: 136-147.

GDW – Global Dam Watch (2019) Curated global dam and reservoir data for all. http://globaldamwatch.org/. Last accessed at May 2019.

Gillespie, B. R., Desmet, S., Kay, P., Tillotson, M. R., and Brown, L. E. (2015). A critical analysis of regulated river ecosystem responses to managed environmental flows from reservoirs. *Freshw. Biol.* 60, 410–425. doi: 10.1111/fwb.12506

Graham D (2014) Introduction to Integrated Hydrologic Modelling. Groundwater, Surface Water and MIKE SHE. Elements of the course MIKE SHE, DHI, Lisbon.

Grove JR, Webb JA, Marren PM, Stewardson MJ, Wealands SR (2012) High and dry: an investigation using the causal criteria methodology to investigate the effects of regulation, and subsequent environmental flows, on floodplain geomorphology. Wetlands; Volume 32: 215-224 pp.

Harrison ET (2010) Fine Sediment in Rivers: Scale of Ecological Outcomes. PhD Dissertation, University of Canberra, Canberra, Australia.

Hart, B. T. (2016a). The Australian Murray-Darling Basin Plan: challenges in its implementation (Part 1). Int. J. Water Resour. Dev. 32, 819–834. doi: 10.1080/07900627.2015.1083847

Hart, B. T. (2016b). The Australian Murray-Darling Basin Plan: challenges in its implementation (Part 2). Int. J. Water Resour. *Dev.* 32, 835–852. doi: 10.1080/07900627.2015.1084494

Hart, B., and Doolan, J. (2017). Decision Making in Water Resources Policy and Management. London: Academic Press.

Harwood, A., Johnson, S., Richter, B., Locke, A., Yu, X., and Tickner, D. (2017) Listen to the River: Lessons From a Global Review of Environmental Flow Success Stories. WWF.

Haury J, Peltre MC, Trémolières M, Barbe J, Thiébaut G, Bernez I, Daniel H, Chatenet P, Haan-Archipof G, Muller S, Dutartre A, Laplace-Treyture C, Cazaubon A, Lambert-Servien E (2006) A new method to assess water trophy and organic pollution – the Macrophyte Biological Index for Rivers (IBMR): its application to different types of river and pollution. Hydrobiologia. 570: 153-158.

Hill MT, Platts WS, Beschta RL (1991) Ecological and geomorphological concepts for instream and out-of-channel flow requirements. Rivers; Volume 2: 198-210.

Hipólito JR, Vaz AC (2012) Hidrologia e Recursos Hídricos. IST Press. ISBN: 9789728469863.

Horne AC, O'Donnell EL, Webb JA, Stewardson MJ, Acreman M, Richter B (2017a). "Chapter1: The Environmental Water Management Cycle" in Water for the Environment: from Policy and Science to Implementation and Management. (Cambridge, MA: Elsevier).

Horne AC, Webb JA, O'Donnell E, Arthington AH, McClain M, Bond N, Acreman M, Hart B, Stewardson MJ, Richter R, and Poff NL (2017b) Research priorities to improve future environmental water outcomes. Frontiers in Environmental Science; Volume 5: 89. doi: 10.3389/fenvs.2017.00089.

Horne AC, Konrad C, Webb JA, Acreman M (2017c). "Chapter10: Visions, Objectives, Targets, and Goals," in Water for the Environment: from Policy and Science to Implementation and Management. (Cambridge, MA: Elsevier).

Hughes JMR, James B (1989) A hydrological regionalization of streams in Victoria, Australia, with implications for stream ecology. Australian Journal of Marine and Freshwater Research; 40 (3): 303-326.

Hughes DA, Hannart P (2003) A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. Journal of Hydrology. 270, 167-181.

Hughes DA, Desai AY, Birkhead AL, Louw D (2014) A new approach to rapid, desktop-level, environmental flow assessments for rivers in South Africa. Hydrol. Sci. J. 59 (3), 1-15.

INAG IP (2008) Tipologia de Rios em Portugal Continental no âmbito da implementação da Directiva Quadro da Água. I – Caracterização abiótica. Ministério do Ambiente, do Ordenamento do Território e do Desenvolvimento Regional. Instituto da Água, I.P.

INAG (2009) Critérios para a classificação do estado das massas de água superficiais – Rios e Albufeiras. Ministério do Ambiente, do Ordenamento do Território e do Desenvolvimento Regional.

INAG, AFN – Autoridade Florestal Nacional (2012) Desenvolvimento de um índice de qualidade para a fauna piscícola. Ministério da Agricultura, Mar, Ambiente e Ordenamento do Território.

IPMA (2018) Produtos e serviços – Base de dados de Precipitação Diária – Portugal Continental. https://www.ipma.pt/pt/produtoseservicos/index.jsp?page=dataset.pt02.xml. Last accessed at July 2019.

IPMA (2019a) Normais Climatológicas. https://www.ipma.pt/pt/oclima/normais.clima/?print=true. Last accessed at July 2019.

IPMA (2019b) Monitorização da Seca – Índice SPI – Evolução. http://www.ipma.pt/pt/oclima/observatorio.secas/spi/monitorizacao/evolucao/. Last accessed at July 2019.

IRI (2019) Climate Data Library. http://iridl.ldeo.columbia.edu/SOURCES/.NASA/.GES-DAAC/.TRMM_L3/.TRMM_3B42RT/.v7/. Last accessed at July 2019.

James C, Mackay SJ, Arthington AH, Capon S (2016) Does flow structure riparian vegetation in subtropical south-east Queensland? Ecol. Evol. 6(16), 5950-5963.

Kendy E, Apse C, Blann K (2012) A Practical Guide to Environmental Flows for Policy and Planning. The Nature Conservancy, Arlington, Virginia.

Kennen JG, Stein ED, Webb JA (2018) Evaluating and managing environmental water regimes in a water-scarce and uncertain future. doi: 10.1111/fwb.13104.

King JM, Tharme RE (1994) Assessment of the Instream Flow Incremental Methodology and Initial Development of Alternative Instream Flow Methodologies for South Africa. Water Research Commission. Report No. 295/1/94.

King JM, Louw MD (1998) Instream flow assessments for regulated rivers in South Africa using the Building Block Methodology. Aquat. Ecosyst. Health Manag. 1, 109-124.

King JM, Tharme RE, de Villiers MS (Eds.) (2000) Environmental flow assessments for rivers: manual for the Building Block Methodology. Water Research Commission Report TT 131/00, Pretoria, South Africa.

King JM, Brown CA, Sabet H (2003) A scenario-based holistic approach to environmental flow assessments for rivers. River Research and Applications; 19: 619-640.

King JM, Brown CA (2010) Integrated basin flow assessments: concepts and method development in Africa and South-east Asia. *Freshw. Biol.* 55, 127–146. doi: 10.1111/j.1365-2427. 2009.02316.

King J, Beuster H, Brown C, Joubert A (2014) Pro-active management: the role of environmental flows in transboundary cooperative planning for the Okavango River system. Hydrol. Sci. J. 59, 786-800.

Konrad CP, Brasher AMD, May JT (2008) Assessing streamflow characteristics as limiting factors on benthic invertebrate assemblages in streams across the western United States. Freshwater Biology; Volume 53: 1983-1998.

Lamouroux N, Jowett IG (2005) Generalized instream habitat models. Can. J. Fish. Aquat. Sci. 62, 7-14.

Law nº 11/87 of April 7. http://www.pgdlisboa.pt/leis/lei_mostra_articulado.php?nid=752&tabela=leis. Last accessed at January 2020.

Law nº 58/2005 of December 29. http://www.pgdlisboa.pt/leis/lei_mostra_articulado.php?nid=1191&tabela=leis. Last accessed at January 2020.

Law nº 44/2012 of August 29. https://dre.pt/pesquisa/-/search/174798/details/maximized. Last accessed at January 2020.

Lehner B, Liermann CR, Revenga C, Vörösmarty C, Fekete B, Crouzet P, Döll P, Endejan M, Frenken K, Magome J, Nilsson C, Robertson JC, Rödel R, Sindorf N, and Wisser D (2011) High-resolution mapping of the world’s reservoirs and dams for sustainable river-flow management. Frontiers in Ecology and the Environment 9 (9): 494-502. doi: 10.1890/100125.

Le Quesne, T., Kendy, E., and Weston, D. (2010). The Implementation Challenge - Taking Stock of Government Policies to Protect and Restore Environmental Flows. The Nature Conservancy and WWF. Available online at: http://www.conservationgateway.org/Files/Pages/implementation-challenge-.aspx

Lloyd N, Quinn G, Thoms M, Arthington A, Gawne B, Humphries P, Walker K (2003) Does Flow Modification Cause Geomorphological and Ecological Response in Rivers? A Literature Review from an Australian Perspective. Technical Report 1/2004, Cooperative Research Centre for Freshwater Ecology: Canberra, Australia.

Lokgariwar C, Chopra V, Smakhtin V, Bharati L, O’Keeffe J (2014) Including cultural water requirements in environmental flow assessment: an example from the upper Ganga River, India. Water Int. 39, 81-96.

Lytle DA, Poff NL (2004) Adaptation to natural flow regimes. Trends Ecol Evol, Volume 19: 94-100.

Maia R (2017) The WFD Implementation in the European Member States. Water Resources Management, 31: 3043-3060.

McClain ME, Subalusky AL, Anderson EP, Dessu SB, Melesse AM, Ndomba PM, Mtamba JOD, Tamatamah RA, Mligo C (2014) Comparing flow regime, channel hydraulics, and biological communities to infer flow-ecology relationships in the Mara River of Kenya and Tanzania. Hydrol. Sci. J. 59:3-4, 801-819.

McKee TB, Doesken NJ, Kleist J (1993) The Relationship of Drought Frequency and Duration to Time Scales. 8th Conferences on Applied Climatology, Anaheim, 17-22 January 1993, 6p.

McManamay RA, Orth DJ, Dolloff CA, Mathews DC (2013) Application of the ELOHA framework to regulated rivers in the Upper Tennessee River Basin: a case study. Environ. Manage. 51, 1210-1235.

Merwade V (2012a) Watershed and Stream Network Delineation using ArcHydro Tools. School of Civil Engineering, Purdue University.

Merwade V (2012b) Terrain Processing and HMS-Model Development using GeoHMS. School of Civil Engineering, Purdue University.

Molnar P (2011) Calibration. Watershed Modelling, SS 2011. Institute of Environmental Engineering, Chair of Hydrology and Water Resources Management, ETH Zürich, Switzerland.

Monk WA, Wood PJ, Hannah DM, Wilson DA (2007) Selection of river flow indices for the assessment of hydroecological change. River Research Applications; Volume 23:113-122.

Monteiro L, Ramos V. Maia R (2017) Aplicação do modelo precipitação-vazão NAM (MIKE HYDRO River) na bacia hidrográfica da barragem do Alto Cávado. XXII Simpósio Brasileiro de Recursos Hídricos, 26th November to 1st December 2017, Florianópolis, Brasil.

Moore M (2004) Perceptions and interpretations of environmental flows and implications for future water resource management: a survey study. Master's thesis, Department of Water and Environmental Studies, Linköping University, Sweden.

Moriasi DN, Gitau MW, Pai N, Daggupati P (2015). Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria. America Society of Agricultural and Biological Engineers; 58: 1763-1785. DOI 10.13031/trans.58.10715

Moussa R, Chahinian N and Bocquillon C (2007) Distributed hydrological modelling of a Mediterranean mountainous catchment Model construction and multi-site validation. J. Hydrology, 337: 35-51.

Myers N (1993) Biodiversity and precautionary principle. Ambio; Volume 22: 74-79.

Naiman RJ, Bunn SE, Nilsson C, Petts GE, Pinay G, Thompson LC (2002) Legitimizing fluvial ecosystems as users of water: an overview. Environmental Management; Volume 30 (4): 455-467.

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models part I – A discussion of principles. Journal of Hydrology. 10 (3): 282-290.

NDMC – National Drought Mitigation Center (2019) Standardized Precipitation Index. https://drought.unl.edu/droughtmonitoring/SPI.aspx. Last accessed at July 2019.

Nelson KC, Palmer MA, Pizzuto JE, Moglen GE, Angermeier PL, Hilderbrand RH, dettinger M, Hayhoe K (2009) Forecasting the combined effects of urbanization and climate change on stream ecosystems: from impacts to management options. J Appl Ecol, 46.

Norris RH, Webb JA, Nichols SJ, Stewardson MJ, Harrison ET (2012) Analyzing cause and effect in environmental assessments: using weighted evidence from the literature. Freshwater Science; Volume 31: 5-21.

O'Brien GC, Dickens C, Hines E, Wepener V, Stassen R, Quayle L, Fouchy K, Mackensie J, Graham PM, Landis WG (2018). A regional-scale ecological risk framework for environmental flow evaluations. *Hydrol. Earth Syst. Sci.* 22, 957–975. doi: 10.5194/hess-22-957-2018

Olden JD, Poff NL (2003) Redundancy and the choice of hydrological indicators for characterizing streamflow regimes. River Research and Applications; 19: 101-121

Olden JD, Naiman RJ (2010) Broadening the science of environmental flows: managing riverine thermal regimes for ecosystem integrity. Freshwater Biology, 55: 86-107.

Olden JD, Konrad CP, Melis TS, Kennard MJ, Freeman MC, Mims MC, Bray EN, Gido KB, Hemphill NP, Lytle DA, McMullen LE, Pyron M, Robinson CT, Schmidt JC, Williams JG (2014) Are large-scale flow experiments informing the science and management of freshwater ecosystems? Frontiers in Ecology and the Environment; Volume 12(3). doi: 10.1890/130076.

Oliveira JM, Santos JM, Teixeira A, Ferreira MT, Pinheiro PJ, Geraldes A, Bochechas J (2007). Projecto AQUARIPORT: Programa Nacional de Monitorização de Recursos Piscícolas e de Avaliação da Qualidade Ecológica de Rios. Direcção-Geral dos Recursos Florestais, Lisboa, 96 pp.

Oliveira JM (2018) Implementing ecological flow release devices in EDP portuguese ancient dams? Challenges and Lessons learned. Oral presentation in 12th International Symposium on Ecohydraulics, Aug 19 – Aug 24. Tokyo, Japan.

Ordinance nº 1450/2007 of November 12. https://dre.pt/pesquisa/-/search/629400/details/maximized. Last accessed at January 2020.

Padrão HM (2013) O papel dos caudais ecológicos no potencial ecológico das massas de água a jusante de aproveitamentos hidroelétricos. Caso de estudo: Aproveitamentos Hidroelétricos do rio Lima.

Petts GE (1989) Perspectives for ecological management of regulated rivers. In Alternatives in Regulated River Management, Gore JA, Petts GE (Eds), 3-24. Boca Raton, FL: CRC Press.

Poff NL, Ward JV (1989) Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. Canadian Journal of Fisheries and Aquatic Sciences; 46: 1805-1818.

Poff NL, Ward JV (1990) Physical habitat template of lotic systems: recovery in the context of historical patterns of spatiotemporal heterogeneity. Environmental Management 14: 629 – 645.

Poff NL (1996) A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. Freshwater biology 36: 71-91.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC (1997) The natural flow regime: a paradigm for river conservation and restoration. BioScience; 47: 769-784.

Poff NL, Allan JD, Palmer MA, Hart DD, Richter BD, Arthington AH, Rogers KH, Meyers JL, Stanford JA (2003) River flows and water wars: emerging science for environmental decision making. Frontiers in Ecology and the Environment; Volume 1 (6): 298-306.

Poff NL, Zimmerman JKH (2010) Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshwater Biology; 55: 194-205.

Poff NL, Richter BD, Arthington AH, Bunn SE, Naiman RJ, Kendy E, Acreman M, Apse C, Bledsoe BP, Freeman MC, Henriksen J, Jacobson RB, Kennen JG, Merrtit DM, O’Keeffe JH, Olden JD, Rogers K, Tharme RC, Warner A (2010) The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshwater Biology, 55: 147-170.

Poff NL, Matthews JH (2013) Environmental flows in the Anthropocence: past progress and future prospects. Current Opinion in Environmental Sustainability; Volume 5 (6): 667-675. doi: 10.1016/j.cosust.2013.11.006.

Poff NL (2014) Rivers of the Anthropocene? Frontiers in Ecology and the Environment; Vol 12 (Issue 8). doi: 10.1890/1540-9295-12.8.427

Poff, N. L., Tharme, R. E., and Arthington, A. H. (2017). “Chapter11: Evolution of environmental flows assessment science, principles, and methodologies,” in Water for the Environment: from Policy and Science to Implementation and Management. (Cambridge, MA: Elsevier).

Postel S, Richter B (2003) Rivers for Life: Managing Water for People and Nature. Washington, DC: Island Press.

Ramos V, Formigo N, Maia R (2017) The challenge of environmental flows in Portugal, under the Water Framework Directive. 20th International River*symposium* and Environmental Flows Conference, Brisbane, Australia.

Ramos V, Formigo N, Maia R (2018) Environmental Flows Under the WFD Implementation. Water Resources Management. 32: 5115-5149.

Rashleigh B (2008) The Role of Ecological Endpoints in Watershed Management. In: Gönenç İ.E., Vadineanu A., Wolflin J.P., Russo R.C. (eds) Sustainable Use and Development of Watersheds. NATO Science for Peace and Security Series (Series C: Environmental Security). Springer, Dordrecht. doi: 10. 1007/978-1-4020-8558-1_20.

Raven PJ, Fox P, Everard M, Holmes NTH, Dawson FH (1997) River habitat survey: a new system for classification rivers according to their habitat quality. Freshwater Quality: Defining the Indefinable?

Raven PJ, Holmes NTH, Dawson FH, Everard m (1998) Quality Assessment Using River Habitat Survey Data. Aquatic Conservation Marine and Freshwater Ecosystems. 8(4): 477-499.

Resh VH, Brown AV, Covich AP, Gurtz ME, Li HW, Minshall GW, Reice SR, Sheldon AL, Wallace JB, Wissmar RC (1988) The role of disturbance in stream ecology. Journal of the North American Benthological Society; Volume 7 (4): 433-455.

Ribeiro R (2016) Simulação hidrodinâmica de condições de exploração em aproveitamentos hidroelétricos. O caso dos reforços de potência de Venda Nova. Dissertação submetida para satisfação parcial dos requisitos do grau de Mestre em Engenharia Civil – Especialização em Hidráulica.

Richter BD, Baumgartner JV, Powell J, Braun DP (1996) A method for assessing hydrologic alteration within ecosystems. Conservation Biology; 10: 1163-1174.

Richter BD, Baumgartner JV, Wigington R, Braun DP (1997) How much water does a river need? Freshwater biology; 37: 231-249.

Richter B, Baumgartner J, Braun DP, Powell J (1998) A spatial assessment of hydrologic alteration within a river network. Regulated Rivers: Research & Management; 14: 329-340.

Riverdene Consultancy (2018a) The survey. http://www.riverhabitatsurvey.org/rhs-doc/the-survey/. Last accessed at 2018.

Riverdene Consultancy (2018b) Habitat Assessment http://www.riverhabitatsurvey.org/rhs-doc/habitat-assessment/. Last accessed at 2018.

Rolls RJ, Arthington AH (2014) How do low magnitudes of hydrologic alteration impact riverine fish populations and assemblage characteristics? Ecol. Indic. 39, 179-188.

Shenton W, Bond NR, Yen JDL, Mac Nally R (2012) Putting the “ecology” into environmental flows: ecological dynamics and demographic modelling. Environ. Manage. 50: 1-10.

Smakhtin V, Revenga C, Döll P (2004) A pilot global assessment of environmental water requirements and scarcity. Water Int, Volume 29: 307-317.

Smakhtin VU, Anputhas M (2006) An assessment of environmental flow requirements of Indian river basins. IWMI Research Report 107. International Water Management Institute, Colombo, Sri Lanka.

Speed R, Binney J, Pusey B, Catford J (2011) Policy measures, mechanisms, and framework for assessing environmental flows. ACEDP Project Report. International Water Centre, Brisbane, Queensland.

Stein, E. D., Sengupta, A., Mazor, R. D., McCune, K., Bledsoe, B. P., and Adams, S. (2017). Application of regional flow-ecology relationships to inform watershed management decisions: application of the ELOHA framework in the San Diego river watershed. Ecohydrology. e1869. doi: 10.1002/eco.1869

Stewardson MJ, Webb JA (2010) Modelling ecological responses to flow alteration: making the most of existing data and knowledge. In Ecosystem Response Modelling in the Murray-Darling Basin, Saintilan N, Overton I (eds.). CSIRO Publishing: Melbourne: 37.49

Stewart-Koster B, Bunn SE, Mackay SJ, Poff NL, Naiman RJ, Lake PS (2010) The use of Bayesian networks to guide investments in flow and catchment restoration for impaired river ecosystems. Freshwater Biology. 55:243-260.

Stewart-Koster B, Olden JD, Gido KB (2014) Quantifying flow-ecology relationships with functional linear models. Hydrol. Sci. J. 59:629-644.

Solans MA, de Jalón DG (2016) Basic tools for setting environmental flows at the regional scale: application of the ELOHA framework in a Mediterranean river basin. Ecohydrology, 9, 1517-1538.

Song BY, Yang J (2003) Discussion on ecological use of water research. Journal of Natural Resources 18: 617-625.

Suen JP, Eheart JW (2006) Reservoir management to balance ecosystem and human needs: Incorporating the paradigm of the ecological flow regime. Water Resour Res, 42.

Tennant DL (1996) Instream flow regimens for fish, wildlife, recreation and related environmental resources. Fisheries 1 (4), 6-10.

Tharme RE (1996) A review of international methodologies for the quantification of the instream flow requirements of rivers. Water law review report for policy development. Department of Water Affairs and Forestry, Pretoria, South Africa.

Tharme RE (2003) A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Research and Applications 19: 397-441.

The Brisbane Declaration (2007) "Environmental flows are essential for freshwater ecosystem health and human well-being" in 10th International Riversymposium and International Environmental Flows Conference (Brisbane, QLD). Available online at: https://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/ELOHA/Pages/Brisbane-Declaration.aspx

The Brisbane Declaration on Environmental Flows (2018) "Environmental flows are essential to protect and restore biodiversity, aquatic ecosystems, and the ecosystem services they provide for all societies" in 20th International Riversymposium and Environmental Flows Conference (Brisbane, QLD).

The Nature Conservancy (2009) Indicators of Hydrologic Alteration Version 7.1 User's Manual.

The Nature Conservancy (2017) Ecological Limits of Hydrologic Alteration (ELOHA). https://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/ELOHA/Pages/ecological-limits-hydrolo.aspx. Last accessed at October 2019.

Thompson JR, Laizé CLR, Green AJ, Acreman MC, Kingston DG (2014) Climate change uncertainty in environmental flows for the Mekong River. Hydrol. Sci. J. 59 (3-4), 935-954.

Thornthwaite CW (1948). An Approach toward a Rational Classification of Climate. Geographical Review, American Geographical Society, Vol. 38, No.1, 55-94 pp.

USAID (2016) Environmental flows in Rufiji River Basin assessed from the perspective of planned development in Kilombero and Lower Rufiji sub-basins. Technical assistance to support the development of irrigation and rural roads infrastructure project (IRRIP2). United States Agency for International Development, final report.

US Army Corps of Engineers (2016) Hydrologic Modelling System HEC-HMS. User's Manual. Version 4.2.

Vogel RM, Sieber J, Archfield SA, Smith MP, Apse CD, Huber-Lee A (2007) Relations among storage, yield and instream flow. Water Resour Res, 43.

Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden PS, Bunn SE, Sullivan CA, Liederman C, Davies PM (2010) Global threats to human water security and river biodiversity. Nature 467: 555-561.

Webb JA, Wealands SR, Lea P, Nichols SJ, de Little SC, Stewardson MJ, Norris RH (2011) Eco Evidence: using the scientific literature to inform evidence-based decision making in environmental management. In: Proceedings of MODSIM 2011 – International Congress on Modelling and Simulation (Eds F. Chan, D. Marinova and R.S. Anderssen), 2472-2478 pp. Modelling and Simulation Society of Australia and New Zealand.

Webb JA, de Little SC, Miller KA, Stewardson MJ (2012a) Eco Evidence Database: a distributed modelling resource for systematic literature analysis in environmental science and management. In: 2012 International Congress on Environmental Modelling and Software. Managing Resources of a Limited Planet: Pathways and Visions under Uncertainty, Sixth Biennial Meeting (Eds R. Seppelt, A.A. Voinov, S. Lange and D. Bankamp). International Environmental Modelling and Software Society (iEMSs).

Webb JA, Wallis EM, Stewardson MJ (2012b) A systematic review of published evidence linking wetland plants to water regime components. Aquatic Botany; Volume 103: 1-14.

Webb JA, Miller KA, King EL, de Little SC, Stewardson MJ, Zimmerman JH, Poff NL (2013) Squeezing the most out of existing literature: a systematic re-analysis of published evidence on ecological responses to altered flows. Freshwater Biology; 58(12): 2439-2451.

Webb JA, de Little SC, Miller KA; Stewardson MJ, Rutherfurd ID, Sharpe AK, Patulny L, Poff NL (2015) A General Approach to Predicting Ecological Responses to Environmental Flows: Making Best Use of the Literature, Expert Knowledge, and Monitoring Data. River Research and Applications; 31(4), 505-514.

Webb JA, Arthington AH, Olden JD (2017). "Chapter14: Models of Ecological Responses to Flow Regime Change to Inform Environmental Flows Assessments" in Water for the Environment: from Policy and Science to Implementation and Management. (Cambridge, MA: Elsevier).

Wilby RL, Orr HG, Hedger M, Forrow D, Blackmore M (2006) Risk posed by climate change to delivery of the Water Framework Directive objectives in the UK. Environ Int, 30:1043-1055.

Wilding TK, Bledsoe B, Poff NL, Sanderson J (2014) Predicting Habitat Response to Flow Using Generalized Habitat Models for Trout in Rocky Mountain Streams. River Research and Applications. 30: 805-824.

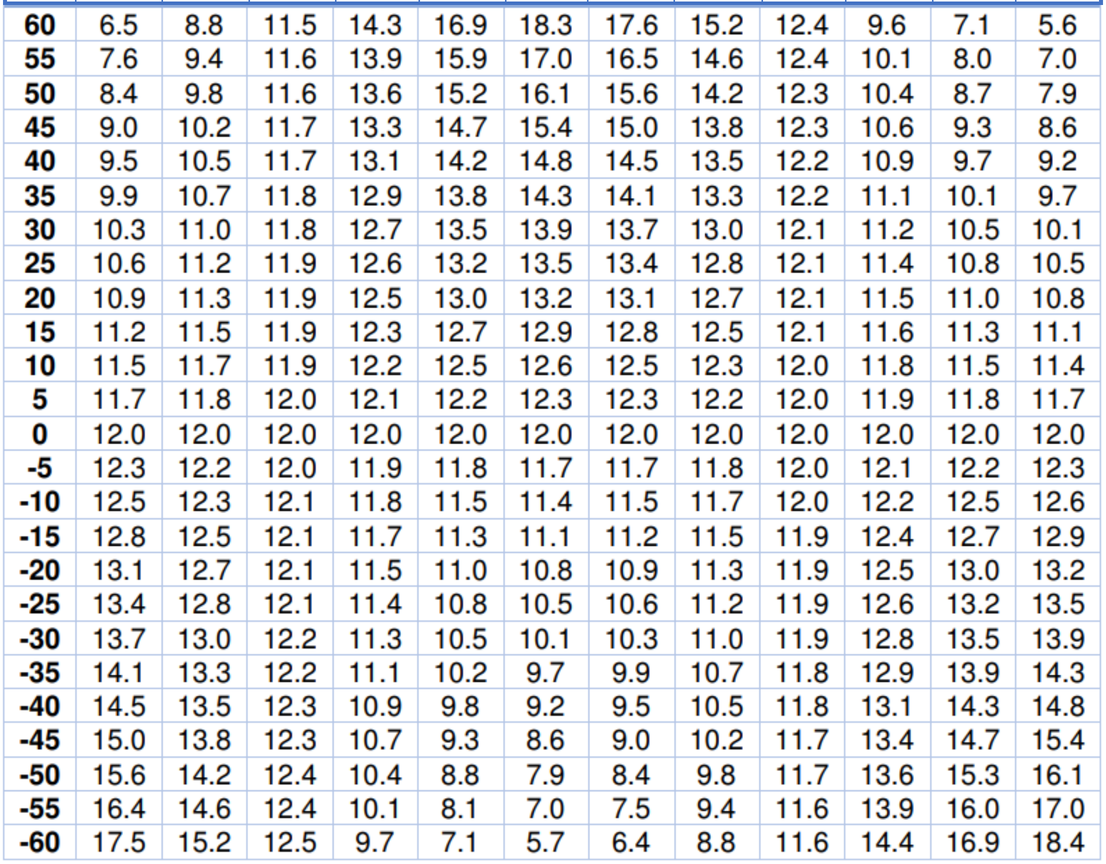
Willmott CJ, Ackleson SG, Davis RE, Feddema JJ, Klink KM, Legates DR, O'Donnell J, Rowe CM (1985) Statistics for the evaluation and comparison of models. Journal of Geophysical Research: Oceans/ Volume 90, Issue C5.

Wohl E, Bledsoe BP, Jacobson RB, Poff NL, Rathburn SL, Walters DM, Wilcox AC (2015) The natural sediment regime in rivers: broadening the foundation for ecosystem management. BioScience 65, 358-371.

Zalasiewicz J, Williams M, Smith A, Barry T, Coe A, Bown P, Brenchley P, Cantrill D, Gale A, Gibbard P, Gregory F, Hounslow M, Kerr A, Pearson P, Knox R, Powell J, Waters C, Marshall J, Oates M, Rawson P, Stone P (2008) Are we now living in the Anthropocene. GSA Today, 18 (2), 4 pp.

Appendices

Appendix A – Mean possible duration of sunlight (hours) (adapted from Hipólito and Vaz 2012).



Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
60	6.5	8.8	11.5	14.3	16.9	18.3	17.6	15.2	12.4	9.6	7.1	5.6
55	7.6	9.4	11.6	13.9	15.9	17.0	16.5	14.6	12.4	10.1	8.0	7.0
50	8.4	9.8	11.6	13.6	15.2	16.1	15.6	14.2	12.3	10.4	8.7	7.9
45	9.0	10.2	11.7	13.3	14.7	15.4	15.0	13.8	12.3	10.6	9.3	8.6
40	9.5	10.5	11.7	13.1	14.2	14.8	14.5	13.5	12.2	10.9	9.7	9.2
35	9.9	10.7	11.8	12.9	13.8	14.3	14.1	13.3	12.2	11.1	10.1	9.7
30	10.3	11.0	11.8	12.7	13.5	13.9	13.7	13.0	12.1	11.2	10.5	10.1
25	10.6	11.2	11.9	12.6	13.2	13.5	13.4	12.8	12.1	11.4	10.8	10.5
20	10.9	11.3	11.9	12.5	13.0	13.2	13.1	12.7	12.1	11.5	11.0	10.8
15	11.2	11.5	11.9	12.3	12.7	12.9	12.8	12.5	12.1	11.6	11.3	11.1
10	11.5	11.7	11.9	12.2	12.5	12.6	12.5	12.3	12.0	11.8	11.5	11.4
5	11.7	11.8	12.0	12.1	12.2	12.3	12.3	12.2	12.0	11.9	11.8	11.7
0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
-5	12.3	12.2	12.0	11.9	11.8	11.7	11.7	11.8	12.0	12.1	12.2	12.3
-10	12.5	12.3	12.1	11.8	11.5	11.4	11.5	11.7	12.0	12.2	12.5	12.6
-15	12.8	12.5	12.1	11.7	11.3	11.1	11.2	11.5	11.9	12.4	12.7	12.9
-20	13.1	12.7	12.1	11.5	11.0	10.8	10.9	11.3	11.9	12.5	13.0	13.2
-25	13.4	12.8	12.1	11.4	10.8	10.5	10.6	11.2	11.9	12.6	13.2	13.5
-30	13.7	13.0	12.2	11.3	10.5	10.1	10.3	11.0	11.9	12.8	13.5	13.9
-35	14.1	13.3	12.2	11.1	10.2	9.7	9.9	10.7	11.8	12.9	13.9	14.3
-40	14.5	13.5	12.3	10.9	9.8	9.2	9.5	10.5	11.8	13.1	14.3	14.8
-45	15.0	13.8	12.3	10.7	9.3	8.6	9.0	10.2	11.7	13.4	14.7	15.4
-50	15.6	14.2	12.4	10.4	8.8	7.9	8.4	9.8	11.7	13.6	15.3	16.1
-55	16.4	14.6	12.4	10.1	8.1	7.0	7.5	9.4	11.6	13.9	16.0	17.0
-60	17.5	15.2	12.5	9.7	7.1	5.7	6.4	8.8	11.6	14.4	16.9	18.4

Appendix B – Monitoring groups for each location.

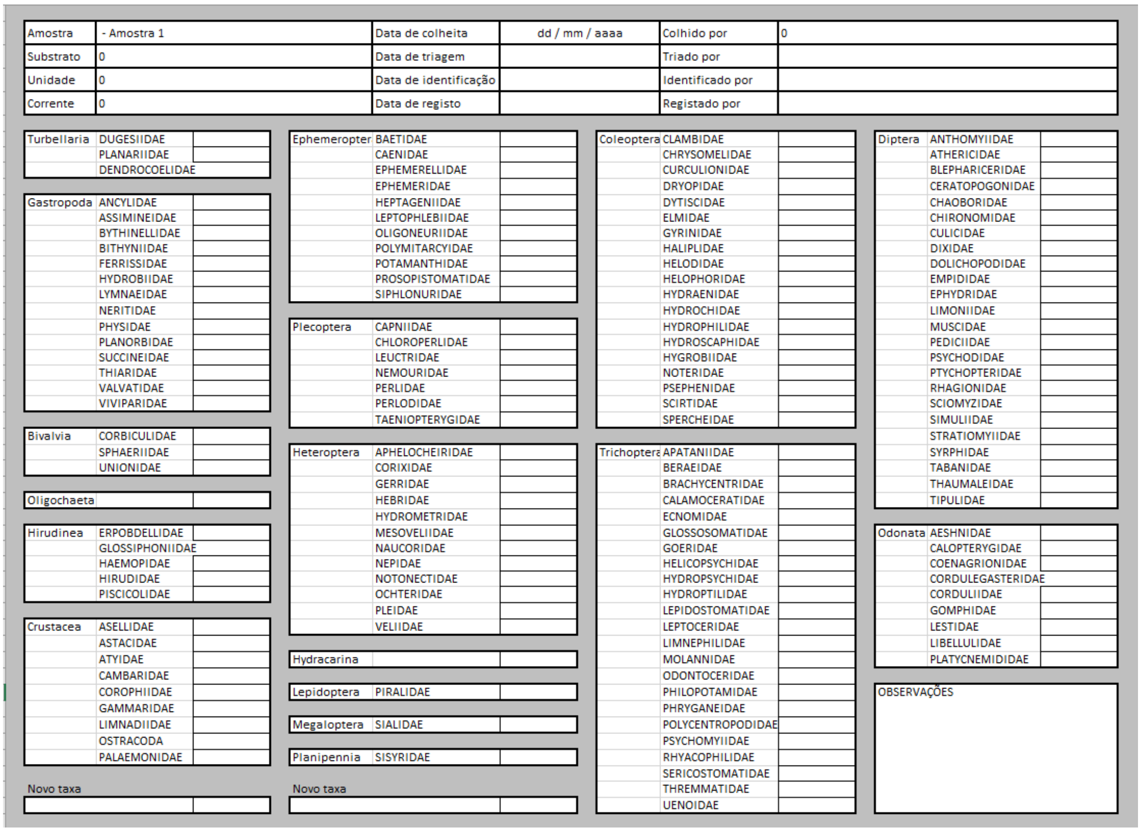
Dams	Selected site (selected as with the representative name of each sampling group)	Sampling points associated to each station (considering their spatial proximity)	Monitoring programs associated to each sampling point, related with:
Alto Rabagão	**AR1**	Ponte na EN 103	Definition of WFD reference water bodies
		Rab_1	Environmental flows definition (AQUALOGUS)
		CA_002	AQUARIPORT project
		AR1	Evaluation before environmental flows release (reference condition) / Evaluation of environmental flows effectiveness
	AR2	Vila da Ponte	Definition of WFD reference water bodies
		Rab_2	Environmental flows definition (AQUALOGUS)
		AR2	Evaluation before environmental flows release (reference condition) / Evaluation of environmental flows effectiveness
Venda Nova	**VN1**	Rab_3	Environmental flows definition (AQUALOGUS)
		CA_004	AQUARIPORT project
		VN1	Evaluation before environmental flows release (reference condition) / Construction of infrastructures (Venda Nova III)
Alto Cávado	**AC1C**	Montalegre	Definition of WFD reference water bodies
		AC1C	Evaluation before environmental flows release (reference condition) and Evaluation of water quality of Cávado

			River in the area surrounding the Cávado dam
	AC2C	Alto Cávado	Definition of WFD reference water bodies
		AC2C	Evaluation before environmental flows release (reference condition) and Evaluation of water quality of Cávado River in the area surrounding the Cávado dam
	AC1	Cav_1	Environmental flows definition (AQUALOGUS)
		CA_003	AQUARIPORT project
		AC1	Evaluation before environmental flows release (reference condition) and Evaluation of water quality of Cávado River in the area surrounding the Cávado dam
	AC2	Cav_2	Environmental flows definition (AQUALOGUS)
		AC2	Evaluation before environmental flows release (reference condition) and Evaluation of water quality of Cávado River in the area surrounding the Cávado dam
	AC3	AC3	Evaluation before environmental flows release (reference condition) and Evaluation of water quality of Cávado River in the area surrounding the Cávado dam
Paradela	**PL2**	Ponte da Peneda	Definition of WFD reference water bodies
		Cav_3	Environmental flows definition (AQUALOGUS)
		PL2	Evaluation before environmental flows release (reference condition) / Evaluation of environmental flows effectiveness
	PL3	Cav_4	Environmental flows definition (AQUALOGUS)

		PL3	Evaluation before environmental flows release (reference condition) / Evaluation of environmental flows effectiveness
Salamonde	**SD1**	Cav_5	Environmental flows definition (AQUALOGUS)
		Salamonde	Elaboration of the 1st RBMPs
		SD1	Evaluation before environmental flows release (reference condition) / Construction of infrastructures (Salamonde II)/ Evaluation of environmental flows effectiveness
Caniçada	**CD1**	Parada do Bouro	Definition of WFD reference water bodies
		CD1	Evaluation before environmental flows release (reference condition) / Construction of infrastructures (complementary spillway)
	CD2	Cav_7	Environmental flows definition (AQUALOGUS)
		CD2	Evaluation before environmental flows release (reference condition) / Construction of infrastructures (complementary spillway)
	CD3	CD3	Evaluation before environmental flows release (reference condition) / Construction of infrastructures (complementary spillway)
Vilarinho das Furnas	**VF1**	VF1	Evaluation before environmental flows release (reference condition) / Evaluation of environmental flows effectiveness
	VF2	Hom_1	Environmental flows definition (AQUALOGUS)
		Sequeirós	Definition of WFD reference water bodies / Elaboration of the 1st RBMPs

		CA_001	AQUARIPORT project
		VF2	Evaluation before environmental flows release (reference condition) / Evaluation of environmental flows effectiveness
	VF2b	Hom_2	Environmental flows definition (AQUALOGUS)
		Cavacadouro	Definition of WFD reference water bodies
		VF2b	Evaluation of environmental flows effectiveness
	VF3	Barral	Definition of WFD reference water bodies
		VF3	Evaluation before environmental flows release (reference condition) / Evaluation of environmental flows effectiveness
	VF3b	VF3b	Evaluation of environmental flows effectiveness

Appendix C – Print of excel sheet used to calculate IPtI$_N$ and associated metrics.



Amostra	- Amostra 1	Data de colheita	dd / mm / aaaa	Colhido por	0
Substrato	0	Data de triagem		Triado por	
Unidade	0	Data de identificação		Identificado por	
Corrente	0	Data de registo		Registado por	

Turbellaria	DUGESIIDAE	
	PLANARIIDAE	
	DENDROCOELIDAE	

Gastropoda	ANCYLIDAE	
	ASSIMINEIDAE	
	BYTHINELLIDAE	
	BITHYNIIDAE	
	FERRISSIDAE	
	HYDROBIIDAE	
	LYMNAEIDAE	
	NERITIDAE	
	PHYSIDAE	
	PLANORBIDAE	
	SUCCINEIDAE	
	THIARIDAE	
	VALVATIDAE	
	VIVIPARIDAE	

Bivalvia	CORBICULIDAE	
	SPHAERIIDAE	
	UNIONIDAE	

Oligochaeta		

Hirudinea	ERPOBDELLIDAE	
	GLOSSIPHONIIDAE	
	HAEMOPIDAE	
	HIRUDIDAE	
	PISCICOLIDAE	

Crustacea	ASELLIDAE	
	ASTACIDAE	
	ATYIDAE	
	CAMBARIDAE	
	COROPHIIDAE	
	GAMMARIDAE	
	LIMNADIIDAE	
	OSTRACODA	
	PALAEMONIDAE	

Novo taxa

Ephemeropter	BAETIDAE	
	CAENIDAE	
	EPHEMERELLIDAE	
	EPHEMERIDAE	
	HEPTAGENIIDAE	
	LEPTOPHLEBIIDAE	
	OLIGONEURIIDAE	
	POLYMITARCYIDAE	
	POTAMANTHIDAE	
	PROSOPISTOMATIDAE	
	SIPHLONURIDAE	

Plecoptera	CAPNIIDAE	
	CHLOROPERLIDAE	
	LEUCTRIDAE	
	NEMOURIDAE	
	PERLIDAE	
	PERLODIDAE	
	TAENIOPTERYGIDAE	

Heteroptera	APHELOCHEIRIDAE	
	CORIXIDAE	
	GERRIDAE	
	HEBRIDAE	
	HYDROMETRIDAE	
	MESOVELIIDAE	
	NAUCORIDAE	
	NEPIDAE	
	NOTONECTIDAE	
	OCHTERIDAE	
	PLEIDAE	
	VELIIDAE	

Hydracarina		

Lepidoptera	PIRALIDAE	

Megaloptera	SIALIDAE	

Planipennia	SISYRIDAE	

Novo taxa

Coleoptera	CLAMBIDAE	
	CHRYSOMELIDAE	
	CURCULIONIDAE	
	DRYOPIDAE	
	DYTISCIDAE	
	ELMIDAE	
	GYRINIDAE	
	HALIPLIDAE	
	HELODIDAE	
	HELOPHORIDAE	
	HYDRAENIDAE	
	HYDROCHIDAE	
	HYDROPHILIDAE	
	HYDROSCAPHIDAE	
	HYGROBIIDAE	
	NOTERIDAE	
	PSEPHENIDAE	
	SCIRTIDAE	
	SPERCHEIDAE	

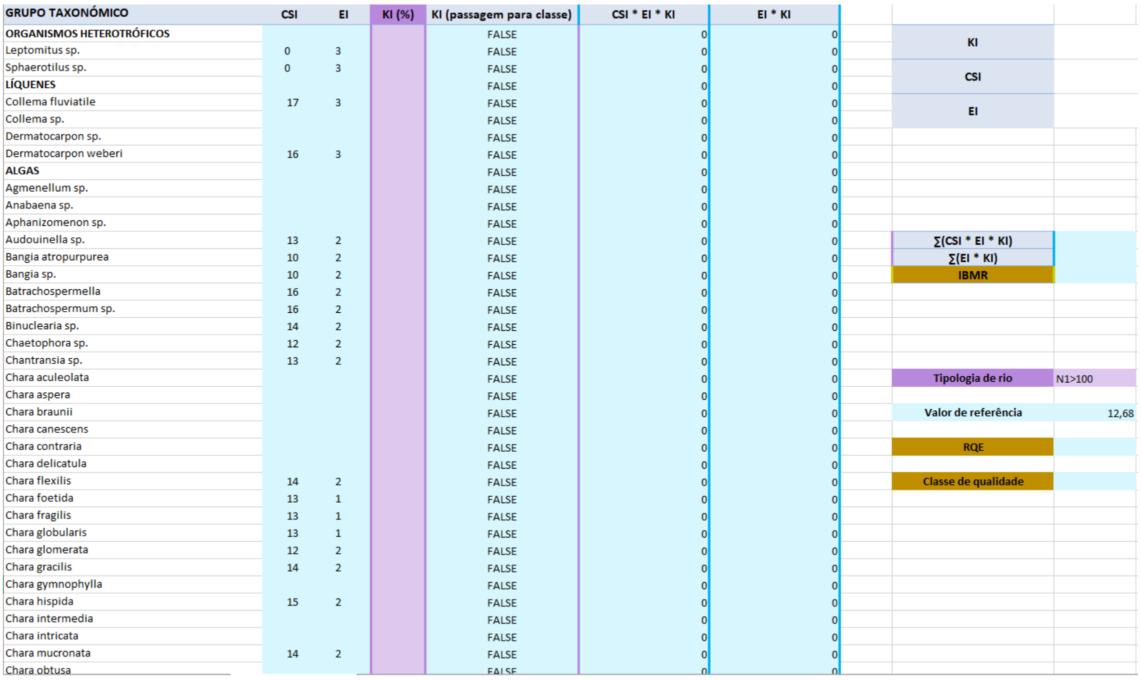
Trichoptera	APATANIIDAE	
	BERAEIDAE	
	BRACHYCENTRIDAE	
	CALAMOCERATIDAE	
	ECNOMIDAE	
	GLOSSOSOMATIDAE	
	GOERIDAE	
	HELICOPSYCHIDAE	
	HYDROPSYCHIDAE	
	HYDROPTILIDAE	
	LEPIDOSTOMATIDAE	
	LEPTOCERIDAE	
	LIMNEPHILIDAE	
	MOLANNIDAE	
	ODONTOCERIDAE	
	PHILOPOTAMIDAE	
	PHRYGANEIDAE	
	POLYCENTROPODIDAE	
	PSYCHOMYIIDAE	
	RHYACOPHILIDAE	
	SERICOSTOMATIDAE	
	THREMMATIDAE	
	UENOIDAE	

Diptera	ANTHOMYIIDAE	
	ATHERICIDAE	
	BLEPHARICERIDAE	
	CERATOPOGONIDAE	
	CHAOBORIDAE	
	CHIRONOMIDAE	
	CULICIDAE	
	DIXIDAE	
	DOLICHOPODIDAE	
	EMPIDIDAE	
	EPHYDRIDAE	
	LIMONIIDAE	
	MUSCIDAE	
	PEDICIIDAE	
	PSYCHODIDAE	
	PTYCHOPTERIDAE	
	RHAGIONIDAE	
	SCIOMYZIDAE	
	SIMULIIDAE	
	STRATIOMYIIDAE	
	SYRPHIDAE	
	TABANIDAE	
	THAUMALEIDAE	
	TIPULIDAE	

Odonata	AESHNIDAE	
	CALOPTERYGIDAE	
	COENAGRIONIDAE	
	CORDULEGASTERIDAE	
	CORDULIIDAE	
	GOMPHIDAE	
	LESTIDAE	
	LIBELLULIDAE	
	PLATYCNEMIDIDAE	

OBSERVAÇÕES

Appendix D – Print of excel sheet used to calculate IBMR.



GRUPO TAXONÓMICO	**CSI**	**EI**	**KI (%)**	**KI (passagem para classe)**	**CSI * EI * KI**	**EI * KI**
ORGANISMOS HETEROTRÓFICOS				FALSE	0	0
Leptomitus sp.	0	3		FALSE	0	0
Sphaerotilus sp.	0	3		FALSE	0	0
LÍQUENES				FALSE	0	0
Collema fluviatile	17	3		FALSE	0	0
Collema sp.				FALSE	0	0
Dermatocarpon sp.				FALSE	0	0
Dermatocarpon weberi	16	3		FALSE	0	0
ALGAS				FALSE	0	0
Agmenellum sp.				FALSE	0	0
Anabaena sp.				FALSE	0	0
Aphanizomenon sp.				FALSE	0	0
Audouinella sp.	13	2		FALSE	0	0
Bangia atropurpurea	10	2		FALSE	0	0
Bangia sp.	10	2		FALSE	0	0
Batrachospermella	16	2		FALSE	0	0
Batrachospermum sp.	16	2		FALSE	0	0
Binuclearia sp.	14	2		FALSE	0	0
Chaetophora sp.	12	2		FALSE	0	0
Chantransia sp.	13	2		FALSE	0	0
Chara aculeolata				FALSE	0	0
Chara aspera				FALSE	0	0
Chara braunii				FALSE	0	0
Chara canescens				FALSE	0	0
Chara contraria				FALSE	0	0
Chara delicatula				FALSE	0	0
Chara flexilis	14	2		FALSE	0	0
Chara foetida	13	1		FALSE	0	0
Chara fragilis	13	1		FALSE	0	0
Chara globularis	13	1		FALSE	0	0
Chara glomerata	12	2		FALSE	0	0
Chara gracilis	14	2		FALSE	0	0
Chara gymnophylla				FALSE	0	0
Chara hispida	15	2		FALSE	0	0
Chara intermedia				FALSE	0	0
Chara intricata				FALSE	0	0
Chara mucronata	14	2		FALSE	0	0
Chara obtusa				FALSE	0	0

KI	
CSI	
EI	
∑(CSI * EI * KI)	
∑(EI * KI)	
IBMR	
Tipologia de rio	N1>100
Valor de referência	12,68
RQE	
Classe de qualidade	