FACULDADE DE ARQUITETURA
UNIVERSIDADE DE LISBOA

INSTITUTO SUPERIOR DE AGRONOMIA
Universidade de Lisboa

TÉCNICO LISBOA

GHOST OF DIADROMOUS FISH PAST:

STREAMLINING RESEARCH ON DIADROMOUS FISH SPECIES USING HISTORICAL DATA AT THE EUROPEAN SCALE

GONÇALO FILIPE FERNANDES DUARTE

SCIENTIFIC ADVISORS:

Ph.D Maria Teresa Marques Ferreira

Ph.D Gertrud Haidvogl

Ph.D Pedro Segurado

THESIS PRESENTED TO OBTAIN THE DOCTOR DEGREE IN

RIVER RESTORATION AND MANAGEMENT

2019

ULISBOA | UNIVERSIDADE DE LISBOA

GHOST OF DIADROMOUS FISH PAST:

STREAMLINING RESEARCH ON DIADROMOUS FISH SPECIES USING HISTORICAL DATA AT THE EUROPEAN SCALE

GONÇALO FILIPE FERNANDES DUARTE

SCIENTIFIC ADVISORS:
Ph.D Maria Teresa Marques Ferreira
Ph.D Gertrud Haidvogl
Ph.D Pedro segurado

THESIS PRESENTED TO OBTAIN THE DOCTOR DEGREE IN
RIVER RESTORATION AND MANAGEMENT

JURY:
President: Doutora Manuela Rodrigues Branco Simões
Professora Auxiliar com Agregação
Instituto Superior de Agronomia
Universidade de Lisboa.

Members:
Doutor Carlos Antonio Granado Lorencio
Catedrático de Universidad
Universidad de Sevilla, Espanha;

Doutora Maria Teresa Marques Ferreira
Professora Catedrática
Instituto Superior de Agronomia
Universidade de Lisboa;

Doutor Pedro Miguel Raposo de Almeida
Professor Auxiliar com Agregação
Escola de Ciências e Tecnologia
Universidade de Évora;

Doutora Maria Filomena de Magalhães
Professora Auxiliar
Faculdade de Ciências
Universidade de Lisboa.

Instituições Financiadoras e âmbito:
Universidade de Lisboa
Programa Doutoral FCT (River Restoration and Management, FLUVIO)
PD/BD/52514/2014

2019

Dedicated to my “Ghosts of Christmas Past”, Dilene e Alberto...

... to my “Ghosts of Christmas Present”, Beatriz, Fernando e Margarida…

… and to my “Ghost of Christmas Yet to come”, Sofia!

A todos o meu profundo agradecimento!

Resumo

O declínio e extinção regional de espécies de peixes diádromas ocorre pelo menos desde o início do século XX. Nesta tese, várias bases de dados europeias foram consultadas e, reconhecendo a falta de informação para Portugal, desenvolveu-se a primeira base de dados históricos para espécies ícticas dulçaquícolas. A existência de bases de dados com diferentes coberturas geográficas e informação a distintas escalas levou ao desenvolvimento de uma estrutura de dados históricos capaz de lidar com as limitações inerentes a este tipo de informação, sendo o resultado uma base de dados fiável, de cobertura geográfica extensa a três escalas: bacia, sub-bacia e segmento. Desenvolveu-se ainda um software que facilita a aquisição de dados ambientais ligados às redes e bacias hidrográficas que podem ser associados às três escalas. As quebras de conectividade longitudinal, as alterações climáticas e as mudanças de uso do solo são das ameças mais relevantes para as espécies diádromas. A influência destas ameaças foi estudada efectuando uma análise espacial e temporal às quebras de conectividade por grandes barragens e, modelando a distribuição das espécies diádromas usando variáveis de clima e uso do solo. Os bloqueios nas redes hidrológicas europeias generalizaram-se na segunda metade do século XX, e têm actualmente mais impacto nas populações de bacias do sul da Europa. A distribuição de espécies diádromas é sobretudo afectada pelo clima, embora os efeitos do uso do solo nas proximidades de estuários possam ser relevantes dado que são locais críticos de passagem e acesso ao resto da rede hidrográfica. A estrutura de dados históricos e o software desenvolvidos foram a chave para alcançar o conhecimento científico sobre a distribuição de espécies diádromas de peixes. Contudo, ainda mais importante é o facto destas ferramentas se poderem estabelecer como uma base de trabalho estrutural para o futuro da investigação sobre estas espécies.

Palavras chave: Redes hidrológicas, Dados históricos, PHish, RivTool, Espécies de peixe diádromas

Abstract

The decline of diadromous fish species has been occurring at least since the beginning of the 20th century. In this thesis, multiple European databases on the historical distribution of diadromous fish were consulted and, acknowledging the lack of data for Portugal, the first database of Portuguese historical data for freshwater fish was created. The existence of multiple databases with distinct geographical coverage and data at different spatial scales lead to the development of an historical data framework able to deal with the limitations of historical data. Its output is a reliable and geographically broad dataset of diadromous species occurrence at the beginning of the 20th century at three spatial scales: basin, sub-basin and segment. Also, a software was developed to facilitate the acquisition of environmental and riverscape variables that can be linked with the data at the three scales. Longitudinal connectivity impairment, climate change and land use alterations are some of the most significant threats to diadromous fish species. The influence of these threats was studied performing a spatial and temporal analysis of the longitudinal connectivity impairment by large dams and, modelling the distribution of diadromous fish at the beginning of the 20th century using climate and land use variables. The longitudinal connectivity impairment of the European freshwater networks became widespread in the second half of the 20th century, and is currently more impactful for populations from basins in southern Europe. The distribution of diadromous fish species is mainly affected by climate, though the effects of land use close to river mouths may be relevant since these are critical passage and entry points for the remaining network. The framework and the software developed were key to achieve the scientific knowledge presented, and more importantly, these can be established as the structural basis for future research on diadromous fish species.

Keywords: Freshwater networks, Historical data, PHish, RivTool, Diadromous fish species,

Resumo alargado

Durante milénios a Humanidade dependeu dos rios para a obtenção de água e alimento. Como tal, as zonas próximas de rios foram escolhidas como locais para a fixação de populações humanas. Os sistemas dulçaquícolas representam 0,8% da superfície terrestre, contêm apenas 0,01% de toda a água na terra, e, no entanto, albergam 9,5% das espécies animais. Os sistemas de água doce são dos mais ameaçados globalmente. Na Europa, 95% das planícies aluviais e 50% das zonas húmidas originais foram severamente alteradas ou perdidas porque quase 50% da população humana vive nessas áreas. Os sistemas dulçaquícolas contêm habitats ricos em espécies endémicas e sensíveis, contudo para a maioria destas espécies a falta de informação sobre a sua distribuição e seu estado de conservação constitui uma importante lacuna de conhecimento. As espécies de peixes diádromas representam um elo energético entre sistemas marinhos e de água doce ao fazerem parte das cadeias alimentares nos dois sistemas. As diádromas são um grupo específico da ictiofauna europeia com uma elevada relevância social e económica, uma vez que durante séculos têm representado uma fonte de proteína para as populações humanas e, nalguns casos, serem das pescarias mais valiosas no mundo.

Sendo um *hotspot* de biodiversidade, os sistemas de água doce são também um *hotspot* de ameaça para esta mesma biodiversidade. Na Europa continental, cerca de 40% das espécies nativas de peixes desapareceram de bacias das quais eram nativas e 13 espécies estão efectivamente extintas. No caso das espécies diádromas, independentemente da qualidade e duração das séries de dados, a tendência global actual é de declínio, nalguns casos para mínimos históricos. As causas mais relevantes para este declínio são: as barreiras nos rios, a regularização destes sistemas, a perda de habitat, a sobrepesca, as alterações e intensificação do uso do solo, as alterações climáticas e a qualidade e quantidade de água. De notar que estas ameaças não estão a actuar de forma independente, pelo contrário as interacções e efeitos sinergísticos são comuns e geralmente as extinções são o resultado da interacção entre várias ameaças, questões naturais e atributos biológicos das espécies.

Todas as espécies animais afectam o ambiente que as rodeia, mas no caso do Homem os impactes são temporalmente muito duradouros e espacialmente omnipresentes. As evidências da presença humana são observáveis na natureza mas também em documentação escrita resultante das actividades humanas ao longo dos séculos. Este tipo de evidências fornece perspectivas e conhecimento que só através deles é possível obter, e que só agora os investigadores em ecologia começam a explorar e a valorizar. De facto, os cientistas têm, cada vez mais, procurado fontes de informação e dados históricos não só para compreender, explicar e gerir melhor os ecossistemas, mas sobretudo para aumentar a capacidade de previsão das respostas que estes sistemas darão às mudanças globais futuras a que estarão sujeitos. Considerando que o Homem alterou durante séculos os sistemas ribeirinhos, os métodos que utilizam informações e dados históricos são seguramente uma abordagem adequada para o estudo dos ecossistemas dulçaquícolas. Estes métodos têm um conjunto importante de limitações e problemas associados ao seu uso que não devem ser negligenciados. Ainda assim, após o cruzamento de fontes e de dados de distintas proveniências espaciais e temporais e se enquadrados com métodos adequados, a sua utilização não deve ser ignorada uma vez que o seu valor para modelação ecológica e para a melhoria do conhecimento ecológico sobre a ictiofauna está amplamente comprovado por inúmeros estudos científicos.

A investigação sobre espécies diádromas tem beneficiado da inclusão e uso de dados históricos, especialmente os estudos que utilizam modelos de distribuição de espécies. A maior parte dos modelos de distribuição de espécies usados no estudo de espécies diádromas tem tentado relacionar ocorrência, abundância e/ou riqueza específica com variáveis climáticas. Tendo em conta que estas abordagens geralmente abrangem toda a Europa, na maioria dos casos tanto a temperatura como a precipitação têm assumido uma elevada importância na definição da distribuição das espécies. Estes modelos bioclimáticos são potencialmente úteis no que toca às previsões sobre os impactes das alterações climáticas. No entanto, estas abordagens ao nível europeu restringem-se à escala de bacia na sua análise, o que é limitante, uma vez que, escalas menores como sub-bacia e segmento poderão mostrar variações relevantes dentro das bacias. Como tal, a investigação sobre diádromas beneficiaria de uma abordagem de modelação que utilize registos históricos, que seja espacialmente abrangente e que utilize diferentes escalas de análise consoante as variáveis ambientais que relaciona com os dados das espécies.

O objectivo principal desta tese é alargar o conhecimento sobre a ocorrência de espécies de peixe diádromas para o início do século XX utilizando dados históricos, bem como adicionalmente perceber como é que factores ambientais e ameaças antropogénicas afectam a distribuição destas espécies. Este trabalho foi executado a três escalas espaciais (bacia, sub-bacia e segmento) sem perder uma abrangência geográfica mais alargada (Europa). Para atingir os objectivos propostos, na primeira parte da tese, para além da criação de uma base de dados portuguesa, estabeleceu-se uma abordagem que permite lidar com múltiplas bases de dados e fontes de dados históricos. A segunda parte diz respeito à criação de um software que facilita a criação e aquisição de dados ambientais e de pressões antropogénicas à escala Europeia. Em seguida, estas duas partes serviram de suporte aos dois últimos trabalhos apresentados, onde a ocorrência de várias espécies diádromas é relacionada com o clima, o uso do solo e a quebra de conectividade longitudinal nas redes hidrológicas europeias.

O primeiro resultado da tese foi a elaboração de uma base de dados históricos sobre peixes de água doce em Portugal continental, denominada PHish (*Portuguese Historical Fish Database*). A base de dados foi estruturada para três escalas (bacia, sub-bacia e segmento) de forma a permitir a utilização de dados com diferente acuidade espacial. Apresenta 2214 registos (557 à escala de bacia, 184 à escala de sub-bacia e 1473 à escala de segmento), obtidos a partir de 194 documentos históricos, para 25 entidades taxonómicas diferentes e abrangendo um espaço temporal de um milénio, com registos desde o século XI ao século XX. O segundo resultado é a elaboração de um método que permite lidar com os problemas e limitações dos dados históricos, e cujo resultado final é um conjunto fiável e espacialmente abrangente de dados de génese histórica para as várias espécies de peixes diádromas a três escalas distintas (bacia, sub-bacia e segmento). A necessidade de dar resposta à intenção de modelar utilizando os dados criados no passo anterior utilizando variáveis ambientais e de pressões antropogénicas levou ao desenvolvimento do software *The River Network Toolkit* (*RivTool*). Toda a arquitectura e funcionamento do software baseiam-se no carácter dendrítico, hierárquico e conexo

das redes hidrológicas. Apesar de pensada e elaborada no âmbito deste doutoramento, esta ferramenta já foi descarregada pelo menos em 37 países de 5 continentes diferentes, o que poderá ser indicativo da sua abrangente aplicabilidade. Os dois trabalhos apresentados na terceira parte tiram partido do que foi desenvolvido anteriormente, nomeadamente da abordagem metodológica aos dados históricos e do software. O quarto trabalho mostrou que a conectividade estrutural das redes hidrológicas europeias está severamente comprometida por grandes barragens, e que isso afecta todas as espécies de peixes diádromas consideradas no estudo. Temporalmente, a perda de conectividade generalizou-se na segunda metade do século XX, e actualmente afecta de forma mais significativa as populações de bacias do sul da Europa. Em várias espécies, o declínio na ocorrência e nos recursos piscatórios das espécies diádromas é subsequente à construção de barragens no curso do rio principal, pelo que tudo indica que estas tiveram um papel decisivo no declínio global deste grupo de animais. O último trabalho mostrou que as variáveis climáticas, nomeadamente a amplitude de temperatura e a precipitação mínima influenciam a distribuição das espécies de peixes diádromas analisadas. Apesar da abordagem hierárquica, em que o clima foi associado à escala de bacia e o uso do solo à de sub-bacia, as variáveis climáticas são aparentemente mais relevantes que as variáveis de uso do solo em ambas as escalas. As variáveis de uso do solo relevantes resultam aparentemente do facto de haver mais presenças junto à foz e de não haver distinção entre habitats de passagem e zonas de acasalamento e reprodução.

No âmbito deste doutoramento, para além do incremento no conhecimento científico sobre a ocorrência de espécies de peixes diádromas tendo em conta o clima o uso do solo e a existência de grandes barragens nas redes hidrológicas europeias, a maior contribuição para futuros avanços na investigação sobre espécies diádromas reside na estrutura metodológica de dados históricos e no software desenvolvidos. Estes foram não só a chave para alcançar novo conhecimento científico ao longo deste trabalho, mas podem sobretudo constituir uma base de trabalho fundamental para o futuro da investigação sobre espécies de peixes diádromas.

Palavras chave: Redes hidrológicas, Dados históricos, PHish, RivTool, Espécies de peixe diádromas

Agradecimentos

Julgo não ter usado uma única vez a primeira pessoa do singular ao longo de toda a extensão do documento… não por desresponsabilização, mas por achar genuinamente que o presente documento, embora sendo da minha inteira responsabilidade, é fruto do trabalho e dedicação de muitas pessoas. Deixo um aqui agradecimento geral a todos com quem me fui cruzando ao longo do doutoramento, abaixo agradeço aos que influenciaram de forma decisiva o meu trabalho durante este período.

À professora Teresa Ferreira pela oportunidade que me deu de percorrer este caminho, e sobretudo por ter acreditado sempre que era capaz de chegar ao fim! As palavras de incentivo, os momentos de partilha de conhecimento e experiência, bem como a sua visão pragmática foram cruciais para a conclusão (inclusive atempada!) deste projecto. Espero sinceramente conseguir retribuir a esperança e confiança que tem depositado em mim e no meu trabalho. Obrigado.

To Gertrud my deepest acknowledgements for all the advices, shared knowledge and for introducing me to history in the context of ecology. Thank you for helping me (over and over again) with my stays in Austria; your kindness and dedication towards me were tremendous and for that I am also truly grateful. Hope I can continue to work and learn from you.

Ao Pedro Segurado um enorme agradecimento pela imensa paciência com que foi lidando comigo quase diariamente. A partilha e debate de ideias, o espírito crítico e sobretudo o teu conhecimento foram muito importantes para o sucesso deste doutoramento. Um enorme obrigado pelos constantes incentivos e por acreditares que conseguia concluir, espero continuar a ter o prazer de trabalhar contigo.

Ao Paulo Branco, que, não sendo oficialmente um dos orientadores da tese, acedeu a “assumir” esse papel e aturar-me constantemente. A partilha de conhecimento, o espírito crítico, o rigor científico, a dedicação, a supervisão, a orientação, os conselhos e incentivos foram absolutamente cruciais para a concretização deste doutoramento. Um enorme obrigado pela amizade honesta e pela tua dedicação.

To Didier for having kick-started this PhD, for having planted the seeds of this work and for the knowledgeable inputs and advices.

Ao Tiago Oliveira pela paciência e dedicação no desenvolvimento “fora de horas” do software. Sem ti, essa empreitada claramente teria sido impossível! Foram serões longos, tempo roubado à família e à cama pelo qual te estou genuinamente agradecido.

Ao Miguel Moreira por ter acreditado numa proposta de trabalho fora do âmbito do seu doutoramento, mas que também graças ao seu empenho arrancou para um trabalho agora publicado.

Aos colegas do programa Doutoral FLUVIO, Filipe Romão, María Diaz, Maria João Costa, Ana Raquel Calapez, Ana Isabel Machado, Rui Rivaes e Rute Vieira pela partilha, pela amizade e interajuda. Seguramente que sem vocês esta aventura teria sido muito menos rica e interessante. Parabéns aos que terminaram, boa sorte para os que ainda estão a concluir.

Aos restantes colegas do grupo, Rosário Fernandes, Francisca Aguiar, José Maria Santos, Rui Rivaes, Susana Amaral, André Fabião, Patrícia Gonzales, João Oliveira, Micaela Silva por todos os incentivos, conselhos e pelo bom ambiente e partilha científica.

Ao Centro de Estudos Florestais (CEF) pelo acolhimento.

To the Institute of Hydrobiology and Aquatic Ecosystem Management of the University of Natural Resources and Life Sciences for having welcomed me.

À Fundação para a Ciência e Tecnologia pelo financiamento, através de uma Bolsa de Doutoramento com a referência PD/BD/52514/2014.

Ao Paulo e a Sofia pela amizade e carinho. Não só de doutoramento vive uma pessoa, e vocês são uma parte importante do resto da vida. Ao Pedro e à Carolina obrigado por existirem, por azucrinarem a cabeça aos vossos pais e por (quase!:) sempre terem um abraço especial guardado para mim!

A todos os familiares que de uma forma ou de outra me apoiaram e incentivaram para atingir os objectivos a que me vou propondo!

Aos meus avós, Alberto e Dilene qualquer agradecimento é parco considerando tudo o me "ofereceram" na vida! Muito antes desta oportunidade, já perguntavam porque não avançava para esta aventura. Não que percebessem exactamente o que significa um doutoramento, mas porque me viam feliz a "estudar"! A eles um enorme obrigado e, um pedido desculpa... ao meu avô por ter estado ausente no fim! Será também uma marca deste projecto, ter-me roubado os teus últimos dias! À minha avó por não conseguir fazer mais nesta recta final!

Aos meus pais, Beatriz e Fernando um sentido obrigado! Há 30 e muitos anos atrás claramente estavam bem longe de pensar que isto poderia um dia ser uma realidade, mas a verdade é que foram vocês os promotores desta vontade de aprender e deste gosto pela "escola". Ainda que vos seja difícil de perceber exactamente o que faço, nunca deixam de apoiar e valorizar o meu percurso. Obrigado por estarem lá nos momentos de felicidade, mas sobretudo obrigado por quererem partilhar também aquilo que não é tão positivo, por estarem presentes quando é difícil fazê-lo.

À minha irmã um obrigado pelo carinho que nos une, pelo apoio e incentivo. Um obrigado especial aos meus sobrinhos por me fazerem sorrir!

À Margarida resta-me agradecer todo o apoio, ajuda, incentivo, carinho, (muita!) paciência e dedicação para que conseguisse avançar e terminar esta aventura. Sem ti este percurso teria sido muito mais complicado e seguramente menos apreciado. Obrigado pela aventura da paternidade, algo que também ficará associado a este doutoramento. Do fundo do coração muito muito obrigado!

À Sofia por me fazer ganhar o dia logo de manhã, simplesmente com a palavra "Papá!!", ou de me encher de felicidade porque quer um abraço grande antes de ir dormir. Talvez a tua maior contribuição tenha sido demostrar que esta aventura faz parte da vida, mas não é a vida inteira. Por isto e por todo amor com que me presenteias diariamente, obrigado!

Table of Contents

List of Figures

List of tables

1. Introduction

"I told you these were shadows of the things that have been," said the Ghost. "That they are what they are, do not blame me!"

Charles Dickens, "A Christmas Carol"

1.1 Why are freshwater ecosystems so relevant?

For millennia, humanity has relied and depended on rivers. Being a permanent source of water and food, locations near rivers were the obvious option for the temporary settlements of nomad human populations. With the emergence of agriculture, this preference became even more relevant given the fertile soils of lowlands, wetlands and riverine areas. Rivers, floodplains, wetlands and watersheds constitute an ecological infrastructure with inestimable value (Postel and Carpenter, 1997). Covering only 0.8% of the earth's surface and representing 0.01% of the world's water (Dudgeon et al., 2006), freshwater ecosystems are home to 9.5% of animal species (Balian et al., 2007). Even nowadays, the freshwater ecological infrastructure and associated biodiversity are crucial resources for humankind providing valuable ecosystem services (Dudgeon et al., 2006; Postel and Carpenter, 1997). These services are the direct or indirect benefits that humans obtain from the functioning of the ecosystems (Costanza et al., 1997; Daily, 1997), and are produced by a network of natural cycles, powered by solar energy, which constitute the mechanisms of the biosphere (Daily, 1997) (Definition box 1.1). Postel and Carpenter (1997) have identified the most relevant services provided by rivers, lakes, aquifers and wetlands establishing three broad-scale categories (Table 1.1.1). This list, though meagre to represent the relevance of freshwater ecosystems is illustrative of the importance of the most relevant services provided.

Economic valuation of ecosystem services is complex and controversial, but definitely useful for decision-making processes. Despite acknowledged limitations, the study of Costanza et al. (1997), estimates that freshwater biomes (Lakes/Rivers, Wetlands and Estuaries) represent 16% (US$5.28 trillion yr^{-1}) of the yearly economic value of ecosystem services provided globally, despite constituting only 1.4% of the global area. In addition, and regardless of the evident lack of data and/or knowledge for the Lakes/rivers biome in this study, the average yearly value per hectare for freshwater biomes was more than 2.4 times the overall average across all biomes. The overall estimations indicate that the economic value of global ecosystem services (US$33 trillion yr^{-1}) was 1.8 times the value of world gross national product, meaning that ecosystem services contribute decisively to human welfare and prosperity (Costanza et al., 1997).

Table 1.1.1 – Categories (in bold) and a respective list of services provided by rivers, lakes, aquifers and wetlands identified by Postel and Carpenter (1997).

Water Supply
Drinking, cooking, washing, and other household uses
Manufacturing, thermoelectric power generation, and other industrial uses
Irrigation of crops, parks, golf courses, etc.
Aquaculture
Supply of Goods Other Than Water
Fish
Waterfowl
Clams and mussels
Pelts
Nonextractive or Instream Benefits & Flood control
Flood control
Transportation
Recreational swimming, boating, etc.
Pollution dilution and water quality protection
Hydroelectric generation
Bird and wildlife habitat
Soil fertilization
Enhanced property values
Non-user values

For centuries, humanity has benefited from freshwater ecosystems without causing global disruption (Daily, 1997). However, nowadays there is an ongoing biodiversity crisis (Chapin III et al., 2000; Hoekstra et al., 2005) and freshwater ecosystems are one of the most endangered environments worldwide (Dudgeon et al., 2006; Ricciardi and Rasmussen, 1999). In Europe, 95% of the floodplains and 50% of the original wetlands have been severely altered or lost because nearly 50% of the human population lives in those areas (Tockner et al., 2009). Human impacts on climate and land-use have intensified the loss or homogenization of biodiversity (McKinney, 2006) and ecological dysfunction (Chapin III et al., 2000; Hoekstra et al., 2005), which will ultimately affect ecosystem services imposing social and economic problems. In particular, threats and stressors such as resources overexploitation, land-use changes, pollution, water abstraction, loss of longitudinal connectivity, habitat destruction and degradation, climate change and invasive species (Dudgeon et al., 2006; Nel et al., 2009; Sala, 2000) have caused deterioration of freshwater environments (Nel et al., 2009), population declines and biodiversity changes (Dudgeon et al., 2006). Furthermore, most of these threats are not predicted to cease or decrease in the near future as they are linked to ongoing anthropogenic river uses.

Land-use change and land management have transformed a great proportion of the planet's surface (Foley et al., 2005), with a deeper impact on highly productive ecosystems (Lindenmayer and Fischer, 2006), which is often the case of riverine areas. Freshwater ecosystems are especially sensitive to both land-use and climatic changes (Kuemmerlen et al., 2015) and, with fewer exceptions, all European rivers have been profoundly changed by human actions (Hildrew and Statzner, 2009). Strategies and actions on the freshwater infrastructure during the 20th century, though leading to relevant improvements on the welfare of human populations, have also resulted in degradation and destruction of natural freshwater ecosystems and often failed to distribute the benefits of these interventions equitably (Postel, 2008). Such deleterious actions also pose a threat to freshwater ecosystem services (Costanza et al., 1997; Postel and Carpenter, 1997), and the full economic impacts of current and further degradation have been underestimated (Postel and Carpenter, 1997). The human population was, is and will be linked to freshwater ecosystems, since these are the basic pillars of life as we know it. Given the pace of climate change, land use alterations, the existing problems in freshwater networks and the foreseeable future problems with water scarcity and extreme events, it will take a serious international effort to restore and prevent degradation in the freshwater infrastructure.

Definition box 1.1 – Ecosystem services

Ecosystems services are the benefits for humans derived from species and natural processes of ecosystems that directly or indirectly sustain and fulfil human life (Costanza et al., 1997; Daily, 1997).

Alcamo et al. (2003) have classified the ecosystem services in 4 categories considering functionality:

- **Provisioning services**, the products obtained from ecosystems
- **Regulating services**, welfares resulting from the regulation of ecosystem processes
- **Cultural services**, nonmaterial benefits obtained through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences
- **Supporting services**, those required for the production of the aforementioned services. Contrary to previous, changes in these services have indirect and long-term impacts.

These services affect the determinants and constituents of human well-being: security, basic material for a good life, health and social and cultural relations (Alcamo et al., 2003). Ultimately, these impact and are influenced by the freedoms and choices available to citizens (Alcamo et al., 2003).

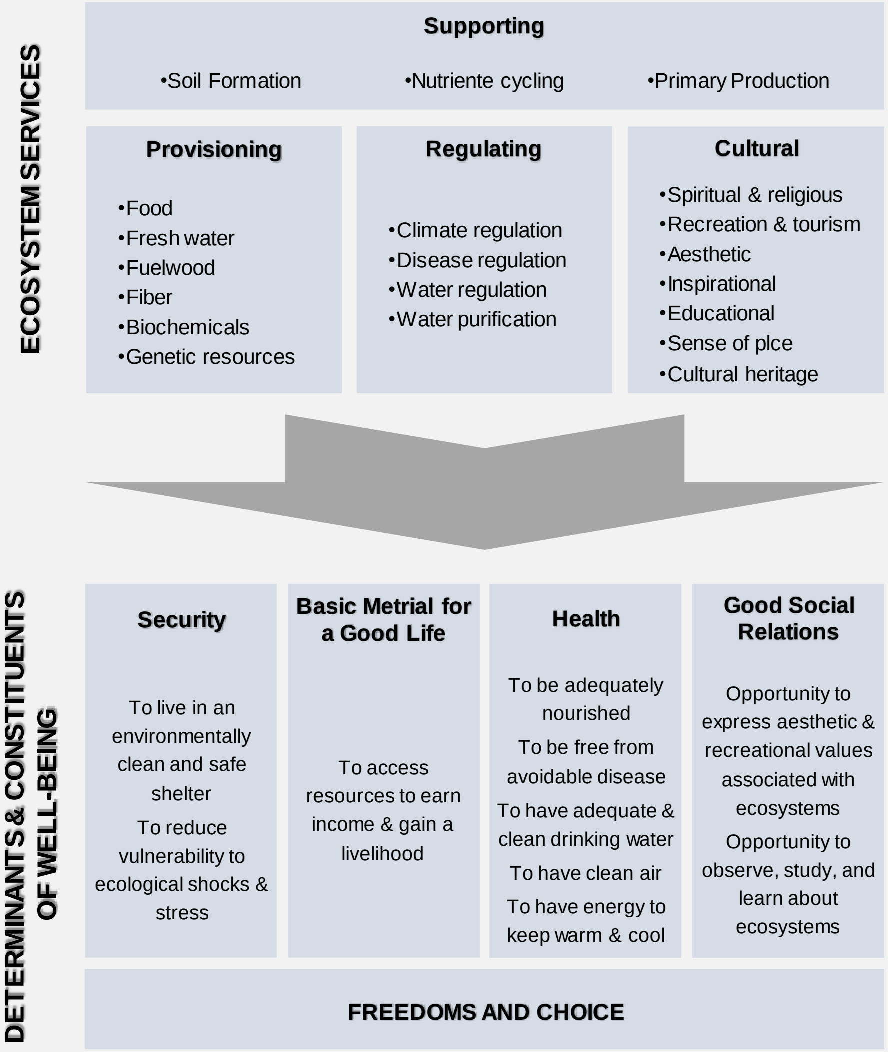


Figure 1.1.1 – Schematic of the categories of ecosystem services and their links to human well-being (Adapted from Alcamo et al., 2003).

1.2 What are the structural characteristics of lotic freshwater systems?

For a long time river ecologists (e.g., Hynes, 1975), managers and decision-makers have recognised the connection between landscape and rivers, and the necessity of landscape information to evaluate river health and prioritise management actions (Tsang et al., 2014). One of the first seminal concepts to clearly recognise the role of organic matter contributions from the surrounding landscape to instream ecosystem structure and function was the River Continuum Concept (Vannote et al., 1980) (Definition box 1.2). Though limited and without providing the notion of a river as a landscape of its own, it proved to be a valuable heuristic approach that provided a conceptual framework for river ecosystem researchers (Fausch et al., 2002). A framework that was throughout time amended and complemented with new concepts and theories such as the "serial discontinuity concept" (Ward and Stanford, 1983) or the flood pulse concept (Junk et al., 1989) (Definition box 1.2). The four-dimensional perspective of lotic ecosystems proposed by Ward (1989) further detailed the complex interactions between rivers and contiguous surroundings (Definition box 1.2). Meanwhile, some researchers started to integrate concepts from terrestrial landscape ecology while trying to conceptualise lotic systems functioning. For instance, the hierarchical framework of river scales (Frissell et al., 1986) (Definition box 1.2) integrated the function of scale and context contributing to alter the thought process about heterogeneity in stream habitats (Fausch et al., 2002). However, despite numerous breakthroughs, fisheries ecologists remained inefficient when providing tools and information aiming for the conservation of fish populations (Fausch et al., 2002). These problems were attributed to the truncated knowledge that researchers have due to small spatial and short temporal scales of observation that tend to be only weakly linked to the management problems at larger spatial and longer temporal scales (Fausch et al., 2002). This said, efforts have been made to conceptualise models and frameworks that improve existing methodologies, and most importantly that look at multiple temporal and spatial scales, prioritising those that are relevant for human disturbance, habitat degradation and management efforts (e.g., Fausch et al., 2002; Schlosser, 1991).

Freshwater systems can be regarded as freshwater networks. Overall, river flow is the overruling force that: drives the transport of sediment; shapes river geomorphology; governs the habitats for fauna and flora; controls food web via carbon transportation and directly affects behaviour and life histories of plants and animals (Fausch et al., 2002; Frissell et al., 1986; Junk et al., 1989; Schlosser, 1991; Vannote et al., 1980). It is also the flow that imposes directionality and a pathway in freshwater networks, making them dendritic and hierarchical (Duarte et al., in press). These features enforce dependency of processes occurring in a given place from processes occurring along the upstream catchment. Conversely, processes such as fish migrations are also dependent on features along the downstream pathway. In both cases, this dependency relies on the connectivity of the freshwater system. Connectivity denotes exchange of water, resources, energy and organisms within the system (Ward and Stanford, 1995), the surrounding landscapes (Allan, 2004) and at multiple scales (Allan et al., 1997). Additionally, because the extent and propagation of the effects along the network are location dependent, the longitudinal component of connectivity assumes particular relevance. This is noticeably important for fish species, especially migratory species because this dimension allows them to move along the network and complete their life cycle. Their dendritic nature has also consequences at population-level (e.g. metapopulation dynamics) and community-level (e.g. interspecific interactions, food web structure and biodiversity patterns) processes (Grant et al., 2007).

Spatial and temporal hierarchy translates into processes operating at different and multiple spatial and temporal scales (Fausch et al., 2002; Johnson et al., 1995; Schlosser, 1991). Thus, adequate and successful river management requires comprehending the spatial and hierarchical relationships between land and water. Freshwater networks are affected by the landscape via multiple pathways and mechanisms (Allan and Johnson, 1997). Landform and land use within the surrounding valley influence the biodiversity of a stream at multiple spatial scales, and this can become more intricate if legacies from prior human occupations are considered (Allan, 2004). Meaning that, apart from present, past human activities and the landscape play a significant role in the ecological integrity of a stream (Allan, 2004), which if unknown often act as the unrevealed ghost of the past.

Definition box 1.2 – Concepts and frameworks for river and fish research.

The influence of landscape on rivers and streams has long been recognised and influenced research in freshwater lotic systems and lotic fish. Below are some of the concepts and frameworks that have marked and shaped research in this field.

The River Continuum Concept (1980)

The River Continuum Concept focuses on the longitudinal resource gradients from the headwaters to the mouth of river systems and identifies the role of organic matter contributions from the surrounding landscape to instream ecosystem function and structure (Vannote et al., 1980) (Figure 1.2.2). This framework integrates predictable and observable biological features of lotic systems (Vannote et al., 1980).

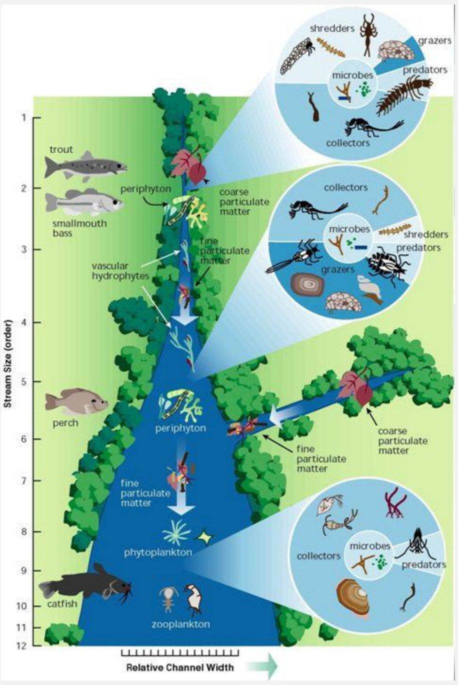


Figure 1.2.2 – Schematic of the River Continuum Concept
(Adapted from FISRWG, 1998).

The hierarchical framework of river scales (1986)

Stream systems are defined as hierarchically organized systems that incorporate successively lower spatial levels of complexity (Frissell et al., 1986) (Figure 1.2.3). This hierarchical framework incorporates the role of scale providing scientists with a tool to organise considerations about heterogeneity in stream habitat (Frissell et al., 1986)

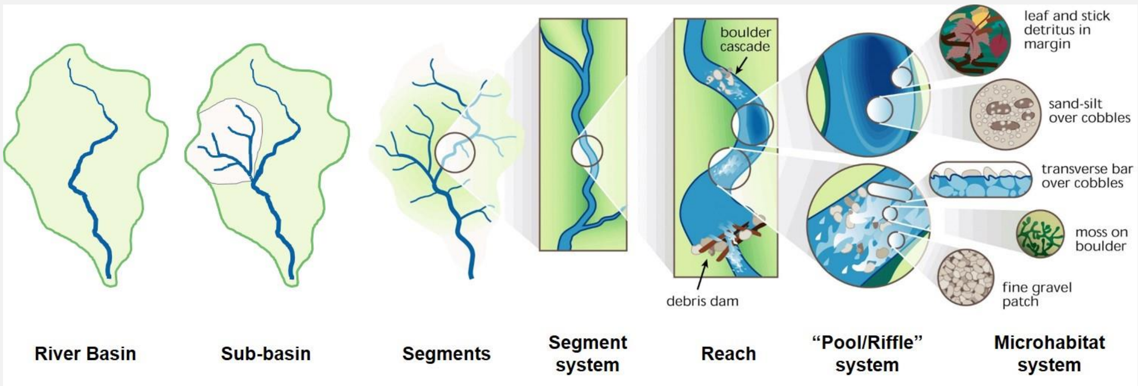


Figure 1.2.3 – Scale levels at river systems. River basin and sub-basin scales were added to the original figure since these are widely acknowledged as relevant scales for management and research of freshwater systems (Adapted from FISRWG, 1998).

The Four-Dimensional Concept (1989)

Lotic ecosystems are integrated in the surrounding landscape with which they interact along four dimensions: longitudinal, lateral, vertical and temporal (Ward, 1989) (Figure 1.2.4). The longitudinal dimension includes the upstream-downstream interactions, while the interactions between the channel and riparian/floodplain systems constitute the lateral dimension and the connection between channel and contiguous groundwater are incorporated in the vertical dimension (Ward, 1989). The last dimension overlays a temporal hierarchy on the other three dimensions (Ward, 1989).

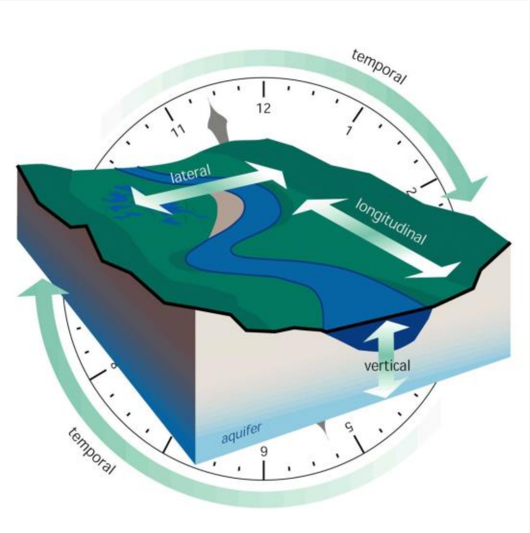


Figure 1.2.4 – The Four-Dimensional Perspective of lotic systems (Adapted from FISRWG, 1998).

The Flood Pulse Concept (1989)

This theory states that the flood pulse, i.e., the yearly pattern of river discharge is the major force governing biota in river floodplains (Junk et al., 1989) (Figure 1.2.5). It states that the life cycle features (annual timing, duration, rate of rise and fall) of the of floodplain biota is related with the flood pulse (Junk et al., 1989).

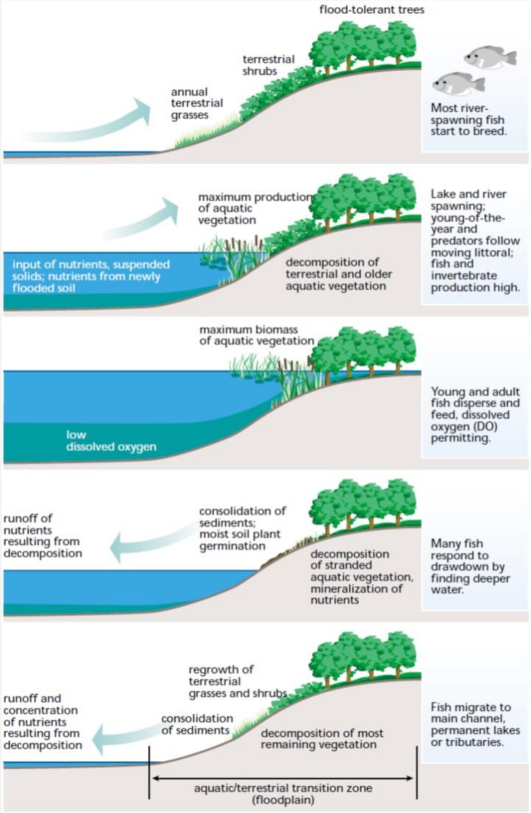


Figure 1.2.5 – The Flood Pulse Concept (Adapted from FISRWG, 1998).

The dynamic landscape model of stream fish population (1991)

This model links relevant physical and biotic processes in stream and riparian zones at scales that are relevant for human disturbance of river basins (Schlosser, 1991). It relies on the pivotal role of fish movements in transporting different life stages across landscape scales to occupy areas of critical habitat essential to complete their life cycle (Schlosser, 1991).

Landscapes to Riverscapes: a new approach for stream fish ecology (2002)

This approach emphasises the heterogeneous nature of stream habitat at intermediate spatial and temporal scales and the temporal linking between habitat patches via fish movement (Fausch et al., 2002). It embraces the continuous, hierarchical, and heterogeneous nature of linear aquatic habitats and focus proposing 5 principles towards effective research and management of lotic fishes (Fausch et al., 2002):

1. “Research must be conducted at appropriate scales for the questions of interest”
2. “The importance of different physical and ecological processes will be revealed at different spatiotemporal scales, and processes will interact among scales”
3. “Rare or unique features in the riverscape, either in space or time, can have overriding effects on stream fishes”
4. “Unintended consequences of habitat degradation will occur in all directions, including upstream”
5. “Fisheries ecologists who study stream fishes must strive to make observations and test predictions at the scale at which managers effect change”

1.3 Why diadromous fish species are such a relevant group of animals?

Freshwater ecosystems represent habitat for rich endemic and sensitive biota, harbouring a much wider number of species than expected given the area that it occupies on Earth's surface (Strayer and Dudgeon, 2010). However, for most freshwater species, information about their distribution and conservation status remains as a knowledge gap (Mittermeier et al., 2004). Fish are the most diverse class of vertebrates but have been recognised in the 1990s also as the class with the highest knowledge gap (Maitland, 1995). This scenario is particularly concerning when realising that more than 40% of the world fish species occur at, or need at some point of their life cycle, freshwater habitats. Freshwater ecosystems provide vital resources for humans (Strayer and Dudgeon, 2010) and, particularly freshwater fish are a valued resource for food, sport and ornament (Lévêque et al., 2007). These animals are responsible for fundamental and demand-derived ecosystem services that benefit humans in multiple ways (Holmlund and Hammer, 1999). Acknowledging the relevance of fisheries (e.g., Feunteun, 2002; Pourkazemi, 2006; Williot et al., 2002) allows to realise that the hampering of ecosystem services generated by fish populations will certainly have economic and social impacts.

Fish species may present distinct life-histories as a result of evolution and selective processes. The migratory behaviour is biologically justified by the necessity of optimising the use of resources that lead to a spatial and temporal displacement during the species' life cycle. Migration can be defined as a movement between two or more distinct habitats involving the majority of the population and occurring at a regular periodicity (Northcote, 1984). Given that it involves a large fraction of the population, a regular periodicity, and a tendency to follow particular pathways, these movements lead to a spatial and temporal concentration of animals (Lucas and Baras, 2001). There are three patterns of fish migration, oceanodromy, potamodromy, and diadromy. Only the last two involve freshwater ecosystems, and solely diadromy involves both freshwater and marine environments (Definition box 1.3). Diadromous fish species can be divided into anadromous, catadromous and amphidromous according to their life cycle. Differences between these species have consequences in their ability to migrate along freshwater networks and in their spatial and temporal usage of the freshwater habitats (McDowall, 1999).

Diadromous fish species represent an energy link between marine and freshwater environments and are part of the food web in both ecosystems (Limburg and Waldman, 2009). European diadromous fish species are a specific group within the European ichthyofauna with pertinent social (Limburg and Waldman, 2009) and economic relevance (Lassalle et al., 2009a). They have represented an important protein source for human populations for centuries (Limburg and Waldman, 2009), and despite the relatively small number of species, some belong to the world's most valuable fisheries (Lucas and Baras, 2001; Pourkazemi, 2006). Their migratory habits often translate into greater risk of extinction when compared with other fish species (Jonsson et al., 1999; McDowall, 1992) since they occupy and move between several habitats in numerous freshwater systems often in 100 or even 1000 kilometres and more distance from each other (Abell, 2002). This puts them not only more exposed to threats from predation and/or fishing exploitation but also increases the probability of being impacted by habitat degradation, especially because both residential, passage and spawning habitats have to be considered (McDowall, 1992). One distinct feature of this conundrum is the universal need to move through estuaries, exposing them to severe impacts of urbanization at river mouths (McDowall, 1999). Another relevant characteristic of many diadromous fish species is their homing behaviour, i.e., their drive to return to their natal spawning grounds and incubation sites for reproduction (Dittman and Quinn, 1996; Leggett, 1977). By synchronising the return of mature animals to spawning grounds when conditions are optimum for egg and larval development, this behaviour maximises reproductive success while regulating the number of animals present in the area, avoiding under or overutilization of that specific habitat (Leggett, 1977). This may lead to reproductive isolation, a relevant feature to develop energetic, behavioural and reproductive adaptations to the occupied habitat (Leggett, 1977). The aforementioned characteristics, resulting from the homing feature, are particularly striking in anadromous fish species.

Definition box 1.3 – Life cycles of migratory fish species

Obligatory migrants between marine and freshwater environments are considered diadromous species, and these can be further divided according with the direction of the movement:

- Anadromous species live, grow and feed in marine ecosystems and then perform migrations towards freshwater systems to find suitable spawning grounds;
- Catadromous species live, grow and feed in freshwater ecosystems and engage into migration towards marine environments to reproduce and complete their life cycle;
- Amphidromous species reproduce in freshwater/estuaries, then larvae migrate/drift towards marine environments where they live and feed for a brief period of time after which juveniles migrate back to freshwater ecosystems to grow into adults and spawn;

Migrant species exclusively within freshwater ecosystems are considered Potamodromous animals. In the case of fish species, animals move upstream to spawn and larvae/juveniles migrate downstream to feed and grow.

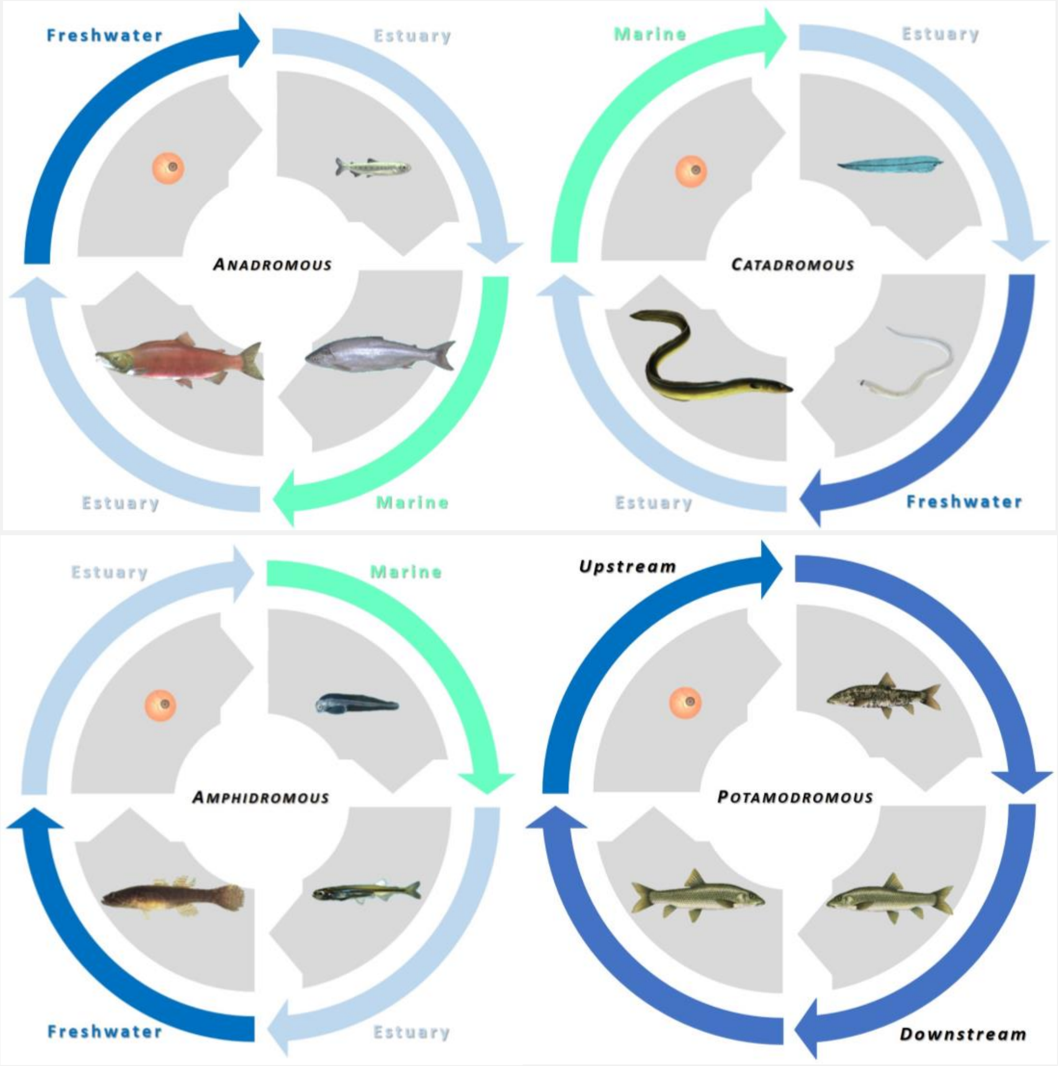


Figure 1.3.6 – Life cycles of migrating fish
(Adapted from www.thefisheriesblog.com and Romão, 2018).

1.4 What are the causes of the decline of diadromous fish species?

While being a hotspot of biodiversity, freshwaters are also a hotspot of biodiversity endangerment (Strayer and Dudgeon, 2010). For instance, in continental Europe, 40% of native fishes have disappeared from catchments of their natural occurrence (Tockner et al., 2009), and 13 have become extinct (Kottelat and Freyhof, 2007). Regardless the length and quality time series of datasets, the overall trend for Atlantic diadromous fish species is a decline, in some cases to historic lows (Limburg and Waldman, 2009). As mentioned previously, the life history and migratory behaviour of these fish species contributes to their increased vulnerability. Roaming through several international borders, crossing and using a wide variety of freshwater, marine and estuary habitats exposes them to multiple threats (Jonsson et al., 1999; McDowall, 1992, 1999) that may change their typology or relevance according to the ecosystem. In the case of marine environments, the most common threat is over-exploitation, which includes direct harvest, incidental catch and bycatch, and indirect effects like trophic cascades, competition for prey, and habitat destruction due to destructive fishing gear (Kappel, 2005). The transition between marine and freshwater environment is critical for these animals since it is in these transition areas where urbanisation and industrialisation tend to have the largest impacts on water environmental quality and hydrology (McDowall, 1999). Additionally, this transition tends to be physiologically challenging for some species in specific periods of their life cycle (e.g., recent spawning grounds closer to the river mouth due to dams blocking access to older spawning areas have resulted in lower survival rates of Beluga (Williot et al., 2002) and Houting (Jepsen et al., 2012) because juveniles end up spending less time in freshwater). Numerous authors have identified multiple disturbances in freshwater networks related to: human land-use (e.g., nutrient and pesticide input (Falcone et al., 2010; Guse et al., 2015)); channel modification (Falcone et al., 2010); deforestation (Tockner et al., 2009); water impoundment (Falcone et al., 2010); agriculture (Tockner et al., 2009); and loss of natural vegetation to developed land (Falcone et al., 2010; Lohse et al., 2008). These promote alterations and disruptions in ecosystems functioning like: changes in discharge and sediment transport (Falcone et al., 2010; Lohse et al., 2008; Tockner et al., 2009); erosion (Falcone et al., 2010); water quality (Falcone et al., 2010; Lohse et al., 2008); run-off alterations (Falcone et al., 2010; López-Moreno et al., 2011); and inevitably affecting aquatic biodiversity (Bradford and Irvine, 2000; Lohse et al., 2008; Ricciardi and Rasmussen, 1999; Trautwein et al., 2012). Concerning diadromous fish species, the most relevant causes of the decline in freshwater systems can be grouped in five categories: river regulation, physical barriers and habitat loss; overfishing; land use alterations; climate change; and water quality and quantity. However, these threats are not isolated from one another and interactions are common (Brink et al., 2018; Limburg and Waldman, 2009; Vorosmarty et al., 2010). Effects may commonly be synergistic (Limburg and Waldman, 2009), and extinctions generally involve the interplay of several threats, natural factors and biological attributes of the species (Jonsson et al., 1999).

1.4.1 River regulation, physical barriers and habitat loss

Physical river barriers have the direct obvious effect of blocking diadromous species access to their migration routes and their spawning and incubation areas, thus leading to population reduction and regional (or even wider) extirpations (Limburg and Waldman, 2009). However, the indirect or collateral ecological effects associated with water impoundment and/or the obstruction of the longitudinal connectivity of freshwater networks are considerably vast and far-reaching: reduction of resident species' movements and of abundances, which may cause alteration to the community and to the functioning of the ecosystem; fragmentation of populations and interruption of gene flow leading to the loss of genetic diversity, over/underrepresentation of genotypes and ultimately to species decline and extirpation; hydrological changes; loss and degradation of habitats; and retention of water, nutrients and sediments (Helfman, 2007). Worldwide, damming has been indicated as the main reason for the decline of stocks from several diadromous species (Larinier, 2001; Nicola et al., 1996). Large dams are the most obvious obstruction, but low dams and weirs may constitute a relevant obstruction to fish migration (Brink et al., 2018; Larinier, 2001) and their cumulative effect may even exceed those of a large dam (Liermann et al., 2012). According to the projected European Barrier Atlas (www.amber.international/european-barrier-atlas/) from the Adaptive Management of Barriers in European Rivers (AMBER) project, there are thousands of small river obstructions in European rivers. River regulation, although interplaying with other stressors, are probably the most impactful anthropogenic pressure for diadromous fish species in freshwater networks. There are examples of populations from nearly all European diadromous fish species impacted by river barriers: European eel (Clavero and Hermoso, 2015; Kettle et al., 2011); Atlantic salmon and Sea trout (Garcia de Leaniz, 2008; Junge et al., 2013; Parrish et al., 1998; Rivinoja et al., 2001); Ponto-Caspian sturgeons (Bacalbaşa-Dobrovici, 1997; Ivanov et al., 1999; Pourkazemi, 2006); Pontic shad (Smederevac-Lalić et al., 2018; Vasil'Eva, 2003); Allis shad and Twait shad (Aprahamian et al., 2003; Bagliniere et al., 2003).

1.4.2 Overfishing

Overfishing in freshwaters threatens both the biodiversity of freshwaters and the respective ecosystem services (Allan et al., 2005). However, since it frequently acts synergistically with other pressures (Allan et al., 2005; Brink et al., 2018), its importance is underappreciated and poorly documented or understood (Allan et al., 2005). It will hardly lead to direct species extinction (Jonsson et al., 1999) but it is has contributed to the decline of diadromous fish populations (Allan et al., 2005; Limburg and Waldman, 2009). Examples of overfishing in diadromous fish species are common: Ponto-Caspian sturgeons (Bacalbaşa-Dobrovici, 1997; Ivanov et al., 1999; Lenhardt et al., 2006; Pourkazemi, 2006; Williot et al., 2002), European shad species (de Groot, 1990b; Maes et al., 2008; Thiel et al., 1996) and European smelt (Doherty and McCarthy, 2004; Hutchinson and Mills, 1987).

1.4.3 Land use alterations

Land use alterations have shaped nearly the entire surface of the planet (Foley et al., 2005), and especially high productivity areas (Lindenmayer and Fischer, 2006) such as lowlands and riverine areas. Hence, the transformation of a landscape is not only related to pure economic development but also with its ecological characteristics (DeFries et al., 2004). Moreover, swift land-use changes have been linked to the decline of economically valuable fisheries and to the disproportioned high number of endangered aquatic species (Ricciardi and Rasmussen, 1999). Land use activities often translate in relevant changes in the population and community dynamics of stream fishes, such as reduction in diversity, shifts in trophic structure and increase in temporal variability of fish abundance (Schlosser, 1991). Urbanisation intensity, urban sprawl and agriculture have been identified as the most detrimental land-use types for fish fauna (Bradford and Irvine, 2000; Lohse et al., 2008; Trautwein et al., 2012). Land-use has been co-responsible for the decline of diadromous species, for example, the probable impact of the reduction of wetland habitats in southwestern Europe and Northern Africa in the European eel recruitment (Kettle et al., 2011). Additionally, this threat is commonly associated with other stressors, for example, declines of Ponto-Caspian species with pollution from heavily agricultural areas and expanding oil extraction exploration (Ivanov et al., 1999; Lenhardt et al., 2006; Pourkazemi, 2006).

1.4.4 Climate change

Climate change has been reckoned as one of the most problematic and troubling challenges for humankind (Ripple et al., 2017). It is altering species distributions (Limburg and Waldman, 2009; Thomas et al., 2006) and leading to regional declines, range retractions and species extinctions (Thomas et al., 2006). As freshwater species have limited options to escape water scarcity, water temperature rise, extreme flows and flooding and water competition with humans, consequences of climate change are likely to be more severe for these organisms (Abell, 2002). At the European scale, temperature has been considered as one of the primary constraints for diadromous species distribution (Béguer et al., 2007; Filipe et al., 2013; Lassalle et al., 2008; Lassalle et al., 2009a), while precipitation is relevant for some species (Filipe et al., 2013; Lassalle et al., 2008; Lassalle et al., 2009a). A multitude of effects from this pressure on diadromous fish species have been identified: decrease in the frequency of successful annual reproduction for anadromous species due to intensification of the harshness of flood and drought periods (Limburg and Waldman, 2009), phenology changes of anadromous species towards earlier spawning runs (Limburg and Waldman, 2009), shifts in species distribution (Lassalle et al., 2008; Lassalle et al., 2009a), near-extinction reduction of suitable areas (Lassalle et al., 2009a) and possible regional extinctions (Filipe et al., 2013; Lassalle et al., 2009a). Given the specialization of some populations to return to their natal spawning and incubation grounds (Dittman and Quinn, 1996; Leggett, 1977), if one river basin becomes unsuitable for species occurrence due to climate change, that could translate into the extinction of a population (Lassalle et al., 2009a). Climate change will also enhance the effects of other stressors. For instance, given the expected changes in flood and drought frequency and magnitude, and in precipitation and temperature values it will probably contribute to aggravate the problems caused by water impoundment and river regulation (Abell, 2002; Vörösmarty et al., 2000). Future threats associated with this stressor include increased temperature, decreased oxygen, increased toxicity of pollutants, effects of changes in water availability and alteration of flow seasonality patterns (Brink et al., 2018).

1.4.5 Water quality and quantity

Water quality is highly connected with intensive land use (Ivanov et al., 1999; Lenhardt et al., 2006; Pourkazemi, 2006; Vorosmarty et al., 2010) or with the presence of large dams (Brink et al., 2018; Helfman, 2007). Water quantity is also connected to water retention (Brink et al., 2018; Helfman, 2007) but in the future, it will be increasingly linked with climate change and extreme events (Abell, 2002; Vörösmarty et al., 2000). Pollution, also included in this group, may represent a serious threat to diadromous fish species (Quigley et al., 2004; Sandøy and Langåker, 2001; Sepulveda et al., 1993; Zaitsev, 1992). Some rivers have received so much untreated wastewater that enabled the creation of chemical barriers to spawning migrations (Brink et al., 2018; Limburg and Waldman, 2009). Water management so far has been directed to human benefit (Postel and Carpenter, 1997) and the growing need for electricity to meet consumer and productivity demands have even increased the social ambition for large hydropower developments (Brink et al., 2018). Thus, water quantity reduction and its corresponding water quality decrease will continue to be significant stressors for freshwater species in the future.

1.4.6 Other threats

Other less broad threats that may lead to declines in diadromous fish populations are: the direct mortality when fish pass through turbines or over spillways (Larinier, 2001); diseases, competition and genetic introgression with escapees from aquaculture and stocking infrastructures (Bakke and Harris, 1998; Limburg and Waldman, 2009) and species introductions (Jonsson et al., 1999; Limburg and Waldman, 2009).

1.5 Why is historical data useful for ecology?

All animals impact their environment, but human impacts throughout time have reached nearly every corner of the planet. Historical evidence of its presence may not only be found in nature but also on man-made documents and/or visual arts throughout the ages. The insights that these evidences and documents provide could not have been generated in any other way (Vellend et al., 2013) and were for a long time confined to history researchers. Ecologists are starting to explore and value these evidences because they can contain information not only about human activities but also, for example, about animals or land features that existed.

Historical Ecology is the discipline that investigates past ecosystems (Szabó, 2010), by looking into human-environment relations in specific temporal, spatial, cultural and biotic context (Hayashida, 2005). Most of the natural areas have a history and a cultural past (Hayashida, 2005; Rackham, 1998) that results from the thousands of years of complex interactions between nature, environment and human activities (Rackham, 1998). Thus, by integrating ecology and history, human activities are accepted as an organic part of natural processes (McDonnell and Pickett, 1993). In Historical Ecology research, the human species is considered a major mechanism of alteration in the natural world because nearly all landscapes are affected by a unique and complex human history (Balée and Erickson, 2006). As a result, nature and culture affect each other and are impossible to tell apart (McDonnell and Pickett, 1993). Recognising the above led to the establishment of the four postulates that govern research in this field (Definition box 1.4). Since research focuses on the ongoing dialectical relation between human actions and nature (Egan and Howell, 2005), it requires an interdisciplinary effort. It initially started with natural scientists and humanists trying to exceed their own discipline's limitations (Szabó, 2010). Nowadays, historical ecologists take a holistic, practical and dialective perspective on environmental change, and draw a broad spectrum of evidence from social sciences and humanities and the natural and physical sciences (Crumley, 2007). As expected in this case, not only interdisciplinary efforts can result in synergetic effects (Szabó, 2010) but also multi-disciplinary research can be complementary (Crumley, 2007). The methods used require a temporal and geographical multiscalar approach (Balée and Erickson, 2006). Ecosystem changes occur in a temporal range that goes from days to millennia, which means that collected data requires a historical insight to better understand the underlying processes (Szabó, 2010). Also, there are some relevant disturbance events (e.g., extreme floods or storms) that can or have shaped the current ecosystem which might not occur during short-term studies (Szabó, 2010). Hence, historical data will not only provide information about ecosystem responses to rare events (Hayashida, 2005) but will provide a long-term vision over ecosystem processes and response to disturbance and environmental change (Hayashida, 2005; Vellend et al., 2013). Historical sources may refer to several spatial scales, from local places to river stretches or regions (e.g., Haidvogl et al., 2013; Stein et al., 2010). It is often the combination of several sources and their integration into a broader spatial scale that allows to cross-check and complement information that enables their most adequate use (e.g., Clavero and Villero, 2014; Haidvogl et al., 2013; Stein et al., 2010). The spatial scale of analysis can go from microscopic to global, just as temporal range can span from very recent events to deep geological time, it is only dependent on the available data and the research question (Crumley, 2007).

In this rapidly changing world, historical sources and data will continue to provide fundamental insights that will reshape our understanding of continuously evolving ecosystems (Vellend et al., 2013). This science field honours the values, knowledge and sensibilities of people at all times and places while aggregating a set of conceptual and practical tools that encourage interdisciplinarity ventures and integrative investigation (Crumley, 2007). However, this new perspective does not come without cost and challenges. Results from retrospective research tend to be complex and challenging to the traditional and rigid approaches to ecological thinking and conservation planning (Foster, 2000). Increased consciousness and concern about the current biodiversity crisis (Chapin III et al., 2000; Hoekstra et al., 2005) has boosted the interest for data sources that are useful in assessing changes in the status and distribution of the world’s species (Boakes et al., 2010). The applications for this type of information may include developing models of global species diversity and its change, designing and assessing conservation actions, and tracking progress in conserving biodiversity (Boakes et al., 2010). If not for any other reason, obtaining data through historical sources or retrospective studies can lead to a relevant increase in sample size and observation range (Foster, 2000). By using environmental and human history as a source of data, it will not only allow to understand and gain knowledge about what happened in the past but also empower scientists, decision makers and citizens to more adequately manage ecosystems and landscapes (Swetnam et al., 1999). Researchers have turned to history in order to explain and manage modern ecosystems and landscapes (Hayashida, 2005) but also to predict future responses of ecosystems to global change (Vellend et al., 2013).

Definition box 1.4 – Postulates for historical ecology research

Balée (2002) has proposed 4 postulates for historical ecology research:

1. **"Much, if not all, of the nonhuman biosphere has been affected by human activity"**

It is assumed that humans have affected mostly all of earth environments. However, this does not deny the function of nature or its evolutionary mechanisms, it states that natural environments subjected to human management have also been physically and biologically determined by culture and history (Balée, 2002).

2. **"Human activity does not necessarily lead to degradation of the non-human biosphere and the extinction of species, nor does it necessarily create a more habitable biosphere for humans and other life forms and increase abundance and speciosity of these"**

Humans are not programmed to be stewards nor destroyers of earth's nonhuman biodiversity (Balée, 2002).

3. **"Different kinds of sociopolitical and economic systems (or political economies) in particular regional contexts tend to result in qualitatively unlike effects on the biosphere, on the abundance and speciosity of nonhuman life forms, and on the historical trajectory of subsequent human sociopolitical and economic systems (or political economies) in the same regions"**

Even in the same regional context, different kinds of societies defined by various socioeconomic, political, and cultural criteria can produce different outcomes in the environment (Balée, 2006; Balée, 2002). As these differences can be positive or negative to the environment, it is clear that it is not human nature who is responsible (Balée, 2002) for the current biodiversity crisis (Chapin III et al., 2000; Hoekstra et al., 2005). This responsibility lies on the political economies of states and multistate organisations (Balée, 2002).

4. **"Human communities and cultures together with the landscapes and regions with which they interact over time can be understood as total phenomena"**

Historical Ecology interprets the relation between culture and nature as a dialogue. Thus, by using concepts and tools of this research field both can be analysed as a single phenomenon in a regional context (Balée, 2002).

1.6 Are historical sources relevant to freshwater fish studies? Are there limitations for their use?

Considering that humans have modified riverine ecosystems for centuries or even millennia (Haidvogl et al., 2013), historical ecology methods are certainly an adequate approach to study these freshwater ecosystems. The most relevant human settlements, urban environments like cities (Dearborn and Kark, 2010; Grimm et al., 2008), have been established close to riverine areas. This fact implies that human impact is profound and complex and that there are several historical sources about these areas to be explored. In terms of freshwater fish ecology, in Europe there are many studies that reveal the existence of many historical sources (e.g. Clavero and Villero, 2014; Haidvogl et al., 2013) and their utility (Alonso et al., 2011; Lassalle and Rochard, 2009; Logez et al., 2012; Segurado et al., 2014).

Limited by whatever historical sources and data are available, historical ecology could be considered an opportunistic science (Vellend et al., 2013). Nonetheless, searching for historical sources and analysing all sorts of different historical data is a complex and challenging task (Haidvogl et al., 2013). Historical records can be classified as natural or documentary (Jackson and Hobbs, 2009; Swetnam et al., 1999). Natural records are those made by earth-system processes like sedimentation, animal deposits, annual plant and animal growth cycles and other layered records (Swetnam et al., 1999). Written, tabulated, mapped or photographic records are considered documentary archives (Swetnam et al., 1999). Haidvogl et al. (2013) have compiled the major historical source types relevant for freshwater fish ecology in a European context (Definition box 1.5). These authors have used the source provenance and the purpose of recording that information as their first criteria, and then the main ecological content and the possibility to gain quantitative or qualitative data on different temporal and spatial scales as further criteria. Comparative and complementary analysis of both types of records improves the assessment and reconstruction of environmental history (Swetnam et al., 1999). As different sources contribute with several parameters and information, merging and cross-checking them could enable the creation of a data-set with basic fish ecological parameters like species presence, relative or absolute abundance or abundance classes (Haidvogl et al., 2013). However, historical sources have limitations that need to be understood to avoid incorrect interpretations (Rackham, 1998) and/or extrapolations (Swetnam et al., 1999). For example, unlike documentary archives, archaeological records are characteristically spatially precise but inaccurate about the temporal scale (Rackham, 1998). Physical and biological processes progressively filter past environmental information affecting the fidelity of a reconstructed environmental variable (Swetnam et al., 1999). If this filtering process is not clearly understood and modelled, the interpretations of natural archives will not be reliable (Swetnam et al., 1999). These processes of degradation, loss of evidence and lack of preservation occur throughout time, giving paleorecords a transient and incomplete nature that results in fragmented, missing or altered records (Swetnam et al., 1999). Also as a consequence, historical time series are affected by the "fading record" problem, where with an increased time lag to the present, time series reliability decreases as there are increasingly fewer records available (Swetnam et al., 1999). This affects spatial and temporal resolution and availability of historical data and, in an extreme situation, the total absence of a record for some ecosystem process or structure that may be of primary concern (Swetnam et al., 1999). Another common problem with the interpretation of the natural historical sources is the so-called no-analogue problem (Swetnam et al., 1999). A no-analogue condition occurs when there is a lack of an analogous situation between the present and past conditions (Hutson, 1977). Such condition may be environmental, biological, or both (Hutson, 1977) and poses several problems for data analysis and interpretations.

About documentary sources, there is a cultural filtering that affects not only the spatial and temporal availability, completeness, and reliability of documentary records but also their quantity and quality (Swetnam et al., 1999). The contents of a document may depend on the set of occurring species, on the producer and its agenda, consequently affecting the potential fish ecological contents and their interpretation (Haidvogl et al., 2013). Moreover, not only several documents were inadvertently destroyed for instance during wars, others were discarded on purpose (Haidvogl et al., 2013). It is also a fact that fish biologists (and also naturalists) relied on questionnaires. Hence, if fisherman (or any other group) answered erroneously, the inventories or scientific surveys compiled based on these questionnaires have incorrect data (Haidvogl et al., 2013). Another common feature is the over-representation of larger, economically valuable or peculiar species, and the absence of data for small and inconspicuous fish (Haidvogl et al., 2013). The same way, sudden and noticeable events (e.g. large deforestation or fire) are more likely to be recorded while slow and gradual occurrences probably have to be inferred (e.g. new trees invading abandoned land). All these problems indicate that gaps in historical information are not neutral (Rackham, 1998). This said, if there is no explicit quote about the absence of a particular species in a given place, it is very difficult to conclude that in fact a species was absent (Haidvogl et al., 2013). Ecosystem processes vary with spatial context, along with spatial gradients and/or in response to human and natural spatial disturbances (White and Walker, 1997). Ecosystems' temporal variation is not only obvious throughout a year or season (e.g. ephemeral species) but also across decades, centuries or longer time spans. These two types of variation are not independent but interconnected, for example, a temporal variation that causes population shifts along a gradient normally implies the existence of available space to accommodate these shifts. Thus, every ecosystem is unique at some scale of analysis (White and Walker, 1997). Considering that historical records are generally not available for all sites and dates of interest, data extrapolation is an option that comes with considerable limitations (Swetnam et al., 1999). Commonly referred as the "distance decay" problem (White and Walker, 1997), the validity of the extrapolation is a function of spatial and temporal distance, which means it decreases with increased distance (Swetnam et al., 1999; White and Walker, 1997). This limitation could be minimised if information from multiple places and times is collected (Swetnam et al., 1999).

Interpretation of historical data can be very subjective and historical science is mostly inductive (Swetnam et al., 1999). For instance, Rackham (1998) states that medieval laws should not be interpreted as in modern times because often their intention was only to obtain revenue from fines. Also, the same author indicates that simple changes in official statistics methods can lead to wrongful interpretations based on this type of historical source. Considering that ecological interpretation is even more ambiguous, due to the difficulty of directly associating physical environmental factors and disturbance regimes with ecosystem structure and function, increasing temporal distance magnifies this ambiguity (White and Walker, 1997). To increase objectivity and guarantee a correct assessment of historical information it is necessary to perform a critical evaluation of sources (Haidvogl et al., 2013) while comparing and combining multiple and independent sources and methods (White and Walker, 1997).

Despite all limitations and questions of interpretation, historical data is still valid for ecological studies and, the utility of historical insight cannot be underestimated (Swetnam et al., 1999). In fact, considering that humans have been changing riverine ecosystems for centuries (Haidvogl et al., 2013), the explanatory value of modelling fish historical presence is relevant and has been demonstrated in several studies (e.g. Lassalle and Rochard, 2009; Logez et al., 2012). Several authors agree that blending different methods (Swetnam et al., 1999), combining information from several independent spatial and temporal sources (Hayashida, 2005; Rackham, 1998; Swetnam et al., 1999; Szabó, 2010), using independent datasets to cross-check lines of evidence (Crumley, 2007) and an interdisciplinary approach (Szabó, 2010) can help mitigate the limitations and lead to more accurate knowledge about past ecosystem conditions. Hence, recognising the existence of constraints and limitations of historical data and combining judicious and careful interpretations with adequate methods will assure a sound knowledge and adequate ecological interpretations. In conclusion, there are several examples of scientific studies that demonstrate the usefulness and power of historical sources and what can be achieved by their interdisciplinary use (e.g., Clavero and Hermoso, 2015; Clavero et al., 2017; Clavero and Villero, 2014; Duarte et al., 2018c; Haidvogl et al., 2015; Haidvogl et al., 2013; Lassalle et al., 2009a; Lassalle and Rochard, 2009; Pont et al., 2015; Segurado et al., 2014).

Definition box 1.5 – Documentary Historical Sources

The classification exposed bellow has 5 main categories and 19 source types and its entirely based on the Haidvogl et al. (2013) work.

Early Scientific fish ecological surveys

Conducted by experts educated in biology, and generally prepared as species inventories, these studies intended to illustrate occurrence and occasionally abundance of fish species in a river, catchment and/or region. Medieval and early modern versions of this source category could be valuable, though they normally require help from a specialist for an adequate interpretation. Until the late 18th century, references to precise rivers or river sections were an exception and, it was only from the middle of the 19th century onwards that fish distribution maps started to be prepared. At best a survey will not only detail the total fish community of a river or river section in a given period, but also information about abundance that can be fitted into abundance classes. Though these sources may be the one of the main sources for species inventories, compiling data from several surveys could be challenging because of the use of different taxonomies and systematics.

Fishery

This source category grants the largest amount of written documents and can be divided into seven source types. The first four inform about commercial species, providing details about stocking of native and non-native species.

- Official surveys of commercial fish and fisheries

These surveys generally contain quantitative or verbal abundance of commercial species on a regional or national level, and were commissioned by governments to gain an overview about the status of fishery. In central Europe and Russia, this source type only appeared when official statistics became increasingly common, i.e., in the second half of the 19th century.

- Catch registers

This information is produced by fisherman and informs about exploited fish, weight/number per species on precise days, months or years in specific fishing areas, as for example rivers sections. To reconstruct historical fish population changes, catch registers are the most valuable type of historical source to assume a relation between catch and actual abundance.

- Fishing district descriptions and Fish inventories of royal, imperial, monastic or aristocratic properties

Fishing district descriptions consist of a large variety of anecdotal sources that inform about stocked and commercial species, average catch values, special threats to particular species. These type of sources were prepared by fishermen, fishing right owners or administrative institutions and, though with similar potential as catch registers they have a lower spatial and temporal resolution. The other sub-source type encloses information about species that occur in royal, imperial, monastic or aristocratic properties.

- Fishing laws

These regulate fishing gears and techniques, allowed weights and lengths per species, indicate temporal and spatial fishing restrictions, thus allowing some careful conclusions about overexploitation, species abundance and distribution.

- Tax and rent payment registers

Organised by fishermen or administrative authorities this source type informs about the average or yearly tax or rent to be paid for the right to fish in a river section. Considering that taxes are related to the catch (total or of a particular species), and that these are reported correctly, a direct relation between tax and catch can be assumed. Though influenced by several factors, in professional fisheries, rents are positively correlated with potential catch and actual abundance.

- Guild documents

Fisherman guild documents comprise a great variety of sources that in Europe could date back from the 13th century. From an ecological point of view, cautious interpretations could be made: an increase of fishermen translates into more fishing pressure that within a time may cause overexploitation; a decrease in fishermen can indicate stock problems and overexploitation. However, other factors (particularly economic ones) can be significant (e.g. shift of fisherman to more advantageous professions, changes in fish prices) and, if not correctly scrutinized contribute to incorrect interpretations.

- <u>Judicial cases</u>

Besides details about occurrence and abundance of fish species, the most relevant feature of this source type is providing information that enables the estimation of the fish exploitation degree.

Fish trading sources (Market Sales registers; Delivery records; Kitchen account books; Fish trading laws; Fish Price)
In all these sources sub-types there is usually information about the number of individuals and/or the total weight per species, while the related temporal scale could range from years (most common) to weeks or even days. Market sale registers, delivery records and kitchen account books generally provide serial quantitative information, while fish trading laws inform about fish provenance and provide insights into the economic importance and customer demand for specific species. Fish prices, though often an existing record, require in-depth research about price history and their influencing factors so that inferences could be made.

LUNGHEZZE MINIME PERMESSE
PER LA VENDITA DEL PESCE
DELLE SEGUENTI QUALITÁ

CENT.
BARBON. TRIA. SARDELLA. SARDON 7
BRANZIN. ORADA. DENTAL. CORBO
SPARO. BOTOLO. BOSEGHET. SOASO
LOTREGAN. MECIATO. VERZELATA 12
LOVO. SFOGIO. PASSARIN. ROMBO
BISATO. 25
OSTREGA. 5
PEOCIO. 3
EL MIO 28 Gm

Figure 1.6.7 – Old stone plate with fish prices in Venetian Market (taken by the author).

Fish Consumption sources (Cook books; Restaurant menus or Menus of elite or monastic households)
Although archaeozoological records are the most important source about fish consumption and, that there is no direct relation between these written sources and fish abundance, they can support findings about the local occurrence of fish species.

Cultural representations of fish (Folk tale; Place names; Family names; Emblems)
This type of information may provide a spatial insight about a particular local fish species occurrence (e.g. if a village near a river has a particular fish species in its emblem it could be an evidence that this species existed in that river section and/or was relevant for this community).

Figure 1.6.8 – "Big Fish Eat Little Fish" painting of Pieter van der Heyden from 1557.

1.7 What is the state of the art on diadromous fish species research using historical data?

The inherent economic, ecological and cultural value did not prevent diadromous fish species from severe anthropogenic impact. Research on diadromous fish species has focused mainly on their biology and physiology, ecology, aquaculture, stock/abundance and fisheries and less on impacts (dams, toxicology, pollutants), modelling and genetics (Nikolic et al., 2011). Some studies aimed at identifying the global threats to these animals (Bacalbaşa-Dobrovici, 1997; Jonsson et al., 1999; Maitland, 1980; McDowall, 1992, 1999) and/or providing information about species stocks and extirpations (Almaça and Elvira, 2000; de Groot, 1990a; Ivanov et al., 1999). More recently, research linked species occurrence and abundance data with environmental variables trying to figure out the relevance of environmental characteristics for species occurrence and to make predictions for future developments (Béguer et al., 2007; Clavero and Hermoso, 2015; Clavero et al., 2017; Lassalle et al., 2008; Lassalle et al., 2009a; Lassalle et al., 2009b; Lassalle and Rochard, 2009; Logez et al., 2012). Commonly, studies tend to focus on one species, or a specific group of species (Clavero and Hermoso, 2015; Filipe et al., 2013; Morais et al., 2011; Švagždys, 2009; Wolter, 2015) and/or a specific region or basin (Pourkazemi, 2006; Sandøy and Langåker, 2001; Smederevac-Lalić et al., 2018).

Species distribution models (SDMs) are a common instrument for biological and ecological research deeply embedded in Hutchinson's (1957) ecological niche concept (Araújo and Guisan, 2006). This correlative approach establishes a relation between species distribution and environmental data through space and time (Pearson and Dawson, 2003), thus providing an indication of relevant environmental variables and enabling the comprehension of the realised niche for the considered species. These methods are useful for management and conservation purposes, and multiple studies focussed on establishing such models about the distribution of diadromous fish species. Some studies taking into account multiple species either use historical (Béguer et al., 2007; Lassalle et al., 2009a; Lassalle and Rochard, 2009) or contemporaneous data (Lassalle et al., 2009b; Logez et al., 2012; Pont et al., 2005), while others use SDM's and historical data for a single species (Clavero and Hermoso, 2015; Clavero et al., 2017).

The inclusion of historical data from prior to the 20th century avoids multiple impacts that affected during the last century riverine habitats and fish species distribution, such as climate changes, deterioration of habitat and water quality, unsustainable fisheries and the damming spree (Lassalle et al., 2009a; Lassalle and Rochard, 2009). The use of historical data at a broad geographical extent (e.g., European scale), has been so far restricted to river basins (Béguer et al., 2007; Lassalle et al., 2009a; Lassalle and Rochard, 2009). If studies using historical information encompass finer scales they have a restricted geographical extent (Clavero and Hermoso, 2015; Clavero et al., 2017).

Modelling has been used to link the status of diadromous fish with climate and global changes (Nikolic et al., 2011). In most studies using SDMs and trying to relate species occurrence, abundance and/or richness with climate, temperature and occasionally precipitation have assumed great relevance (Béguer et al., 2007; Clavero et al., 2017; Filipe et al., 2013; Lassalle et al., 2008; Lassalle et al., 2009a; Logez et al., 2012; Pont et al., 2005; Pont et al., 2015). Studies relating land use alteration with diadromous species presence or abundance have been mainly descriptive or associated with catch statistics, without any modelling approach (Armstrong et al., 2003; Feunteun, 2002; Lenhardt et al., 2006; Sandøy and Langåker, 2001). Studies debating how impaired longitudinal connectivity affects diadromous species tend to focus on a restricted area (Garcia de Leaniz, 2008; Junge et al., 2013; Rivinoja et al., 2001) and so far, to my best knowledge only Lassalle et al. (2009b) used variables associated with dams in a modelling approach.

Continental-scale distributions tend to be primarily determined by climate, thus using bioclimatic models may potentially return valid predictions of impacts from climate change on species distribution (Pearson and Dawson, 2003). However, modelling using a finer resolution such as river segment or sub-basin enables the acquisition of detailed information about intra-basin variations (Branco et al., 2013; Clavero and Hermoso, 2015; Clavero et al., 2017; Filipe et al., 2013), without losing the holistic distribution perspective, if performed for the entire environmental range of the species. Thus, research on diadromous fish species using historical data may benefit from progressing towards modelling at finer scales, such as sub-basin and segment, maintaining the focus on the European geographical extent. Yet, this is inevitably dependent on the existence of reliable and homogeneous historical data for all Europe, which is increasingly becoming a reality (Chassaing et al., 2013; Clavero and Revilla, 2014; Duarte et al., 2018c; Haidvogl et al., 2013; Lassalle et al., 2011; Ludwig et al., 2011). To date, there are no European-wide analyses that quantify the potential impairment of diadromous fish species movements considering the longitudinal connectivity hindrances. The work of Lassalle et al. (2009b), despite using variables related with dams to model diadromous fish species occurrence at European scale, does not directly quantifies potential losses associated with longitudinal connectivity impairment. Being one of the most pervasive anthropogenic threats to diadromous fish species, research that supports quantifying potential losses and assessing links between dam construction and species extirpations is important. More interestingly, having data from an SDM approach that has used historical data and multiple environmental information reflecting several threats to diadromous fish species, and afterwards relating it with longitudinal connectivity impairment can provide valuable information for conservation and management of these species.

1.8 Objectives

The present thesis aims to broaden the knowledge about diadromous species occurrence at the beginning of the 20th century using historical data. In addition, we aim to understand what are the environmental factors or anthropogenic threats constraining their occurrence. There has been much research focused on the impact of climate change on European diadromous fish species, but generally confined to the basin scale or, if using finer resolution, at a restricted geographical extent. We aim to use historical information at three spatial scales (basin, sub-basins and segment) while maintaining the full European geographical extent of the species occurrence. To achieve this, in the first part of the thesis, a framework is established allowing to cope with historical sources and databases. The second part encompasses the development of a software that facilitates the creation of environmental and anthropogenic variables at a European scale. Both these parts set the scene for the last part where species occurrence is related to climate and land use variables, and also with the hampering of the longitudinal connectivity of European freshwater networks.

1.8.1 Specific objectives

Specific objectives reflect the three aforementioned parts of the thesis objectives.

Part 1 – Setting the framework

1. Compile and curate Portuguese historical data about fish species occurrence at basin, sub-basin[1] and segment scale to create a database
2. Create a methodology that allows dealing with multiple historical databases and their inherent limitations and caveats
    - 2.1. Establish a procedure that enables the integration of multiple databases from distinct spatial scales
    - 2.2. Develop a procedure to create pseudo-occurrences based on historical data-informed thresholds

---

[1] In the context of this thesis, the term sub-basin refers to the drainage area of the tributaries from the main river of a basin.

Part 2 – Developing a facilitating tool

3. Developing a software that enables obtaining data about freshwater networks at both segment and sub-basin scales
   3.1. Facilitate the acquisition of riverscape/environmental variables for large geographic extents at finer scales
   3.2. Expedite the calculations using the freshwater networks hierarchical, dendritic and longitudinal connectivity features

Part 3 – Researching European diadromous fish species occurrence using historical data

4. Determine the structural and functional hampering of longitudinal connectivity in European freshwater networks for 15 diadromous fish taxonomic entities using historical data
5. Establish the probability of occurrence for 8 diadromous fish species at the beginning of the 20th century with a spatial hierarchical approach using climate and land use variables

1.9 Thesis structure

The thesis is organised in eight chapters. It comprises five chapters that correspond to two published articles in scientific journals[2], two peer-reviewed published conference proceedings, and an article in preparation. Minor changes have been made in the format of published manuscripts to ensure homogeneity amongst works and throughout the thesis document.

Chapter 1: This includes the introduction, the general and specific objectives of this thesis and the detail about thesis structure. It comprises a general background of the thesis subject and the detailed definition of its main and specific objectives

---

[2] Slight alterations to the published versions were promoted to create homogeneity in this manuscript.

Chapter 2: Gonçalo Duarte, Miguel Moreira, Paulo Branco, Luís da Costa, Maria Teresa Ferreira & Pedro Segurado. 2018. *One millennium of historical freshwater fish occurrence data for Portuguese rivers and streams*. Scientific Data 5: 180163. DOI: 10.1038/sdata.2018.163.

Chapter 3: Gonçalo Duarte, Paulo Branco, Gertrud Haidvogl, Didier Pont, Maria Teresa Ferreira & Pedro Segurado. 2018. *Integrating historical fish data – Selecting pseudo-occurrences*. International Symposium on Ecohydraulics. Tokyo, Japan. 6 pp.

Chapter 4: Gonçalo Duarte, Pedro Segurado, Tiago Oliveira, Gertrud Haidvogl, Didier Pont, Maria Teresa Ferreira & Paulo Branco. 2018. The River Network Toolkit – RivTool. Ecography 42. DOI: 10.1111/ecog.04192. (published only online)

Chapter 5: Gonçalo Duarte, Paulo Branco, Gertrud Haidvogl, Didier Pont, Maria Teresa Ferreira & Pedro Segurado. *Damn those damn dams: European-wide historical analysis of dam obstruction to diadromous fish movements*. In preparation.

Chapter 6: Gonçalo Duarte, Paulo Branco, Gertrud Haidvogl, Didier Pont, Maria Teresa Ferreira & Pedro Segurado. 2018. Early 20th-century potential distributions of Diadromous fish species in Europe. International Symposium on Ecohydraulics. Tokyo, Japan. 4 pp.

Chapter 7: This chapter presents a general discussion of the works presented in the previous five chapters taking into consideration the main and specific objectives. It also comprises brief final remarks and debates the future potential application of the framework created and future research possibilities.

Chapter 8: This chapter contains the supplementary materials belonging to chapters 2, 4 and 5.

1.10 References

Abell, R. (2002) Conservation Biology for the Biodiversity Crisis: a Freshwater Follow-up. Conservation Biology 16, 1435-1437.

Alcamo, J., Ash, N.J., Butler, C.D., Callicott, J.B., Capistrano, D., Carpenter, S.R., Castilla, J.C., Chambers, R., Chopra, K., Cropper, A., Daily, G.C., Dasgupta, P., Groot, R.d., Dietz, T., Duraiappah, A.K., Gadgil, M., Hamilton, K., Hassan, R., Lambin, E.F., Lebel, L., Leemans, R., Jiyuan, L., Malingreau, J.-P., May, R.M., McCalla, A.F., McMichael, T.A.J., Moldan, B., Mooney, H., Naeem, S., Nelson, G.C., Wen-Yuan, N., Noble, I., Zhiyun, O., Pagiola, S., Pauly, D., Percy, S., Pingali, P., Prescott-Allen, R., Reid, W.V., Ricketts, T.H., Samper, C., Scholes, R.B., Simons, H., Toth, F.L., Turpie, J.K., Watson, R.T., Wilbanks, T.J., Williams, M., Wood, S., Shidong, Z., Zurek, M.B. (2003) Ecosystems and human well-being: a framework for assessment. Island Press, Washington, D.C., USA.

Allan, D., Erickson, D., Fay, J. (1997) The influence of catchment land use on stream integrity across multiple spatial scales. Freshwater Biology 37, 149-161.

Allan, J.D. (2004) Landscapes and Riverscapes: The Influence of Land Use on Stream Ecosystems. Annual Review of Ecology, Evolution and Systematics 35, 257-284.

Allan, J.D., Abell, R., Hogan, Z., Revenga, C., Taylor, B.W., Welcomme, R.L., Winemiller, K. (2005) Overfishing of Inland Waters. Bioscience 55, 1041-1051.

Allan, J.D., Johnson, L. (1997) Catchment-scale analysis of aquatic ecosystems. Freshwater Biology 37, 107-111.

Almaça, C., Elvira, B. (2000) Past and present distribution of Acipenser sturio L., 1758 on the Iberian Peninsula. Boletín-Instituto Español de Oceanografía 16, 11-16.

Alonso, C., Jalón, D.G.d., Marchamalo, M. (2011) Fish communities as indicators of biological conditions of rivers: methods for reference conditions. Ambientalia, 1-12.

Aprahamian, M.W., Bagliniere, J.-L., Sabatie, M.R., Alexandrino, P., Thiel, R., Aprahamian, C.D., (2003) Biology, status, and conservation of the anadromous Atlantic twaite shad Alosa fallax fallax, American Fisheries Society Symposium, pp. 103-124.

Araújo, M.B., Guisan, A. (2006) Five (or so) challenges for species distribution modelling. Journal of Biogeography 33, 1677-1688.

Armstrong, J.D., Kemp, P.S., Kennedy, G.J.A., Ladle, M., Milner, N.J. (2003) Habitat requirements of Atlantic salmon and brown trout in rivers and streams. Fisheries Research 62, 143-170.

Bacalbaşa-Dobrovici, N. (1997) Endangered migratory sturgeons of the lower Danube River and its delta. Environmental Biology of Fishes 48, 201-207.

Bagliniere, J.-L., Sabatié, M.R., Rochard, E., Alexandrino, P., Aprahamian, M.W., (2003) The Allis shad Alosa alosa: biology, ecology, range, and status of populations, American Fisheries Society Symposium, pp. 85-102.

Bakke, T.A., Harris, P.D. (1998) Diseases and parasites in wild Atlantic salmon (Salmo salar) populations. Canadian Journal of Fisheries and Aquatic Sciences 55, 247-266.

Balée, W. (2006) The Research Program of Historical Ecology. Annual Review of Anthropology 35, 75-98.

Balée, W., Erickson, C., (2006) Time and complexity in historical ecology, in: Balée, W., Erickson, C. (Eds.), Time and Complexity in Historical Ecology: Studies in the Neotropical Lowlands. Columbia University Press, New York, pp. 1-20.

Balée, W.L., (2002) Historical ecology: Promises and Postulates, in: Balée, W.L. (Ed.), Advances in historical ecology. Columbia University Press, pp. 13-29.

Balian, E.V., Segers, H., Lévèque, C., Martens, K. (2007) The Freshwater Animal Diversity Assessment: an overview of the results. Hydrobiologia 595, 627-637.

Béguer, M., Beaulaton, L., Rochard, E. (2007) Distribution and richness of diadromous fish assemblages in Western Europe: large-scale explanatory factors. Ecology of Freshwater Fish 16, 221-237.

Boakes, E.H., McGowan, P.J.K., Fuller, R.A., Chang-qing, D., Clark, N.E., O'Connor, K., Mace, G.M. (2010) Distorted Views of Biodiversity: Spatial and Temporal Bias in Species Occurrence Data. PLoS Biology 8, e1000385.

Bradford, M.J., Irvine, J.R. (2000) Land use, fishing, climate change, and the decline of Thompson River, British Columbia, coho salmon. Canadian Journal of Fisheries and Aquatic Sciences 57, 13-16.

Branco, P., Segurado, P., Santos, J.M., Ferreira, M.T., (2013) Upscaling fish habitat suitability to the basin scale using boosted regression trees, 35th International Association for Hydro-Environment Engineering and Research World Congress, Chengdu, China.

Brink, K., Gough, P., Royte, J., Schollema, P.P., Wanningen, H. (2018) From Sea to Source 2.0. Protection and restoration of fish migration in rivers worldwide. World Fish Migration Foundation, www.fromseatosource.com.

Chapin III, F.S., Zavaleta, E.S., Eviner, V.T., Naylor, R.L., Vitousek, P.M., Reynolds, H.L., Hooper, D.U., Lavorel, S., Sala, O.E., Hobbie, S.E., Mack, M.C., Diaz, S. (2000) Consequences of changing biodiversity. Nature 405, 234-242.

Chassaing, O., Desse-Berset, N., Duffraisse, M., Hughes, S., Hänni, C., Berrebi, P. (2013) Palaeogenetics of western French sturgeons spotlights the relationships between Acipenser sturio and Acipenser oxyrinchus. Journal of Biogeography 40, 382-393.

Clavero, M., Hermoso, V. (2015) Historical data to plan the recovery of the European eel. Journal of Applied Ecology 52, 960-968.

Clavero, M., Ninyerola, M., Hermoso, V., Filipe, A.F., Pla, M., Villero, D., Brotons, L., Delibes, M. (2017) Historical citizen science to understand and predict climate-driven trout decline. Proceedings of the Royal Society B: Biological Sciences 284, 20161979.

Clavero, M., Revilla, E. (2014) Mine centuries-old citizen science. Nature 510, 35.

Clavero, M., Villero, D. (2014) Historical Ecology and Invasion Biology: Long-Term Distribution Changes of Introduced Freshwater Species. Bioscience 64, 145-153.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M. (1997) The value of the world's ecosystem services and natural capital. Nature 387, 253-260.

Crumley, C., (2007) Historical ecology: integrated thinking at multiple temporal and spatial scales, in: Hornborg, A., Crumley, C. (Eds.), The World System and the Earth System: Global Socioenvironmental Change and Sustainability Since the Neolithic, . Left Coast Press, Walnut Creek, CA, pp. 15-28.

Daily, G.C., (1997) Introduction: What are ecosystem services?, in: Daily, G.C. (Ed.), Nature's services : societal dependence on natural ecosystems. Island Press, Washington, DC, p. 392.

Dearborn, D.C., Kark, S. (2010) Motivations for Conserving Urban Biodiversity/Motivaciones para Conservar la Biodiversidad Urbana. Conservation Biology 24, 432-440.

DeFries, R.S., Foley, J.A., Asner, G.P. (2004) Land-use choices: balancing human needs and ecosystem function. Frontiers in Ecology and the Environment 2, 249-257.

Dittman, A., Quinn, T. (1996) Homing in Pacific salmon: mechanisms and ecological basis. The Journal of Experimental Biology 199, 83-91.

Doherty, D., McCarthy, T.K. (2004) The Ecology and Conservation of European smelt (Osmerus eperlanus L.) from Waterford Estuary, in Southeastern Ireland. Biology and Environment: Proceedings of the Royal Irish Academy 104B, 125-130.

Duarte, G., Moreira, M., Branco, P., da Costa, L., Ferreira, M.T., Segurado, P. (2018) One millennium of historical freshwater fish occurrence data for Portuguese rivers and streams. Scientific Data 5, 180163.

Duarte, G., Segurado, P., Oliveira, T., Haidvogl, G., Pont, D., Ferreira, M.T., Branco, P. (in press) The River Network Toolkit – RivTool. Ecography 42, 1-9.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.-I., Knowler, D.J., Lévêque, C., Naiman, R.J., Prieur-Richard, A.-H., Soto, D., Stiassny, M.L.J., Sullivan, C.A. (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. Biological Reviews 81, 163-182.

Egan, D., Howell, E.A., (2005) Introduction, in: Egan, D. (Ed.), The historical ecology handbook: a restorationist's guide to reference ecosystems. Island Press, Washington, pp. 1-23.

Falcone, J.A., Carlisle, D.M., Weber, L.C. (2010) Quantifying human disturbance in watersheds: Variable selection and performance of a GIS-based disturbance index for predicting the biological condition of perennial streams. Ecological Indicators 10, 264-273.

Fausch, K.D., Torgersen, C.E., Baxter, C.V., Li, H.W. (2002) Landscapes to Riverscapes: Bridging the Gap between Research and Conservation of Stream Fishes: A Continuous View of the River is Needed to Understand How Processes Interacting among Scales Set the Context for Stream Fishes and Their Habitat. Bioscience 52, 483-498.

Feunteun, E. (2002) Management and restoration of European eel population (Anguilla anguilla): An impossible bargain. Ecological Engineering 18, 575-591.

Filipe, A.F., Markovic, D., Pletterbauer, F., Tisseuil, C., De Wever, A., Schmutz, S., Bonada, N., Freyhof, J. (2013) Forecasting fish distribution along stream networks: brown trout (Salmo trutta) in Europe. Diversity and Distributions 19, 1059-1071.

FISRWG (1998) Stream Corridor Restoration: Principles, Processes, and Practices. Federal Interagency Stream Restoration Working Group (FISRWG).

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K. (2005) Global Consequences of Land Use. Science 309, 570-574.

Foster, D.R., (2000) Conservation lessons & challenges from ecological history, Forest History Today, pp. 2-11.

Frissell, C.A., Liss, W.J., Warren, C.E., Hurley, M.D. (1986) A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. Environmental Management 10, 199-214.

Garcia de Leaniz, C. (2008) Weir removal in salmonid streams: implications, challenges and practicalities. Hydrobiologia 609, 83-96.

Grant, E.H., Lowe, W.H., Fagan, W.F. (2007) Living in the branches: population dynamics and ecological processes in dendritic networks. Ecology Letters 10, 165-175.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., Briggs, J.M. (2008) Global Change and the Ecology of Cities. Science 319, 756-760.

Groot, S.J. (1990a) Decline of the catches of coregonids and migratory smelt in the lower Rhine, The Netherlands. Journal of Applied Ichthyology 6, 247-251.

Groot, S.J. (1990b) The former allis and twaite shad fisheries of the lower Rhine, The Netherlands. Journal of Applied Ichthyology 6, 252-256.

Guse, B., Kail, J., Radinger, J., Schroder, M., Kiesel, J., Hering, D., Wolter, C., Fohrer, N. (2015) Eco-hydrologic model cascades: Simulating land use and climate change impacts on hydrology, hydraulics and habitats for fish and macroinvertebrates. Science of the Total Environment 533, 542-556.

Haidvogl, G., Hoffmann, R., Pont, D., Jungwirth, M., Winiwarter, V. (2015) Historical ecology of riverine fish in Europe. Aquatic Sciences 77, 315-324.

Haidvogl, G., Lajus, D., Pont, D., Schmid, M., Jungwirth, M., Lajus, J. (2013) Typology of historical sources and the reconstruction of long-term historical changes of riverine fish: a case study of the Austrian Danube and northern Russian rivers. Ecology of Freshwater Fish 23, 498–515.

Hayashida, F.M. (2005) Archaeology, Ecological History, and Conservation. Annual Review of Anthropology 34, 43-65.

Helfman, G.S. (2007) Fish conservation: a guide to understanding and restoring global aquatic biodiversity and fishery resources. Island Press, Washington, DC, USA.

Hildrew, A.G., Statzner, B., (2009) Chapter 19 - European Rivers: A Personal Perspective, Rivers of Europe. Academic Press, London, pp. 685-698.

Hoekstra, J.M., Boucher, T.M., Ricketts, T.H., Roberts, C. (2005) Confronting a biome crisis: global disparities of habitat loss and protection. Ecology Letters 8, 23-29.

Holmlund, C.M., Hammer, M. (1999) Ecosystem services generated by fish populations. Ecological Economics 29, 253-268.

Hutchinson, P., Mills, D.H. (1987) Characteristics of spawning-run smelt, Osmerus eperlanus (L.), from a Scottish river, with recommendations for their conservation and management. Aquaculture Research 18, 249-258.

Hutson, W.H. (1977) Transfer functions under no-analog conditions: Experiments with Indian Ocean planktonic Foraminifera. Quaternary Research 8, 355-367.

Hynes, H.B.N. (1975) The stream and its valley. SIL Proceedings, 1922-2010 19, 1-15.

Ivanov, V.P., Vlasenko, A.D., Khodorevskaya, R.P., Raspopov, V.M. (1999) Contemporary status of Caspian sturgeon (Acipenseridae) stock and its conservation. Journal of Applied Ichthyology 15, 103-105.

Jackson, S.T., Hobbs, R.J. (2009) Ecological Restoration in the Light of Ecological History. Science 325, 567-569.

Jepsen, N., Deacon, M., Koed, A. (2012) Decline of the North Sea Houting: and protective measures for an endangered anadromous fish. Endangered Species Research 16, 77-84.

Johnson, B.L., Richardson, W.B., Naimo, T.J. (1995) Past, Present, and Future Concepts in Large River Ecology: How rivers function and how human activities influence river processes. Bioscience 45, 134-141.

Jonsson, B., Waples, R.S., Friedland, K.D. (1999) Extinction considerations for diadromous fishes. ICES Journal of Marine Science: Journal du Conseil 56, 405-409.

Junge, C., Museth, J., Hindar, K., Kraabøl, M., Vøllestad, L.A. (2013) Assessing the consequences of habitat fragmentation for two migratory salmonid fishes. Aquatic Conservation: Marine and Freshwater Ecosystems 24, 297-311.

Junk, W.J., Bayley, P.B., Sparks, R.E. (1989) The flood pulse concept in river-floodplain systems. Canadian special publication of fisheries and aquatic sciences 106, 110-127.

Kappel, C.V. (2005) Losing pieces of the puzzle: threats to marine, estuarine, and diadromous species. Frontiers in Ecology and the Environment 3, 275-282.

Kettle, A.J., Asbjørn Vøllestad, L., Wibig, J. (2011) Where once the eel and the elephant were together: decline of the European eel because of changing hydrology in southwest Europe and northwest Africa? Fish and Fisheries 12, 380-411.

Kottelat, M., Freyhof, J. (2007) Handbook of European freshwater fishes. Publications Kottelat Cornol.

Kuemmerlen, M., Schmalz, B., Cai, Q., Haase, P., Fohrer, N., Jähnig, S.C. (2015) An attack on two fronts: predicting how changes in land use and climate affect the distribution of stream macroinvertebrates. Freshwater Biology 60, 1443-1458.

Larinier, M., (2001) Environmental issues, dams and fish migration, in: Marmulla, G. (Ed.), Dams, fish and fisheries. Opportunities, challenges and conflict resolution. FAO Fisheries Technical Paper, Rome, pp. 45-90.

Lassalle, G., Béguer, M., Beaulaton, L., Rochard, E. (2008) Diadromous fish conservation plans need to consider global warming issues: An approach using biogeographical models. Biological Conservation 141, 1105-1118.

Lassalle, G., Béguer, M., Beaulaton, L., Rochard, E., (2009a) Learning from the past to predict the future: responses of European diadromous fish to climate change, American Fisheries Society Symposium, pp. 175-193.

Lassalle, G., Béguer, M., Rochard, E., (2011) An Overview on Geographical Distribution from Past Descriptions, in: Williot, P., Rochard, E., Desse-Berset, N., Kirschbaum, F., Gessner, J. (Eds.), Biology and Conservation of the European SturgeonAcipenser sturioL. 1758: The Reunion of the European and Atlantic Sturgeons. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 81-90.

Lassalle, G., Crouzet, P., Rochard, E. (2009b) Modelling the current distribution of European diadromous fishes: an approach integrating regional anthropogenic pressures. Freshwater Biology 54, 587-606.

Lassalle, G., Rochard, E. (2009) Impact of twenty-first century climate change on diadromous fish spread over Europe, North Africa and the Middle East. Global Change Biology 15, 1072-1089.

Leggett, W.C. (1977) The Ecology of Fish Migrations. Annual Review of Ecology and Systematics 8, 285-308.

Lenhardt, M., Jaric, I., Kalauzi, A., Cvijanovic, G. (2006) Assessment of Extinction Risk and Reasons for Decline in Sturgeon. Biodiversity & Conservation 15, 1967-1976.

Lévêque, C., Oberdorff, T., Paugy, D., Stiassny, M.L.J., Tedesco, P.A. (2007) Global diversity of fish (Pisces) in freshwater. Hydrobiologia 595, 545-567.

Liermann, C.R., Nilsson, C., Robertson, J., Ng, R.Y. (2012) Implications of Dam Obstruction for Global Freshwater Fish Diversity. Bioscience 62, 539-548.

Limburg, K.E., Waldman, J.R. (2009) Dramatic Declines in North Atlantic Diadromous Fishes. Bioscience 59, 955-965.

Lindenmayer, D.B., Fischer, J. (2006) Habitat fragmentation and landscape change: an ecological and conservation synthesis. Island Press.

Logez, M., Bady, P., Pont, D. (2012) Modelling the habitat requirement of riverine fish species at the European scale: sensitivity to temperature and precipitation and associated uncertainty. Ecology of Freshwater Fish 21, 266-282.

Lohse, K.A., Newburn, D.A., Opperman, J.J., Merenlender, A.M. (2008) Forecasting relative impacts of land use on anadromous fish habitat to guide conservation planning. Ecological Applications 18, 467-482.

López-Moreno, J.I., Vicente-Serrano, S.M., Moran-Tejeda, E., Zabalza, J., Lorenzo-Lacruz, J., García-Ruiz, J.M. (2011) Impact of climate evolution and land use changes on water yield in the ebro basin. Hydrology and Earth System Sciences 15, 311-322.

Lucas, M.C., Baras, E. (2001) Migration and Spatial Behaviour. Blackwell Science Ltd

Ludwig, A., Morales-Muñiz, A., Roselló-Izquierdo, E., (2011) Sturgeon in Iberia from Past to Present, in: Williot, P., Rochard, E., Desse-Berset, N., Kirschbaum, F., Gessner, J. (Eds.), Biology and Conservation of the European Sturgeon Acipenser sturio L. 1758: The Reunion of the European and Atlantic Sturgeons. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 131-146.

Maes, J., Stevens, M., Breine, J. (2008) Poor water quality constrains the distribution and movements of twaite shad Alosa fallax fallax (Lacépède, 1803) in the watershed of river Scheldt. Hydrobiologia 602, 129-143.

Maitland, P.S. (1980) Review of the Ecology of Lampreys in Northern Europe. Canadian Journal of Fisheries and Aquatic Sciences 37, 1944-1952.

Maitland, P.S. (1995) The conservation of freshwater fish: Past and present experience. Biological Conservation 72, 259-270.

McDonnell, M., Pickett, S.A., (1993) Introduction: Scope and Need for an Ecology of Subtle Human Effects and Populated Areas, in: McDonnell, M., Pickett, S.A. (Eds.), Humans as Components of Ecosystems. Springer New York, pp. 1-5.

McDowall, R.M. (1992) Particular problems for the conservation of diadromous fish. Aquatic Conservation: Marine and Freshwater Ecosystems 2, 351-355.

McDowall, R.M. (1999) Different kinds of diadromy: Different kinds of conservation problems. ICES Journal of Marine Science 56, 410-413.

McKinney, M.L. (2006) Urbanization as a major cause of biotic homogenization. Biological Conservation 127, 247-260.

Mittermeier, R.A., Gil, P.R., Hoffman, M., Pilgrim, J., Brooks, T., Mittermeier, C.G., Lamoreux, J., Fonseca, G.A.B.d. (2004) Hotspots Revisited. Earth's Biologically Richest and Most Endangered Terrestrial Ecoregions, 1st ed. CEMEX, México.

Morais, P., Dias, E., Babaluk, J., Antunes, C. (2011) The migration patterns of the European flounder Platichthys flesus (Linnaeus, 1758) (Pleuronectidae, Pisces) at the southern limit of its distribution range: Ecological implications and fishery management. Journal of Sea Research 65, 235-246.

Nel, J.L., Roux, D.J., Abell, R., Ashton, P.J., Cowling, R.M., Higgins, J.V., Thieme, M., Viers, J.H. (2009) Progress and challenges in freshwater conservation planning. Aquatic Conservation: Marine and Freshwater Ecosystems 19, 474-485.

Nicola, G., Elvira, B., Almodóvar, A. (1996) Dams and fish passage facilities in the large rivers of Spain: effects on migratory species. Large Rivers 10, 375-379.

Nikolic, N., Baglinière, J.L., Rigaud, C., Gardes, C., Masquilier, M.L., Taverny, C. (2011) Bibliometric analysis of diadromous fish research from 1970s to 2010: a case study of seven species. Scientometrics 88, 929-947.

Northcote, T.G., (1984) Mechanisms of Fish Migration in Rivers, in: McCleave, J.D., Arnold, G.P., Dodson, J.J., Neill, W.H. (Eds.), Mechanisms of Migration in Fishes. Springer US, Boston, MA, pp. 317-355.

Parrish, D.L., Behnke, R.J., Gephard, S.R., McCormick, S.D., Reeves, G.H. (1998) Why aren't there more Atlantic salmon (Salmo salar)? Canadian Journal of Fisheries and Aquatic Sciences 55, 281-287.

Pearson, R.G., Dawson, T.P. (2003) Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? Global Ecology and Biogeography 12, 361-371.

Pont, D., Hugueny, B., Oberdorff, T. (2005) Modelling habitat requirement of European fishes: do species have similar responses to local and regional environmental constraints? Canadian Journal of Fisheries and Aquatic Sciences 62, 163-173.

Pont, D., Logez, M., Carrel, G., Rogers, C., Haidvogl, G. (2015) Historical change in fish species distribution: shifting reference conditions and global warming effects. Aquatic Sciences 77, 441-453.

Postel, S., Carpenter, S., (1997) Freshwater ecosystem services, in: Daily, G.C. (Ed.), Nature's services : societal dependence on natural ecosystems. Island Press, Washington, DC, p. 392.

Postel, S.L. (2008) The forgotten infrastructure: safeguarding freshwater ecosystems. Journal of International Affairs 61, 75-90.

Pourkazemi, M. (2006) Caspian Sea sturgeon Conservation and Fisheries: Past present and Future. Journal of Applied Ichthyology 22, 12-16.

Quigley, D.T.G., Igoe, F., O'Connor, W. (2004) The European smelt Osmerus eperlanus L. in Ireland: General Biology, Ecology, Distribution and Status with Conservation Recommendations. Biology and Environment: Proceedings of the Royal Irish Academy 104B, 57-66.

Rackham, O., (1998) Implications of historical ecology for conservation, in: Sutherland, W.J. (Ed.), Conservation Science and Action, 1st ed. Blackwell Publishing Company, pp. 152-175.

Ricciardi, A., Rasmussen, J.B. (1999) Extinction Rates of North American Freshwater Fauna. Conservation Biology 13, 1220-1222.

Ripple, W.J., Wolf, C., Newsome, T.M., Galetti, M., Alamgir, M., Crist, E., Mahmoud, M.I., Laurance, W.F. (2017) World Scientists' Warning to Humanity: A Second Notice. Bioscience 67, 1026-1028.

Rivinoja, P., McKinnell, S., Lundqvist, H. (2001) Hindrances to upstream migration of Atlantic salmon (Salmo salar) in a northern Swedish river caused by a hydroelectric power-station. Regulated Rivers: Research & Management 17, 101-115.

Romão, F., (2018) Assessment and development of vertical slot fishways for Iberian cyprinids, Instituto Superior Técnico. University of Lisbon, p. 192.

Sala, O.E. (2000) Global Biodiversity Scenarios for the Year 2100. Science 287, 1770-1774.

Sandøy, S., Langåker, R.M. (2001) Atlantic salmon and Acidification in Southern Norway: A Disaster in the 20th Century, but a Hope for the Future? Water, Air, and Soil Pollution 130, 1343-1348.

Schlosser, I.J. (1991) Stream Fish Ecology: A Landscape Perspective. Bioscience 41, 704-712.

Segurado, P., Branco, P., Avelar, A., Ferreira, M. (2014) Historical changes in the functional connectivity of rivers based on spatial network analysis and the past occurrences of diadromous species in Portugal. Aquatic Sciences, 1-14.

Sepulveda, A., Thiel, R., Nellen, W. (1993) Distribution patterns and production of early life stages of European smelt, Osmerus eperlanus L., from the Elbe River. ICES CM 39, 22.

Smederevac-Lalić, M., Kalauzi, A., Regner, S., Navodaru, I., Višnjić-Jeftić, Ž., Gačić, Z., Lenhardt, M. (2018) Analysis and forecast of Pontic shad (Alosa immaculata) catch in the Danube River. Iranian journal of fisheries sciences 17, 443-457.

Stein, E., Dark, S., Longcore, T., Grossinger, R., Hall, N., Beland, M. (2010) Historical Ecology as a Tool for Assessing Landscape Change and Informing Wetland Restoration Priorities. Wetlands 30, 589-601.

Strayer, D.L., Dudgeon, D. (2010) Freshwater biodiversity conservation: recent progress and future challenges. Journal of the North American Benthological Society 29, 344-358.

Švagždys, A. (2009) Impact of environmental conditions on smelt catch fluctuations in the Nemunas River and the Curonian Lagoon. Ekologija 55.

Swetnam, T.W., Allen, C.D., Betancourt, J.L. (1999) Applied Historical Ecology: using the past to manage for the future. Ecological Applications 9, 1189-1206.

Szabó, P. (2010) Why history matters in ecology: an interdisciplinary perspective. Environmental Conservation 37, 380-387.

Thiel, R., Sepülveda, A., Oesmann, S., (1996) Occurrence and distribution of twaite shad (Alosa fallax Lacépède) in the lower Elbe River, Germany, in: Kirchhofer, A., Hefti, D. (Eds.), Conservation of Endangered Freshwater Fish in Europe. Birkhäuser Basel, Basel, pp. 157-170.

Thomas, C.D., Franco, A.M.A., Hill, J.K. (2006) Range retractions and extinction in the face of climate warming. Trends in Ecology & Evolution 21, 415-416.

Tockner, K., Tonolla, D., Uehlinger, U., Siber, R., Robinson, C.T., Peter, F.D., (2009) Chapter 1 - Introduction to European Rivers, Rivers of Europe. Academic Press, London, pp. 1-21.

Trautwein, C., Schinegger, R., Schmutz, S. (2012) Cumulative effects of land use on fish metrics in different types of running waters in Austria. Aquatic Sciences 74, 329-341.

Tsang, Y.-P., Wieferich, D., Fung, K., Infante, D.M., Cooper, A.R. (2014) An approach for aggregating upstream catchment information to support research and management of fluvial systems across large landscapes. SpringerPlus 3, 1-9.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E. (1980) The River Continuum Concept. Canadian Journal of Fisheries and Aquatic Sciences 37, 130-137.

Vasil'Eva, E.D. (2003) Main alterations in ichthyofauna of the largest rivers of the northern coast of the Black Sea in the last 50 years: A review. FOLIA ZOOLOGICA-PRAHA- 52, 337-358.

Vellend, M., Brown, C.D., Kharouba, H.M., McCune, J.L., Myers-Smith, I.H. (2013) Historical ecology: Using unconventional data sources to test for effects of global environmental change. American Journal of Botany 100, 1294-1305.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B. (2000) Global Water Resources: Vulnerability from Climate Change and Population Growth. Science 289, 284-288.

Vorosmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., Davies, P.M. (2010) Global threats to human water security and river biodiversity. Nature 467, 555-561.

Ward, J.V. (1989) The Four-Dimensional Nature of Lotic Ecosystems. Journal of the North American Benthological Society 8, 2-8.

Ward, J.V., Stanford, J.A., (1983) The serial discontinuity concept of lotic ecosystems. , in: Fontaine, T.D., Bartell, S.M. (Eds.), Dynamics of lotic ecosystems. Ann Arbor Science, Ann Arbor, Michigan, pp. 29-42.

Ward, J.V., Stanford, J.A. (1995) Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers: Research & Management 11, 105-119.

White, P.S., Walker, J.L. (1997) Approximating Nature's Variation: Selecting and Using Reference Information in Restoration Ecology. Restoration Ecology 5, 338-349.

Williot, P., Arlati, G., Chebanov, M., Gulyas, T., Kasimov, R., Kirschbaum, F., Patriche, N., Pavlovskaya, L.P., Poliakova, L., Pourkazemi, M., Kim, Y., Zhuang, P., Zholdasova, I.M. (2002) Status and Management of Eurasian Sturgeon: An Overview. International Review of Hydrobiology 87, 483-506.

Wolter, C. (2015) Historic catches, abundance, and decline of Atlantic salmon Salmo salar in the River Elbe. Aquatic Sciences 77, 367-380.

Zaitsev, Y.P. (1992) Recent changes in the trophic structure of the Black Sea. Fisheries Oceanography 1, 180-189.

2. One millennium of historical freshwater fish occurrence data for Portuguese rivers and streams

---

Gonçalo Duarte, Miguel Moreira, Paulo Branco, Luís da Costa, Maria Teresa Ferreira & Pedro Segurado

Published on Scientific Data

14 August 2018

DOI: 10.1038/sdata.2018.163

2.1 Abstract

The insights that historical evidence of human presence and man-made documents provide are unique. For example, using historical data may be critical to adequately understand the ecological requirements of species. However, historical information about freshwater species distribution remains largely a knowledge gap. In this Data Descriptor, we present the Portuguese Historical Fish Database (PHish–DB), a compilation of 2214 records (557 at the basin scale, 184 at the sub-basin scale and 1473 at the segment scale) resulting from a survey of 194 historical documents. The database was developed using a three-scale approach that maximises the inclusion of information by allowing different degrees of spatial acuity. PHish database contains records of 25 taxonomical groups and covers a time span of one millennium, from the 11th until the 20th century. This database has already proven useful for two scientific studies, and PHish further use will contribute to correctly assess the full range of conditions tolerated by species, by establishing adequate benchmark conditions, and/or to improve existing knowledge of the species distribution limits.

2.2 Background & Summary

Collecting historical data on species diversity and occurrence from time periods earlier than the major impactful human activities taking place (e.g., damming, the Industrial Revolution, modern fishing, and river channelisation), may lead to an improvement of knowledge about species ecology. However, historical documents have limitations that need to be understood to avoid incorrect interpretations (Rackham, 1998) and/or extrapolations (Swetnam et al., 1999). There is cultural filtering that affects not only the spatial and temporal availability, completeness, and reliability of documentary records but also their quantity and quality (Swetnam et al., 1999). Most historical records rely factually on questionnaires/interviews, hence if there are erroneous answers, the inventories or scientific surveys will present incorrect data (Haidvogl et al., 2013). Nevertheless, the utility of historical insight cannot be underestimated and using historical data for ecological studies is valid (Swetnam et al., 1999). Using an interdisciplinary approach (Szabó, 2010), combining information from several independent spatial and temporal sources (Hayashida, 2005; Rackham, 1998;

Swetnam et al., 1999; Szabó, 2010), cross-checking lines of evidence with independent datasets (Crumley, 2007) and blending different methods (Swetnam et al., 1999) can help mitigate the limitations and lead to more accurate knowledge about past ecosystem conditions.

For some organisms and specific purposes, historical data might be essential to model the potential species distribution (e.g., Clavero and Hermoso, 2015; Lassalle and Rochard, 2009) because current distributions are often highly constrained by anthropogenic pressures that alter the natural realised ecological niche. A typical example is the case of diadromous fish species with their inland progression being gradually constrained by the presence of artificial barriers (Clavero and Hermoso, 2015; Lassalle et al., 2009b). Consequently, current occurrence data will only cover a restricted range of the full conditions tolerated by species. To create the Portuguese Historical Fish Database (PHish–DB) we scouted 194 historical documents, resulting in 2214 records from 30 basins, 280 sub-basins and 490 segments. Data collection started in 2007 and was performed by researchers in history and ecology. Despite some underrepresentation of coastal areas, the spatial distribution of the historical records is homogeneous throughout the country and covers all the major river basins (Figure 2.2.9). Three international river basins stand out (Douro, Minho and Guadiana) with a high number of records (Figure 2.2.9a). The sub-basins with the highest number of records are from the River Tâmega (Douro) and River Zêzere (Tagus) (Figure 2.2.9b). Spatial acuity of the records depended on the information present in the historical source. Thus, we opted for a three-scale approach to maximise the collected information. This has resulted in 557 records limited to the basin scale, 184 reaching the sub-basin scale, and 1473 records identified down to the highest accurate spatial scale, the river segment. PHish database covers a time span of one millennium, from the 11th until the 20th century, having a larger number of records for the second half of the millennium and particularly for the 18th and 19th centuries (Figure 2.2.9c). The Interpretation of historical data can be very subjective (Swetnam et al., 1999), and matching ancient fish common names with current taxonomy was challenging. To minimise uncertainty in the taxonomical classification of a fish record, a conservative approach was followed to establish the adequate taxonomical groups. Of the 25 group names defined from the records gathered, three stood out: Petromizontidae, *Chondrostoma* sp. and *Salmo trutta* (Figure 2.2.9d).

The information present in the database has been partially used in the work of Segurado et al. (2014), and also incorporated in a relevant European project, the European Fish Index – Plus (EFI+) (http://efi-plus.boku.ac.at/). This database can nevertheless be useful to: improve existing scientific knowledge in Iberian context (e.g., Clavero and Hermoso, 2015; Clavero et al., 2017); expand scientific knowledge in European context via an Iberian occurrence scenario of a species with broad-European distribution (e.g., Filipe et al., 2013); be used for research where historical interactions between human activities and riverine fish communities and population are relevant.

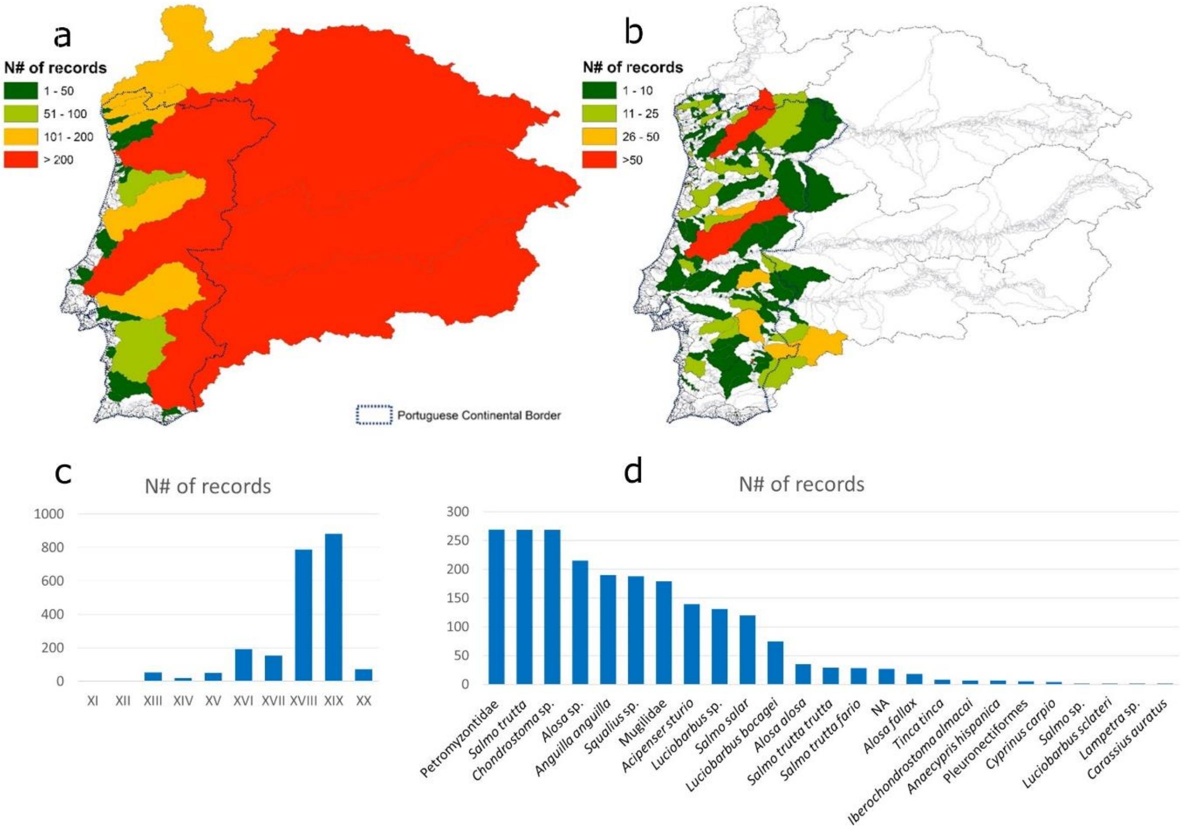


Figure 2.2.9 – Summary results of the PHish database. a – Number of Records per river basin; b – Number of Records per river sub-basin; c – Number of Records per century; d – Number of Records per taxonomical group present in the field “Group Name”.

2.3 Methods

These methods are expanded and updated versions of descriptions in our related work Segurado et al. (2014).

2.3.1 Historical sources

The present historical records compilation of riverine fish distribution was based on geographical dictionaries and other published information for Portugal, dated between the 11th and early 20th centuries. Portugal is the most south-western part of the European continent, representing 15% of the Iberian Peninsula. There are four major international rivers (Douro, Guadiana, Minho, and Tagus) and numerous other relevant national rivers. The available historical information on fish populations for this period was almost exclusively based on qualitative data of species occurrence. Available sources dated before the 16th century included charters, inquiries, donations, and monastic chronicles. From the 16th century onwards, more thorough recordings of the patrimony of the Portuguese kingdom were available, with the emergence of chorographies, historical-geographical memos, parish inquiries and dictionaries that recorded historically and geographically the Portuguese landscape. In addition to these sources, information from private libraries was also included. A total of 194 documents were consulted (sea supplementary material in Annexe 8.1, Table 8.1.7). These historical sources contain information varying from aspects of the Portuguese physical territory, records about the natural resources of rivers, or cultural context of fisheries exploitation. Most of this data were compiled in the context of the EU projects EFI+ (http://efi-plus.boku.ac.at/) and DURERO (Douro River Basin: Water Resources, Water Accounts and Target Sustainability Indices; http://138.100.137.130/ durero_project_2014/), with the main purpose of providing data on reference conditions to compute biotic indicators based on diadromous species. Many regions of Europe have been shaped for centuries by human activities, leading to an absence of natural reference conditions for many water body types (Hohensinner et al., 2008). Hence, the definition of benchmark conditions may depend on the availability of historical sources of information on species occurrence (Béguer et al., 2007). This is especially relevant in the context of the Water Framework Directive of the European Union (WFD) (European Commission, 2000), which involves the assessment of the ecological quality of water bodies using the reference condition approach, in which quality classes are defined according to deviations from benchmark conditions.

2.3.2 Taxonomical precision

Taxonomic acuity is critical to provide the best possible taxonomy insights from historical records and to derive reliable databases to be used as sources of information to test scientific or management hypotheses. However, this condition is rather challenging to attain when looking at large spatial scales. Indeed, in historical texts, the norm is to use local common names, mostly because many of the records predate the scientific description of the species. Therefore, the first step to produce this database was to establish a reference list by collecting and compiling ancient and current common names with their correspondence to scientific nomenclature. The second step was to attribute a valid species to each record, with an extra challenge when distinct common names are attributed to the same species among different regions. However, the most challenging issues are posed when several species share common names in certain regions or when very similar and even congener species are sympatric. Despite these caveats, because of the known present distribution of species, the reduced sympatry of similar species and the fact that most shared common names are of similar allopatric species, it is possible to attribute valid scientific identities to each record without errors. Whenever this attribution was impossible or uncertain, the genus, family or order was attributed to the record, instead of the species-specific epithet. This was the case for the genera *Alosa*¸ *Luciobarbus, Lampetra, Salmo* and *Squalius*, for the families Petromyzontidae and Mugilidae, and for order Pleuronectiformes. For the nases, it was decided to use an older genus' name – *Chondrostoma*, valid in Europe, but with no current taxonomic validity in the Iberian Peninsula – that currently represents seven species in this database. This older genus aggregates three recently described genera (*Achondrostoma*, *Iberochondrostoma* and *Pseudochondrostoma*) (Robalo et al., 2007) that are, basin-wise, sympatric, coexisting at least two of these genera per basin with historical records. For Pleuronectiformes, the decision was made because it was unsure whether the species record corresponded to a freshwater species (*Plactichthys flesus*) or to a marine fish, of which there are several species. A conservative approach was followed and whenever a possibility for misinterpretation existed, the species were aggregated to the corresponding upper taxonomic level under the column “Group Name” (information that we recommend to use without any uncertainty). Whenever there were plausible reasons to believe that the record belonged to a given species, the full scientific binomial nomenclature was attributed to the column “Sub-group Name”. This has some associated uncertainty as the decision was made by expert judgement based on the available information. Whenever no plausibility existed, the higher taxonomic group (genus or family) was maintained without the attribution of a “Sub-group Name”. If there existed a possibility of confusion between species that did not fit the higher taxonomical groups defined, an NA was attributed to the “Group Name”. If plausible, an educated guess, for a species or a taxonomical group, was made into the “Sub-group Name”, based on the interpretation of the historical text extract. All the species and species groups considered are detailed in Table 2.3.2. To add value to the database, whenever available, information about the phenology and conservation status (national and international) was included.

Table 2.3.2– Combination of “Group Name” field and “Sub-group Name” field occurring in the historical records table of the PHish database. NA – Non-applicable.

Group Name	Sub-group Name
Acipenser sturio	NA
Alosa alosa	NA
Alosa fallax	NA
Alosa sp.	*Alosa alosa*
Alosa sp.	*Alosa fallax*
Alosa sp.	NA
Anaecypris hispanica	NA
Anguilla anguilla	NA
Carassius auratus	NA
Chondrostoma sp.	*Achondrostoma occidentale*
Chondrostoma sp.	*Achondrostoma oligolepis*
Chondrostoma sp.	*Iberochondrostoma lemmingii*

Group Name	Sub-group Name
Chondrostoma sp.	*Iberochondrostoma lusitanicum*
Chondrostoma sp.	*Iberochondrostoma sp.*
Chondrostoma sp.	NA
Chondrostoma sp.	*Pseudochondrostoma duriense*
Chondrostoma sp.	*Pseudochondrostoma polylepis*
Chondrostoma sp.	*Pseudochondrostoma willkommii*
Cyprinus carpio	NA
Iberochondrostoma almacai	NA
Lampetra sp.	*Lampetra fluviatilis*
Luciobarbus bocagei	NA
Luciobarbus sclateri	NA
Luciobarbus sp.	*Luciobarbus comizo*
Luciobarbus sp.	NA
Mugilidae	NA
NA	*Alosa* sp.
NA	*Anguilla anguilla*
NA	*Cyprinus carpio*
NA	*Luciobarbus bocagei*
NA	*Luciobarbus* sp.
NA	NA
NA	*Salmo* sp.
Petromyzontidae	NA
Petromyzontidae	*Petromyzon marinus*
Pleuronectiformes	NA
Salmo salar	NA
Salmo sp.	*Salmo salar*
Salmo trutta	NA

Group Name	Sub-group Name
Salmo trutta	
	Salmo trutta fario
Salmo trutta	*Salmo trutta trutta*
Salmo trutta fario	NA
Salmo trutta trutta	NA
Squalius sp.	*Squalius alburnoides*
Squalius sp.	*Squalius aradensis*
Squalius sp.	*Squalius carolitertii*
Squalius sp.	*Squalius pyrenaicus*

2.3.3 Georeferencing

To create a spatial representation of the historical data we have used the Catchment Characterisation and Modelling– River and Catchment database v2.1 (CCM2) (http://data.europa.eu/89h/fe1878e8-7541-4c66-8453-afdae7469221). An advantage of this pan-European database is its hierarchical structure, besides representing a fully integrated system between rivers and drainage catchments (Vogt et al., 2007). Using three spatial scales (basin, sub-basin and segment) allowed storing historical records with distinct spatial accuracy. Even though finer scales are more informative, historical data at a coarser scale is not irrelevant. For the basin scale, we used the identification code that CCM2 gives for each basin (WSO_ID) to link an historical record to this scale level. The same procedure was established at the segment scale, using the ID code that CCM2 assigns for each segment (WSO1_ID). Since CCM2 does not have any identification or spatial representation of the sub-basins within each sea outlet basin, we used a free software to create this information, the River Network Toolkit (RivTool). This software (available at www.rivtoolkit.com) uses integrated data about river networks and landscape/environmental datasets to produce new or aggregated data via calculations that consider the directional hierarchical network nature of rivers. The set of natural sub-basins of all sea outlet basins of the study area was created using the “sub-basin ID” function of RivTool.

The descriptions found in the historical sources varied greatly in their geographical precision. Most presence records referred to a given river or stream within a restricted region, usually described as being near a given village, township or city. When the geographic location was available, the record was georeferenced in a Geographical Information System (GIS) using CCM2. These were the most spatially precise records, the segment scale, where a segment corresponds to a river reach between two consecutive tributaries. In some cases, regions or town names were obsolete and further investigation was needed to clarify the current location and/or designation associated with that former nomination. Nevertheless, for some historical records, the former names did not have any information or relation with the current designations or did not have enough precision to be linked to a river segment. In those cases, the record was attributed to a higher spatial scale (Sub-basin or Basin). Data entries that could only be related to a watercourse that is a major river or stream that flows to the Atlantic Ocean, coastal lagoons or estuaries, were considered as low precision records and spatially defined at the basin scale. When the watercourse was identified as a tributary (i.e., smaller river or stream not flowing to the Ocean, coastal lagoon or estuary), the precision was considered higher and the record was spatially defined at the Sub-basin scale.

2.4 Data Records

A relational database structure (Figure 2.2.9) was created in Microsoft Access® (available in the .accdb file extension) to adequately organise and store the historical data collected with their spatial and temporal dependencies, and also to maintain their link to the historical sources (sea supplementary material in Annexe 8.1, Table 8.1.7). The PHish database is publicly available at the Open Science Framework (Data Citation 1) and at the University of Lisbon, School of Agriculture repository http://www.isa.ulisboa.pt/proj/PHish/. The database contains six tables: three related with spatial organisation, “Basins”, “Sub-basins”, “Segments”; one with taxonomical identification, “Taxonomical Groups”; one establishing the details of historical sources, “Historical Documents”; and finally, one aggregating historical record information with respective spatial, taxonomical and historical source information, “Historical Records” (Table 8.1.8). The latter table is the core of the relational database structure, relating to all other tables (Figure 2.2.10) and where resulting historical data are stored (Table 8.1.8).

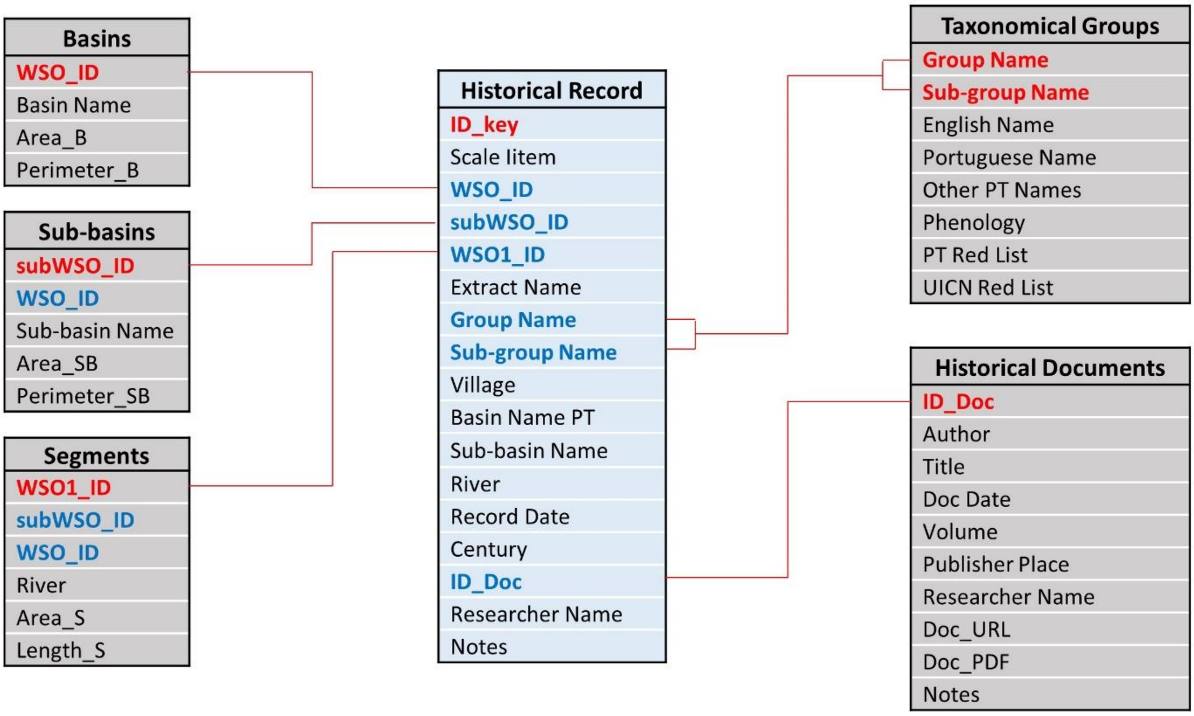


Figure 2.2.10 – The relational structure of the Portuguese Historical Fish Database. Each box represents one table, with the header of a box indicating the name of the table, followed by the list of fields included in the table. The red lines indicate the primary relationship between tables; red fields are the primary key of each table; fields in blue indicate secondary relationships between tables.

2.5 Technical Validation

Interpretation of historical data can be very subjective and historical science is mostly inductive (Swetnam et al., 1999). To increase objectivity and guarantee a correct assessment of historical information it is necessary to perform a critical evaluation of sources (Haidvogl et al., 2013), while comparing and combining multiple and independent sources and methods (White and Walker, 1997). Special attention was taken to verify if authors were not just replicating information from other sources, and by that leading to duplication of results in the database. This was done not only while researchers were reading and surveying the historical documents and sources, but also by analysing, comparing and searching within the final set of historical records for similarities. For example, combined similarities in taxonomical groups and spatial references, similarities in paragraphs, sentences or parts of sentences were normally an indication that the author was just citing text from another document without acknowledging it explicitly. Whenever there was reasonable doubt about the originality of the information present in the historical source, or of the historical record, only the oldest one was included in the database.

Despite the numerous hurdles, taxonomical identification of ancient species common names followed a conservative approach that guaranteed no uncertainty for the “Group Name” field. Concerning the “Sub-group Name” field, the integration of information between spatial location and taxonomical identification of a record, the reliable considerations based on literature and the knowledge of experienced ecologists assured low levels of uncertainty. Moreover, when there was reasonable doubt or lack of plausibility, no consideration was made.

Spatial information for the records location was primarily accessed based on three Portuguese official water management and administrative sources at GIS environment: 1) Rivers map (Shapefile from www.hidrografico.pt); 2) Administrative regions and municipalities map (Shapefile from www.dgterritorio.pt); and 3) Online orthophotomaps (WMS link from www.igeo.pt). When the record city/council name or region was not easily connected to the information available in maps, numerous municipalities and parish websites were consulted, along with other websites from relevant local or regional associations, to help identify the more site-specific or out-dated spatial references. The connection with the CCM2 database was performed only after this thorough process. Records for places or historical locations which were not geographically identifiable were conservatively handled, either by discarding or including them in upper spatial scales (sub-basin or basin scale) when the river name was objectively identified.

2.6 Usage Notes

Just like every database of historical records, the PHish database is neither definitive nor complete. All reasonable and possible updates will be held, though nevertheless dependent on resources and future funding. Methods will be maintained to avoid usage biases and/or interpretation issues. Future surveys for historical data should focus on rectifying spatial and temporal data heterogeneity. Obtaining information for older times (backward from the 16th century) and focusing on the coastal areas of Portugal should bridge the spatial and temporal knowledge disparity.

Despite our best efforts, and even considering future updates to this database, true species occurrence will inevitably be broader than what historians and chroniclers may have reported. The cultural filtering (Swetnam et al., 1999), accidental or intentional destruction of documents, doubtful sources of the historians/chroniclers and bias towards certain species (Haidvogl et al., 2013) affect both spatial and temporal availability, completeness, and reliability of documentary records (Swetnam et al., 1999). In England, copyright law was limited to a special group of people until the 18th century; indeed documents availability was still censored and limited to printers and publishers rights rather than to authors properties (Patterson, 1968). The concept of author’s intellectual property over its work only proliferated during the 19th century, particularly in culturally developed countries such as France and Great Britain (Geller, 2000). This means that at least until the 18th century, and in Portugal most likely until the 19th century, authors could quote other works without acknowledging them. Thus, data duplication is a possibility within this database, though we consider it in a very low probability given to our cautious approach to this conundrum. Also, users must be aware that PHish database is a presence-only compilation of historical records. Without a wary systematic sampling, absence data is inevitably prone to a high degree of uncertainty, and to our best knowledge, no modern-day systematic survey of fish assemblages across the country was undertaken in Portugal until the end of the 20th century.

The lack of data for coastal areas, and more specifically for the southern coastal regions of Portugal may result from several particular circumstances. Smaller basins are composed of smaller rivers and inevitably with less human settlements. Adding to this, southern Iberian rivers are Mediterranean-type freshwater ecosystems strongly shaped by autumn/winter flooding and summer drought events (Gasith and Resh, 1999). This seasonal instability has implications in the structure of freshwater communities (Pires et al., 1999), meaning that these rivers will probably tend to support less interesting fishing areas and species. The database is also temporally unbalanced, i.e., although covering a vast time-scale it does not represent a consistent time-series due to lack or reduced number of records for the first half of the millennium. Future updates to this database will probably not fully overcome this as it is also the result of temporal filtering (Haidvogl et al., 2013) of historical sources. Another relevant issue is the heterogeneity of the established taxonomical groups in the user recommended field (Group Name). Our conservative approach followed herein avoids uncertainty in this classification, translating into correct and objective taxonomical information. However, for example, it may be thwarting to use some taxonomical groups (e.g., "Mugilidae*"* or *"Chondrostoma")* when the objective is to perform species environmental niche modelling.

All mentioned issues, biases and unbalances are normal for historical databases, and none of them hampers the usage of the database. To our knowledge, this database is the first public compilation of historical distribution data based on freshwater fish species in Portuguese rivers and South-western Europe. Notwithstanding, users should keep in mind all these features and caveats whenever making any considerations or extrapolation based on this database. The PHish database is geographically limited since it is restricted to inland Portugal. However, the current database contains valuable information by covering data for the Portuguese areas, including sea outlets, of four Iberian international rivers and most Portuguese major watercourses. Moreover, because Portuguese data were not compiled and made available until now, researchers have been using only Spanish records to study fish species distribution for the whole Iberian Peninsula, minimizing its importance as a meaningful biogeographical entity (Ribeiro et al., 2008). By using only Spanish data, authors concede to uncertain premises (e.g., Clavero and Villero, 2014) and/or extrapolate when predicting for the entire Iberian Peninsula (e.g., Clavero and Hermoso, 2015). Hence, this database will fill an important gap in the current knowledge and contribute to the development of new studies covering the whole Iberian Peninsula without being hindered by political borders.

2.7 Acknowledgements

The authors would like to thank Paula Avelar, Armanda Rodrigues, Inês Vila, José Maria Santos, João Oliveira, Paulo Pinheiro and José Neiva for their participation in this work. Gonçalo Duarte is part of the FLUVIO doctoral program and financed by a grant from the Fundação para a Ciência e Tecnologia (FCT) (SFRH/BD/52514/2014). Miguel Moreira is also part of the FLUVIO doctoral program and financed by a grant from the Fundação para a Ciência e Tecnologia (FCT) (PD/BD/114558/2016). Paulo Branco was financed by a post-doc grant from FCT (SFRH/BPD/94686/2013). Luís da Costa was financed by the MARS Project (Managing Aquatic ecosystems and water Resources under multiple Stress) funded under the 7th EU Framework Programme, Work Package 4 (Multiple stressors at the river basin scale). Pedro Segurado is supported by a contract funded by the Fundação para a Ciência e Tecnologia (FCT) under the IF Researcher Programme (IF/01304/2015). Centro de Estudos Florestais (CEF; “Forest Research Centre”) is a research unit funded by Fundação para a Ciência e a Tecnologia I.P. (FCT), Portugal (UID/AGR/00239/2013). Part of the historical compilation has been supported by the EU project FP6-2005-SSP-5A-044096 (http://efiplus.boku.ac.at/). Part of the historical compilation has been supported by the project DURERO (Douro River Basin: Water Resources, Water Accounts and Target Sustainability Indices; http://138.100.137.130/durero_project_2014/).

2.7.1 Author contributions

GD supervised and collaborated in the historical sources analysis and data collection, helped establishing the spatial location for the historical records, helped preparing the data for the relational database, created the access relational database, wrote part of the Data Descriptor, and reviewed the full manuscript.

MM collaborated in the historical sources analysis and data collection, searched and established the spatial location for the historical records, prepared the data for the relational database, wrote part of the Data Descriptor, and reviewed the full manuscript.

PB helped establishing the taxonomical groups, helped establishing the structure of the relational database, wrote part of the Data Descriptor, and reviewed the full manuscript.

LC collaborated in the historical sources analysis and data collection, helped searching and establishing the spatial location for the historical records, helped establishing the taxonomical groups, helped creating the access relational database, and reviewed the full manuscript.

MTF coordinated the interaction between institutions, coordinated the work of all the researchers involved, and reviewed the full manuscript.

PS coordinated the historical sources analysis and data collection, helped establishing the structure of the relational database, wrote part of the Data Descriptor, and reviewed the full manuscript.

2.8 Competing interests

The authors declare no competing financial interests.

2.9 Data Citations

1. Duarte, G., Moreira, M., Branco, P., da Costa, L., Ferreira, M.T., Segurado, P. Open Science Framework https://dx.doi.org/10.17605/OSF.IO/TXCYS (2018)

2.10 References

Béguer, M., Beaulaton, L., Rochard, E. (2007) Distribution and richness of diadromous fish assemblages in Western Europe: large-scale explanatory factors. Ecology of Freshwater Fish 16, 221-237.

Clavero, M., Hermoso, V. (2015) Historical data to plan the recovery of the European eel. Journal of Applied Ecology 52, 960-968.

Clavero, M., Ninyerola, M., Hermoso, V., Filipe, A.F., Pla, M., Villero, D., Brotons, L., Delibes, M. (2017) Historical citizen science to understand and predict climate-driven trout decline. Proceedings of the Royal Society B: Biological Sciences 284, 20161979.

Clavero, M., Villero, D. (2014) Historical Ecology and Invasion Biology: Long-Term Distribution Changes of Introduced Freshwater Species. Bioscience 64, 145-153.

Crumley, C., (2007) Historical ecology: integrated thinking at multiple temporal and spatial scales, in: Hornborg, A., Crumley, C. (Eds.), The World System and the Earth System: Global Socioenvironmental Change and Sustainability Since the Neolithic, . Left Coast Press, Walnut Creek, CA, pp. 15-28.

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 in: Parliament, E. (Ed.), L 327, The Official Journal of the European Union, p. 93.

Filipe, A.F., Markovic, D., Pletterbauer, F., Tisseuil, C., De Wever, A., Schmutz, S., Bonada, N., Freyhof, J. (2013) Forecasting fish distribution along stream networks: brown trout (Salmo trutta) in Europe. Diversity and Distributions 19, 1059-1071.

Gasith, A., Resh, V.H. (1999) Streams in Mediterranean Climate Regions: Abiotic Influences and Biotic Responses to Predictable Seasonal Events. Annual Review of Ecology and Systematics 30, 51-81.

Geller, P.E. (2000) Copyright history and the future: What's culture got to do with it. Journal of the Copyright Society of the U.S.A. 47, 209.

Haidvogl, G., Lajus, D., Pont, D., Schmid, M., Jungwirth, M., Lajus, J. (2013) Typology of historical sources and the reconstruction of long-term historical changes of riverine fish: a case study of the Austrian Danube and northern Russian rivers. Ecology of Freshwater Fish 23, 498–515.

Hayashida, F.M. (2005) Archaeology, Ecological History, and Conservation. Annual Review of Anthropology 34, 43-65.

Hohensinner, S., Herrnegger, M., Blaschke, A.P., Habereder, C., Haidvogl, G., Hein, T., Jungwirth, M., Weiβ, M. (2008) Type-specific reference conditions of fluvial landscapes: A search in the past by 3D-reconstruction. CATENA 75, 200-215.

Lassalle, G., Crouzet, P., Rochard, E. (2009) Modelling the current distribution of European diadromous fishes: an approach integrating regional anthropogenic pressures. Freshwater Biology 54, 587-606.

Lassalle, G., Rochard, E. (2009) Impact of twenty-first century climate change on diadromous fish spread over Europe, North Africa and the Middle East. Global Change Biology 15, 1072-1089.

Patterson, L.R. (1968) Copyright in historical perspective. Vanderbilt University Press.

Pires, A.M., Cowx, I.G., Coelho, M.M. (1999) Seasonal changes in fish community structure of intermittent streams in the middle reaches of the Guadiana basin, Portugal. Journal of Fish Biology 54, 235-249.

Rackham, O., (1998) Implications of historical ecology for conservation, in: Sutherland, W.J. (Ed.), Conservation Science and Action, 1st ed. Blackwell Publishing Company, pp. 152-175.

Ribeiro, F., Elvira, B., Collares-Pereira, M.J., Moyle, P.B. (2008) Life-history traits of non-native fishes in Iberian watersheds across several invasion stages: a first approach. Biological Invasions 10, 89-102.

Robalo, J.I., Almada, V.C., Levy, A., Doadrio, I. (2007) Re-examination and phylogeny of the genus Chondrostoma based on mitochondrial and nuclear data and the definition of 5 new genera. Molecular Phylogenetics and Evolution 42, 362-372.

Segurado, P., Branco, P., Avelar, A., Ferreira, M. (2014) Historical changes in the functional connectivity of rivers based on spatial network analysis and the past occurrences of diadromous species in Portugal. Aquatic Sciences, 1-14.

Swetnam, T.W., Allen, C.D., Betancourt, J.L. (1999) Applied Historical Ecology: using the past to manage for the future. Ecological Applications 9, 1189-1206.

Szabó, P. (2010) Why history matters in ecology: an interdisciplinary perspective. Environmental Conservation 37, 380-387.

Vogt, J., Soille, P., Jager, A.d., Rimavičiūtė, E., Mehl, W., Foisneau, S., Bódis, K., Dusart, J., Paracchini, M.L., Haastrup, P., Bamps, C., (2007) A pan-European River and Catchment Database. European Commission - Joint Research Centre - Institute for Environment and Sustainability, Luxembourg, p. 120.

White, P.S., Walker, J.L. (1997) Approximating Nature's Variation: Selecting and Using Reference Information in Restoration Ecology. Restoration Ecology 5, 338-349.

3. Integrating historical fish data – Selecting pseudo-occurrences

Gonçalo Duarte, Paulo Branco, Gertrud Haidvogl, Didier Pont, Maria Teresa Ferreira, Pedro Segurado

Proceeding from the 12th International Symposium on Ecohydraulics

19 August 2018

3.1 Abstract

Historical information on freshwater ecosystems is very important since there is a considerable knowledge gap about factors affecting the potential freshwater species distribution. Diadromous species have been noticeably declining at least for more than a century as a result of impactful human activities. Thus, information about their occurrence and distribution prior to these actions is essential. Long-term and large-scale historical data about freshwater organisms are rare. In Europe, most sources/databases are regional or national and with variable spatial coverage and resolution. With this work, we have created a method that can use multiple historical sources to create a coherent set of historical data with large spatial coverage, different levels of resolution, and for which sources were verified and cross-checked with each other.

3.2 Introduction

Freshwaters are only 0.01% of the surface of the planet, home to 9.5% of animal species (Balian et al., 2007) and one of the most endangered ecosystems worldwide (Sala, 2000). Information about freshwater species, their distribution and conservation status remains as a knowledge gap (Mittermeier et al., 2004). In continental Europe, 40% of native fishes have disappeared from catchments of their natural occurrence (Tockner et al., 2009), and 13 have become extinct (Kottelat and Freyhof, 2007). Diadromous fish species are migratory animals with a specialised life cycle (McDowall, 1992) and a relevant role in ecosystem services (Limburg and Waldman, 2009). They are an important component of the marine and freshwater food chains and an energy flow link between these environments (Limburg and Waldman, 2009). Moreover, it is widely acknowledged that diadromous fish populations have been severely declining or going extinct at least since the beginning of the 20th century (Béguer et al., 2007; Limburg and Waldman, 2009) mainly as a result of the construction of dams in main rivers, water quality deterioration and unsustainable fisheries (Béguer et al., 2007). Thus, it is very important to have broad-scale historical information about species biodiversity and occurrence prior to major impactful human activities such as these. The insights that historical evidence of human presence and man-made documents provide are unique since they could not have been generated in any other way (Vellend et al., 2013), and were for a long time confined to history researchers. At the continental scale, long-term data and historical information about freshwater organisms are rare (Tockner et al., 2009).

Datasets covering large spatial and temporal scales allow researchers to reveal macroecological patterns in biodiversity (Gaston and Blackburn, 2007). This distant viewpoint allows observing patterns that otherwise would be hard to predict or even disregarded (Gaston and Blackburn, 2007), thus emphasizing the importance of large databases to validate and disclose ecological general patterns (Cadotte et al., 2006). In Europe, sources of biological information about freshwater systems are commonly truncated by country or region and heterogeneously distributed across the continent (Tockner et al., 2009). River basin is the key spatial unit to manage and understand freshwater ecosystem processes and biodiversity patterns (Tockner et al., 2009). Each river basin is naturally independent of neighbouring basins and contains a freshwater network with respective drainage area and hydrological, environmental and hydromorphological characteristics.

There are already some species generic databases (e.g., FADA project (Balian et al., 2008), BioFresh project, http://project.freshwaterbiodiversity.eu/) and initiatives to aggregate all freshwater information into a common platform (Freshwater information Platform, http://www.freshwaterplatform.eu/). Our work intends to contribute to these efforts by establishing a method to integrate several diadromous species occurrence databases, covering different regions and with different scales of analysis. We also aim to establish a method to create pseudo-occurrences using thresholds based on known general species ecological traits to downscale information from the basin scale to the segment scale.

3.3 Methods

3.3.1 Data Integration

Our method proposes that the output of the integration process should occur at the basin scale. Not only this is the most adequate unit to group and study freshwater systems, but it is also the scale at which all data sources have at least one common identifier Thus, the main output of the integration procedure should be the occurrence of a given species at the basin level, though it is also possible to create an output at the sub-basin scale. To account for the overlapping geographic coverage of sources, and to keep this as a conservative method, a rule of consensus is established in the procedure at both sub-basin and basin scale. Hence, an overall presence/absence at these scales can only be considered if no source indicates the opposite. If one or several sources are not compliant about a species occurrence for the same scale unit, then it is considered as “unknown”. This consensus rule is very important at the basin scale since it is more common and easy to confirm absence at this scale (eg, non-native species, known distribution limits) than at finer scales (e.g. segment or sub-basin). For historical data, confirming absence at the segment is extremely difficult and inevitable doubtful due to the lack of systematic surveying. On the other hand, presence at segment level represents detailed information, and thus for this procedure it translates immediately to presence at coarser scales, independently of other sources.

3.3.2 Validation of the integration procedure

To verify if the outputs of the integration process comply with the overall existing knowledge of the species distribution, we recommend cross-checking it with reliable ichthyofauna bibliographic references (e.g., Handbook of European Freshwater fishes (Kottelat and Freyhof, 2007); Freshwater Fishes of North America (Warren Jr. et al., 2014), the FishBase website (www.fishbase.org/search.php) and the International Union for Conservation of Nature (IUCN) Red List of Threatened Species website (www.iucnredlist.org/). This may help to exclude an error or a misinterpretation of a historical source.

3.3.3 Pseudo Occurrences creation

When referring to diadromous fish species occurrence there is one relevant particularity that has to be taken in consideration: presence in one segment means that all segments towards the segment of the river mouth are “presence” segments. Animals will have to pass through all the segments during migration. The procedure to create pseudo-occurrences at segment scale is species specific and its implementation requires summarising and collecting information from the confirmed segment presences for every species. This summarisation will retrieve the threshold for every species that will be used along the implementation of the procedure. A large number and geographically widespread “presence” data at the segment scale will imply more accurate and robust thresholds. It is also relevant for this procedure to specify that main river segments are those belonging to the river course flowing directly to the sea, while tributary segments are those belonging to rivers that directly or indirectly flow towards the main river course. Independently of the source (output of the integration procedure or database), only basins where a species occurrence has been acknowledged (present or absent) will be used in this procedure. The output of this procedure is to provide presences, absences, pseudo-presences and pseudo-absences at the segment scale.

The first part of the procedure will establish the data confirmed presences and absences (Figure 3.3.11). In basins where the species is absent, it immediately establishes absence for all their segments. For basins where the species is present, segments where presence was confirmed lead to presence segments, while no data segments may be classified into two alternative decision groups: main river and tributary segments (Figure 3.3.11). This separation is necessary because these two groups of segments tend to have distinct characteristics. One of the most important reasons is the usual larger availability of historical information for the main river of a basin than for most of its tributaries (e.g., EFI+ historical, unpublished). Moreover, most of the main river segments have distinct hydrological (Strahler, 1957), environmental and biological (Nilsson et al., 1994) characteristics than numerous segments in the basin where source segments, small streams segments, and small river segments are contained. Finally, it is possible for a diadromous species to occur only in the main river course, being absent from tributary segments.

The second part of the procedure uses the segments from the two mentioned groups. This part is not only species-specific but also basin Strahler specific. Basin Strahler is the highest order number within the basin. Thus, all thresholds used to establish pseudo-occurrence in a given segment are not only from data of the same species but also from basins comparable in size and hydrological complexity. Before the application of rules based on data-informed presences, both groups divide into two groups for similar reasons, the mouth segments of the main river and of its tributaries.

In the case of the main river segments group, the segments corresponding to the river mouths are separated from the other because this is the absolute minimum of segment presence in a basin where a species is present. For the tributaries group, the separation takes into account the fact that generally there is less information for segments of the tributaries. Also, this is a precautionary and conservative option because it excludes the possibility of having a pseudo-absence contiguous to main river presence segment.

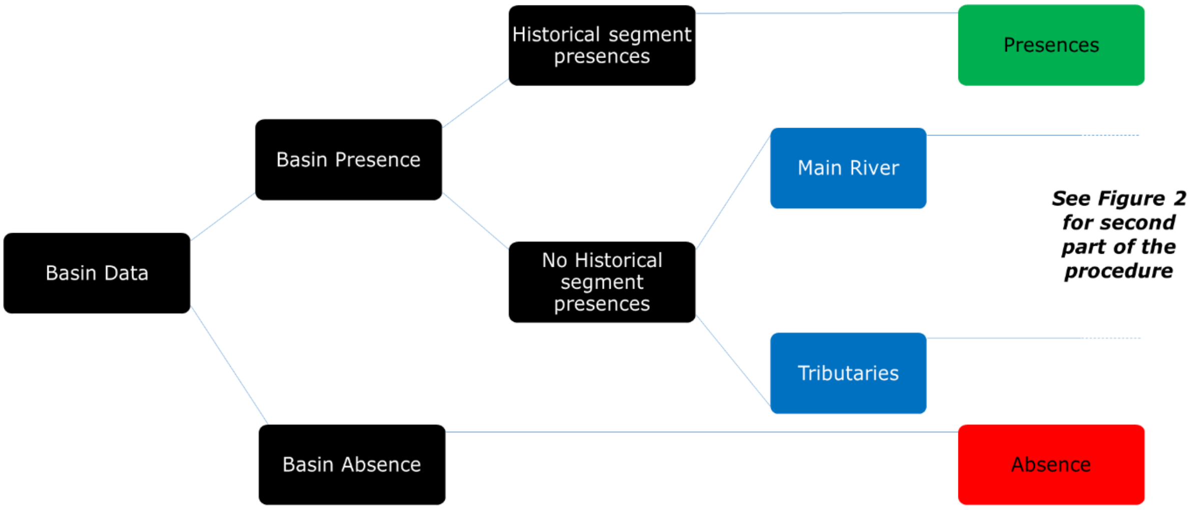


Figure 3.3.11 – Representation of the first part of the procedure.

The first rule of this decision tree (boxes in orange in Figure 3.3.12) is related to the ability of a certain species to progress within the river basin. The threshold used is the maximum relative distance verified in the historical presence data for main river segments in one group and for all segments in the tributaries group. Relative distance allows direct comparison between different-sized drainage basins, for instance, it enables the prediction of eel occurrence in one basin considering the knowledge of the pattern from another basin (Imbert et al., 2008). Using this threshold excludes the possibility of establishing a pseudo-presence beyond the maximum obtained by the known presence data. On the contrary, pseudo-absence is never considered if the relative distance of a segment is lower than the considered threshold. The second rule (boxes in purple in Figure 3.3.12) is related to Strahler stream order, and its direct proportionality to relative watershed dimensions, channel size, and stream discharge (Strahler, 1957). Thus, using the order number, two different basins in linear scale can be comparable with respect to corresponding locations in their geometry (Strahler, 1957). The thresholds used are the highest and lowest Strahler value of the most upstream segments in the historical presence data for main river segments, and for all segments in the case of the tributaries group. In the group of the main river segments (Figure 3.3.12A), the highest Strahler value threshold is used for the segments abiding rule one, and thus with the possibility of leading to pseudo-presences. The threshold of the lowest Strahler value is used on the group that does not abide rule one and that may lead to pseudo-absences. In the group of the tributaries (Figure 3.3.12B), the main difference is that the highest Strahler values threshold is applied to validate presence in the mouth segments contiguous to a main river presence segment. The lowest Strahler value threshold in this group is still applied just like in the previous group. Applying these two different thresholds creates a spatial gap between pseudo-presences and pseudo-absences, i.e., it will inevitably exist a buffer of no data segments between pseudo-presence and pseudo-absence segments for a given species. If a segment has a maximum relative distance equal or lower than the considered threshold, and the Strahler of that segment is equal or higher than the highest Strahler value of the most main river upstream segments, then a pseudo-presence is considered. On the contrary, if a segment has a maximum relative distance higher than the considered threshold, and the Strahler of that segment is lower or equal than the lowest Strahler value of the most main river upstream segments, then a pseudo-absence is considered.

Both rule one and two are generic, ancillary and intend to screen most of the segments for which there is no information. Rule one tends to be non-conservative as it uses the maximum progression within a basin as the possibility for establishing pseudo-presences. Rule two is very restrictive because the highest Strahler value inevitably translates into the species lowest progression within a basin. Finally, in the tributaries decision group (Figure 3.3.12B), the small correction in the path leading to pseudo-absences (relative distance larger than the threshold and segment Strahler lower than the threshold) guarantees the maintenance of the spatial gap between pseudo-occurrences in sub-basins where a pseudo-presence is attributed to tributary segment contiguous to a main river presence segment. This exception imposes that to be considered a pseudo-absence, the segment Strahler value has to be equal or lower than the maximum Strahler values registered in the sub-basin minus two.

Figure 3.3.12 – Representation of the second part of the procedure.

3.4 Results and Discussion

This method, though applicable to present-day source or databases, was developed to be used mainly with historical data. Ancient information that researchers are able to retrieve is generally incomplete and spatially heterogeneous. Historical documents have limitations that need to be understood to avoid incorrect interpretations (Rackham, 1998) and/or extrapolations (Swetnam et al., 1999). There is a cultural filtering that affects not only the spatial and temporal availability, completeness, and reliability of documentary records but also their quantity and quality (Swetnam et al., 1999). Nevertheless, coalescing information from several independent spatial and temporal sources (Hayashida, 2005; Rackham, 1998; Swetnam et al., 1999; Szabó, 2010), cross-checking lines of evidence with independent datasets (Crumley, 2007) and combining different methods (Swetnam et al., 1999) mitigates the limitations and may lead to more accurate knowledge about past ecosystem conditions. The procedure to integrate multiple sources of species occurrence data helps to overcome the incompleteness of this type of data, while also enabling the detection and possible correction of errors or misinterpretations of historical sources.

In Europe, most freshwater biological information is scattered by country and its availability is spatially unequally distributed (Tockner et al., 2009). The integration procedure described allows users to go from nationally or regionally truncated data to verified and congruent broad-scale information. Being a consensus-driven method it verifies compliance amongst sources to deem a presence or absence, making it a conservative approach. Regardless of the different spatial resolution of the sources, the scale of the output of the integration procedure is the river basin. This is the most adequate unit to acknowledge ecosystem processes and biodiversity patterns (Tockner et al., 2009), while also adequate for research with populations of diadromous fish species where homing and fidelity to natal origins are a common feature (e.g. (Dittman and Quinn, 1996; Jolly et al., 2012; Stabell, 1984).

Species distribution models are a powerful tool to understand geography and ecology of species (Araújo and Peterson, 2012; Soberón and Nakamura, 2009). However, results of these models can be erroneous if distributional data are incomplete or at inappropriate spatial resolution or extent (Araújo and Peterson, 2012). Using multiple sources, the pseudo-occurrence creation procedure enables the possibility of having a broad-scale occurrence of a diadromous fish species at the segment level. In terms of diadromous fish species, data at segment scale enables the possibility to understand the ability of a species to occupy a river basin and investigate the variation of this intra-basin occurrence with environmental, geomorphological, hydrological and anthropogenic changes throughout time.

This method enables the possibility of having a coherent set of historical data with large spatial coverage, different levels of resolution (basin, sub-basin and segment), for which sources were verified and cross-checked with each other. Nevertheless, and despite being a consensus and conservative method, there are caveats to be taken into consideration. If a given region is only covered by one source, the consensus rule of the integration process cannot be applied. Thus, for instance, errors present in this source will pass on to the results of the method. Despite using careful and data-informed thresholds users must keep in mind that pseudo-occurrences are not equal to confirmed occurrences. They are a result of a decision process and dependent on the thresholds used which were obtained via the information at segment level of the sources. A large amount of data at segment scale from a broad geographic range will lead to reliable thresholds, and thus to the adequate establishment of pseudo-occurrences. The pseudo-occurrence procedure is not prepared to be applied in braided rivers. Hence, to use it in these type of systems, adaptations to the rules and the decision process might have to be accomplished.

3.5 Acknowledgements

Gonçalo Duarte is part of the FLUVIO doctoral program and financed by a grant from the Fundação para a Ciência e Tecnologia (FCT) (SFRH/BD/52514/2014). Paulo Branco was financed by a post-doc grant from FCT (SFRH/BPD/94686/2013). Pedro Segurado is supported by a contract funded by the Fundação para a Ciência e Tecnologia (FCT) under the IF Researcher Programme (IF/01304/2015). CEF is a research unit funded by Fundação para a Ciência e a Tecnologia I.P. (FCT), Portugal (UID/AGR/00239/2013).

3.6 References

Araújo, M.B., Peterson, A.T. (2012) Uses and misuses of bioclimatic envelope modeling. Ecology 93, 1527-1539.

Balian, E.V., Segers, H., Lévèque, C., Martens, K. (2007) The Freshwater Animal Diversity Assessment: an overview of the results. Hydrobiologia 595, 627-637.

Balian, E.V., Segers, H., Lévêque, C., Martens, K. (2008) An introduction to the Freshwater Animal Diversity Assessment (FADA) project. Hydrobiologia 595, 3-8.

Béguer, M., Beaulaton, L., Rochard, E. (2007) Distribution and richness of diadromous fish assemblages in Western Europe: large-scale explanatory factors. Ecology of Freshwater Fish 16, 221-237.

Cadotte, M.W., Murray, B.R., Lovett-Doust, J. (2006) Ecological Patterns and Biological Invasions: Using Regional Species Inventories in Macroecology. Biological Invasions 8, 809-821.

Crumley, C., (2007) Historical ecology: integrated thinking at multiple temporal and spatial scales, in: Hornborg, A., Crumley, C. (Eds.), The World System and the Earth System: Global Socioenvironmental Change and Sustainability Since the Neolithic, . Left Coast Press, Walnut Creek, CA, pp. 15-28.

Dittman, A., Quinn, T. (1996) Homing in Pacific salmon: mechanisms and ecological basis. The Journal of Experimental Biology 199, 83-91.

Gaston, K.J., Blackburn, T.M., (2007) The Macroecological Perspective, Pattern and Process in Macroecology. Blackwell Science Ltd, United Kingdom, pp. 1-34.

Hayashida, F.M. (2005) Archaeology, Ecological History, and Conservation. Annual Review of Anthropology 34, 43-65.

Imbert, H., De Lavergne, S., Gayou, F., Rigaud, C., Lambert, P. (2008) Evaluation of relative distance as new descriptor of yellow European eel spatial distribution. Ecology of Freshwater Fish 17, 520-527.

Jolly, M.T., Aprahamian, M.W., Hawkins, S.J., Henderson, P.A., Hillman, R., O'Maoiléidigh, N., Maitland, P.S., Piper, R., Genner, M.J. (2012) Population genetic structure of protected Allis shad (Alosa alosa) and twaite shad (Alosa fallax). Marine Biology 159, 675-687.

Kottelat, M., Freyhof, J. (2007) Handbook of European freshwater fishes. Publications Kottelat Cornol.

Limburg, K.E., Waldman, J.R. (2009) Dramatic Declines in North Atlantic Diadromous Fishes. Bioscience 59, 955-965.

McDowall, R.M. (1992) Particular problems for the conservation of diadromous fish. Aquatic Conservation: Marine and Freshwater Ecosystems 2, 351-355.

Mittermeier, R.A., Gil, P.R., Hoffman, M., Pilgrim, J., Brooks, T., Mittermeier, C.G., Lamoreux, J., Fonseca, G.A.B.d. (2004) Hotspots Revisited. Earth's Biologically Richest and Most Endangered Terrestrial Ecoregions, 1st ed. CEMEX, México.

Nilsson, C., Ekblad, A., Dynesius, M., Backe, S., Gardfjell, M., Carlberg, B., Hellqviist, S., Jansson, R. (1994) A Comparison of Species Richness and Traits of Riparian Plants between a Main River Channel and Its Tributaries. Journal of Ecology 82, 281-295.

Rackham, O., (1998) Implications of historical ecology for conservation, in: Sutherland, W.J. (Ed.), Conservation Science and Action, 1st ed. Blackwell Publishing Company, pp. 152-175.

Sala, O.E. (2000) Global Biodiversity Scenarios for the Year 2100. Science 287, 1770-1774.

Soberón, J., Nakamura, M. (2009) Niches and distributional areas: Concepts, methods, and assumptions. Proceedings of the National Academy of Sciences of the United States of America 106, 19644-19650.

Stabell, O.B. (1984) Homing and olfaction in salmonids: a critical review with special reference to the Atlantic salmon. Biological Reviews 59, 333-388.

Strahler, A.N. (1957) Quantitative analysis of watershed geomorphology. Eos, Transactions American Geophysical Union 38, 913-920.

Swetnam, T.W., Allen, C.D., Betancourt, J.L. (1999) Applied Historical Ecology: using the past to manage for the future. Ecological Applications 9, 1189-1206.

Szabó, P. (2010) Why history matters in ecology: an interdisciplinary perspective. Environmental Conservation 37, 380-387.

Tockner, K., Tonolla, D., Uehlinger, U., Siber, R., Robinson, C.T., Peter, F.D., (2009) Chapter 1 - Introduction to European Rivers, Rivers of Europe. Academic Press, London, pp. 1-21.

Vellend, M., Brown, C.D., Kharouba, H.M., McCune, J.L., Myers-Smith, I.H. (2013) Historical ecology: Using unconventional data sources to test for effects of global environmental change. American Journal of Botany 100, 1294-1305.

Warren Jr., M.L., Burr (Editors), B.M., Bemis, W.E., Bennett, M.G., Burns, M.D., Echelle, A.L., Gidmark, N.J., Gilbert, C.R., Gill, H.S., Grande, L., Haro, A., Harris, P.M., Hilton, E.J., Hopman, L.J., Hubbard, G., Kuhajda, B.R., Matthews, W.J., McLennan, D.A., Potter, I.C., Renaud, C.B., Ross, S.T., Sandel, M., Simons, A.M. (2014) Freshwater Fishes of North America: Volume 1: Petromyzontidae to Catostomidae. Johns Hopkins University Press, Baltimore SN.

4. The River Network Toolkit – RivTool

Gonçalo Duarte, Pedro Segurado, Tiago Oliveira,
Gertrud Haidvogl, Didier Pont, Maria Teresa Ferreira
and Paulo Branco

Published on Ecography (online)

Accepted 11 September 2018

DOI: 10.1111/ecog.04192

4.1 Abstract

Freshwater ecosystems are some of the most endangered environments in the world, being affected at multiple scales by the surrounding landscape and human activities therein. Effective research, conservation and management of these ecosystems requires integrating environmental and landscape data with hierarchic river networks by means of summarisation and synthesis of information for large and comprehensive areas at different scales (e.g.: basin, sub-basin, upstream drainage area). The dendritic nature of river networks, the need to tackle multiple scales and the ever-growing sources of digital information (e.g. temperature or land use data grids) have increasingly led to hardly manageable processing time and stringent hardware requirements when integrating and working with this information. Here we present the River Network Toolkit (RivTool), a software that uses only tabular data to derive and calculate new information at multiple scales for riverine landscapes. It uses data from linear hierarchical river networks and the environmental/landscape data from their respective drainage areas. The software allows the acquisition of: (1) information that characterises river networks based on its topographic nature; (2) data obtained via mathematical calculations that account for the hierarchical and network nature of these systems; and (3) output information using different spatial data sources (e.g., climatic, land use, topologic) that result from up and downstream summarisations. This user-friendly software considers two units of analysis (segment and sub-basin) and is time effective even with large datasets. RivTool facilitates and reduces the time required for extracting information for freshwater ecosystems, and may thus contribute to increase scientific productivity, efficiency and accurateness when generating new or improving existing knowledge on large-scale patterns and processes in river networks.

4.2 Keywords

River networks, landscape data, RivTool

4.3 Background

Freshwater supports almost 6% of all known species though covering only 0.8% of the earth's surface and representing 0.01% of the world's water (Dudgeon et al., 2006). These ecosystems are amongst the most endangered environments worldwide (Dudgeon et al., 2006; Ricciardi and Rasmussen, 1999). River systems are linked to their adjacent landscape via multiple mechanisms and pathways (Allan and Johnson, 1997). River ecologists, managers and decision makers recognise the connection between landscape and watercourses and the necessity of landscape information to evaluate river health and prioritise management actions (Allan, 2004; Fausch et al., 2002; Tsang et al., 2014). Moreover, they realise that successful river management requires a sound knowledge of spatial and hierarchical relationships between land and water, at different spatial and temporal scales (Johnson et al., 1995; Vogt et al., 2007). The landscape in a river basin and human activities acting upon it affect the ecological integrity of a stream (Allan, 2004; Yates and Bailey, 2006). Likewise, the multi-dimensional nature of lotic systems conceptualised by Ward (1989) and the river continuum concept described by Vannote et al. (1980) are important frameworks to understand the dynamic nature of river ecosystems. The dendritic nature of river networks has implications at both population-level (e.g. metapopulation dynamics) and community-level (e.g. interspecific interactions, food web structure and biodiversity patterns) processes (Grant et al., 2007). Additionally, the directional properties of river networks generally enforce dependency of processes occurring at a given river segment from processes taking place along the upstream catchment. Likewise, other processes, such as fish migrations, depend also on features along the downstream pathway. However, only recently, analytical methods specifically designed to cope with the particular structural and dynamic processes imposed by the hierarchical and branching geometry of whole river network systems have been developed (Grant et al., 2007; Peterson et al., 2013). Thus, research in freshwater ecology at landscape scale requires the ability to integrate environmental landscape data with hierarchic river network information. Such studies require acquiring data considering exclusively the network nature of a river or integrating it with environmental/landscape information, e.g.: upstream drainage area (Filipe et al., 2013), relative distance to mouth (Clavero and Hermoso, 2015; Imbert et al., 2008) and cumulative length (Markovic et al., 2012), upstream and downstream average slope (Leathwick et al., 2005), stream power (Béguer et al., 2007; Logez et al., 2012) and land-use in the upstream drainage area (Trautwein et al., 2012). Such measures are challenged by the need to summarise and synthesise information for diverse areas that represent different landscape scales (e.g.: basin, sub-basin, upstream drainage area) (Tsang et al., 2014). As technology progresses, digital information about the landscape in a river basin is increasingly available and better documented. Tools specifically tailored to deal with the singularities of river networks are still scarce and commonly implemented as geographic information systems (GIS) extensions with a limited set of functions and for specific applications.

GIS software, software such as R (R Development Core Team, 2017) or development software (e.g., Microsoft Visual Basic, Android, etc.) enable creating, developing and performing any calculation, operation or application at will, but this is not something for common or sometimes even proficient users. General purpose GIS software, hydrological related GIS toolbox's and related river network toolsets may contain some functionalities to cope with the challenges of data integration and summarisation. However, these tools are normally more focused on creating and characterising river networks and/or catchments based on digital elevation models, on topologically managing and improving existing digital river networks, and on assigning key attributes to these networks. Table 4.4.3 provides a comparison between the capabilities of existing applications/software/R packages able to deal with freshwater networks and those provided by the River Network Toolkit (RivTool). To perform summarisations or automatized calculations considering the directed, hierarchical pathways of a river network, most of these applications are either unsuitable or of limited use for the common user. There is no software that integrates environmental information with hydrological units that afterwards allows, in a user-friendly fashion, to calculate and derive information taking into consideration the hierarchical network structure of the river systems. Investigating hierarchical river networks faces a first challenge of using existing linear directional information (1 dimension) to establish specifically selected pathways for multiple calculations and summarisations; and a second challenge of executing these one dimensional mathematical processes while acknowledging the drainage areas (2 dimensions) of the network and the landscape data that can be associated to them. To help researchers integrate and generate information related with currently existing river networks while accounting for these challenges we have developed RivTool.

Table 4.4.3 – Comparison of the River Network Toolkit (RivTool) with other existing software, hydrological related GIS toolbox's and river-related R packages. In red features not available; in orange features partially available (e.g., from several types of a feature only one or a few are available) or features achieved indirectly (e.g., lacking functionality for a specific feature that otherwise can be achieved via one or several generalist options); in green specific available functionality.

	RivTool	**TauDEM**	**Whitebox Geospatial Analysis Tools**	**r.stream toolbox**	**ArcHydro Toolbox**	**STARS toolset**	**SSN package**	**RiverTools**	**Riverdist package**
Network pre-processing, creation and maintenance									
DEM-based processes	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟥
Network creation and maintenance	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟧
Network adjustments									
Establish main river course automatically	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
User-defined main river course	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Sub-basin delineation	🟩	🟩	🟩	🟩	🟩	🟧	🟥	🟩	🟥
Calculation of features associated with network topology									
Distances computed along the watercourse	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Up and Downstream drainage areas	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Stream order numbers	🟧	🟧	🟩	🟩	🟧	🟥	🟥	🟩	🟥
Basin features and summary statistics	🟩	🟧	🟧	🟩	🟩	🟩	🟥	🟥	🟥
Adjacency matrix	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Transport and Deposition analysis	🟥	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥
Multiple units of analysis									
point	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
segment	🟩	🟧	🟧	🟧	🟩	🟩	🟩	🟥	🟩
Sub-basin	🟩	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥
Randomisation of samples using multiple criteria									
Labels	🟩	🟥	🟥	🟥	🟧	🟥	🟥	🟥	🟥

	RivTool	TauDEM	Whitebox Geospatial Analysis Tools	r.stream toolbox	ArcHydro Toolbox	STARS toolset	SSN package	RiverTools	Riverdist package
Environmental/landscape data	🟩	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥
n# per basin	🟩	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥
% per basin	🟩	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥
Contiguity	🟩	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥
Distance between samples	🟩	🟥	🟥	🟥	🟨	🟥	🟩	🟥	🟥
Environmental/landscape data pre-processing									
Grid data resampling	🟩	🟥	🟩	🟥	🟨	🟨	🟥	🟥	🟥
Calculations using multiple grid layers	🟩	🟥	🟩	🟥	🟨	🟩	🟥	🟥	🟥
Associating grid data with network analysis units	🟩	🟥	🟩	🟥	🟩	🟩	🟥	🟥	🟥
Missing data patch considering network hierarchy and segment adjacency	🟩	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥
Integration of network data with other data									
Environmental/landscape data	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟥	🟥
Label data	🟩	🟥	🟥	🟥	🟩	🟥	🟩	🟥	🟥
Calculations using both integrated data									
Generic Mathematical calculations	🟩	🟥	🟥	🟥	🟩	🟨	🟥	🟥	🟥
Custom calculations (e.g., stream power, relative occupancy in UDA)	🟩	🟥	🟨	🟥	🟨	🟥	🟥	🟥	🟥
Relevant characteristics of the Application/package									
Standalone program	🟩	🟥	🟩	🟥	🟥	🟥	🟥	🟩	🟨
32-bit and 64-bit versions	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟥	🟩
Calculations based on tabular data	🟩				🟥	🟥	🟨	🟥	🟨
Freely available	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟥	🟩
User-friendliness for common or inexperienced users	🟩	🟨		🟨	🟨	🟥	🟥	🟨	🟨
Comprehensive ready-to-use libraries	🟩	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨

4.4 The River Network Toolkit

A simple representation of a river (Figure 4.4.13A) though useful is not very informative. In contrast, having a hierarchical river database (Figure 4.4.13B) with information about flow direction (first dimension) and respective drainage areas (second dimension) enables numerous possibilities of analysis. To account for the first challenge mentioned above, the software uses the one-dimension information provided by flow direction to obtain information characterising the river network (main river and sub-basins in Figure 4.4.13C-1) and to perform network-related calculations (Figure 4.4.13C-2 and 3). After, to account for the second challenge, the drainage information can be incorporated to make a 2-dimension analysis. For example, the primary drainage areas linked to specific segments enables obtaining sub-basins, upstream and downstream drainage areas (UDA, DDA; Figure 4.4.13C). When this is achieved, associating environmental or landscape data (Figure 4.4.13D) with the river network allows the software to use it in the analysis. Using general purposes GIS software to generalise these analysis and summarisations for large rivers or databases such as the Catchment Characterisation and Modelling– River and Catchment database v2 (CCM2) (Vogt et al., 2007) (80 549 basins and 1 347 978 river segments) is extremely time-consuming. RivTool enables faster computing and additionally, it gives users the possibility to work on a second scale of analysis, sub-basin. Spatial information and representation of sub-basins are not commonly available, not even for instance in such complete and large database as the CCM2. Nevertheless, the sub-basin scale is considered very relevant from a management perspective (Bhave et al., 2013; Ficklin et al., 2013), and has been used in a broad-range of study topics (e.g., hydromorphology (Bullard et al., 2008; Schmitt et al., 2014), geomorphology (Bullard et al., 2008), land use/land cover (Ahearn et al., 2005; Bolker et al., 2009; López-Moreno et al., 2011), climate change (Bhave et al., 2013; Ficklin et al., 2013; López-Moreno et al., 2011; Ziegler et al., 2005) and basin management (Bhave et al., 2013; Ficklin et al., 2013)). Establishing the sub-basins can be achieved automatically or manually. The latter is a useful feature since some main rivers may not correspond to the longest course in a basin (see Garonne river, France in CCM2) nor to the one with the most upstream drainage area (see Guadiana river, Portugal in CCM2).

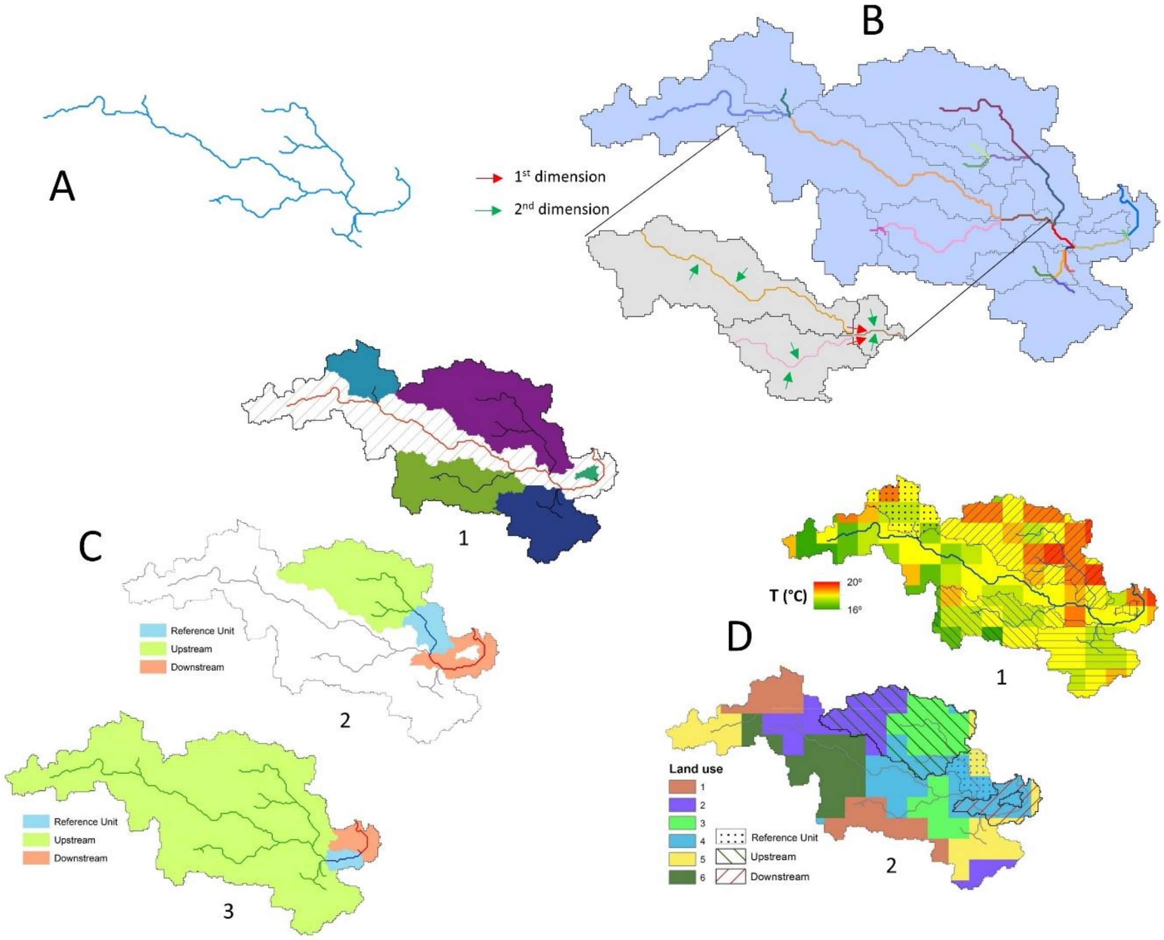


Figure 4.4.13 – Graphical representation of the challenges solved by RivTool. A – common schematic representation of a river; B – representation of a river network with basin, segments and correspondent primary catchments and a schematic indicating the 2 dimensions considered in a hierarchical river network database; C – examples of summarisations that a river networks enables: 1 – identification of the main river (red) and respective direct drainage area (striped area), main river tributaries and respective sub-basins (coloured); 2 and 3 – examples of upstream drainage areas (green) and the downstream drainage areas (light red) of two different segments of the same basin; D – examples of superimpositions of summarisation outputs with environmental data: 1 – Sub-basin areas with temperature data; 2 – up and downstream areas of a given segment with land use data.

RivTool is an innovative user-friendly software of universal applicability. It allows users to: (1) integrate broad-scale raster data with river hydrological units (segment and sub-basin), (2) obtain information that characterises the river network based only on its topographic nature; (3) extract new and/or specific data through mathematical calculations that account for the hierarchical and network nature of these systems and (4) calculate different types of data resulting from up and downstream summarisations. Developed to work with two distinct basic units (segment and sub-basin), it is table driven, reading both .csv and .txt file types, and the output tables can be exported for further use in other software (e.g., GIS, statistical software). The Network River toolkit was written in C# and runs on Windows systems. It is freely available at the RivTool website (www.rivtoolkit.com) and at a repository of the School of Agriculture from the University of Lisbon (http://www.isa.ulisboa.pt/proj/rivtool/) under a freeware licence.

4.4.1 Pre-requisites and functioning

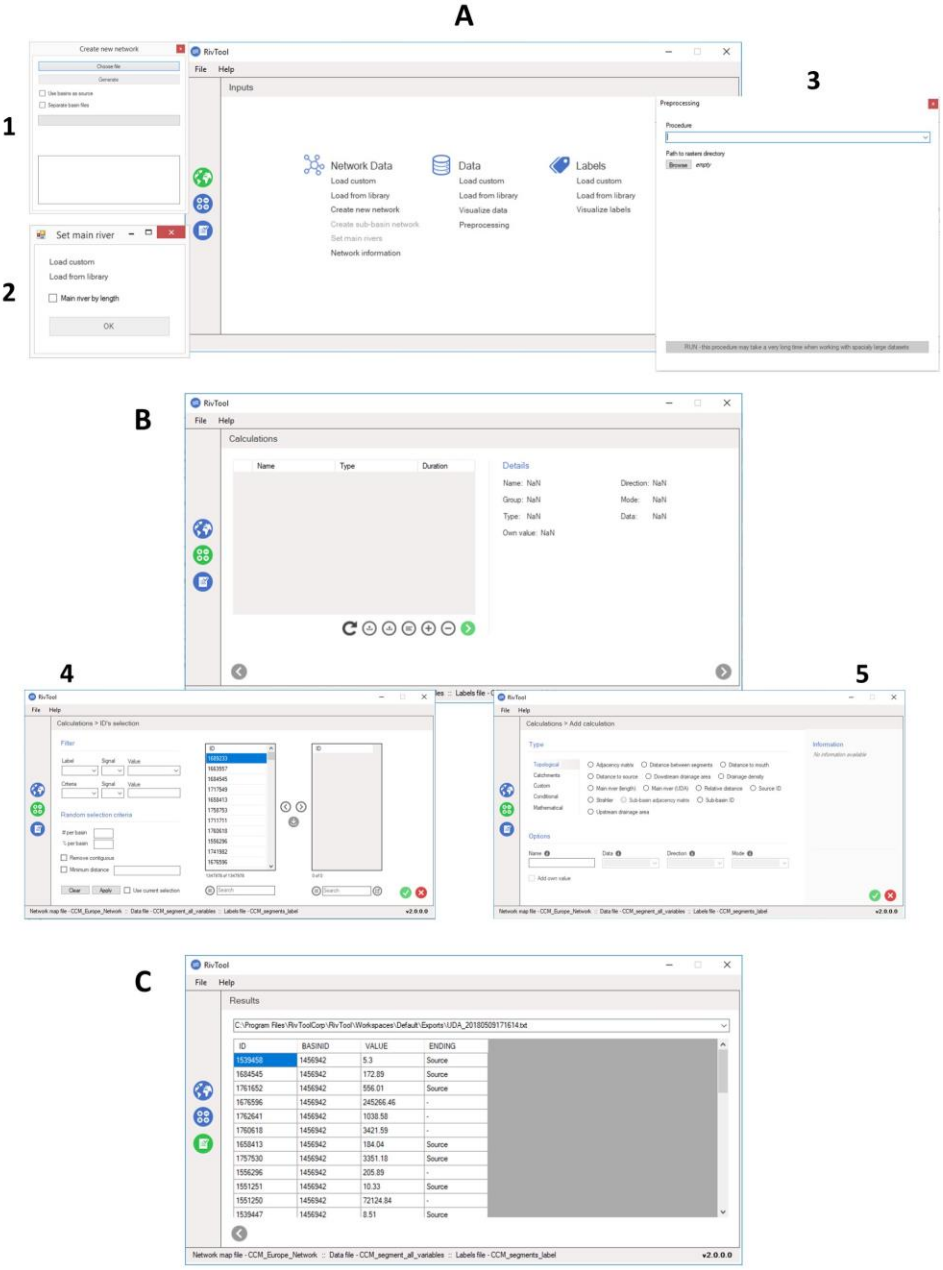
RivTool works based on data tables of river networks, landscape, environmental or hydrological data and label data. The minimum input required is information about a river network. This must abide by some pre-requisites in order to be used: (1) all units, either segment or sub-basin (unit of analysis), must have a unique identifier, defined hereafter as unit ID; (2) similarly, all basins must also have a unique identifier (defined from now on as basin ID); (3) for every unit of analysis the unique identifier of the next contiguous unit of analysis, defined hereafter as nextdown ID, is required; (4) the value of drainage area of the unit of analysis in squared meters, defined henceforth as primary catchment; finally (5) the length of the unit of analysis in meters or, when working with sub-basins the sum of all segments' length. Optionally, a sixth field containing the name of the basin can be added. These attributes follow the structure of the CCM2 database because this is the first all-inclusive, hierarchically structured and a fully integrated database of river networks and catchments for the pan-European continent (Vogt et al., 2007). Nevertheless, similar attributes are usually available for river networks that exist in a digital geospatial format (e.g.: The European Catchments and Rivers Network System – ECRINS (EEC, 2012); National Hydrography Dataset Plus Version 2 (NHDPlusV2, http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php)). Tables containing these attributes enable RivTool to create the pivotal file for its functioning, the “network data”. This file will either have the extension .smap or .bmap, depending on whether the unit of analysis is segment or sub-basin, respectively. If the file contains the optional field with the name of the basin, the user can select to create a file per basin. When creating the ”network data” file, for each unit of analysis the following attributes will be retained: unit ID, basin ID, nextdown ID, primary catchment area, length of the segment or the sum of the length of all segments in the sub-basin and the ID's of all the units within the path towards the mouth of the river. The software provides river network libraries of both the CCM2 and the ECRINS (the geodatabase of the Managing Aquatic Ecosystems and Resources under Multiple Stress project (MARS) (Globevnik et al., 2016) was also used to create the latter library). Errors in the CCM2 database have been acknowledged (Jager, 2016), and since ECRINS was developed based on CCM2 (EEC, 2012) some are likely to subsist. Thus, their use does not come without limitations (Vogt et al., 2007), but these are, nonetheless, reliable and useful databases. Users have also the possibility to create a custom "network data" file based on a network table that they provided to the software. In addition, when defining main rivers and creating sub-basin network data, there is the possibility of using the built-in libraries, applying automatic procedures or follow a more manual approach, both described in the software's manual (Supplementary material Appendix 8.2).

Landscape information is commonly valuable for research and modelling, but climate, hydrological, hydraulic and other specific data may also be of interest. RivTool enables the user to integrate any type of numerical data within a river network. The software has libraries providing data from the CCM2 database and from the geodatabase of the MARS project, but it also allows the user to load a custom table. To create a "Data" table from spatial digital layers, the information must be assigned to each unit of analysis, i.e., either segment or sub-basin. Commonly, large-scale information about climate and land use is available in continuous grid data (raster). Creating a custom table can be achieved using the "Preprocessing" option of the Data inputs, where four distinct functions allow users to deal with large-scale grid data and integrate it with the unit of analysis. The functions allow changing a raster resolution, performing calculations using multiple raster data, perform zonal statistics and undertaking corrections to missing data. This part of the program was achieved integrating r.net in the programming structure, thus scripts using r packages and functions are available within the software installation files.

There are also libraries for "Label" data (grouping data) and creating a table with user-defined labels according to study objectives can also be achieved. Contrary to the “network data”, the other two inputs (“Data” and “Label”) are not mandatory for the software to proceed. However, their presence increases significantly the number of functionalities available and allows the user to take full advantage of RivTool capabilities.

4.4.2 Software Interface

The software has a “user-friendly” interface minimizing “user-distress” and promoting its usage. The first window of the software interface (Figure 4.4.14 – A), named “Inputs”, is dedicated to three types of data inputs (river network data, landscape/environmental data and label data). “Create new network” opens a new window where the user can create its own custom “network data” file (Figure 4.4.14 – A1). This feature gives users the possibility of loading networks with different resolutions and from any region of the world. “Set main rivers” gives users the possibility to define the segments that belong to the main river course of each basin (Figure 4.4.14– A2). If left undefined, by default, the software will assume that the main river course is the one with the largest distance between a source and the mouth. “Create sub-basins network” allows users to create a sub-basin network data file based on inputted segment network data file. The “Preprocessing” sub-window allows users to access the functions that may help create a custom data input from any large scale grid data (Figure 4.4.14– A3). Loading a “Network data” file is required to disclose the “Calculations” window (Figure 4.4.14– B). In this window, the options for ID selection becomes available (Figure 4.4.14– B4). Partial selection of the available unit ID’s list may be performed using label features, data criteria, random selection options or just by loading a file with a custom list. Calculations will be performed for all selected unit ID’s. By default, if no selection is done, the software will use the complete set of unit ID’s available from the “Network data”. In the “Calculations” window, the “Add Calculation” sub-window can be accessed and users may establish the calculations to be performed (Figure 4.4.14 – B5). These are grouped into 5 categories: (1) “Topological”, i.e. data that only depend on the topology of the network data; (2) “Catchment”, data that retrieve descriptive information about entire basins; (3) “Custom”, ready-to-use calculations often sought for when integrating and summarising river networks with landscape or environmental data; (4) “Conditional”, operations where a condition before calculation is imposed; and (5) “Mathematical”, general arithmetic calculations performed using both network and environmental/landscape data considering the river network hierarchy. In this last type, in all calculations there are 2 options that require user specification: (1) “Direction” allows to indicate whether upstream or downstream segments or sub-basins shall be included in the calculations; and (2) “Mode”, indicates which set of unit ID’s will be used to perform the calculations (“Path” selects only those in the path towards river mouth or sources; “Relatives” selects all units in the defined direction starting at the selected unit). Details and descriptions of all the available functions in the software indicating to which type they belong, and for which units of analysis are they available can be consulted in the software manual (Supplementary material in Annexe 8.2). After defining the calculations to be performed the user may visualise its options in the “Calculations” window and then have RivTool perform the operations and create the tables with the results in the workspace file. After finishing the calculations, the software will automatically shift to the “Results” window (Figure 4.4.14 – C) where the user can explore and visualise the results.



C:\Program Files\RivToolCorp\RivTool\Workspaces\Default\Exports\UDA_20180509171614.txt

ID	BASINID	VALUE	ENDING
1539458	1456942	5.3	Source
1684545	1456942	172.89	Source
1761652	1456942	556.01	Source
1676596	1456942	245266.46	-
1762641	1456942	1038.58	-
1760618	1456942	3421.59	-
1658413	1456942	184.04	Source
1757530	1456942	3351.18	Source
1556296	1456942	205.89	-
1551251	1456942	10.33	Source
1551250	1456942	72124.84	-
1539447	1456942	8.51	Source

Network map file - CCM_Europe_Network :: Data file - CCM_segment_all_variables :: Labels file - CCM_segments_label v2.0.0.0

Figure 4.4.14 – River Network Toolkit interface: A) screenshots of the “Inputs” window, the 1) “Create New Network” sub-window, 2) “Set main rivers” sub-window and (3) the 'Preprocessing' sub-window; B) screenshots of the “Calculations” windows and their sub-windows, 4) “IDs selection” (selection of the unique identifiers of a unit) selection and 5) “Add calculation”; C) screenshot of the “Results” window.

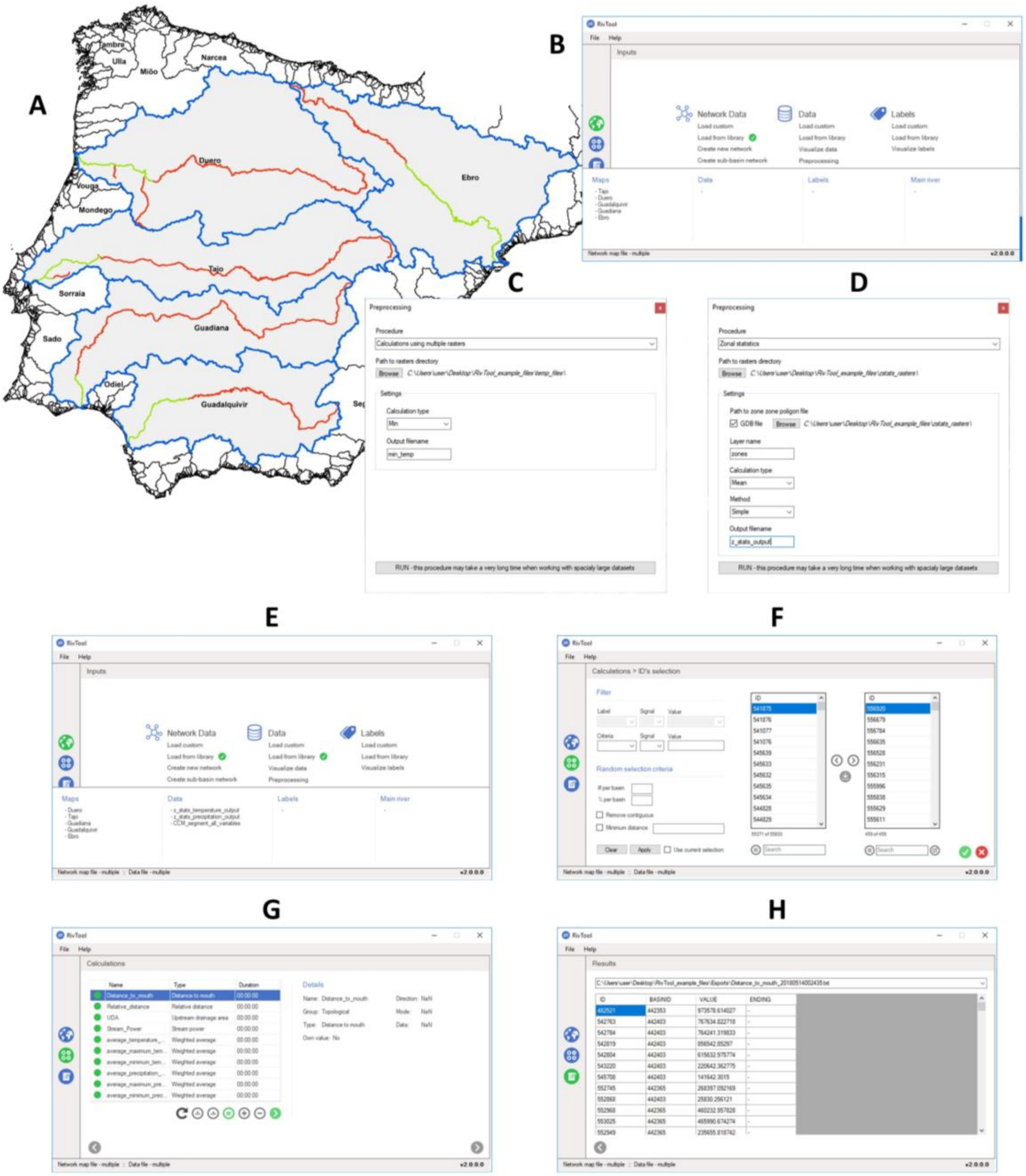
4.4.3 Example and evaluation

RivTool is fast-performing, but the time taken to undertake a given task may vary according to the size of the river network, the number and type of calculations to be performed, and with computer specifications and capabilities. For RivTool v2 a 32-bit systems version and a 64-bit system version were created, but it is recommended using the later due to the increased memory addressability. The software was designed to run with a minimum of 4 gigabytes random access memory (RAM), but we recommend running it with at least 8 GB of RAM. RivTool uses parallel processing, which means it will use all available processor resources. Thus, a minimum of a 2-core computer is recommended.

To demonstrate the utility of this software a small case example shall demonstrate the utility of the software. It starts from the research objective of modelling the potential distribution of a species based on occurrence data obtained from sampling I. Diadromous fish migratory habits exposes them to threats from predation and/or fishing exploitation, also increasing the probability of being affected by habitat changes and degradation since both residential and passage habitats have to be considered (McDowall, 1992). Consequences of climate change are likely to be more severe for freshwater species since they have limited options to escape extreme flows and flooding, water scarcity, water temperature rise, and water competition with humans (Abell, 2002). It is widely acknowledged that climate change forces shifts in species distributions, changing species interactions and disrupting communities (Chen et al., 2011; Parmesan and Yohe, 2003; Thomas et al., 2006). Hence, climate and the hydrological characteristics of a river network will influence the occurrence of diadromous fish species.

To achieve the objective it is necessary to establish and calculate several river network and climate related covariates (such as distance to river mouth, relative distance, upstream drainage area (UDA), Stream Power, average temperature and precipitation in the UDA) for all relevant segments, and this is where RivTool becomes useful and reliable. In our example, we have fish occurrence data from the five largest basins of the Iberian Peninsula (Douro, Ebro, Tagus, Guadiana and Guadalquivir). In 485 segments the species was considered present and in 1426 absent (Figure 3A). Thus, in the “Inputs” window of the software, network data from the libraries should be loaded for these 5 basins (Figure 3B). Next, climate layers are necessary and can be obtained, for example, at the Climate Research Unit website (http://www.cru.uea.ac.uk/) where numerous datasets are available for download. Most climate datasets come in the

NetCDF file type, which can be converted into tiff using GIS software, online applications, R software or more specific applications such as E-Clic (Tarroso and Rebelo, 2010). Using the climate layers in the .tif format, the preprocessing of the data inputs can be started. The “Calculations using multiple rasters” function can be used to obtain raster layers of the average, maximum and minimum of the precipitation and the temperature over a time period, in this case, a decade (Figure 3C). Afterwards, these layers will serve as inputs in the “Zonal statistics” function to create tables with climate information for each primary catchment (Figure 3D). For this function, it is also required to provide a vector layer (accepted extensions .shp or .mdb) of the primary catchments of the five basins, which can be obtained in the CCM2 website (selecting the “2004 South west” dataset). Optionally, this layer can be prepared outside RivTool to eliminate irrelevant polygons, which speeds up the processes. The outputs of the “Zonal statistics” function are tables that will serve as input data. For this example, in addition to the zonal statistics outputs created in the preprocessing procedure, the library table “CCM_segment_all_variables.txt” should also be loaded (Figure 3E). After having all the network and data inputs, the segment selection can be performed in the “ID’s selection” sub-window. A list of the segments where species occurrence is known must be provided in order to limit RivTool calculations to those segments. Also, since spatial auto-correlation is a problem for most of the modelling techniques, the “remove contiguous” option can be used to minimise this statistical conundrum (the “minimum distance” criteria might also be helpful in such cases) (Figure 3F). Afterwards, calculations to be performed are established considering the intended covariates and the calculation specifications will be listed in a table of the “Calculations” window (Figure 3G). In this table, it is also possible to verify if a calculation has been performed (red circle goes green) and the duration of the process. Running these calculations will create tables with the required information that can be visualised in the results window (Figure 3H). This simple example shows the ability of Rivtool to integrate landscape data – in this case temperature and precipitation – with hydrological units and to derive and calculate new data taking into consideration the hierarchical network nature of a river system.



B – Maps: Tajo, Duero, Guadalquivir, Guadiana, Ebro

C – Procedure: Calculations using multiple rasters
Path to rasters directory: C:\Users\user\Desktop\RivTool_example_files\temp_files\
Calculation type: Min
Output filename: min_temp
RUN - this procedure may take a very long time when working with spacialy large datasets

D – Procedure: Zonal statistics
Path to rasters directory: C:\Users\user\Desktop\RivTool_example_files\zstats_rasters\
Path to zone zone poligon file: ☑ GDB file C:\Users\user\Desktop\RivTool_example_files\zstats_rasters\
Layer name: zones
Calculation type: Mean
Method: Simple
Output filename: z_stats_output
RUN - this procedure may take a very long time when working with spacialy large datasets

E – Maps: Duero, Tajo, Guadiana, Guadalquivir, Ebro
Data: z_stats_temperature_output, z_stats_precipitation_output, CCM_segment_all_variables

G – Calculations

Name	Type	Duration
Distance_to_mouth	Distance to mouth	00:00:00
Relative_distance	Relative distance	00:00:00
UDA	Upstream drainage area	00:00:00
Stream_Power	Stream power	00:00:00
average_temperature_...	Weighted average	00:00:00
average_maximum_tem...	Weighted average	00:00:00
average_minimum_tem...	Weighted average	00:00:00
average_precipitation_...	Weighted average	00:00:00
average_maximum_pre...	Weighted average	00:00:00
average_minimum_prec...	Weighted average	00:00:00

Details
Name: Distance_to_mouth
Group: Topological
Type: Distance to mouth
Own value: No
Direction: NaN
Mode: NaN
Data: NaN

Figure 4.4.15 – Application of the example described. A – Map with species data. Absence indicated in red, presence in green; B – Load of the network data file for the 5 basins; C – Preprocessing procedure using the function “calculation using multiple rasters”; D – Preprocessing procedure using the function “zonal statistics”; E – Load of the zonal statistic files created and the file from the Rivtool library; F – Segment selection using the “remove contiguous” criteria (only 459 segments are selected), G – Calculations performed with the correspondent time taken (given the small number of segments used, all calculations took less than 1 second), (H) table with the results of one of the calculations.

4.5 Applications

Aquatic ecosystem research or management which address the relationship between a river and the surrounding basin (Allan, 2004; Allan and Johnson, 1997; Tsang et al., 2014), requires an integration of relevant data. The River Network Toolkit was developed to proficiently integrate these two landscape elements, to perform calculations using the directional hierarchical network nature of rivers and to allow for an efficient aggregation of landscape information throughout river catchments. This software helps reduce computation time for such tasks, and hence the required economic resources. Thus, it contributes to increase scientific productivity and help generate new and more accurate knowledge on large-scale patterns and processes in river networks. Additionally, by facilitating data retrieval it contributes to better management planning. Contrary to other applications, packages or software, RivTool was not developed to create or improve hydrological networks, but to take advantage from the existing ones (Table 1). The focus of the software is to integrate broad-scale data (e.g., landscape, climate, environmental, land-use) with existing hydrological networks and obtain/derive information per hydrological unit (segment or sub-basin) via summarisations and other specific calculations reflecting the connectivity and hierarchical nature of river systems. It solves in a time-efficient and straightforward mode numerous hurdles researchers may find to derive or obtain new information for hierarchical river networks (e.g., connect landscape information with river network spatial data, random selection of segments using distance criteria, summarisations using environmental data linked to a river network taking into consideration the connectivity and hierarchical nature of the river network, perform custom calculations for multiple segments such as Stream Power). Taking full advantage of any hierarchical river network and of large-scale datasets grants RivTool universal applicability and flexibility to perform numerous calculations, making it a unique software. The available set of libraries with processed environmental data (e.g., climate data) and river “network data” files provides information from the CCM2, the ECRINS and the MARS project. Being completely independent of other applications avoids going obsolete after updates of any other software to which it is integrated. Though the preprocessing procedures are dependent on R engine, these are nevertheless internal processing features that do not require any installation process other than RivTool.

The functionalities dependent on R computation are inevitably slower since they deal with raster images, and especially if these are spatially large datasets. Other than these functionalities, RivTool works exclusively based on tabular processes that do not require spatial data, meaning it is able to deal with large datasets while maintaining fast performance.

With the proliferation, availability and increasing quality of valuable spatial datasets and surveys, their applicability increases for many scientific fields including freshwater ecology. Their usage may contribute to a better understanding and thus management of freshwater systems (Tsang et al., 2014). RivTool makes their use possible, fast and correct, promoting the usage of geospatial data in several research fields, such as freshwater ecology, hydrology, engineering and river management, from the basin level up to continent or worldwide level. This software eases analyses required for the implementation of frameworks such as the European Water Framework Directive (European Commission, 2000). In fact, looking at numerous publications it is possible to recognise the broad-ranging possible applicability of the River Network Toolkit (e.g.: Clapcott et al., 2012; Pont et al., 2005; Markovic et al., 2012; Trautwein et al., 2012; Filipe et al., 2013; Clavero and Hermoso, 2015; Kuemmerlen et al., 2015; and Fernandes et al., 2016). This software solves the problem of dealing with large datasets and acts as a bridge that connects topological, environmental and landscape variables, allowing further information to be calculated with the program. The software is flexible enough to accommodate, in the future, other functions, add-ons or plug-ins. Its structure and basic functioning easily allow for the development of, for instance, a plug-in exclusively for river network connectivity analysis or a field app that informs users about segment, sub-basin or basin characteristics while on site. The sharing of networks or landscape datasets between users can also easily be achieved by relying on the RivTool as a platform.

4.6 Acknowledgements

The authors would like to thank Maxime Logez for the comments about this work. GD is part of the FLUVIO doctoral program and financed by a grant from the Fundação para a Ciência e Tecnologia (FCT) (SFRH/BD/52514/2014). PB was financed by a post-doc grant from FCT (SFRH/BPD/94686/2013). PS is supported by a contract funded by the Fundação para a Ciência e Tecnologia (FCT) under the IF Researcher Programme (IF/01304/2015). CEF is a research unit funded by Fundação para a Ciência e a Tecnologia I.P. (FCT), Portugal (UID/AGR/00239/2013). The development of this software was indirectly supported by the MARS Project (Managing Aquatic ecosystems and water Resources under multiple Stress) funded under the 7th EU Framework Programme, Theme 6 (Environment including Climate Change).

4.7 References

Abell, R. (2002) Conservation Biology for the Biodiversity Crisis: a Freshwater Follow-up. Conservation Biology 16, 1435-1437.

Ahearn, D.S., Sheibley, R.W., Dahlgren, R.A., Anderson, M., Johnson, J., Tate, K.W. (2005) Land use and land cover influence on water quality in the last free-flowing river draining the western Sierra Nevada, California. Journal of hydrology 313, 234-247.

Allan, J.D. (2004) Landscapes and Riverscapes: The Influence of Land Use on Stream Ecosystems. Annual Review of Ecology, Evolution and Systematics 35, 257-284.

Allan, J.D., Johnson, L. (1997) Catchment-scale analysis of aquatic ecosystems. Freshwater Biology 37, 107-111.

Béguer, M., Beaulaton, L., Rochard, E. (2007) Distribution and richness of diadromous fish assemblages in Western Europe: large-scale explanatory factors. Ecology of Freshwater Fish 16, 221-237.

Bhave, A.G., Mishra, A., Groot, A. (2013) Sub-basin scale characterization of climate change vulnerability, impacts and adaptation in an Indian River basin. Regional Environmental Change 13, 1087-1098.

Bolker, B.M., Brooks, M.E., Clark, C.J., Geange, S.W., Poulsen, J.R., Stevens, M.H.H., White, J.-S.S. (2009) Generalized linear mixed models: a practical guide for ecology and evolution. Trends in Ecology & Evolution 24, 127-135.

Bullard, J., Baddock, M., McTainsh, G., Leys, J. (2008) Sub-basin scale dust source geomorphology detected using MODIS. Geophysical Research Letters 35, L15404.

Chen, I.-C., Hill, J.K., Ohlemüller, R., Roy, D.B., Thomas, C.D. (2011) Rapid Range Shifts of Species Associated with High Levels of Climate Warming. Science 333, 1024-1026.

Clapcott, J.E., Collier, K.J., Death, R.G., Goodwin, E.O., Harding, J.S., Kelly, D., Leathwick, J.R., Young, R.G. (2012) Quantifying relationships between land-use gradients and structural and functional indicators of stream ecological integrity. Freshwater Biology 57, 74-90.

Clavero, M., Hermoso, V. (2015) Historical data to plan the recovery of the European eel. Journal of Applied Ecology 52, 960-968.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.-I., Knowler, D.J., Lévêque, C., Naiman, R.J., Prieur-Richard, A.-H., Soto, D., Stiassny, M.L.J., Sullivan, C.A. (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. Biological Reviews 81, 163-182.

EEC, (2012) Catchments and Rivers Network System ECRINS v1.1 - Rationales, building and improving for widening uses to water Accounts and WISE applications. European Environment Agency, European Union, Copenhagen, p. 111.

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 in: Parliament, E. (Ed.), L 327, The Official Journal of the European Union, p. 93.

Fausch, K.D., Torgersen, C.E., Baxter, C.V., Li, H.W. (2002) Landscapes to Riverscapes: Bridging the Gap between Research and Conservation of Stream Fishes: A Continuous View of the River is Needed to Understand How Processes Interacting among Scales Set the Context for Stream Fishes and Their Habitat. Bioscience 52, 483-498.

Fernandes, M.R., Segurado, P., Jauch, E., Ferreira, M.T. (2016) Riparian responses to extreme climate and land-use change scenarios. Science of the Total Environment 569-570, 145-158.

Ficklin, D.L., Stewart, I.T., Maurer, E.P. (2013) Climate Change Impacts on Streamflow and Subbasin-Scale Hydrology in the Upper Colorado River Basin. PLOS ONE 8, e71297.

Filipe, A.F., Markovic, D., Pletterbauer, F., Tisseuil, C., De Wever, A., Schmutz, S., Bonada, N., Freyhof, J. (2013) Forecasting fish distribution along stream networks: brown trout (Salmo trutta) in Europe. Diversity and Distributions 19, 1059-1071.

Globevnik, L., Koprivsek, M., Snoj, L., (2016) MARS spatial database - European data base for management of water resources under multiple stress, http://www.fgg.uni-lj.si/~/mars/MARSgeoDB/MARSgeoDB_v2.zip.

Grant, E.H., Lowe, W.H., Fagan, W.F. (2007) Living in the branches: population dynamics and ecological processes in dendritic networks. Ecology Letters 10, 165-175.

Imbert, H., De Lavergne, S., Gayou, F., Rigaud, C., Lambert, P. (2008) Evaluation of relative distance as new descriptor of yellow European eel spatial distribution. Ecology of Freshwater Fish 17, 520-527.

Jager, A.d., (2016) Findings of the CCM pre-conference workshop at AGILE Helsinki 2016, 19th AGILE International Conference on Geographic Information Science, Helsinki, p. 3.

Johnson, B.L., Richardson, W.B., Naimo, T.J. (1995) Past, Present, and Future Concepts in Large River Ecology: How rivers function and how human activities influence river processes. Bioscience 45, 134-141.

Kuemmerlen, M., Schmalz, B., Cai, Q., Haase, P., Fohrer, N., Jähnig, S.C. (2015) An attack on two fronts: predicting how changes in land use and climate affect the distribution of stream macroinvertebrates. Freshwater Biology 60, 1443-1458.

Leathwick, J.R., Rowe, D., Richardson, J., Elith, J., Hastie, T. (2005) Using multivariate adaptive regression splines to predict the distributions of New Zealand's freshwater diadromous fish. Freshwater Biology 50, 2034-2052.

Logez, M., Bady, P., Pont, D. (2012) Modelling the habitat requirement of riverine fish species at the European scale: sensitivity to temperature and precipitation and associated uncertainty. Ecology of Freshwater Fish 21, 266-282.

López-Moreno, J.I., Vicente-Serrano, S.M., Moran-Tejeda, E., Zabalza, J., Lorenzo-Lacruz, J., García-Ruiz, J.M. (2011) Impact of climate evolution and land use changes on water yield in the ebro basin. Hydrology and Earth System Sciences 15, 311-322.

Markovic, D., Freyhof, J., Wolter, C. (2012) Where Are All the Fish: Potential of Biogeographical Maps to Project Current and Future Distribution Patterns of Freshwater Species. PLoS ONE 7, e40530.

McDowall, R.M. (1992) Particular problems for the conservation of diadromous fish. Aquatic Conservation: Marine and Freshwater Ecosystems 2, 351-355.

Parmesan, C., Yohe, G. (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421, 37-42.

Peterson, E.E., Ver Hoef, J.M., Isaak, D.J., Falke, J.A., Fortin, M.J., Jordan, C.E., McNyset, K., Monestiez, P., Ruesch, A.S., Sengupta, A., Som, N., Steel, E.A., Theobald, D.M., Torgersen, C.E., Wenger, S.J. (2013) Modelling dendritic ecological networks in space: an integrated network perspective. Ecology Letters 16, 707-719.

Pont, D., Hugueny, B., Oberdorff, T. (2005) Modelling habitat requirement of European fishes: do species have similar responses to local and regional environmental constraints? Canadian Journal of Fisheries and Aquatic Sciences 62, 163-173.

R Development Core Team, (2017) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ricciardi, A., Rasmussen, J.B. (1999) Extinction Rates of North American Freshwater Fauna. Conservation Biology 13, 1220-1222.

Schmitt, R., Bizzi, S., Castelletti, A. (2014) Characterizing fluvial systems at basin scale by fuzzy signatures of hydromorphological drivers in data scarce environments. Geomorphology 214, 69-83.

Tarroso, P., Rebelo, H. (2010) E- Clic – easy climate data converter. Ecography 33, 617-620.

Thomas, C.D., Franco, A.M.A., Hill, J.K. (2006) Range retractions and extinction in the face of climate warming. Trends in Ecology & Evolution 21, 415-416.

Trautwein, C., Schinegger, R., Schmutz, S. (2012) Cumulative effects of land use on fish metrics in different types of running waters in Austria. Aquatic Sciences 74, 329-341.

Tsang, Y.-P., Wieferich, D., Fung, K., Infante, D.M., Cooper, A.R. (2014) An approach for aggregating upstream catchment information to support research and management of fluvial systems across large landscapes. SpringerPlus 3, 1-9.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E. (1980) The River Continuum Concept. Canadian Journal of Fisheries and Aquatic Sciences 37, 130-137.

Vogt, J., Soille, P., Jager, A.d., Rimavičiūtė, E., Mehl, W., Foisneau, S., Bódis, K., Dusart, J., Paracchini, M.L., Haastrup, P., Bamps, C., (2007) A pan-European River and Catchment Database. European Commission - Joint Research Centre - Institute for Environment and Sustainability, Luxembourg, p. 120.

Ward, J.V. (1989) The Four-Dimensional Nature of Lotic Ecosystems. Journal of the North American Benthological Society 8, 2-8.

Yates, A.G., Bailey, R.C. (2006) The Stream and Its Altered Valley: Integrating Landscape Ecology into Environmental Assessments of Agro-Ecosystems. Environmental Monitoring and Assessment 114, 257-271.

Ziegler, A.D., Maurer, E.P., Sheffield, J., Nijssen, B., Wood, E.F., Lettenmaier, D.P. (2005) Detection Time for Plausible Changes in Annual Precipitation, Evapotranspiration, and Streamflow in Three Mississippi River Sub-Basins. Climatic Change 72, 17-36.

5. Damn those damn dams: European-wide historical analysis of dam obstruction to diadromous fish movements

---

Gonçalo Duarte, Paulo Branco, Gertrud Haidvogl, Didier Pont,
Maria Teresa Ferreira & Pedro Segurado

Article in preparation

5.1 Abstract

Rivers have always been a source of food and energy. The longitudinal dimension of connectivity is the most relevant for ecological processes and for diadromous fish species. In this work, we aim to evaluate the impact of large dams on the structural longitudinal connectivity at the European scale, while also assessing the functional connectivity losses using the historical distribution of 14 diadromous fish species and one species complex. To obtain the historical distribution we used multiple databases and an established framework that copes with the disparity of geographical extent and distinct scales of data from input databases, providing a reliable output dataset of historical occurrence. The GranD Database provided the information about large dams. Basins of large rivers represent 78% of Europe's area, being the most relevant freshwater networks for diadromous fish species. Considering only large rivers, large dams have affected 69.5% of all basins, totally impaired 55.4% of the number and 60.1% of length of sub-basins and affected 70.3% of the number and 68.4% of length of river segments. Temporally, the number of large dams increased significantly in the second half of the 20th century, especially main stem dams whose distance to river mouth decreased throughout the century. The structural impairment resulted in functional connectivity losses to all species considered. More than 47% of large basins exhibited functional losses and some species have potentially lost more than 60% of their segment or basin occurrence length. European freshwater networks have a severely impacted structural longitudinal connectivity and this affects all diadromous species analysed. Decline in the occurrence and stocks of several diadromous species seems to follow temporally the construction of main stem dams. Thus, it seems that large dams may have contributed decisively to the European decline of diadromous fish species.

5.2 Keywords

Diadromous fish species, Large dams, Europe, Freshwater networks, Longitudinal connectivity, structural and functional losses, spatial and temporal assessment

5.3 Introduction

Rivers have always been essential to humans. Their location and energy (flow) helped shape communities and forged societies. Rivers have always been seen as an ever-renewing source of food, water, raw material, energy, and viewed as a prime communication and connection network system. This lead to an unsustainable exploration of resources, culminating in rivers being amongst the most endangered systems in the world (Haidvogl et al., 2013; Sala, 2000). Dam construction was considered as option to increase safety (flood reduction), maintain year-long resource availability (water storage), augment agricultural outputs (irrigation), produce energy (hydropower), increase navigability (regulation and depth increase) and as culturally important (leisure activities and scenic value), to name the most relevant. Along with these societal services came change in natural flow regimes, alteration of flow velocity and water depth, the creation of vertical outflow drops that modify hydrology and thermal regimes, promote fragmentation of the network and deteriorate water quality through wastewaters (urban, industrial and agricultural) (Bergkamp et al., 2000; de Groot, 2002; Pizzuto et al., 2000; Warren and Pardew, 1998; Wheeler et al., 2005). Flow alteration has potential impacts in river geomorphology, sediment transportation, habitats requirements for fauna and flora, through carbon transport flow controls food webs and has a direct impact over behaviour and life histories of animals and plants (Calow and Petts, 1992; Fausch et al., 2002; Frissell et al., 1986; Junk et al., 1989; Matthews, 1998; Thorp and Delong, 1994; Vannote et al., 1980). Fish species, particularly diadromous, have been severely affected by the presence of instream transversal barriers (Larinier, 2001; Nicola et al., 1996). These preclude them to complete their life cycle by interrupting their pathways towards spawning grounds since vital habitats for fish are usually spatially and temporally separated (Fausch et al., 2002).

River networks are dendritic, hierarchical and have a directionality imposed by flow (Duarte et al., in press). Therefore, impacts imposed in one given place will have correspondent site-wise effects while also affecting downstream areas (Allan, 2004). Moreover, the propagation and extent of the effect along the river depends on impact (i.e. dam, pollution source) location. Given these particular properties, the longitudinal connectivity is, among the four main dimensions of river connectivity (Ward, 1989), an especially relevant dimension for ecological processes taking place in rivers. In the case of fish species it determines their displacement along the network, and it is, arguably, the dimension most affected by human-induced alterations (Branco et al., 2012). This has been particularly noticeable for diadromous fish species, which are obligatory migrants moving between two different environments (freshwater and sea) to be able to reproduce and grow. If their migratory pathways are interrupted, these species are not only unable to complete their life cycle, they also experience reducing intraspecific diversity, creating genetic bottlenecks and leading to an extinction spiral (Branco et al., 2014; Larinier, 2001) that forces species towards localized or total extinction in the wild. Contrary to terrestrial animals that move in a two-dimensional space, fish are secluded to move along predefined one-dimensional river routes.

The placement of dams within river systems has been a common practice since the beginning of civilization as we know it, and the increasing human population and modern societal trends have led to a significant higher need of the services provided by dams. Hence, the bulk of the real impact of large dam construction can be assigned to the 20th century, especially considering main rivers and relevant tributaries (Chao, 1995; Lehner et al., 2011b). However, still to this day, even though dam impacts are known and consensually accepted as true, dam numbers are increasing, mainly as the consequence of the threat of climate change and population growth (Vörösmarty et al., 2000), and out-pacing dam removal actions. Fifty per cent of the world's largest rivers are affected by longitudinal connectivity impairment due to dams (Nilsson et al., 2005), and predictively more large rivers will be impounded. Of course, the extent to which the positioning of the dam, within those rivers, will affect diadromous fish is dependent on life-history of the species and changes dramatically if it is an anadromous or a catadromous species (Cote et al., 2009). Also, it is a function of the relative progression each species incurs within the river network – something that changes with the specific ecology and habitat requirements of a species.

The presence of barriers plays an important role in river dynamics and is co-occurrent with several other stressors with which, connectivity fragmentation, as a stressor, may interact synergistically, increasing its deleterious effect on fish (Branco et al., 2016). The impact (effect size) of this physical stressor is so large that experimental work on potamodromous fish has shown that although individual stressor (oxygen depletion) expressed itself on fish behaviour (Hayes et al., in prep), when in conjunction with connectivity fragmentation, movement response was solely responsive to connectivity (Branco et al., 2016). So, connectivity infringement overrode the effect of oxygen depletion at the movement response level. It has also been hypothesized that even partial connectivity infringement, by increasing movement friction, can lead to the selection of certain behavioural phenotypes having potential impacts on population structures and meta-community balances (Branco et al., 2017).

Historical ecology exposes human imprint on ecological systems (Jackson and Hobbs, 2009), thus value of past information is related with the identification of components that have contributed to the structure and function of present ecosystems (Humphries and Winemiller, 2009). Collecting historical data about rivers prior to the most relevant impactful human activities (e.g., damming, the industrial revolution, modern fishing, and river channelisation) could upturn the ability to interpret existing freshwater processes and ecosystems (Foster, 2000).

Other studies have made some commendable efforts, but usually only for large rivers (Nicola et al., 1996), for few well-known species, and versing on reduced spatial scales (Clavero and Hermoso, 2015; Segurado et al., 2014). We propose to bridge this knowledge gap by evaluating the impact of dam placement, decade-wise, since the beginning of the 20th century until the present day, looking at potential habitat loss. Our reference condition is the potential historical distribution of 14 diadromous species and one species complex (beginning of the 20th century) at the European scale for river segment (basic analysis unit) and tributary sub-basin. Having a large scope approach that focuses on several diadromous species in Europe has undeniable value for conservation and management planning. By following a decade-by-decade approach, this study will also allow understanding how habitat reduction evolved, which species were the most affected and how long they have been impacted by dam placement. Finally, this work aims also at raising awareness towards a threat that is increasing and whose effects will linger in time to an extent that is still to be fully evaluated.

5.4 Materials & Methods

Studying diadromous fish species occurrence in freshwater systems at the European scale requires using an adequate and detailed representation of the freshwater systems in the European continent. The Catchment Characterisation and Modelling–River and Catchment database v2.1 (CCM2) (http://data.europa.eu/89h/fe1878e8-7541-4c66-8453-afdae7469221) was developed by the Joint Research Centre (JRC) and is a homogeneous and completely integrated hierarchical representation of rivers and drainage catchments for the pan-European continent (Vogt et al., 2007). Complementary, to create an intermediate scale between segment and basin, we used the River Network Toolkit (Duarte et al., in press) (www.rivtoolkit.com) to establish the sub-basin scale, corresponding to the watercourse and drainage areas of the tributaries of all main rivers of all basins. We have also used the software to calculate the values for the metrics of longitudinal connectivity impairment. The Water Framework Directive (WFD) defines very large rivers has those with catchment area above 10 000 km^2 (European Commission, 2000). For the sake of simplicity, throughout the document the term “large river” will be used to mention these systems. Our study area is the entire pan-European continent, from Scandinavia and Iceland to Spain, Italy and Greece, from Portugal and the British Isles to the Urals in Russia, the Caucasus and Turkey.

5.4.1 Datasets

Diadromous fish species data was acquired using the Historical EFI+ database (unpublished), EFI+ database (http://efi-plus.boku.ac.at), EuroDiad 2.0 database (Irstea, Cestas, France), FAME database (https://fame.boku.ac.at), PHish Database (Duarte et al., 2018b) and the “Freshwater fishes of the U.S.S.R. and adjacent countries” (Berg, 1962-65a, b, c) (Berg data collection). The EFI+ and Phish databases were already associated with CCM2 database structure. The FAME and EuroDiad datasets had no association with a freshwater network representation, thus the association was performed with the CCM2. Data collected from Berg (1962-65a, b, c) was from the start associated with the CM2. The selected set of species/complex of species encompasses the majority of the European diadromous fish species, including catadromous (e.g., European eel, European flounder) and anadromous species (e.g., Allis shad, Atlantic salmon). The inclusion of the complex European/Atlantic sturgeon is necessary due to recent discoveries that the Atlantic sturgeon (*A. oxyrinchus*) has colonized French rivers (Chassaing et al., 2013) and rivers of the Baltic Sea some 1000 years ago or in the Middle Ages (Ludwig et al., 2002; Tiedemann et al., 2007). Overall, 15 taxonomic entities were included (*Alosa alosa*, Allis shad; *A. fallax*, Twait shad; *A. immaculata*, Pontic shad; *Anguilla anguilla*, European eel; *Acipenser gueldenstaedtii*, Russian sturgeon; *A. stellatus*, Stellate sturgeon; *A. sturio/A. oxyrinchus*, European sea sturgeon/Atlantic sturgeon; *Huso huso*, Beluga; *Coregonus oxyrinchus*, Houting; *Osmerus eperlanus*, European smelt; *Lampetra fluviatilis*, European river lamprey; *Petromyzon marinus*, Sea lamprey; *Salmo salar*, Atlantic salmon; *S. trutta*, Sea trout).

The International Commission on Large Dams (ICOLD) defines a large dam as a “dam with a height of 15 metres or greater from lowest foundation to crest or a dam between 5 metres and 15 metres impounding more than 3 million cubic metres”. The information about large dams location was obtained using mainly the Global Reservoir and Dam Database (GRanD) from the Global Water System Project (GWSP) (Lehner et al., 2011a). The GranD project aimed to establish a worldwide database of the reservoirs with a storage capacity of over 0.1 km³ (Lehner et al., 2011b). We confronted this dataset with the dam geo-referenced dataset of the global water information system (AQUASTAT) of the Food and Agriculture Organisation (FAO) to check for inconsistencies (data and georeferencing). The geographic location of the dams was integrated with the segments/primary catchments of the CCM2. This integration procedure was afterwards checked for georeferencing inconsistencies and inaccuracies in order to coincide the exact location of the dam (not the reservoir) with the correspondent segment. Overall, 1352 large dams were used in this study.

5.4.2 Database integration and pseudo occurrence procedure

Spatial or temporal large-scale datasets allows researchers to acquire a distant viewpoint that helps revealing macroecological patterns in biodiversity (Gaston and Blackburn, 2007). However, such large datasets are, most commonly, a result of the aggregation of national databases, of regional efforts or the amalgam of data from several distinct research projects. This results in spatial, temporal and methodologically heterogeneous and incomplete data, and/or data affected/truncated by political, administrative, or economic constraints. Both following procedures have been described in detail and more theoretically in Duarte et al. (2018a).

Data integration procedure

Contrary to just aggregating or compiling multiple sources, establishing a procedure to integrate multiple databases overcomes or minimises some of the aforementioned problems. The Historical EFI+ database, the EFI+ database, the EuroDiad 2.0 database, the FAME database, the PHish Database and the data from the Berg data collection were used for the integration procedure. This was performed at basin scale (usable at sub-basin scale with minor adaptations), and the output is the diadromous species occurrence (presence, absence or unknown) for every unit of the considered spatial scale. Basin scale, being the coarser scale possible, allows every database to contribute with information. This method is based on an absolute consensus rule, meaning that concordance amongst all the data inputs yields a presence or absence output, while a single dissonance results in an unknown output. Because we are working with historical data, where data reliance and interpretation is often questionable and requires careful considerations (Haidvogl et al., 2013; Rackham, 1998; Swetnam et al., 1999), this rule of absolute consensus is relevant to keep it as a conservative method. Finally, the Handbook of European Freshwater Fishes (Kottelat and Freyhof, 2007), the FishBase website (http://www.fishbase.org/) and the UICN Red List of Threatened Species website (http://www.iucnredlist.org/) were used to check for misleads, lapses or defects in the databases or in the integration procedure. This last step assures that there is an overall compliance between the outcome and the current knowledge of the species distribution.

Pseudo-occurrence creation procedure

The datasets used in this work have data at different spatial scales: basin (FAME, EuroDiad, PHish), sub-basin (PHish), segment (EFI+ databases, PHish, Berg dataset). Thus, compiling data at segment and sub-basin scales, requires not only an integration process but also a procedure that establishes pseudo-occurrence (Pigott et al. (2014)

uses the term "pseudo-data"[3]), i.e., pseudo-absences (Barbet-Massin et al., 2012; Elith et al., 2006) and pseudo-presences (Fourcade, 2016; Sinka et al., 2010) in basins where a species is present but there is no information about the occurrence at given segments or sub-basins. Duarte et al. (2018a), along with the integration procedure, also developed a method to establish pseudo-occurrence at the segment scale. Steaming from the rules of EFI+ and PHish databases, the procedure relies on one important premise: presence in one segment translates into presence in all segments from there to the mouth of the river because of the migratory nature of these species. The first part of this procedure identifies and separates segments where historical occurrence (presence and absence) can be asserted given the databases, from others where the occurrence is unknown. The later are then separated into "segments of the main river" (those belonging to the river course flowing directly to the sea) and "segments of tributaries" (those belonging to rivers that directly or indirectly flow towards the main river course). The main reason for this separation is the larger availability of historical information for the main river group (ex.: EFI+ historical data and PHish database), allowing the procedure to adjust to this bias, while also having the possibility to relate sub-basin scale historical data directly with tributary segments. Furthermore, the majority of the main river segments tend to have different hydrological (Strahler, 1957), environmental and biological (Nilsson et al., 1994) characteristics from most of the tributary segments (source segments, small streams segments and small river segments). The second part of the procedure allows establishing pseudo-occurrences in a basin where a species is considered to be present but no historical information at the segment scale is available. This is a data-informed process that uses thresholds obtained from occurrence data and these are not only species-specific but also basin Strahler-specific (maximum Strahler value present in the basin). The thresholds used are related with the ability of a species to progress within the river basin (relative distance; Imbert et al., 2008) and to hydrological and geomorphological properties of watercourses that can be directly proportional to the relative watershed dimensions (Strahler stream order; Strahler, 1957). In this work, these thresholds arise from the historical EFI+ database, the PHish database and Berg's data collection. Having multiple

---

[3] The term "pseudo-occurrence" is maintained for the sake of coherence throughout this document. In further work and publication, the terminology already in use, "pseudo-data", will be adopted.

databases generally translates into a larger spatial coverage (larger number and geographically widespread "presence" data) and permits a cross-validation amongst datasets, providing more reliability to the thresholds obtained. Additional limits and corrections are incorporated in the procedure to guaranty the maintenance of a spatial gap between presences or pseudo-presences and absence or pseudo-absences.

5.4.3 Structural and functional connectivity losses analysis

To investigate, how large dams affected diadromous fish species occurrence in the European continent from the late 18th century until the beginning of the 21st century, we have looked at both structural and species functional connectivity losses using 20 metrics (Table 5.4.4). For structural losses, we calculated the total upstream losses in the network associated with the implementation of a large dam. For species functional losses, we have looked at the losses restricted to the potential presence of each of the 15 diadromous fish taxonomical groups. Two tables were compiled containing the values of the metrics for structural and functional connectivity losses at 3 scales (basin, sub-basin and segment). Additionally, to observe the development of the large dams and their consequence throughout the continent, we performed an analysis considering 12 periods of time (10 coincide with the decades of the 20th century, and the other two represent the periods before and after).

Table 5.4.4 – Metrics used to describe the structural and functional connectivity losses associated with the existence of large dams in Europe. Metrics can be calculated as an absolute value or as a percentage. Hence, one of the two symbols will be aggregated to the metric acronym identifying the calculation type: "#" for absolute values and "%" for percentage values.

Metric	Description
Dams_Mr	Main stem dams, i.e., dams located in the segments of the main river
Dams_Tb	Dams located in the segments of a tributary of the main river
Avg_dist_mouth_Mr	Average distance of main stem dams to the mouth of the basin, considering the mid-point of the segment
Avg_dist_mouth_Tb	Average distance of dams located in the segments of a tributary of the main river to the mouth of the basin, considering the mid-point of the segment
B_aff	basins where connectivity is hindered by the presence of a large dam
B_aff	basins where connectivity is hindered by the presence of a large dam

Metric	Description
B_aff_Lr	basins from large rivers (drainage area ≥ 10 000 Km^2) where connectivity is hindered by the presence of a large dam
B_Taff	basins that are completely hindered by the presence of a dam in the mouth segment
SB_aff	sub-basins where connectivity is hindered by the presence of a dam within the basin or downstream
SB_Taff	sub-basins where connectivity to the entire sub-basin watercourses is hindered by the presence of a large dam at the mouth segment of the sub-basin or downstream
SB_Taff_length (m)	river length of sub-basins where connectivity to the entire sub-basin watercourses is hindered by the presence of a large dam at the mouth segment of the sub-basin or downstream
SB_Non_Taff_length (m)	river length of sub-basins where connectivity to the entire sub-basin watercourses that has not been affected by the presence of a large dam at the mouth segment of the sub-basin or downstream (1 - SB_Taff_length)
SB_Taff_Lr	sub-basins of large river basins where connectivity to the entire sub-basin watercourses is hindered by the presence of a large dam at the mouth segment of the sub-basin or downstream
SB_Taff_Lr_length (m)	river length of large river sub-basins where connectivity to the entire sub-basin watercourses is hindered by the presence of a large dam at the mouth segment of the sub-basin or downstream
S_aff	segments where connectivity is hindered by the presence of a dam in the segment or downstream
S_aff_length (m)	river length of segments where connectivity is hindered by the presence of a dam in the segment or downstream
S_aff_length2-4 (m)	river length of segments where connectivity is hindered by the presence of 2 to 4 dams in the path towards the basin mouth segment
S_aff_length5+ (m)	river length of segments where connectivity is hindered by the presence of 5 or more dams in the path towards the basin mouth segment
S_aff_Lr	segments of large rivers where connectivity is hindered by the presence of a dam in the segment or downstream
S_aff_Lr_length (m)	river length of segments of large rivers where connectivity is hindered by the presence of a dam in the segment or downstream

Graphically, at segment scale, we represented the percentage river length impaired considering three classes of a number of dams downstream: 1 dam, 2 to 4 dams and 5 or more dams (%S_aff_length, %S_aff_length2-4, %S_aff_length5+). The accumulation of dams in the migratory route of a diadromous fish inevitably decreases connectivity and this could be defined as “dam pressure effect”. Accordingly, the established classes reflect an increasing dam pressure effect and provide a more thorough idea of the severity of the problem in particular areas. At sub-basin scale, considering the sub-basins where a species was deemed present, we represented the remaining percentage of river length in available sub-basins (%SB_Non_Taff_length) and the percentage of sub-basins totally affected by at least one large dam at the mouth segment of the sub-basin or downstream (%SB_Taff).

Database management and curation, layer creation and spatial calculation were performed using ArcGIS 10 (ESRI, 2011). Calculations and summarisations related to freshwater network directionality and paths was achieved using the River Network Toolkit (RivTool) software (Duarte et al., in press).

5.5 Results

The historical distributions obtained for the taxonomic groups illustrate distinct occurrences: a broad European distribution (e.g., Twait shad); a narrow distribution (e.g., Houting); southern limited (e.g., Russian sturgeon); or northern limited (e.g., Atlantic salmon); mainly limited to main river courses (e.g., Stellate sturgeon); reaching very lower strahler value segments in the tributaries (e.g., Sea trout). On average there are more than 10 000 presence segments per species ($\bar{x} = 10041.2$, $\sigma = 9216.3$), but only five are above this threshold. Three species have an elevated number of occurrence segments (European eel – 33401, Atlantic salmon – 20244 and Sea trout – 23064), and six species have less than half of the average values (Pontic shad – 1602, Russian sturgeon – 4667, Stellate sturgeon, Beluga – 4927, European smelt – 2056 and the Houting – 636).

After checking for inconsistencies and integration with the CCM2, we obtained 1352 dams (Figure 5.5.16). In six of them, we were not able to obtain information about their height. Among those for which we have information, 96.4% have a height equal or above 15 meters. In the remaining 42 dams, all but one abide by the other criteria of large dam defined by the ICOLD. The one dam that does not comply with the criteria is the one from the largest lake in Norway, the Mjøsa lake, with a water volume of 5600 million cubic metres (MCM) (Seppälä, 2005). The dams without height information all surpass greatly the 3 MCM threshold, being the lowest 100 MCM. Hence, we have considered that it would be relevant to maintain these dams in our analysis. The maximum value of dam height amongst the dataset is 285 m, while the average is 56.4 m ($\sigma = 36.9$ m). The decade that registers the largest increment of new dams is the

1960s (n = 314), followed by the 1950s (n = 250), the 1970s (n = 245) and the 1980s (n = 203). These four decades amount for more than 73% of all the large dams considered. The time intervals not belonging to the 20th century are those with less new dams.

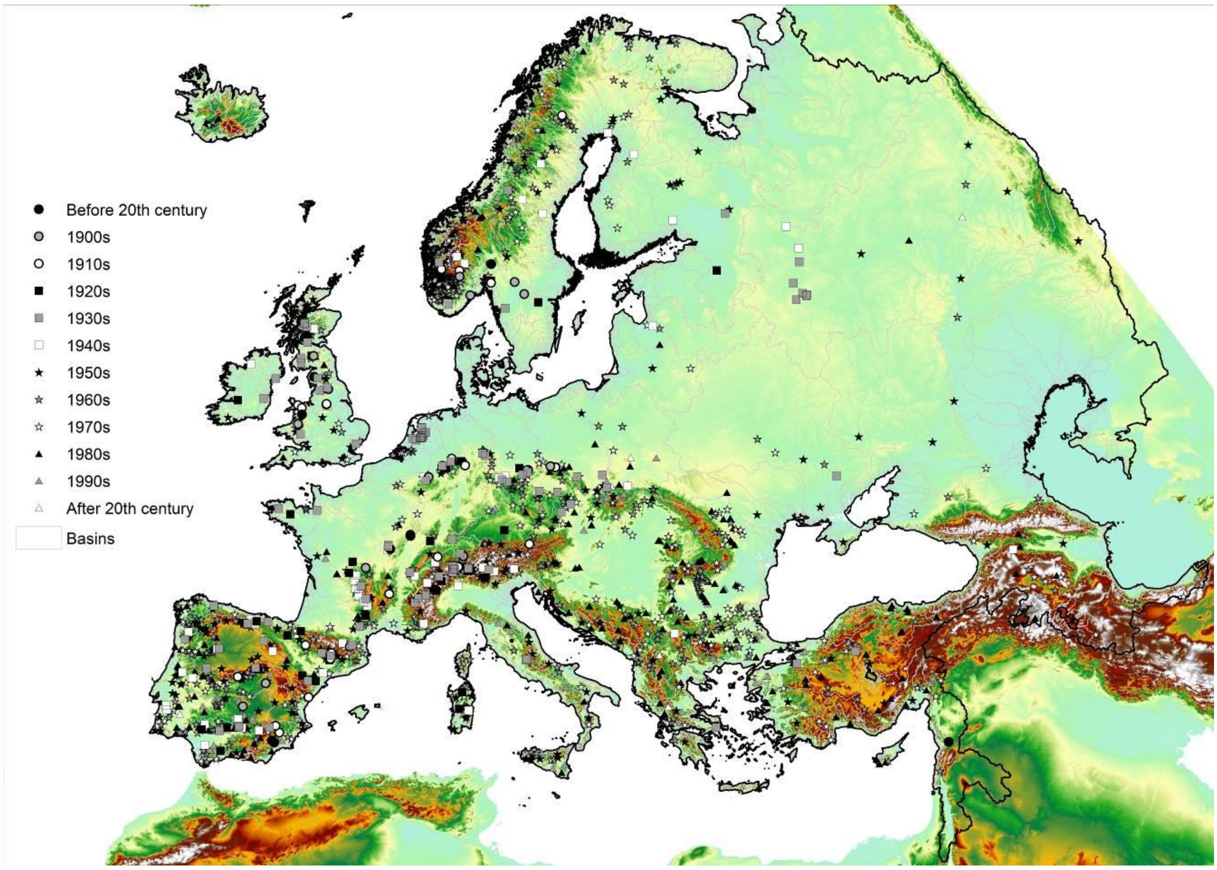


Figure 5.5.16 – Spatial representation of the large dams used in this study. The graphic representation of the dams takes into account the 12 time periods.

5.5.1 Network structural connectivity losses

Overall, the percentage of European basins affected by large dams is very low (0.4%) (Table 5.5.5). However, when looking at large river basins, nearly 70% have structural connectivity impaired by large dams. The area of these large basins represents more than 78% of Europe, thus large dams impact over 54% of Europe’s area. The metrics associated with the sub-basin scale indicate that around 22% of all sub-basins are totally or partially affected, while in large rivers this percentage is over 55%. Observing the river length metrics of all the sub-basins, values rise above 51% and for large rivers over 60%. At the finer scale of analysis, metrics of structural connectivity loss are homogeneous between number and length values, but not between the total amount of segments (%S_aff = 56.3%; %S_aff_length = 55.9%) and the large river segments (%S_aff_Lr = 70.3% ; %S_aff_Lr_length = 68.4%).

Table 5.5.5 – Overall number of basins, sub-basins and segments for the entire CCM2 network and those of the large rivers present and summary of the structural connectivity losses using metrics of three spatial scales: basin, sub-basin and segment. See acronyms explanation in Table 5.4.4

	Global Freshwater Network data		
Basins	# basins	80 548	
	# Large river basins (m)	118	
Sub-basins	# Sub-basins	74 827	
	# Large rivers Sub-basins	23 061	
	Sub-basins river length (m)	3 125 364 002.8	
	Large river Sub-basins river length (m)	2 611 613 879.7	
Segments	# Segments	1 305 188	
	# Large river segments	994 139	
	Segments length (m)	3 425 830 066	
	Large river segments length (m)	2 696 588 699.7	
	Structural loss		
	Metrics	**#**	**%**
Basins	B_aff	352	0.4%
	B_aff_Lr	82	69.5%
	B_Taff	36	0.0%
Sub-basins	SB_aff	16 884	22.6%
	SB_Taff	16 816	22.5%
	SB_Taff_length (m)	1 621 856 451.04	51.9%
	SB_Taff_Lr	12 784	55.4%
	SB_Taff_Lr_length (m)	1 569 693 633.77	60.1%
Segments	S_aff	735 119	56.3%
	S_aff_length (m)	1 916 066 357.00	55.9%
	S_aff_Lr	699 143	70.3%
	S_aff_Lr_length (m)	1 844 467 694.72	68.4%

Large dam construction in European rivers has started before the 20th century. The number of large dams located in tributaries peaked in the 1960s, and their average distance to the river mouth has increased slightly throughout time (Figure 5.5.17). On the contrary, the average distance to the river mouth of main stem dams has decreased since the 1940s. The number of main stem dams also peaked in the 1960s and in this case, they were almost non-existent before the 1950s. It is only after the 1920s that the number of segments affected by the presence of one large dam is over 1%. It overcomes the 10% in the 1940s, and increases until the 1980s to reach 55% and stabilising. Sub-basin metrics show a similar pattern of growth and stabilization, with the highest increment coinciding with the 1950s and the stabilisation from the 1970s onwards (see Figure 8.3.20 of Supplementary material in the Annexe 8.3 for a geographical spatial representation of the potential losses throughout the decades).

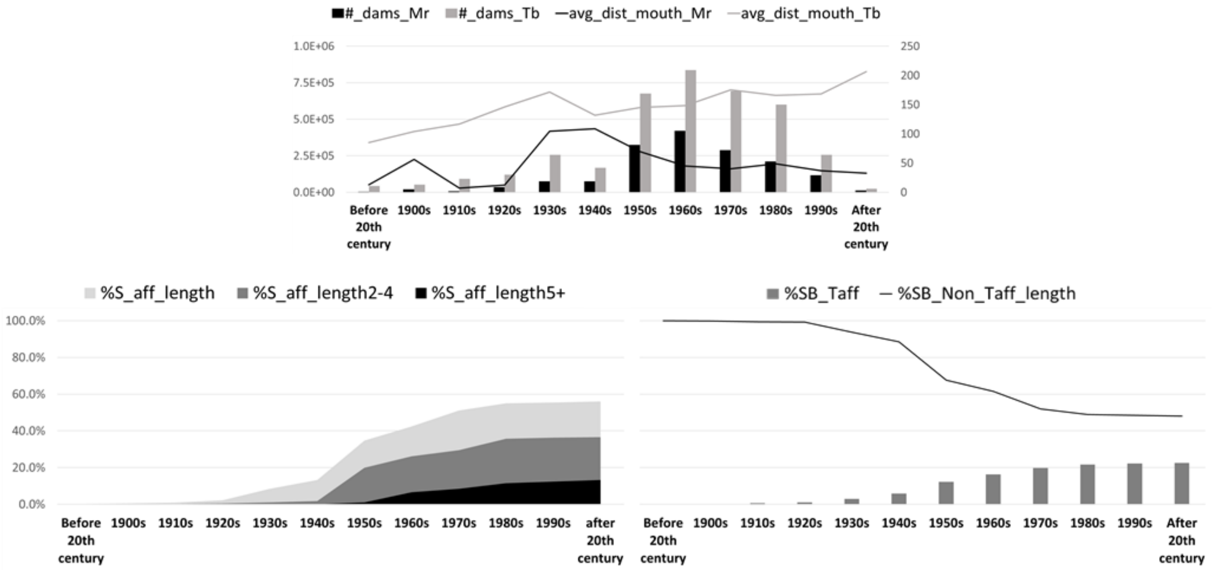


Figure 5.5.17 – Impairment of structural connectivity in European rivers by time period since the end of the 19th century until the beginning of the 21st century. On top, the number of large dams and average distance to basin mouth for main stem dams and dams present in tributaries throughout the considered time intervals. On the bottom left column, analysis at segment scale using three metrics: %S_aff_length, %S_aff_length2-4 and %S_aff_length5+. This shows the percentage of river length hindered considering 3 classes of the number of large dams downstream (1 dam, 2 to 4 dams and 5 dams or more). In the bottom right, analysis at sub-basin scale using two metrics: %SB_Taff and % SB_Non_Taff_length. In this graphic we show the percentage of sub-basins that may be totally hampered by the existence of a dam downstream of the sub-basin or at the mouth segment of the sub-basin; and also the decrease in the percentage of sub-basins river

length available from those sub-basins that are not totally hampered by the existence of a dam downstream of the sub-basin or at the mouth segment of the sub-basin. Metrics description can be found in Table 5.4.4.

5.5.2 Species functional connectivity losses

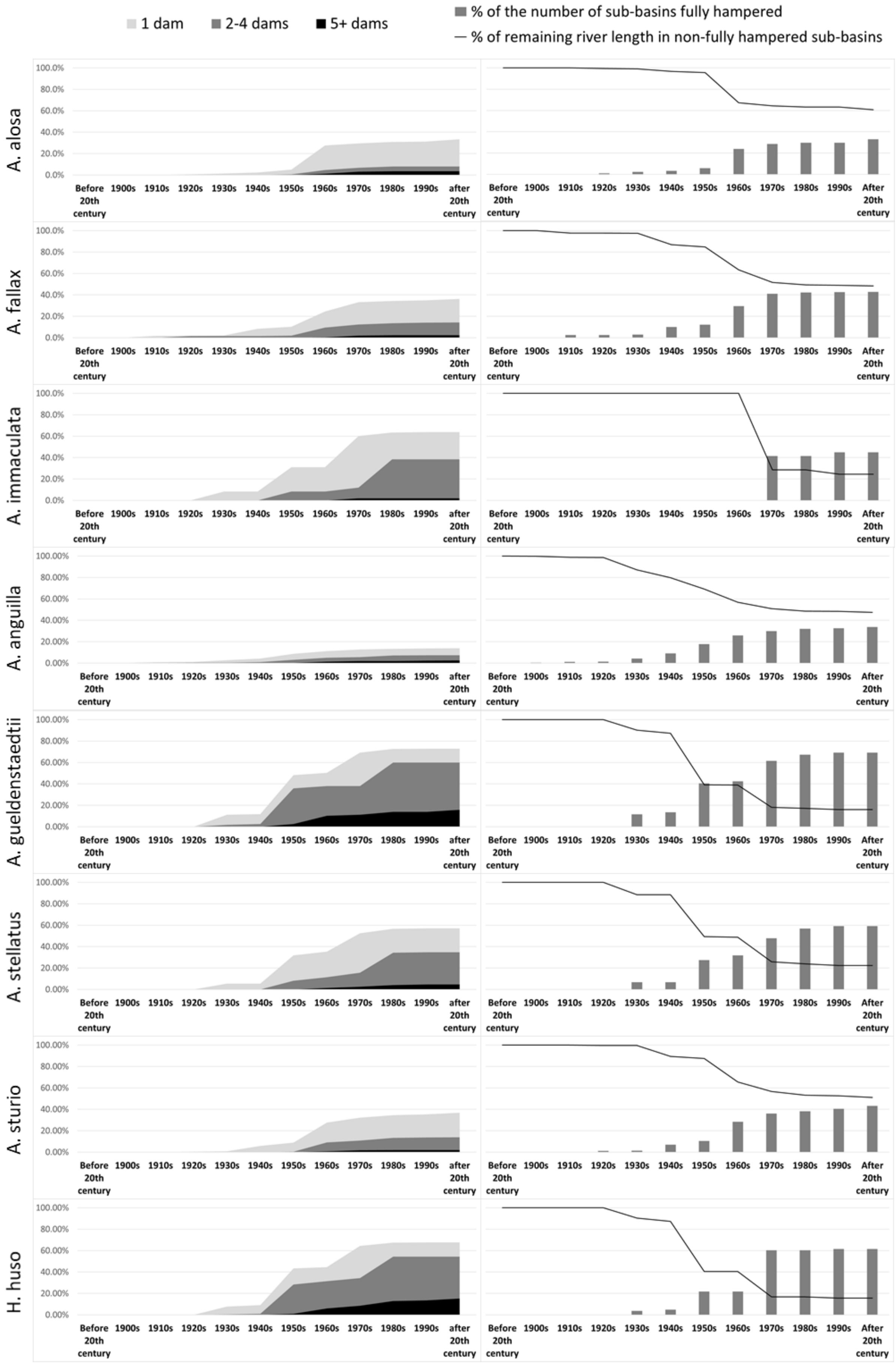
On average, more than 25% of the basins (B_aff – $\bar{x}$ = 26.9%, σ = 16.8%) where species occur are affected by large dams (Table 5.5.6). This number rises to 50% or above for three sturgeon species: Russian sturgeon, Stellate sturgeon and the Beluga. For large river basins, the average number of basins with functional connectivity losses almost doubles the value from all basins (Baff_Lr – $\bar{x}$ = 47.7%, σ = 12.1%). It increases for all species and though the aforementioned sturgeon species are amongst the ones with highest values, Pontic shad exhibits the highest losses. Looking at the difference between the %B_aff and %B_aff_Lr metrics other species stand out: European eel, Sea lamprey, Atlantic salmon and Sea trout show the highest increases. The Houting (%B_Taff – 33.3%) is the only species where the number of basins fully hampered by the presence of a dam at the mouth segment exceeds 5% (%B_Taff – $\bar{x}$ = 3.8%, σ = 8.3%). The sub-basin metrics show higher values of functional connectivity losses than the basin metrics. On average, more than 36% of the sub-basins (%SB_Taff – $\bar{x}$ = 36.3%, σ = 18.6%) are entirely affected by the presence of a large dam, and length-wise (%SB_Taff_length – $\bar{x}$ = 49.8%, σ = 25.9%) the values are even higher. The sturgeon and shad species of the Black and Caspian Seas are the most affected. At segment scale, while on average there is a higher percentage of segments (%S_aff – $\bar{x}$ = 46.3%, σ = 4.1%) affected by the presence of large dams than of sub-basins, length-wise (%S_aff_length – $\bar{x}$ = 37.5%, σ = 3.8%) the percentage is lower than the average sub-basins value. For the latter metric, only two species (Houting and European smelt) are the exception to this trend, increasing 33.4% and 16.6% respectively. The species with the larger negative difference between %S_aff_length and %SB_aff_length are the European eel, European flounder, Atlantic salmon and Sea trout. Only two species present a lower percentage of affected segments than of totally affected sub-basins: the Twait shad and the complex of European sea sturgeon/Atlantic sturgeon. Considering all metrics, the species that stand out are the Pontic shad, the Russian sturgeon, the Stellate sturgeon and the Beluga. On the contrary, the species with regular lower values across all metrics are the European smelt and the European river lamprey.

Table 5.5.6 – Summary of the overall functional connectivity losses for 15 diadromous fish taxonomical groups using metrics of three spatial scales: basin, sub-basin and segment. Metrics description can be found in Table 5.4.4.

		B_aff		**B_aff_Lr**		**B_Taff**		**SB_Taff**		**SB_Taff_length (m)**		**S_aff**		**S_aff_length (m)**	
		#	**%**	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**
Functional Connectivity Losses	***A. alosa***	21	22.3%	9	40.9%	4	4.3%	539	33.0%	139029569	39.3%	2704	38.0%	7717033.46	33.4%
	A. fallax	28	21.4%	19	44.2%	4	3.1%	374	42.8%	238083605.6	51.7%	3073	41.8%	8511288.78	36.2%
	A. immaculata	6	46.2%	6	66.7%	0	0.0%	13	44.8%	170264987	75.6%	1155	72.1%	4295198.52	63.7%
	A. anguilla	88	13.3%	34	50.0%	7	1.1%	2143	33.6%	566774039	52.6%	14890	44.6%	15041081.65	13.9%
	A. gueldenstaedtii	9	50.0%	9	60.0%	0	0.0%	36	69.2%	668985485	84.0%	3966	85.0%	12801841.38	72.8%
	A. stellatus	12	57.1%	11	64.7%	0	0.0%	26	59.1%	479932920.5	77.6%	2517	70.1%	8344022.82	57.0%
	A. sturio/oxyrinchus	25	30.9%	18	48.6%	3	3.7%	384	43.1%	266235432	48.9%	3437	41.1%	10534081.46	36.8%
	H. huso	11	52.4%	10	62.5%	0	0.0%	51	61.4%	627680533	84.5%	3920	79.6%	13154473.21	67.6%
	C. oxyrinchus	3	33.3%	2	40.0%	3	33.3%	1	5.6%	315034.0546	1.0%	245	38.5%	885774.54	34.4%
	O. eperlanus	11	10.9%	9	20.5%	4	4.0%	1	3.2%	315034.0546	2.3%	446	21.7%	1475219.60	18.9%
	L. fluviatilis	28	11.2%	18	38.3%	4	1.6%	697	23.9%	225875674.1	37.1%	3187	24.8%	10938092.42	22.1%
	P. marinus	41	16.0%	18	48.6%	4	1.6%	931	28.0%	259679112.3	39.4%	4140	30.1%	12428805.42	26.6%
	P. flesus	29	13.4%	21	38.9%	5	2.3%	204	32.7%	316656918	60.4%	2585	37.0%	7715026.94	31.6%
	S. salar	51	12.8%	26	47.3%	6	1.5%	937	23.7%	208142480.3	31.8%	5917	29.2%	6906549.29	9.8%
	S. trutta	61	12.9%	35	44.3%	6	1.3%	2349	39.6%	1174098619	60.8%	9393	40.7%	30872227.01	36.9%

The progression of functional connectivity losses since the beginning of the 20th century until early 21st century varies greatly considering the species (Figure 4.4.15). However, at segment scale, the progression along the time of the %S_aff_length is similar amongst all taxonomic entities with a loss rate always elevated between the 1940s and 1960s. At segment scale, considering the class “1 dam”, functional connectivity losses in some species exceed the 60% (e.g., Beluga), while for others the value is below 20% (e.g., European eel). For the subsequent dam pressure metric (%S_aff_length2-4), most taxonomic groups are affected but only four exceed the 20%. For the next dam pressure metric (%S_aff_length5+), the values are either inexistent or very low for all taxa. The results from the progression of functional connectivity analysis losses at sub-basin scale are even more dependent on the species, not having a pattern across all taxonomic entities. In some cases there is hardly any evidence of losses at this scale (e.g., Houting and European smelt), in others the results are similar in pattern and value to the one from the segment scale (e.g., Pontic shad, Allis shad), while others despite similar progression pattern have higher values of losses (e.g., European flounder and Sea trout). Overall, considering all metrics, the most affected species are the Pontic shad, the Russian sturgeon, the Stellate sturgeon and the Beluga. These are not only the species where metrics reveal more differences between starting and end values, but they are also those that show higher rates or more abrupt changes between the considered time intervals.

The Allis shad and Twait shad have a very similar result for all metrics at segment scale. At basin scale, Pontic shad and Twait shad have similar losses in the %SB_Taff metric, but this translates into a higher value in the %SB_Taff_length metric for the Pontic shad. At the segment scale, the European eel losses do not reach the 20%, but the sub-basin scale analysis reveals a steady progression from the 1930s reaching elevated values in both metrics by the 1970s. For all four sturgeon taxonomic groups, considering both scales, the surge of the functional connectivity losses begins in the 1930s and plateaus in the 1970s. For the Black and Caspian Sea species, the values of %SB_Taff_length show a very steep progression, reaching 50% before the 1950s. The Houting and the European smelt show a very similar pattern for the sub-basin metrics, with hardly any evidence of losses. At segment scale, values of the %S_aff_length metric for Houting increase abruptly in the 1960s and reach nearly 40%. For the European smelt values of the %S_aff_length increase slowly between the 1920s and the 1960s getting around 20%. For these species, the values of %S_aff_length2-4 never reach 10%. For the Lamprey species results are very similar at both scales, concerning progression and values of all metrics, though slightly more elevated for the Sea lamprey. For the European flounder, the functional connectivity losses progression is gentle across six decades. At segment scale, all three metrics have values higher than zero since the 1960s, but the progression of the values from the sub-basin metrics reveal higher connectivity losses. The results of the salmonid species are very distinct, with higher values in all metrics for the Sea trout. The progression of all metric values for the Atlantic salmon stagnates around the 1960s, reaching close to the 10% in the %S_aff_length metric, around 5% in the %S_aff_length2-4 metric and 68% in the %SB_Non_Taff_length metric. The evolution of connectivity losses for the Sea trout is pronounced between the 1940s and the 1970s, and gets around 37% for the %S_aff_length metric and goes to 39% in the %SB_Non_Taff_length metric.


1 dam
2-4 dams
5+ dams
% of the number of sub-basins fully hampered
— % of remaining river length in non-fully hampered sub-basins
A. alosa
A. fallax
A. immaculata
A. anguilla
A. gueldenstaedtii
A. stellatus
A. sturio
H. huso
0.0%
20.0%
40.0%
60.0%
80.0%
100.0%
0.00%
20.00%
40.00%
60.00%
80.00%
100.00%
Before 20th century
1900s
1910s
1920s
1930s
1940s
1950s
1960s
1970s
1980s
1990s
after 20th century
After 20th century

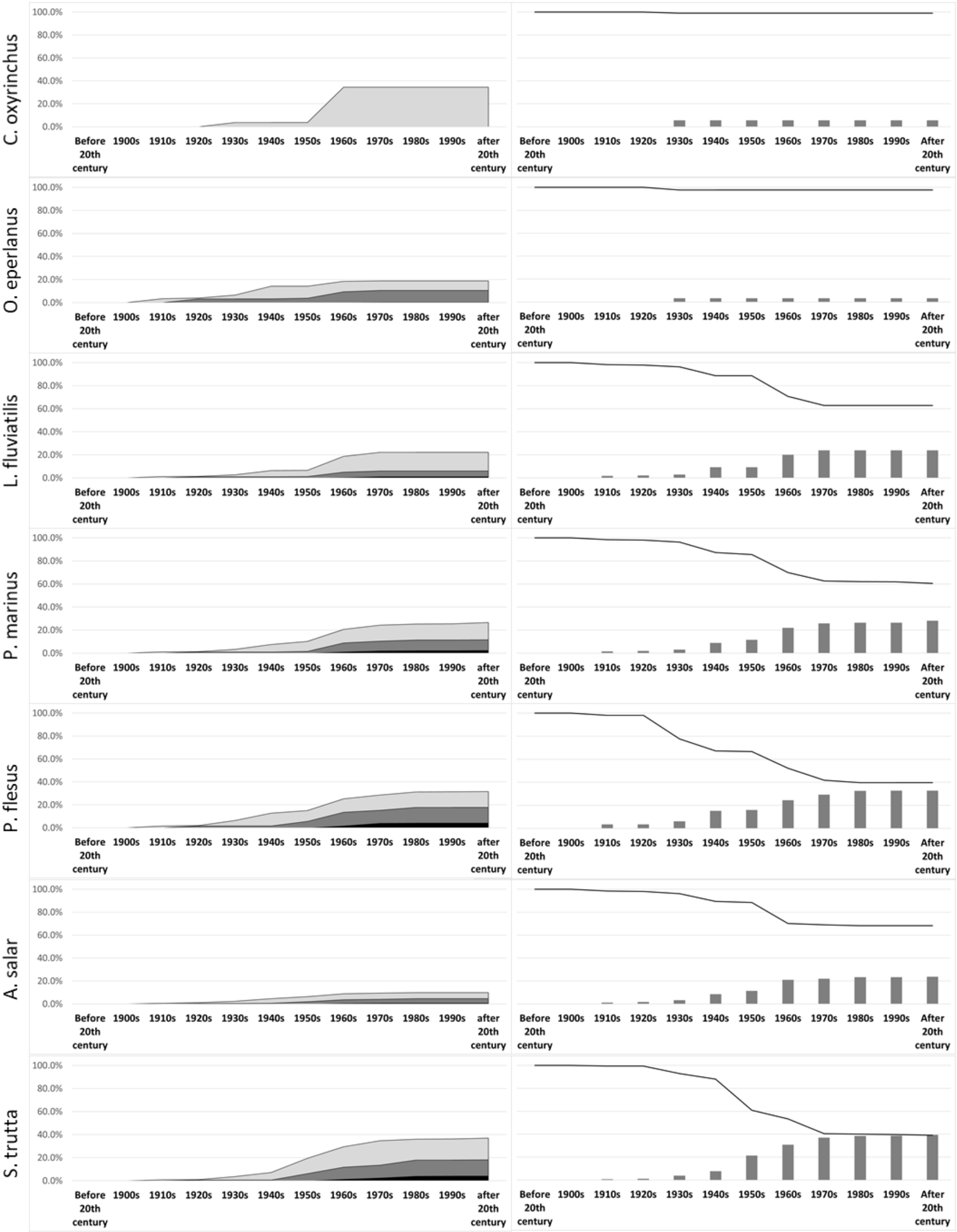


Figure 5.5.18 – Hampering of the distribution of 15 diadromous taxonomical groups in the European continent by time period since the end of the 19th century until the beginning of 21st century. In the left column, analysis at segment scale using those where a species is potentially present. The graphics show the percentage of river length that is hampered

considering 3 classes of the number of dams downstream (1 dam, 2 to 4 dams and 5 or more dams). In the right column, analysis at sub-basin scale using those where a species is potentially present. The graphics show the percentage of sub-basins that may be totally hampered by the existence of a dam downstream of the sub-basin or at the mouth segment of the sub-basin. In addition, the graphics also indicate the decrease in the percentage of sub-basins river length available from those that may be totally hampered by the existence of a dam downstream of the sub-basin or at the mouth segment of the sub-basin.

5.6 Discussion

Overall, the number of basins affected by large dams across Europe looks irrelevant, but this is related with the great amount of very small coastal basins included in the CCM2 database, in some cases not even accommodating any river segments. According to our results, in more than half of the length of watercourses and over 20% of all sub-basins longitudinal connectivity is affected by large dams. Considering only large basins gives a more adequate notion of the magnitude of structural longitudinal connectivity impairment in Europe: more than two-thirds of the networks of the basins, over half of the sub-basins and above to two-thirds of the large river segments have been, connectivity-wise, structurally impacted. Large dams have been present in Europe before the 20th century, but longitudinal connectivity impacts started to increase and becoming spatially widespread from the 1940s onwards. This corresponds to the post World War II (WWII) epoch, a period of rapid socio-economic and technologic development, along with urgent rebuilding needs, where the demand for materials, energy and water increased multiple-fold (Krausmann et al., 2009). The number of dams built in the second half of the 20th century by far exceeds the first half, especially for the dams on the main stem. Moreover, the latter have increasingly been implemented at lower distances to the river mouth and consequently their potential impact on structural longitudinal connectivity considering diadromous fish continuously raised throughout the decades.

Structural connectivity problems due to large dams exist all over Europe but have surfaced in distinct periods throughout Europe. Until the 1930s, relevant losses of diadromous species migration routes and habitats were confined to Scandinavia and northern Europe since it was where main stem dams existed. From the 1940s onwards, a boom of dam construction is evident, peaking in the 1950s and 1960s. Main stem dams became a Europe-wide trend, starting to be numerous in Iberia and Scandinavia in the 1940s and spreading to East and Southeast in the 1950s to the 1960s, thus explaining the elevated rates of structural connectivity losses in this period. Beyond the 1980s, the damming spree begins to subside resulting in a stabilisation of structural connectivity impairement. Overall, southern Europe and Scandinavia have the highest concentration of large dams, and coastal Central European areas seem to have less longitudinal connectivity impairment. This probably results from the necessity to store water in southern Mediterranean areas where the climate is hot and dry with less water availability. Furthermore, the global spatial position of the dams can be attributed to high slopes, which is reasonable given that the purpose of most dams is hydroelectric production.

We have only considered large dams but small dams and weirs may constitute a relevant obstruction to fish migration (Larinier, 2001) and their cumulative effects may even exceed those of a large dam (Liermann et al., 2012). Information about structural losses may give an overall idea of the status of the networks but it is a rather incomplete information when trying to assess how species have been affected. The functional connectivity losses provide a valid complementary information since it takes into consideration species occurrence and not only the topologic structure of the network. In this work, we have used historical data to establish species presence at the beginning of the 20th century, thus providing information about species occurrence prior to most large dams construction in Europe. Our work indicates that, although to a different extent, the distribution of all 15 taxonomical groups have been affected by the existence of dams in European river networks. Functional connectivity losses may be more evident at sub-basin scale than at segment scale, especially for species capable of reaching headwaters, like the European river lamprey, Sea lamprey, European flounder, Atlantic salmon and Sea trout.

The two studied salmonid species, Atlantic salmon and Sea trout, are known to spawn in small river reaches with characteristics common of low Strahler values (Armstrong et al., 2003), and thus, known to be affected by the fragmentation and consequent longitudinal connectivity loss (Garcia de Leaniz, 2008; Junge et al., 2013; Parrish et al., 1998; Rivinoja et al., 2001). The losses predicted in this work for Atlantic salmon are relatively low for a species that has been declining despite multiple and costly conservation and management efforts (Helfman, 2007). The fact that these species occur in small basins that are less interesting for the installation of a large dam may partially explain the reduced functional connectivity losses. In addition, it is possible that barriers not accounted in this work could exist in these small basins. Moreover, being just one threat amongst the myriad of natural and anthropogenic threats to these animals (e.g.: pollution (Sandøy and Langåker, 2001), climate change (Jonsson and Jonsson, 2009), dewatering of freshwater networks (Parrish et al., 1998), overfishing, interactions with aquaculture stocks (Hansen and Windsor, 2006), diseases and parasites (Bakke and Harris, 1998)) also contextualises these results. The situation of the Sea trout is somehow similar (Helfman, 2007) although, contrary to the Atlantic salmon whose distribution is restricted to north-western Europe, this species occurs all over Europe. Southern Europe freshwater networks have more dams, resulting in higher functional losses especially at the sub-basin scale in the case of the Sea trout.

The European distribution of the European eel is almost ubiquitous. Contrary to anadromous species, adult catadromous fish need to negotiate the barrier to progress downstream. Hindrances of upstream movement are the most studied, but dams are a bi-directional network blockage and downstream movement obstruction must be considered and addressed (Pelicice et al., 2015). The decline of this species has been reported since the 1940s in northern Europe, and since 1980s in other areas of their continental range. Since then, catches in reported commercial fisheries have been reduced by 90% or more (Feunteun, 2002; Kettle et al., 2011). Given that there is a delay of 10 to 20 years between recruitment failure and fishery decline to be considered (Feunteun, 2002), and despite our results are meagre to explain such a harsh decline, it matches the spatial-temporal surge of dams and the evolution of functional losses we observed for eel. Around 1920s/1930s, main stem dams were more common in northern Europe, after WWII large dams were built throughout Europe (especially on the southern area), and potentially only half of the length of tributary rivers where this species occurred at the beginning of the 20th century are currently completely available. This probably contributes significantly to the decline of the European eel populations, however, it is widely acknowledged that there are contributions from multiple factors (Feunteun, 2002; Kettle et al., 2011).

Populations of both Sea lamprey and European river lamprey are known to be affected by obstruction to longitudinal connectivity (Lucas et al., 2009; Mateus et al., 2012). Declines in anadromous lamprey stocks throughout Europe have been consistently reported since the 1970s (Kelly and King, 2001; Maitland, 1980; Mateus et al., 2012). Given the time-lag between recruitment failure and beginning of fisheries decline, 5-10 years to achieve reproduction maturity (Kelly and King, 2001), these declines can be partially explained by the European damming spree after the WWII. Still, not only our results show moderated losses, but also the genomics of the *Lampetra* genus is an evolving field where genetic diversity is still being assessed (e.g., Pereira et al., 2010) raising legitimate questions about historical data usage.

The European flounder uses freshwater networks though not progressing far away from estuaries, i.e., not occupying consistently low Strahler value segments independent of the basin size (Daverat et al., 2012). The lesser economic relevance of the species compared to sturgeon, salmon or eel may explain why it is scientifically understudied, justifying the scarcity of information about distribution and population dynamics (Skerritt, 2010). Nevertheless, recent studies have shown that this species exhibits an elevated plasticity in several of its life traits suggesting that catadromy is facultative (Calvès et al., 2013; Daverat et al., 2012). Observed functional losses do not seem to have affected species stocks since no severe decline has been reported. However, much like the lack of information about distribution, estuaries and inshore fisheries have been insufficiently studied and reported (Skerritt, 2010).

Contrary to previous species, functional connectivity losses for Houting and European smelt are higher at segment than sub-basin scale. The anadromous Houting species is absent of nearly all of its natural occurrence since its population declined and collapsed in many countries (e.g., Germany, Netherlands, Denmark) from early until the middle of the 20th century (de Groot, 1990a; Freyhof, 2002; Jepsen et al., 2012). One hypothesis for the bottleneck mortality of some populations is the premature arrival of juveniles into salt water (Jepsen et al., 2012). This may result from dams blocking access to upstream spawning grounds and species starting to utilise new areas further close to the sea, and thus taking less time for juveniles to migrate downwards. Pollution and overfishing are also indicated as factors contributing to their collapse (Freyhof and Schöter, 2005). This means that probably, small dams and other threats were already heavily affecting the species presence at the beginning of the 20th century making it absent from sub-basins. The taxonomical uncertainty associated with the Coregonidae family (Freyhof and Schöter, 2005) is also something that may have had a confounding effect in historical records and thus affected the presence data used.

The European smelt has both migratory (anadromous) and non-migratory (landlocked) forms (de Groot, 1990a; Švagždys, 2009). The migratory form occurs in estuaries and coastal areas and migrates to lower reaches of rivers, brackish tidal areas, and inlets of low salinity to spawn (de Groot, 1990a; Doherty and McCarthy, 2004; Quigley et al., 2004; Shpilev et al., 2005). In this context, the reduced progression of this species into freshwater networks explains the low amount of functional losses in our results at both segment and sub-basin scale. Nevertheless, one of the examples of a population extirpation is due to a dam constructed at the delta of the river Rhine (de Groot, 1990a).

Ponto-Caspian species (Russian sturgeon, Stellate sturgeon, Beluga and Pontic shad), i.e., species restricted to the freshwater networks draining to the Black, Azov and Caspian seas are the ones with higher functional connectivity losses. The four mentioned species are the only ones showing elevated losses at segment scale for two dam pressure classes and, all sturgeon species have lost access to half of the sub-basins where they were present. The number of main stem dams constructed in relevant basins (Volga, Don, Dnieper, Dniester Danube, Sakarya, Kisil and Yesil) during the 1950s, 1970s and 1980s explains the elevated loss rates in those decades. These dams have prevented sturgeon species from reaching their historical spawning grounds (Bacalbaşa-Dobrovici, 1997; Ivanov et al., 1999; Pourkazemi, 2006). In the case of Beluga, the spawning grounds were completely eliminated in the Caspian basins (Pourkazemi, 2006). Although damming is one of the major threats to affect Ponto-Caspian sturgeon species distribution and fisheries, there are two other severe threats: overfishing/poaching and pollution (Ivanov et al., 1999; Lenhardt et al., 2006; Williot et al., 2002). Sturgeon fishes have been exploited for many centuries, meaning that declines linked to overfishing both pre-date and have occurred alongside the emergence of large dams in the 20th-century (Bacalbaşa-Dobrovici, 1997; Ivanov et al., 1999; Pourkazemi, 2006). During the 1980s there were events of sturgeon mass mortalities in Caspian basins due to the excess of pesticides (Pourkazemi, 2006). Changes in the Black sea fauna, the presence of regions of hypoxia and anoxia and the eutrophication process during the second half of the 20th century (Zaitsev, 1992) are known to have affected the areas where sturgeons spend the marine period of their life cycle (Bacalbaşa-Dobrovici, 1997). Given that these are intensively used agricultural areas, with ion and oil extraction industries and a further potential to increase oil exploration (Ivanov et al., 1999; Lenhardt et al., 2006; Pourkazemi, 2006), pollution will probably remain as a threat. The Pontic shad occurs only in the Black and Azov seas, and has slightly lower functional losses comparing to species present in Caspian basins. Nevertheless, it was observed that Pontic shad occurrence and access to spawning grounds in multiple Black sea basins was reduced due to damming (Smederevac-Lalić et al., 2018; Vasil'Eva, 2003). Like the Ponto-Caspian sturgeons, damming is just one amongst many threats causing decline, other include temperature changes, habitat and water quality degradation, pollution and most importantly the increasing fishing effort (Ciolac and Patriche, 2004; Lenhardt et al., 2012). Contrary to sturgeons species, fish landings for Pontic shad have not collapsed entirely and remain a commercially important fishing resource (Ciolac and Patriche, 2004; Lenhardt et al., 2012; Rozdina et al., 2013) despite the low years and an overall decline (Smederevac-Lalić et al., 2018; Vasil'Eva, 2003).

European/Atlantic sturgeon complex shows also significant functional connectivity losses at both segment and sub-basin scale. These species were exploited for consumption and other by-products in most rivers which had vital populations (Williot et al., 2011). Subsequently, stocks started to decline at the latest in the early 19th century, partially due to dams but also because of overfishing poaching, pollution, water pumping and dredging (Lassalle et al., 2011; Ludwig et al., 2011; Williot et al., 2002). In Europe, the European/Atlantic sturgeon is virtually extinct except in the French Gironde-Garonne-Dordogne complex (Lassalle et al., 2011).

The Allis shad and the Twaite shad show relevant functional connectivity losses at both segment and sub-basin scale, higher for Twaite shad due to its occurrence in some Mediterranean basins where the number of impoundments is higher. Populations of these species are known to be seriously affected by dams given that a small obstruction can translate into an insurmountable obstacle (Aprahamian et al., 2003; Bagliniere et al., 2003), and there are examples of spawning grounds lost due to the construction of dams (de Groot, 1990b). However, other threats should be taken into consideration (e.g., channelisation, pollution, overfishing) because in most cases, fisheries and/or population declines or extirpation are a consequence of different or a combination of anthropogenic pressures that is basin specific (de Groot, 1990b; Maes et al., 2008; Thiel et al., 1996).

This is probably the first ever study to be made aiming to assess the status of structural and functional longitudinal connectivity impairment, for diadromous fish species, of all European freshwater networks throughout the 20th century, using historical data for several species and considering three spatial scales. This work offers a retrospective look at the impact of large dams on European freshwater networks, showing that European freshwater network have their structural longitudinal connectivity severely affected. It took only 60 years to go from hardly any impairment from large dams to nowadays situation in which more than two thirds of Europe’s very large rivers with structural connectivity problems. All diadromous fish species analysed have been affected by the hampering of longitudinal connectivity. Moreover, large dams have contributed to population extirpations and aggravated other threats, contributing decisively to the European decline of diadromous fish species. Considering that the longitudinal connectivity dimension of freshwater networks is one of the most relevant and defining characteristics of these ecosystems, the current situation is certainly debilitating the ecological status of the majority of European rivers. Dam removal is becoming an increasingly studied, analysed and pondered option to deal with freshwater networks longitudinal disconnectivity (Bednarek, 2001; Fox et al., 2016; Stanley and Doyle, 2003). Multiple publications dwell on barrier removal prioritisation (e.g., Branco et al., 2014; Kemp and O'Hanley, 2010; O'Hanley et al., 2013). When looking at large dams, and considering particularly anadromous species, the structural connectivity results give a clear indication of a general guideline to improve connectivity. Removal should look first at the main stem dams, preferably starting from the one closer to the mouth. Whatever the options may be, in the context of the implementation of the Water Frame Directive, the current scenario of diadromous fish species decline and the hampering of longitudinal connectivity must be addressed.

5.7 References

Allan, J.D. (2004) Landscapes and Riverscapes: The Influence of Land Use on Stream Ecosystems. Annual Review of Ecology, Evolution and Systematics 35, 257-284.

Aprahamian, M.W., Bagliniere, J.-L., Sabatie, M.R., Alexandrino, P., Thiel, R., Aprahamian, C.D., (2003) Biology, status, and conservation of the anadromous Atlantic twaite shad Alosa fallax fallax, American Fisheries Society Symposium, pp. 103-124.

Armstrong, J.D., Kemp, P.S., Kennedy, G.J.A., Ladle, M., Milner, N.J. (2003) Habitat requirements of Atlantic salmon and brown trout in rivers and streams. Fisheries Research 62, 143-170.

Bacalbaşa-Dobrovici, N. (1997) Endangered migratory sturgeons of the lower Danube River and its delta. Environmental Biology of Fishes 48, 201-207.

Bagliniere, J.-L., Sabatié, M.R., Rochard, E., Alexandrino, P., Aprahamian, M.W., (2003) The Allis shad Alosa alosa: biology, ecology, range, and status of populations, American Fisheries Society Symposium, pp. 85-102.

Bakke, T.A., Harris, P.D. (1998) Diseases and parasites in wild Atlantic salmon (Salmo salar) populations. Canadian Journal of Fisheries and Aquatic Sciences 55, 247-266.

Barbet-Massin, M., Jiguet, F., Albert, C.H., Thuiller, W. (2012) Selecting pseudo-absences for species distribution models: how, where and how many? Methods in Ecology and Evolution 3, 327-338.

Bednarek, A.T. (2001) Undamming Rivers: A Review of the Ecological Impacts of Dam Removal. Environmental Management 27, 803-814.

Berg, L. (1962-65a) Freshwater fishes of the U.S.S.R. and adjacent countries. Israel Program for Scientific Translations, Jerusalem.

Berg, L. (1962-65b) Freshwater fishes of the U.S.S.R. and adjacent countries. Israel Program for Scientific Translations, Jerusalem.

Berg, L. (1962-65c) Freshwater fishes of the U.S.S.R. and adjacent countries. Israel Program for Scientific Translations, Jerusalem.

Bergkamp, G., McCartney, M.P., Dugan, P., McNeely, J., Acreman, M.C., Resources, Environment, Dams, W.C.o., (2000) Dams, Ecosystem Functions and Environmental Restoration. Prepared for the World Commission on Dams (WCD), Cape Town, South Africa.

Branco, P., Amaral, S.D., Ferreira, M.T., Santos, J.M. (2017) Do small barriers affect the movement of freshwater fish by increasing residency? Science of the Total Environment 581-582, 486-494.

Branco, P., Santos, J.M., Amaral, S., Romão, F., Pinheiro, A.N., Ferreira, M.T. (2016) Potamodromous fish movements under multiple stressors: Connectivity reduction and oxygen depletion. Science of the Total Environment 572, 520-525.

Branco, P., Segurado, P., Santos, J.M., Ferreira, M.T., Strecker, A. (2014) Prioritizing barrier removal to improve functional connectivity of rivers. Journal of Applied Ecology 51, 1197-1206.

Branco, P., Segurado, P., Santos, J.M., Pinheiro, P., Ferreira, M.T. (2012) Does longitudinal connectivity loss affect the distribution of freshwater fish? Ecological Engineering 48, 70-78.

Calow, P.P., Petts, G.E. (1992) The Rivers Handbook. Blackwell Scientific Publications, Oxford.

Calvès, I., Lavergne, E., Meistertzheim, A.L., Charrier, G., Cabral, H., Guinand, B., Quiniou, L., Laroche, J. (2013) Genetic structure of European flounder Platichthys flesus: effects of both the southern limit of the species' range and chemical stress. Marine Ecology Progress Series 472, 257-273.

Chao, B.F. (1995) Anthropogenic impact on global geodynamics due to reservoir water impoundment. Geophysical Research Letters 22, 3529-3532.

Chassaing, O., Desse-Berset, N., Duffraisse, M., Hughes, S., Hänni, C., Berrebi, P. (2013) Palaeogenetics of western French sturgeons spotlights the relationships between Acipenser sturio and Acipenser oxyrinchus. Journal of Biogeography 40, 382-393.

Ciolac, A., Patriche, N. (2004) Structure of Danube shad (Alosa pontica Eichwald, 1838) spawner flocks migrating for reproduction in Danube River (Migration of fishes in Romanian Danube River Nº 2). Applied Ecology and Environmental Research 2, 53-58.

Clavero, M., Hermoso, V. (2015) Historical data to plan the recovery of the European eel. Journal of Applied Ecology 52, 960-968.

Cote, D., Kehler, D.G., Bourne, C., Wiersma, Y.F. (2009) A new measure of longitudinal connectivity for stream networks. Landscape Ecology 24, 101-113.

Daverat, F., Morais, P., Dias, E., Babaluk, J., Martin, J., Eon, M., Fablet, R., Pécheyran, C., Antunes, C. (2012) Plasticity of European flounder life history patterns discloses alternatives to catadromy. Marine Ecology Progress Series 465, 267-280.

de Groot, S.J. (1990a) Decline of the catches of coregonids and migratory smelt in the lower Rhine, The Netherlands. Journal of Applied Ichthyology 6, 247-251.

de Groot, S.J. (1990b) The former allis and twaite shad fisheries of the lower Rhine, The Netherlands. Journal of Applied Ichthyology 6, 252-256.

de Groot, S.J. (2002) A review of the past and present status of anadromous fish species in the Netherlands: is restocking the Rhine feasible? Hydrobiologia 478, 205-218.

Doherty, D., McCarthy, T.K. (2004) The Ecology and Conservation of European smelt (Osmerus eperlanus L.) from Waterford Estuary, in Southeastern Ireland. Biology and Environment: Proceedings of the Royal Irish Academy 104B, 125-130.

Duarte, G., Branco, P., Haidvogl, G., Pont, D., Ferreira, M.T., Segurado, P., (2018a) Integrating historical fish data – Selecting pseudo-occurrences, International Symposium on Ecohydraulics, Tokyo, Japan.

Duarte, G., Moreira, M., Branco, P., Costa, L.d., Ferreira, M.T., Segurado, P., (2018b) Portuguese Historical Fish Database (PHish–DB). Open Science Framework, Portugal, Lisbon.

Duarte, G., Segurado, P., Oliveira, T., Haidvogl, G., Pont, D., Ferreira, M.T., Branco, P. (in press) The River Network Toolkit – RivTool. Ecography 42, 1-9.

Elith, J., H. Graham, C., P. Anderson, R., Dudík, M., Ferrier, S., Guisan, A., J. Hijmans, R., Huettmann, F., R. Leathwick, J., Lehmann, A., Li, J., G. Lohmann, L., A. Loiselle, B., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., McC. M. Overton, J., Townsend Peterson, A., J. Phillips, S., Richardson, K., Scachetti-Pereira, R., E. Schapire, R., Soberón, J., Williams, S., S. Wisz, M., E. Zimmermann, N. (2006) Novel methods improve prediction of species' distributions from occurrence data. Ecography 29, 129-151.

ESRI, (2011) ArcGIS Desktop: Release 10. Environmental Systems Research Institute, Redlands, CA.

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 in: Parliament, E. (Ed.), L 327, The Official Journal of the European Union, p. 93.

Fausch, K.D., Torgersen, C.E., Baxter, C.V., Li, H.W. (2002) Landscapes to Riverscapes: Bridging the Gap between Research and Conservation of Stream Fishes: A Continuous View of the River is Needed to Understand How Processes Interacting among Scales Set the Context for Stream Fishes and Their Habitat. Bioscience 52, 483-498.

Feunteun, E. (2002) Management and restoration of European eel population (Anguilla anguilla): An impossible bargain. Ecological Engineering 18, 575-591.

Foster, D.R., (2000) Conservation lessons & challenges from ecological history, Forest History Today, pp. 2-11.

Fourcade, Y. (2016) Comparing species distributions modelled from occurrence data and from expert-based range maps. Implication for predicting range shifts with climate change. Ecological Informatics 36, 8-14.

Fox, C.A., Magilligan, F.J., Sneddon, C.S. (2016) "You kill the dam, you are killing a part of me": Dam removal and the environmental politics of river restoration. Geoforum 70, 93-104.

Freyhof, J., (2002) Freshwater fish diversity in Germany, threats and species extinction, in: Collares-Pereira, M.J., Cowx, I.G., Coelho, M.M. (Eds.), Conservation of Freshwater Fishes: Options for the Future. Blackwell Science, Oxford, pp. 3-22.

Freyhof, J., Schöter, C. (2005) The Houting Coregonus oxyrinchus(L.)(Salmoniformes: Coregonidae), a globally extinct species from the North Sea basin. Journal of Fish Biology 67, 713-729.

Frissell, C.A., Liss, W.J., Warren, C.E., Hurley, M.D. (1986) A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. Environmental Management 10, 199-214.

Garcia de Leaniz, C. (2008) Weir removal in salmonid streams: implications, challenges and practicalities. Hydrobiologia 609, 83-96.

Gaston, K.J., Blackburn, T.M., (2007) The Macroecological Perspective, Pattern and Process in Macroecology. Blackwell Science Ltd, United Kingdom, pp. 1-34.

Haidvogl, G., Lajus, D., Pont, D., Schmid, M., Jungwirth, M., Lajus, J. (2013) Typology of historical sources and the reconstruction of long-term historical changes of riverine fish: a case study of the Austrian Danube and northern Russian rivers. Ecology of Freshwater Fish 23, 498–515.

Hansen, L., Windsor, M. (2006) Interactions between Aquaculture and Wild Stocks of Atlantic salmon and other Diadromous Fish Species: Science and Management, Challenges and SolutionsAn introduction by the Conveners. ICES Journal of Marine Science 63, 1159-1161.

Hayes, D.S., Branco, P., Santos, J.M., Ferreira, M.T. (in prep) Oxygen depletion affects kinematics and shoaling cohesion of cyprinid fish. River Research and Applications.

Helfman, G.S. (2007) Fish conservation: a guide to understanding and restoring global aquatic biodiversity and fishery resources. Island Press, Washington, DC, USA.

Humphries, P., Winemiller, K.O. (2009) Historical Impacts on River Fauna, Shifting Baselines, and Challenges for Restoration. Bioscience 59, 673-684.

Imbert, H., De Lavergne, S., Gayou, F., Rigaud, C., Lambert, P. (2008) Evaluation of relative distance as new descriptor of yellow European eel spatial distribution. Ecology of Freshwater Fish 17, 520-527.

Ivanov, V.P., Vlasenko, A.D., Khodorevskaya, R.P., Raspopov, V.M. (1999) Contemporary status of Caspian sturgeon (Acipenseridae) stock and its conservation. Journal of Applied Ichthyology 15, 103-105.

Jackson, S.T., Hobbs, R.J. (2009) Ecological Restoration in the Light of Ecological History. Science 325, 567-569.

Jepsen, N., Deacon, M., Koed, A. (2012) Decline of the North Sea Houting: and protective measures for an endangered anadromous fish. Endangered Species Research 16, 77-84.

Jonsson, B., Jonsson, N. (2009) A review of the likely effects of climate change on anadromous Atlantic salmon Salmo salar and brown trout Salmo trutta, with particular reference to water temperature and flow. Journal of Fish Biology 75, 2381-2447.

Junge, C., Museth, J., Hindar, K., Kraabøl, M., Vøllestad, L.A. (2013) Assessing the consequences of habitat fragmentation for two migratory salmonid fishes. Aquatic Conservation: Marine and Freshwater Ecosystems 24, 297-311.

Junk, W.J., Bayley, P.B., Sparks, R.E. (1989) The flood pulse concept in river-floodplain systems. Canadian special publication of fisheries and aquatic sciences 106, 110-127.

Kelly, F.L., King, J.J. (2001) A Review of the Ecology and Distribution of Three Lamprey Species, Lampetra fluviatilis (L.), Lampetra planeri (Bloch) and Petromyzon marinus (L.): A Context for Conservation and Biodiversity Considerations in Ireland. Biology and Environment: Proceedings of the Royal Irish Academy 101B, 165-185.

Kemp, P.S., O'Hanley, J.R. (2010) Procedures for evaluating and prioritising the removal of fish passage barriers: a synthesis. Fisheries Management and Ecology 17, 297-322.

Kettle, A.J., Asbjørn Vøllestad, L., Wibig, J. (2011) Where once the eel and the elephant were together: decline of the European eel because of changing hydrology in southwest Europe and northwest Africa? Fish and Fisheries 12, 380-411.

Kottelat, M., Freyhof, J. (2007) Handbook of European freshwater fishes. Publications Kottelat Cornol.

Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.-H., Haberl, H., Fischer-Kowalski, M. (2009) Growth in global materials use, GDP and population during the 20th century. Ecological Economics 68, 2696-2705.

Larinier, M., (2001) Environmental issues, dams and fish migration, in: Marmulla, G. (Ed.), Dams, fish and fisheries. Opportunities, challenges and conflict resolution. FAO Fisheries Technical Paper, Rome, pp. 45-90.

Lassalle, G., Béguer, M., Rochard, E., (2011) An Overview on Geographical Distribution from Past Descriptions, in: Williot, P., Rochard, E., Desse-Berset, N., Kirschbaum, F., Gessner, J. (Eds.), Biology and Conservation of the European SturgeonAcipenser sturioL. 1758: The Reunion of the European and Atlantic Sturgeons. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 81-90.

Lehner, B., Reidy Liermann, C., Revenga, C., Vorosmarty, C., Fekete, B., Crouzet, P., Doll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J.C., Rodel, R., Sindorf, N., Wisser, D., (2011a) Global Reservoir and Dam Database, Version 1 (GRanDv1): Dams, Revision 01. Global Water System Project, Palisades, NY.

Lehner, B., Reidy Liermann, C., Revenga, C., Vorosmarty, C., Fekete, B., Crouzet, P., Doll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J.C., Rodel, R., Sindorf, N., Wisser, D. (2011b) High-Resolution Mapping of the World's Reservoirs and Dams for Sustainable River-Flow Management. Frontiers in Ecology and the Environment 9, 494-502.

Lenhardt, M., Jaric, I., Kalauzi, A., Cvijanovic, G. (2006) Assessment of Extinction Risk and Reasons for Decline in Sturgeon. Biodiversity & Conservation 15, 1967-1976.

Lenhardt, M., Višnjić-Jeftić, Ž., Navodaru, I., Jarić, I., Vassilev, M., Gačić, Z., Nikčević, M., (2012) Fish Stock Management Cooperation in the Lower Danube Region: A Case Study of Sturgeons and Pontic shad. Springer Netherlands, Dordrecht, pp. 127-140.

Liermann, C.R., Nilsson, C., Robertson, J., Ng, R.Y. (2012) Implications of Dam Obstruction for Global Freshwater Fish Diversity. Bioscience 62, 539-548.

Lucas, M.C., Bubb, D.H., Jang, M.-H., Ha, K., Masters, J.E.G. (2009) Availability of and access to critical habitats in regulated rivers: effects of low-head barriers on threatened lampreys. Freshwater Biology 54, 621-634.

Ludwig, A., Debus, L., Lieckfeldt, D., Wirgin, I., Benecke, N., Jenneckens, I., Williot, P., Waldman, J.R., Pitra, C. (2002) When the American sea sturgeon swam east. Nature 419, 447.

Ludwig, A., Morales-Muñiz, A., Roselló-Izquierdo, E., (2011) Sturgeon in Iberia from Past to Present, in: Williot, P., Rochard, E., Desse-Berset, N., Kirschbaum, F., Gessner, J. (Eds.), Biology and Conservation of the European Sturgeon Acipenser sturio L. 1758: The Reunion of the European and Atlantic Sturgeons. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 131-146.

Maes, J., Stevens, M., Breine, J. (2008) Poor water quality constrains the distribution and movements of twaite shad Alosa fallax fallax (Lacépède, 1803) in the watershed of river Scheldt. Hydrobiologia 602, 129-143.

Maitland, P.S. (1980) Review of the Ecology of Lampreys in Northern Europe. Canadian Journal of Fisheries and Aquatic Sciences 37, 1944-1952.

Mateus, C.S., Rodríguez-Muñoz, R., Quintella, B.R., Alves, M.J., Almeida, P.R. (2012) Lampreys of the Iberian Peninsula: distribution, population status and conservation. Endangered Species Research 16, 183-198.

Matthews, W.J. (1998) Patterns in freshwater fish ecology. Chapman & Hall, New York, USA.

Nicola, G., Elvira, B., Almodóvar, A. (1996) Dams and fish passage facilities in the large rivers of Spain: effects on migratory species. Large Rivers 10, 375-379.

Nilsson, C., Ekblad, A., Dynesius, M., Backe, S., Gardfjell, M., Carlberg, B., Hellqviist, S., Jansson, R. (1994) A Comparison of Species Richness and Traits of Riparian Plants between a Main River Channel and Its Tributaries. Journal of Ecology 82, 281-295.

Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C. (2005) Fragmentation and Flow Regulation of the World's Large River Systems. Science 308, 405-408.

O'Hanley, J.R., Wright, J., Diebel, M., Fedora, M.A., Soucy, C.L. (2013) Restoring stream habitat connectivity: a proposed method for prioritizing the removal of resident fish passage barriers. Journal of Environmental Management 125, 19-27.

Parrish, D.L., Behnke, R.J., Gephard, S.R., McCormick, S.D., Reeves, G.H. (1998) Why aren't there more Atlantic salmon (Salmo salar)? Canadian Journal of Fisheries and Aquatic Sciences 55, 281-287.

Pelicice, F.M., Pompeu, P.S., Agostinho, A.A. (2015) Large reservoirs as ecological barriers to downstream movements of Neotropical migratory fish. Fish and Fisheries 16, 697-715.

Pereira, A.M., Robalo, J.I., Freyhof, J., Maia, C., Fonseca, J.P., Valente, A., Almada, V.C. (2010) Phylogeographical analysis reveals multiple conservation units in brook lampreys Lampetra planeri of Portuguese streams. Journal of Fish Biology 77, 361-371.

Pigott, D.M., Bhatt, S., Golding, N., Duda, K.A., Battle, K.E., Brady, O.J., Messina, J.P., Balard, Y., Bastien, P., Pratlong, F., Brownstein, J.S., Freifeld, C.C., Mekaru, S.R., Gething, P.W., George, D.B., Myers, M.F., Reithinger, R., Hay, S.I. (2014) Global distribution maps of the leishmaniases. eLife 3, e02851.

Pizzuto, J.E., Hession, W.C., McBride, M. (2000) Comparing gravel-bed rivers in paired urban and rural catchments of southeastern Pennsylvania. Geology 28, 79-82.

Pourkazemi, M. (2006) Caspian Sea sturgeon Conservation and Fisheries: Past present and Future. Journal of Applied Ichthyology 22, 12-16.

Quigley, D.T.G., Igoe, F., O'Connor, W. (2004) The European smelt Osmerus eperlanus L. in Ireland: General Biology, Ecology, Distribution and Status with Conservation Recommendations. Biology and Environment: Proceedings of the Royal Irish Academy 104B, 57-66.

Rackham, O., (1998) Implications of historical ecology for conservation, in: Sutherland, W.J. (Ed.), Conservation Science and Action, 1st ed. Blackwell Publishing Company, pp. 152-175.

Rivinoja, P., McKinnell, S., Lundqvist, H. (2001) Hindrances to upstream migration of Atlantic salmon (Salmo salar) in a northern Swedish river caused by a hydroelectric power-station. Regulated Rivers: Research & Management 17, 101-115.

Rozdina, D., Raikova-Petrova, G., Mirtcheva, P. (2013) Age composition and growth rate of the spawning part of the population of Pontic shad Alosa immaculata (Bennett, 1835) in the Bulgarian sector of Danube River, Bulg. J. Agric. Sci., Supplement 1, 118-125.

Sala, O.E. (2000) Global Biodiversity Scenarios for the Year 2100. Science 287, 1770-1774.

Sandøy, S., Langåker, R.M. (2001) Atlantic salmon and Acidification in Southern Norway: A Disaster in the 20th Century, but a Hope for the Future? Water, Air, and Soil Pollution 130, 1343-1348.

Segurado, P., Branco, P., Avelar, A., Ferreira, M. (2014) Historical changes in the functional connectivity of rivers based on spatial network analysis and the past occurrences of diadromous species in Portugal. Aquatic Sciences, 1-14.

Seppälä, M. (2005) The Physical Geography of Fennoscandia. Oxford University Press.

Shpilev, H., Ojaveer, E., Lankov, A. (2005) Smelt (Osmerus eperlanus L.) in the Baltic Sea. Proc. Estonian Acad. Sci. Biol. Ecol Biol. Ecol 54, 230-241.

Sinka, M.E., Rubio-Palis, Y., Manguin, S., Patil, A.P., Temperley, W.H., Gething, P.W., Van Boeckel, T., Kabaria, C.W., Harbach, R.E., Hay, S.I. (2010) The dominant Anopheles vectors of human malaria in the Americas: occurrence data, distribution maps and bionomic précis. Parasites & Vectors 3, 72.

Skerritt, D., (2010) A review of the European flounder Platichthys flesus–biology, life history and trends in population, Eastern Sea Fisheries Joint Committee Report. . Newcastle University, Newcastle, p. 13.

Smederevac-Lalić, M., Kalauzi, A., Regner, S., Navodaru, I., Višnjić-Jeftić, Ž., Gačić, Z., Lenhardt, M. (2018) Analysis and forecast of Pontic shad (Alosa immaculata) catch in the Danube River. Iranian journal of fisheries sciences 17, 443-457.

Stanley, E.H., Doyle, M.W. (2003) Trading off: the ecological effects of dam removal. Frontiers in Ecology and the Environment 1, 15-22.

Strahler, A.N. (1957) Quantitative analysis of watershed geomorphology. Eos, Transactions American Geophysical Union 38, 913-920.

Švagždys, A. (2009) Impact of environmental conditions on smelt catch fluctuations in the Nemunas River and the Curonian Lagoon. Ekologija 55.

Swetnam, T.W., Allen, C.D., Betancourt, J.L. (1999) Applied Historical Ecology: using the past to manage for the future. Ecological Applications 9, 1189-1206.

Thiel, R., Sepülveda, A., Oesmann, S., (1996) Occurrence and distribution of twaite shad (Alosa fallax Lacépède) in the lower Elbe River, Germany, in: Kirchhofer, A., Hefti, D. (Eds.), Conservation of Endangered Freshwater Fish in Europe. Birkhäuser Basel, Basel, pp. 157-170.

Thorp, J.H., Delong, M.D. (1994) The Riverine Productivity Model: An Heuristic View of Carbon Sources and Organic Processing in Large River Ecosystems. Oikos 70, 305-308.

Tiedemann, R., Moll, K., Paulus, K.B., Scheer, M., Williot, P., Bartel, R., Gessner, J., Kirschbaum, F. (2007) Atlantic sturgeons (Acipenser sturio, Acipenser oxyrinchus): American females successful in Europe. Naturwissenschaften 94, 213-217.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E. (1980) The River Continuum Concept. Canadian Journal of Fisheries and Aquatic Sciences 37, 130-137.

Vasil'Eva, E.D. (2003) Main alterations in ichthyofauna of the largest rivers of the northern coast of the Black Sea in the last 50 years: A review. FOLIA ZOOLOGICA-PRAHA- 52, 337-358.

Vogt, J., Soille, P., Jager, A.d., Rimavičiūtė, E., Mehl, W., Foisneau, S., Bódis, K., Dusart, J., Paracchini, M.L., Haastrup, P., Bamps, C., (2007) A pan-European River and Catchment Database. European Commission - Joint Research Centre - Institute for Environment and Sustainability, Luxembourg, p. 120.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B. (2000) Global Water Resources: Vulnerability from Climate Change and Population Growth. Science 289, 284-288.

Ward, J.V. (1989) The Four-Dimensional Nature of Lotic Ecosystems. Journal of the North American Benthological Society 8, 2-8.

Warren, M.L., Pardew, M.G. (1998) Road Crossings as Barriers to Small-Stream Fish Movement. Transactions of the American Fisheries Society 127, 637-644.

Wheeler, A.P., Angermeier, P.L., Rosenberger, A.E. (2005) Impacts of New Highways and Subsequent Landscape Urbanization on Stream Habitat and Biota. Reviews in Fisheries Science 13, 141-164.

Williot, P., Arlati, G., Chebanov, M., Gulyas, T., Kasimov, R., Kirschbaum, F., Patriche, N., Pavlovskaya, L.P., Poliakova, L., Pourkazemi, M., Kim, Y., Zhuang, P., Zholdasova, I.M. (2002) Status and Management of Eurasian Sturgeon: An Overview. International Review of Hydrobiology 87, 483-506.

Williot, P., Rochard, E., Desse-Berset, N., Gessner, J., Kirschbaum, F., (2011) Brief Introduction to Sturgeon with a Special Focus on the European Sturgeon, Acipenser sturio L. 1758, in: Williot, P., Rochard, E., Desse-Berset, N., Kirschbaum, F., Gessner, J. (Eds.), Biology and Conservation of the European SturgeonAcipenser sturioL. 1758: The Reunion of the European and Atlantic Sturgeons. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 3-11.

Zaitsev, Y.P. (1992) Recent changes in the trophic structure of the Black Sea. Fisheries Oceanography 1, 180-189.

6. Early 20th-century potential distributions of diadromous fish species in Europe

---

Gonçalo Duarte, Paulo Branco, Gertrud Haidvogl, Didier Pont, Maria Teresa Ferreira, Pedro Segurado

Proceeding from the 12th International Symposium on Ecohydraulics

19 August 2018

6.1 Abstract

Several European diadromous fish species have been declining or going regionally extinct at least since the beginning of the 20th century. In this work, we combined historical information and empirical modelling techniques to estimate the potential distribution of several European diadromous fish species at the beginning of the 20th century. The models also included, as explanatory variables, historical climate, historical land use and river network features. A hierarchically structured effect among explanatory variables was taken into account in the modelling procedure, assuming that different set of variables operated at different spatial resolutions in the European river networks. Climate variables were overall more relevant than land use variables and most species seem to be sensitive to elevated temperature ranges. This work can help identify and establish adequate management and restoration objectives.

6.2 Introduction

Freshwater covers 0.8% of the surface of the Earth and represents 0.01% of all the water in the world but are home to nearly 6% of all know species (Dudgeon et al., 2006). Freshwater ecosystems are also one of the most endangered environments worldwide (Dudgeon et al., 2006; Ricciardi and Rasmussen, 1999). Biodiversity loss, population declines (Dudgeon et al., 2006) and habitat deterioration (Nel et al., 2009) have been caused by numerous threats and stressors such as: overexploitation, land-use changes, pollution, water abstraction, loss of longitudinal connectivity, habitat destruction and degradation, climate change and invasive species (Dudgeon et al., 2006; Nel et al., 2009). These underlying causes of biodiversity decline will not cease or decrease in the near future due to their anthropogenic nature. In fact, some are expected to seriously be aggravated (e.g., climate change, land-use, water abstraction). Freshwater ecosystems are especially sensitive to both land-use and climatic changes (Kuemmerlen et al., 2015). Climate change has been reckoned as one of the most problematic and troubling challenge for mankind (Ripple et al., 2017). It is altering species distributions (Limburg and Waldman, 2009; Thomas et al., 2006) and leading to regional declines, range retractions and species extinctions (Thomas et al., 2006). Several authors have identified various effects of climate change on diadromous fish species, e.g.: decrease in the frequency of successful annual reproduction for anadromous species due to intensification of the harshness of flood and drought periods (Limburg and Waldman, 2009); phenology changes of anadromous species towards earlier spawning runs (Limburg and Waldman, 2009); shifts in species distribution (Lassalle et al., 2008); reduction of suitable areas to a close to extinction situation (Lassalle et al., 2009a); possible regional extinctions (Filipe et al., 2013; Lassalle et al., 2008). The future dynamically changing climate and environment will probably impose complex and unpredictable alterations to the relationship of saltwater and freshwater habitats (Limburg and Waldman, 2009) to which diadromous fish populations will have to adjust. Climate change is both a driver and a consequence of the alteration of land-use activities (Rounsevell et al., 2006). Anthropogenic induced changes in the landscape affect freshwater ecosystems at different scales via multiple processes (Allan et al., 1997). Several authors have identified numerous disturbances related with human land-use (e.g., nutrient and pesticide input (Falcone et al., 2010), channel modification (Falcone et al., 2010), deforestation (Tockner et al., 2009), water impoundment (Falcone et al., 2010), conversion of natural vegetation to developed land (Falcone et al., 2010; Lohse et al., 2008), causing alteration and disruption in freshwater system functioning (e.g., changes in discharge and sediment transport (Falcone et al., 2010; Lohse et al., 2008), erosion (Falcone et al., 2010), water quality (Falcone et al., 2010; Lohse et al., 2008), run-off alterations (Falcone et al., 2010) and inevitably affecting aquatic biodiversity (Bradford and Irvine, 2000; Lohse et al., 2008; Ricciardi and Rasmussen, 1999). In fact, swift land-use alterations have been linked to the decline of economically valuable fisheries and to disproportioned elevated number of endangered aquatic species (Ricciardi and Rasmussen, 1999). Several studies have identified detrimental impacts of types of land-use on fish fauna (Bradford and Irvine, 2000; Lohse et al., 2008). Riverine ecosystems have been modified by humans for centuries (Haidvogl et al., 2013), meaning that historical ecology can provide fundamental insights that can reshape and improve our understanding of these constantly evolving ecosystems (Vellend et al., 2013). Looking for historical sources and analyzing the historical data therein is a challenging task (Haidvogl et al., 2013). Notwithstanding all interpretation uncertainties, such as data fragmentation and multiple limitations, the utility and relevance of using historical fish occurrence data for modelling purposes has been proved by numerous studies (Clavero et al., 2017; Lassalle et al., 2008; Segurado et al., 2014). In terms of European fish ecology, the large number of available fish biological surveys since the 19th century may be helpful to improve the insight about potential future trends related with climate change or biological conservation (Haidvogl et al., 2013). In this work, we combined historical information and empirical modelling techniques to estimate the potential distribution of several European diadromous fish species at the beginning of the 20th century. Historical climate, historical land use and several river network features were used as explanatory variables, which allows the assessment of what variables are relevant for European diadromous fish species distribution.

6.3 Methods

European diadromous fish species are migratory animals with pertinent social (Limburg and Waldman, 2009) and economic relevance (Lassalle et al., 2009a). These animals are an energy link between oceans and freshwater systems and part of the food web in both environments (Limburg and Waldman, 2009). For the empirical modelling of diadromous fish species historical distribution we used generalised linear mixed models (GLMMs) because they are one of the best tools to analyse data involving random effects and may deal with error distributions other than the normal distribution (Bolker et al., 2009). A hierarchically structured effect among explanatory variables was taken into account in the modelling procedure, assuming that different set of variables operated at different spatial resolutions in the European river networks. Hence, climate variables were used at the basin scale and land-use variables at the sub-basin scale. Fish species historical data was obtained using the Historical EFI+ database (unpublished), EFI+ database (http://efi-plus.boku.ac.at), EuroDiad 2.0 database (Irstea, Cestas, France), FAME database (https://fame.boku.ac.at), PHish Database (unpublished) and the Handbook of European Freshwater Fishes (Kottelat and Freyhof, 2007). The hydrological network digital database used was the Catchment Characterisation and Modelling (CCM 2.1) (http://inspire-geoportal.ec.europa.eu/demos/ccm). The historical climate dataset used was the CRU TS3.23 (https://crudata.uea.ac.uk/cru/data/hrg), and the historical land-use dataset was the LUHa.v1 (http://luh.umd.edu). We have also used The River Network Toolkit

(RivTool) (http://rivtoolkit.com) to perform summarisations and calculations using the mentioned datasets and taking into account the hierarchical and network nature of freshwater networks represented in the CCM2.1.

6.4 Results and Discussion

In accordance with other studies (Filipe et al., 2013; Lassalle et al., 2008), our results indicate that climate affects the distribution of European diadromous fish species. According to our work these species are more prone to occur: in larger basins, which is probably related with the tendency to have larger environmental heterogeneity in larger areas (Williams, 1964) and the species-area theory (MacArthur, 1972); in areas where there is a lower average range of temperatures, which indicates species tend to be sensitive to elevated ranges between maximum and minimum yearly temperatures; and a higher minimum precipitation, normally occurring during summer and related with habitat features (e.g., discharge, depth, speed) of river pathways towards spawning grounds. More specifically, Salmon tends to occur in areas with lower summer temperatures, which is expectable since salmon is a cold water species (Kottelat and Freyhof, 2007). Climate variables were overall more relevant than land use variables. The selected land-use variables reflect that migratory species inevitably are more present closer to the river mouth. Additionally, fish have to enter and exit rivers to migrate, and therefore fisheries and historical records are available in larger quantity at river mouths. Other relevant feature of this methodological approach is the ability to improve predictions from one scale to another. Despite the fact that climate variables (basin scale) are more important than land-use variables (sub-basin scale), using the later helped gaining discriminative power in the predictions (Figure 1). Climate predictions for 2100 indicate an increase in temperature, but more importantly, they indicate a higher frequency of extreme events involving both precipitation and temperature. Hence, yearly temperature range will increase while minimum precipitation will tend to decrease, rendering some European areas probably unsuitable for diadromous fish species. This work can be used as a basis to obtain adequate predictions that would inform about the potential unsuitable areas. Thus, it will contribute to identify and establish adequate management and restoration objectives, allowing for a more comprehensive and accurate conservation strategy to be pursued

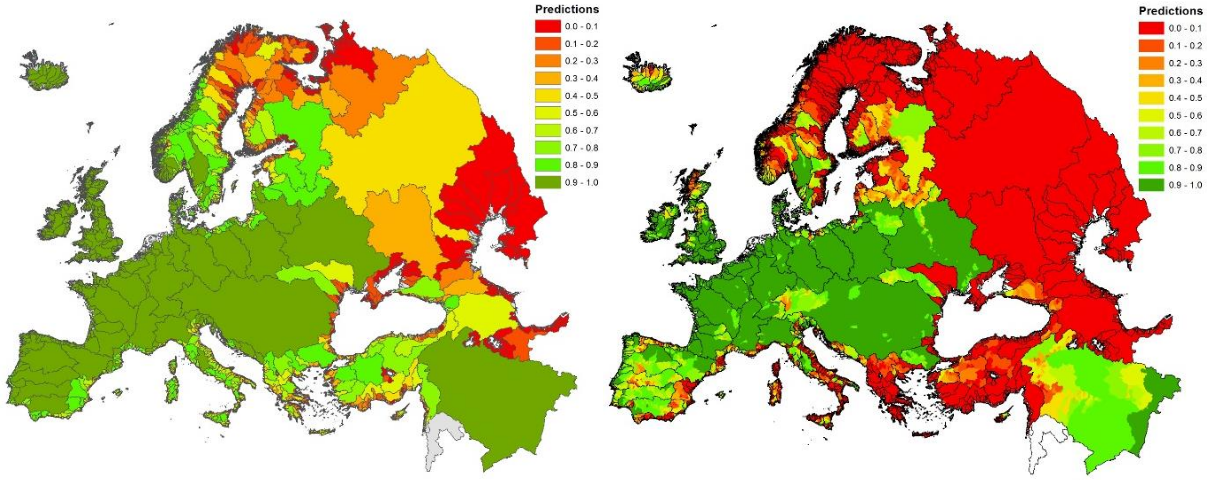


Figure 6.4.19 – Representation of the predictions obtained for *Petromizon marinus*. Left: representation of the predictions at the basin scale where only climate variables were used; Right: representation of the predictions at the sub-basin scale incorporating results from the model at the basin scale and using the land-use variable.

6.5 Acknowledgments

Gonçalo Duarte is part of the FLUVIO doctoral program and financed by a grant from the Fundação para a Ciência e Tecnologia (FCT) (SFRH/BD/52514/2014). Paulo Branco was financed by a post-doc grant from FCT (SFRH/BPD/94686/2013). Pedro Segurado is supported by a contract funded by the Fundação para a Ciência e Tecnologia (FCT) under the IF Researcher Programme (IF/01304/2015). CEF is a research unit funded by Fundação para a Ciência e a Tecnologia I.P. (FCT), Portugal (UID/AGR/00239/2013).

6.6 References

Allan, D., Erickson, D., Fay, J. (1997) The influence of catchment land use on stream integrity across multiple spatial scales. Freshwater Biology 37, 149-161.

Bolker, B.M., Brooks, M.E., Clark, C.J., Geange, S.W., Poulsen, J.R., Stevens, M.H.H., White, J.-S.S. (2009) Generalized linear mixed models: a practical guide for ecology and evolution. Trends in Ecology & Evolution 24, 127-135.

Bradford, M.J., Irvine, J.R. (2000) Land use, fishing, climate change, and the decline of Thompson River, British Columbia, coho salmon. Canadian Journal of Fisheries and Aquatic Sciences 57, 13-16.

Clavero, M., Ninyerola, M., Hermoso, V., Filipe, A.F., Pla, M., Villero, D., Brotons, L., Delibes, M. (2017) Historical citizen science to understand and predict climate-driven trout decline. Proceedings of the Royal Society B: Biological Sciences 284, 20161979.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.-I., Knowler, D.J., Lévêque, C., Naiman, R.J., Prieur-Richard, A.-H., Soto, D., Stiassny, M.L.J., Sullivan, C.A. (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. Biological Reviews 81, 163-182.

Falcone, J.A., Carlisle, D.M., Weber, L.C. (2010) Quantifying human disturbance in watersheds: Variable selection and performance of a GIS-based disturbance index for predicting the biological condition of perennial streams. Ecological Indicators 10, 264-273.

Filipe, A.F., Markovic, D., Pletterbauer, F., Tisseuil, C., De Wever, A., Schmutz, S., Bonada, N., Freyhof, J. (2013) Forecasting fish distribution along stream networks: brown trout (Salmo trutta) in Europe. Diversity and Distributions 19, 1059-1071.

Haidvogl, G., Lajus, D., Pont, D., Schmid, M., Jungwirth, M., Lajus, J. (2013) Typology of historical sources and the reconstruction of long-term historical changes of riverine fish: a case study of the Austrian Danube and northern Russian rivers. Ecology of Freshwater Fish 23, 498–515.

Kottelat, M., Freyhof, J. (2007) Handbook of European freshwater fishes. Publications Kottelat Cornol.

Kuemmerlen, M., Schmalz, B., Cai, Q., Haase, P., Fohrer, N., Jähnig, S.C. (2015) An attack on two fronts: predicting how changes in land use and climate affect the distribution of stream macroinvertebrates. Freshwater Biology 60, 1443-1458.

Lassalle, G., Béguer, M., Beaulaton, L., Rochard, E. (2008) Diadromous fish conservation plans need to consider global warming issues: An approach using biogeographical models. Biological Conservation 141, 1105-1118.

Lassalle, G., Béguer, M., Beaulaton, L., Rochard, E., (2009) Learning from the past to predict the future: responses of European diadromous fish to climate change, American Fisheries Society Symposium, pp. 175-193.

Limburg, K.E., Waldman, J.R. (2009) Dramatic Declines in North Atlantic Diadromous Fishes. Bioscience 59, 955-965.

Lohse, K.A., Newburn, D.A., Opperman, J.J., Merenlender, A.M. (2008) Forecasting relative impacts of land use on anadromous fish habitat to guide conservation planning. Ecological Applications 18, 467-482.

MacArthur, R.H. (1972) Geographical ecology: patterns in the distribution of species. Princeton University Press.

Nel, J.L., Roux, D.J., Abell, R., Ashton, P.J., Cowling, R.M., Higgins, J.V., Thieme, M., Viers, J.H. (2009) Progress and challenges in freshwater conservation planning. Aquatic Conservation: Marine and Freshwater Ecosystems 19, 474-485.

Ricciardi, A., Rasmussen, J.B. (1999) Extinction Rates of North American Freshwater Fauna. Conservation Biology 13, 1220-1222.

Ripple, W.J., Wolf, C., Newsome, T.M., Galetti, M., Alamgir, M., Crist, E., Mahmoud, M.I., Laurance, W.F. (2017) World Scientists' Warning to Humanity: A Second Notice. Bioscience 67, 1026-1028.

Rounsevell, M.D.A., Reginster, I., Araújo, M.B., Carter, T.R., Dendoncker, N., Ewert, F., House, J.I., Kankaanpää, S., Leemans, R., Metzger, M.J., Schmit, C., Smith, P., Tuck, G. (2006) A coherent set of future land use change scenarios for Europe. Agriculture, Ecosystems & Environment 114, 57-68.

Segurado, P., Branco, P., Avelar, A., Ferreira, M. (2014) Historical changes in the functional connectivity of rivers based on spatial network analysis and the past occurrences of diadromous species in Portugal. Aquatic Sciences, 1-14.

Thomas, C.D., Franco, A.M.A., Hill, J.K. (2006) Range retractions and extinction in the face of climate warming. Trends in Ecology & Evolution 21, 415-416.

Tockner, K., Tonolla, D., Uehlinger, U., Siber, R., Robinson, C.T., Peter, F.D., (2009) Chapter 1 - Introduction to European Rivers, Rivers of Europe. Academic Press, London, pp. 1-21.

Vellend, M., Brown, C.D., Kharouba, H.M., McCune, J.L., Myers-Smith, I.H. (2013) Historical ecology: Using unconventional data sources to test for effects of global environmental change. American Journal of Botany 100, 1294-1305.

Williams, C.B. (1964) Patterns in the balance of nature. Academic.

7. General Discussion

"I will live in the Past, the Present, and the Future. The Spirits of all Three shall strive within me. I will not shut out the lessons that they teach. "

Charles Dickens, "A Christmas Carol"

Populations of diadromous fish species have been globally declining all over Europe, in some cases falling to overwhelming historical lows (Kettle et al., 2011; Pourkazemi, 2006) or even to confirmed basin extirpations (Jepsen et al., 2012; Williot et al., 2002). To have a more informative insight about this problematic, it is important to have data at least about species distribution pre-dating the multiple impacts on riverine habitats that have been identified as contributors for this decline. Thus, obtaining detailed and geographically extent historical data about European diadromous fish species was key to accomplish the objectives proposed in the present work. However, caveats and limitations to the use of historical information are serious and may lead to interpretation bias (Swetnam et al., 1999). Being so, searching, curating, cross-checking and validating historical sources, data and databases assumed particular relevance to avoid skewed data analyses. The comprehensive understanding of these caveats and processes led to the development of the historical data framework proposed in this work. This fulfilled the objective of the first part of the thesis, i.e., to provide a reliable and adequate pool of historical data for the research topic. Moreover, information for Portuguese basins was either missing or impaired at all searched European databases, as well as in literature focused in Iberian Peninsula (e.g., Clavero and Hermoso, 2015; Clavero and Villero, 2014). This demonstrated the need to increase the amount of data for Portugal, resulting in the first work of this thesis. Despite the availability of adequate historical fish data, methodological implementation was still problematic because performing calculations with the underlying features of freshwater networks using environmental/riverscape data for broad geographic ranges and at a fine scale is challenging. This conduced to the need of developing a software (RivTool) that relies on the hierarchical, dendritic and network nature of freshwater systems for its functioning. Although it was developed with the aim of analysing river networks at the European scale, this tool has proven to have a wider geographical application, as it has been downloaded from at least 37 countries in all five continents. Taking advantage of the established historical data framework and of the software, the third part of the thesis focuses on research about diadromous fish species occurrence in the 20th century considering three (climate change, land use alterations and connectivity infringement) of the main drivers responsible for the global decline of this group of animals.

Next, a set of four questions allows the summarisation of the results and findings developed during this thesis, while also offering an integrated and overall perspective and discussion of the relevance and usefulness of the full scope of the thesis.

7.1 What were the main lessons learned after dealing with multiple databases and compiling the Portuguese historical database on diadromous fish occurrences?

In a nutshell:

- Being thorough with the spatial resolution of sources and data is essential for the quality of the historical data
- Lack of taxonomic precision of historical records can affect ecological interpretations
- Global declines in diadromous fish species resulted from unparalleled impacts since 19th century
- Detailed historical context at local and regional scale may be decisive for restoration efforts of specific river basins

The set of European databases consulted were not all compiled at the same spatial scale; these included point/segment and basin scale resolutions. In this context, a multi-scale approach to data usage would allow to maximise data inclusion and take advantage of data cross-checking and validation. In addition, when collecting the data for the Portuguese database (PHish), spatial resolution was something that required specific attention. Sometimes sources would indicate an occurrence at a basin or a tributary of the main river and not exactly at a specific location in the river. Moreover, even when a historical reference of a precise location in a stream was available, often the name of the location did not have any equivalency with any current designation that would allow a precise georeferencing. Hence, the idea of having data for multiple scales would also be useful for the implementation of this database. Overall, the need to deal with spatial scale issues and the will to maximize data usage were the genesis of the multi-scale approach to the overall framework of historical data, and consequently to the PHish database structure. This has not only improved the crosschecking and validation of historical sources and data but also lead to the broadening of the geographical extent of the framework output and inevitably of the presented studies.

When using historical data, taxonomic precision is also a serious concern. European databases used already portrait this idea, and took it into consideration for their output data (e.g., the inclusion of the complex of *A. sturio/oxyrinchus* due to the recent discovery of the historical presence of *A. oxyrinchus* in Europe (Ludwig et al., 2002)), and debated it in the reports associated with databases (e.g., the task 3.4 of the EFI+ 3.4 report). In the PHish database, a significant part of the data is prior to the 18th century, thus pre-dating scientific taxonomical considerations and systematisation. Moreover, by including Cyprinid species of lower commercial interest, the possibility of misclassification increases, especially for those with recent taxonomic changes (e.g., those belonging to the old genus *chondrostoma* (Robalo et al., 2007)). To cope with this, in the PHish database two fields with taxonomic classification are provided, one with a very low level of uncertainty and another with some degree of uncertainty associated with the expert judgement based on the available information. This precautionary reasoning and methods are very important since such errors and interpretations can alter the underlying interpretations and hamper future usages of this type of databases.

Since the 19th century, human actions became more impactful with the capability to alter profoundly any ecosystem in a very short time-frame, rendering more wide-spread pressures with unparalleled intensity. Numerous publication mention deleterious degrees of pollution (Maes et al., 2008; Pourkazemi, 2006; Sandøy and Langåker, 2001), main stem dams at river mouth that cause species extirpations (de Groot, 1990b), urbanisation growth becoming exponential (Antrop, 2004), severely over-fished diadromous species (Bacalbaşa-Dobrovici, 1997; Ludwig et al., 2002); land use alterations, especially aimed at the elimination of wetlands (Kettle et al., 2011) all occurring in the late 19th century, and most often during the 20th century. This, along with the limited temporal availability of global environmental and riverscapes data, has shaped the approach followed in this thesis, of using historical occurrence data from the 19th until the beginning of 20th century. However, human actions on rivers were not neutral before the 19th century. This became very clear during collecting and the curation of historical data for the PHish database. Although probably the exception, specific interventions in rivers might have had even long-term benefits for migratory species. In Portugal, in the Douro river, there was a natural waterfall (Cascade of Valeira) that constituted a natural permanent barrier for fish movements. To promote navigability plans were made in the 16th century to demolish this cascade and widen the river. During the 18th century, the obstacle was removed and navigability achieved. With that, a societal intervention made an overwhelming area of the Douro basin available for migratory species. Also, problems in diadromous fish species stocks existed prior to the 19th century. In Portugal, narrations and issued royal legislations give the idea that there were locally some detrimental pressures (e.g., watermills, small barriers, overfishing in spawning areas) to some species. Lenders et al. (2016) mention that in the Paleo-Rhine area, Atlantic salmon stocks suffered their most dramatic decline in the Middle Ages, i.e., before the 1600s. Conversely, the same authors mention that Scottish stocks reveal stable numbers during this period and that the same was verified for the Alaskan sockeye salmon. It seems that, during the 19th, and most particularly in the 20th century, threats from anthropogenic actions have resulted in the global decline of diadromous fish species (Limburg and Waldman, 2009). Prior to the 19th century, the effects from human actions were restricted to local and regional scales. Considering this, a detailed historical context may be decisive for the success of basin restoration efforts at both regional and local scale (Lenders et al., 2016).

7.2 In what way the software and framework developed in this thesis may contribute to the knowledge on diadromous fish?

In a nutshell:

- The conceptual framework provides solid outputs since it deals adequately with limitation of historical data
- Because it establishes pseudo-absences, the obligation of using presence-only techniques for modelling is eliminated
- It provides outputs at multiple scales, allowing to work within the scope of the riverscape concept
- Combining the historical data framework and the software may provide material for relevant research in years to come

The historical data framework used multiple historical sources and was developed taking into consideration both the migratory behaviour of diadromous fish and the characteristics of freshwater networks. To do so we have used the River and Catchment Database for Europe v2 (CCM – Catchment Characterisation and Modelling) (CCM2) (Vogt et al., 2007) as a spatial geographic support. CCM2 is a pan-European database of river networks and catchments that are hierarchically structured and is a fully integrated system (Vogt et al., 2007). However, the conceptual framework developed in this thesis can be applied to other regions of the globe because it abides only to diadromous ecology and river networks features. This characteristic along with the consensus rule in the integration procedure and the establishing of thresholds based on the existing historical information makes this framework an adequate method for dealing with historical data of diadromous fish occurrence. Multiple authors state that, to override caveats and limitations of historical data, multiple and independent sources (Crumley, 2007; Haidvogl et al., 2013), preferably from distinct spatial and temporal scale should be used (Hayashida, 2005; Rackham, 1998; Swetnam et al., 1999; Szabó, 2010). In addition, for modelling purposes, by establishing pseudo-occurrence, and more specifically pseudo-absences it avoids the obligatory usage of presence-only modelling techniques which have some problems associated to their use (Phillips et al., 2009; Veloz, 2009), and they tend to perform poorly comparing to methods using presence and absence data (Brotons et al., 2004; Elith et al., 2006). Data-wise, the output of the historical data framework is unique since it includes information covering three spatial scales for a 15 diadromous fish species/group with distinct distributions that encompass the entire geographical range of Europe. The existence of data related to different spatial resolution provided the decisive contribution to work within the scope of the riverscapes concept (Fausch et al., 2002), and the development of the hierarchical modelling approach, where climate and land use exert their effect at different spatial scales. Working within this concept is useful as it enables the possibility of answering questions coming from different spatial scales. In order to achieve this, it was imperative to obtain complementary data such as climate, land use and damming at all the necessary spatial scales. RivTool has the ability to undertake this task efficiently and it discloses a set of functionalities that may be used not only for diadromous fish species studies but also for multiple research topics within the scope of freshwater networks.

To achieve the main goal of the thesis it was necessary to create the conceptual historical data framework and to develop a software capable of dealing with large data sets while taking into account the freshwater network properties. Without this prior stage-setting, the pursuit of wide-scale studies in Europe dealing with diadromous fish species and historical fish records would be inconsequent. The combination of the framework with detailed historical datasets such as the one created and those used within this thesis, along with the correct use of the Rivtool may provide valuable material for research on diadromous fish species in years to come.

7.3 Are climate, land use and longitudinal connectivity hindrance spatially affecting European diadromous fish occurrence homogeneously?

In a nutshell:

- Diadromous fish species distribution is mostly affected by climate, but also by land use close to river mouths
- European freshwater longitudinal connectivity impairment became widespread after WWII
- Current longitudinal connectivity constraints affect more severely populations from basins in southern Europe
- Given the predictions for multiple threats, populations from basins in southern Europe and species with spatial narrow distributions will be those facing more challenges in the future

Results presented previously indicate that diadromous fish species occurrence is constrained by temperature range and minimum precipitation. This means that climate affects the distribution of these animals, which is compliant with the findings of other authors (Filipe et al., 2013; Lassalle et al., 2009a; Lassalle and Rochard, 2009). Land use variables were less relevant than climate, however, models indicate that land use in areas closer to the mouth of the river may be important. For diadromous fish species transition areas between marine and freshwater and river mouth are critical (McDowall, 1999) and their usage as passage habitats is inevitable. In the beginning of the 21st century, the number of large dams and large main stem dams in basins from southern Europe (defined as those belonging to Iberia and draining to the Mediterranean, Black, Azov and Caspian seas) is higher than that of Central and Northern Europe, meaning higher structural longitudinal connectivity losses in Southern Europe. Structural impairment anticipated higher functional losses in southern regions, which is confirmed by looking at functional losses from species mostly confined to each of the regions and by species of ubiquitous distribution (European eel and Sea trout) whose southern losses highly surpass those of the northern area considered. Average functional losses of species confined to the southern area (Pontic shad, Russian sturgeon, Stellate sturgeon and Beluga) are higher in both segments and sub-basins totally affected than those confined to the northern area (Houting, European smelt and Atlantic salmon). The disparity in the number of dams might be a reflection of the necessity to store water in southern areas, where climate tends to be hotter and dryer. Given the findings of this work, populations of species from basins in southern Europe are currently more affected by the losses of longitudinal connectivity due to large dams.

The temporal analysis performed revealed that, in European freshwater networks, the hampering of longitudinal connectivity became widespread in the second half of the 20th century, where the number of dams is far superior to those in the first half of the century. Additionally, the most noticeable difference is in the number of main stem dams and their increasing closeness to the river mouth in the post-World War II (WWII) period. At this time, energy and water demands increased tremendously given immediate rebuilding needs and all the subsequent social, economic and technological progresses. Inevitably, this resulted in unprecedented functional losses for most of the European diadromous fish species. Concerning the future, Zarfl et al. (2015) indicate that in Europe there are 652 large dams (over 1 MW capacity) under construction or planned, over 80% in the Balkan area. Though not entirely part of Europe but relevant for the Mediterranean, Black and Caspian seas, the Caucasus and Anatolia areas also present an elevated number of large dams to be implemented in the future. River impoundment interplays with climate change and might augment its effects, because the resulting reservoirs are responsible for the emission of greenhouse gases due to the trapped organic material (Helfman, 2007). The Mediterranean area is one of the world’s most affected regions (Giorgi, 2006). Climate change models predict that: meteorological and hydrological droughts will be stronger in southern Europe; river flow will decrease in southern areas; the greatest increase in one-in-a-century floods are projected for multiple areas in the Mediterranean and the greatest increase in drought conditions is projected for southern Europe (Alfieri et al., 2015; EEA, 2017; Rojas et al., 2012). In Northern Europe, a decrease in the flood hazard, water temperature increase, less snow accumulation, higher precipitation and less probability of drought events is predicted (Alfieri et al., 2015; EEA, 2017; Rojas et al., 2012). Land-use is both a causal factor and an expression of the effect of climate (Dale, 1997). Human settlements tend to occur near high productive areas, hence the major type of land use close to estuaries, deltas and coastal area is nowadays urban land. Urbanisation is inevitably linked with industrialisation and pollution, which translates into impacts on water environmental quality and hydrology (McDowall, 1999). Globally, demography predictions indicate that by 2030 nearly 60% of the population will be urban and in 2050 it will reach the 67%, being 86% in developed regions (Cohen, 2006; UN – DESA, 2012). It is also noteworthy that the implementation of a dam translates into habitat loss and alteration of land use in the area affected and surrounding the reservoir, thus contributing to additional impacts beyond connectivity impairment.

In conclusion, the future of freshwater networks in southern regions is predicted to have increased pressure from larger urban areas, less longitudinal connectivity, less flowing water and higher frequency of extreme events such as large floods and long droughts. The combination of all these threats will most likely render significant impacts on water quality and quantity. In northern areas, alterations promoted by climate changes in the freshwater network will be less detrimental, and no substantial alteration to current rivers longitudinal connectivity is forecasted. Milder climate conditions will lead to land use changes, possibly promoting the increase of human presence and urbanisation. This said, southern species already more affected by longitudinal connectivity hindrances, will face even more threats and pressures than those present in northern areas. Moreover, Lassalle and Rochard (2009) predict that overall diadromous fish species will invade higher latitudes and disappear from lower latitudes, though losses of suitable basins would not be balanced by gains. Thus, species with broad European distribution (e.g., Sea trout and European flounder) will lose several suitable basins in their southern distribution limit, but will also have some basins turning favourable around their northern distribution limit (Lassalle and Rochard, 2009). Predicted consequences of climate change are more concerning for spatially confined coldwater (e.g., Baltic sea) and warmwater (e.g. Black, Azov and Caspian seas) species that have few or no basins at higher altitudes to become suitable with new climatic conditions. (Lassalle and Rochard, 2009).

7.4 Is the research on diadromous fish species, using historical data and distribution constraints, useful for river restoration and for conservation and management of freshwater fish?

In a nutshell:

- Information about European wide functional connectivity losses combined with research at local and regional scale about dam removal prioritisation could provide valuable management actions
- Dam removal actions should be inserted into a wider context of threats to avoid inconsequent results
- Historical data may be used to establish reference conditions metrics and then used to assess current and future deviations values
- Guidelines from broad-scale analysis should be complemented with relevant local/regional events or features

According to several authors, these broad spatial scale analyses of diadromous species occurrence using historical data and distribution constraints are useful for both conservation and management efforts (Béguer et al., 2007; Lassalle et al., 2008; Lassalle et al., 2009a; Lassalle et al., 2009b). Humans have changed freshwater ecosystems for centuries (Haidvogl et al., 2013), thus historical context may provide valuable insights (Swetnam et al., 1999) with explanatory value for modelling purposes (e.g. (Lassalle and Rochard, 2009; Logez et al., 2012), increasing their predictor ability. Historical data renders a wider temporal knowledge, providing a broader context to changes in species occurrence.

Damming is one of the main threats to diadromous fish species in the world (Larinier, 2001; Limburg and Waldman, 2009; Nicola et al., 1996). In Europe, functional longitudinal connectivity losses are elevated, especially for populations of diadromous fish species occurring in southern European basins. For some species, losses of historical occurrence in river length are higher than 50%. From a conservation perspective, using these outputs allows to determine what species are more affected, what are the basins where connectivity hindrance is more severe and which dams are causing higher losses. Also, combining this research with studies such as those of Segurado et al. (2014) and Branco et al. (2014), it could render management actions to improve current functional connectivity for multiple species. River restoration projects tend to be expensive and only become cost-effective if they meet the restoration goals and restore valuable ecosystem services (Bullock et al., 2011). Thus, restoration via dam removal prioritisation actions should include a broad context to avoid inconsequent results (Magilligan et al., 2016). Although obstacle removing will always translate into improvements of freshwater ecosystems, it may not produce significant results for a specific group of animals. Economic resources should be spent on actions leading to long-lasting alterations that promote restoring habitats and biodiversity. In the case of diadromous fish species, if there is some other underlying threat that prevents species occurrence (e.g., chemical barrier at the mouth, severe alteration of climate conditions) simply removing dams may not suffice. For instance, progressing with the research presented in chapter 6 will allow predicting for three spatial scales where each species will occur in the future. Combining the connectivity approach followed in chapter 5 with the modelling approach undertaken in chapter 6 can further be used to acknowledge where restoration efforts should be applied. Moreover, using this type of predictive analyses with multiple species might provide locations where restoration efforts may benefit a larger array of species and overall community functioning.

From a conservation standpoint, looking at multiple scales using several species and considering numerous threats is the most adequate approach, because it will allow a holistic perspective. For example, in the context of the implementation of the Water Frame Directive (WFD), historical data of all diadromous fish species may be used to establish metrics expressing a reference condition for all European basins and sub-basins. Afterwards, modelling the established metrics using information from multiple threats (e.g., climate, land use and dams) may allow obtaining predictions of current and future values for entire Europe. It is then possible to measure the deviation from the established reference condition, expressing lack of suitability and connectivity impairment issues for diadromous fish species at all basins and sub-basins in Europe.

Aiming to manage freshwater networks for the conservation of diadromous fish species will probably benefit a multitude of freshwater species since it means protecting spawning and reproduction grounds but also passage habitats (Abell, 2002). Thus, these can be seen as an umbrella species, where protecting one leads to the protection of others. Nevertheless, though broad-scale European wide approaches are valuable they do not come without caveats. There are some resolution limitations that probably require complementary historical and research studies undertaken to assess features and threats at a finer scale (e.g., determining historical and current spawning grounds, looking for small river obstructions, riverbed modifications, point-source pollution). The assessment of these local/regional spatially and temporally confined events or features would be an effective complement to the guidelines from the wider spatial analysis.

7.5 Final Remarks

This thesis has contributed significantly to the development of the research about diadromous fish species by:

- providing a methodological framework that takes full advantage of historical data without neglecting the limitations and caveats associated with this type of information. It is an open framework in the sense that by adding data it may lead to updates in the outcome, and because it can be used with data from other areas of the globe.
- developing a software that facilitates methodological work and that helps to deal with large datasets and geographically broad-ranging studies. RivTool is not limited to European freshwater networks and it is flexible enough to accommodate future developments resulting from research or management demands.
- presenting research works that not only display the utility of the other outputs of the thesis but also produced relevant research outcomes about the constrains to European diadromous fish species distribution.

It is also noteworthy that the work developed during this thesis has tried to overcome the common limitations of using small spatial and temporal scales by trying to incorporate the concept of riverscapes. The outcome of the framework is the historical occurrence of diadromous fish species. However, the process not only relies on multiple historical databases but uses current distribution data to cross-validate and check for misleads, lapses or defects in the databases or in the integration procedure. This outcome is also made available at three spatial scales that are relevant for data sources, species distribution and river management. In addition, this has enabled advocating for a hierarchical modelling where threats are related to a proper scale and encompassing the full range of the species' European distribution. Also, it facilitated analysing functional longitudinal connectivity hindrance using segment and sub-basin scales. The ability of the software to perform calculations at both segment and sub-basin scales reinforces the commitment to help other researchers work within the riverscapes concept. Concluding, notwithstanding the increment in the scientific knowledge about diadromous species occurrence considering climate, land use and connectivity loss, it is the methodological framework and the software that are probably the most enduring footprint of this thesis. These features can provide a structural basis for future research aiming to contribute decisively to comprehend the evolution of diadromous fish species occurrence and provide reliable information and guidelines for their management and conservation.

7.6 Future Research

Creating the possibility of having multiple scale information about the European occurrence of several diadromous fish species prior to the most impactful threats opens a world of research possibilities. Also, because the developed framework allows for new data inputs and is able to update the output dataset accordingly, new information will further consolidate the adequacy and usefulness of this approach. Relating the historical data framework information with climate, land use, and possibly other pressures to perform predictions for the beginning, mid and the end of the 21st century considering multiple climate scenarios is a valuable and useful information for management purposes. Such a research output would offer the possibility to compare the potential situation with the real occurrence of species, assessing impacts from other threats and enabling the development of diadromous fish species richness metrics to assess river quality within the scope of the WFD. Also, it would provide an idea of the marine areas where respective basins will be more threatened, lose more species and/or become unsuitable at multiple scales of analysis. About marine areas and the transition waters, given their relevance for diadromous fish species life cycle, progressing towards the inclusion of these areas in the research would be interesting. Since climate changes tend to affect more severely coastal areas which have a higher proportion of urban land use, one may wonder if in the future potentially suitable freshwater networks may become inaccessible because of unsuitable ecological conditions at the river mouth and surrounding coastal areas. Integrating research from marine coastal areas and transition waters with studies from freshwater networks may provide a broader picture to the future occurrence of diadromous fish species in Europe.

At a more spatially confined range, the existence of the PHish database enables the development of research focused on Portugal and/or Iberia, aiming for instance to complement and improve those performed considering only Spanish data. In addition, having a software that facilitates co-variable creation and acquisition, also at multiple scales, offers a powerful tool for research in general. The characteristics of Rivtool and the set of freshwater structure concepts that guided the software development open the possibility of evolving into a platform where add-ons and plug-ins enhance the functionalities and broaden its scope. It would be interesting to develop an add-on that would partially automatize the processes of the framework developed in this thesis or to develop a tool focused on connectivity metrics and measurements that would be useful to analyse longitudinal connectivity losses in freshwater systems. About the latter topic, it would be worth to continue the work of this thesis by adding information about small barriers and/or the permeability of all barriers. To improve the functional connectivity analysis, it would be relevant to characterise the ability of each species, considering distinct life stages, to negotiate and overcome a barrier, in either way, considering the characteristics of each obstacle.

The above suggestions are just representative of the multiple topics and research options that are now more easily achievable. By pursuing such ideas, or others that increase the utilisation and/or take advantage of the thesis’ outputs, it is possible to broaden and achieve a more holistic knowledge on a declining group of fish that has a relevant ecological and cultural significance.

7.7 References

Abell, R. (2002) Conservation Biology for the Biodiversity Crisis: a Freshwater Follow-up. Conservation Biology 16, 1435-1437.

Alfieri, L., Burek, P., Feyen, L., Forzieri, G. (2015) Global warming increases the frequency of river floods in Europe. Hydrology and Earth System Sciences 19, 2247-2260.

Antrop, M. (2004) Landscape change and the urbanization process in Europe. Landscape and Urban Planning 67, 9-26.

Bacalbaşa-Dobrovici, N. (1997) Endangered migratory sturgeons of the lower Danube River and its delta. Environmental Biology of Fishes 48, 201-207.

Béguer, M., Beaulaton, L., Rochard, E. (2007) Distribution and richness of diadromous fish assemblages in Western Europe: large-scale explanatory factors. Ecology of Freshwater Fish 16, 221-237.

Branco, P., Segurado, P., Santos, J.M., Ferreira, M.T., Strecker, A. (2014) Prioritizing barrier removal to improve functional connectivity of rivers. Journal of Applied Ecology 51, 1197-1206.

Brotons, L., Thuiller, W., Araújo, M.B., Hirzel, A.H. (2004) Presence-absence versus presence-only modelling methods for predicting bird habitat suitability. Ecography 27, 437-448.

Bullock, J.M., Aronson, J., Newton, A.C., Pywell, R.F., Rey-Benayas, J.M. (2011) Restoration of ecosystem services and biodiversity: conflicts and opportunities. Trends in Ecology & Evolution 26, 541-549.

Clavero, M., Hermoso, V. (2015) Historical data to plan the recovery of the European eel. Journal of Applied Ecology 52, 960-968.

Clavero, M., Villero, D. (2014) Historical Ecology and Invasion Biology: Long-Term Distribution Changes of Introduced Freshwater Species. Bioscience 64, 145-153.

Cohen, B. (2006) Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability. Technology in Society 28, 63-80.

Crumley, C., (2007) Historical ecology: integrated thinking at multiple temporal and spatial scales, in: Hornborg, A., Crumley, C. (Eds.), The World System and the Earth System: Global Socioenvironmental Change and Sustainability Since the Neolithic, . Left Coast Press, Walnut Creek, CA, pp. 15-28.

Dale, V.H. (1997) The relationship between land-use change and climate change. Ecological Applications 7, 753-769.

de Groot, S.J. (1990) The former allis and twaite shad fisheries of the lower Rhine, The Netherlands. Journal of Applied Ichthyology 6, 252-256.

EEA, (2017) Climate change, impacts and vulnerability in Europe 2016, in: European Environment Agency, E. (Ed.). European Environment Agency, Copenhagen, Denmark.

Elith, J., H. Graham, C., P. Anderson, R., Dudík, M., Ferrier, S., Guisan, A., J. Hijmans, R., Huettmann, F., R. Leathwick, J., Lehmann, A., Li, J., G. Lohmann, L., A. Loiselle, B., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., McC. M. Overton, J., Townsend Peterson, A., J. Phillips, S., Richardson, K., Scachetti-Pereira, R., E. Schapire, R., Soberón, J., Williams, S., S. Wisz, M., E. Zimmermann, N. (2006) Novel methods improve prediction of species' distributions from occurrence data. Ecography 29, 129-151.

Fausch, K.D., Torgersen, C.E., Baxter, C.V., Li, H.W. (2002) Landscapes to Riverscapes: Bridging the Gap between Research and Conservation of Stream Fishes: A Continuous View of the River is Needed to Understand How Processes Interacting among Scales Set the Context for Stream Fishes and Their Habitat. Bioscience 52, 483-498.

Filipe, A.F., Markovic, D., Pletterbauer, F., Tisseuil, C., De Wever, A., Schmutz, S., Bonada, N., Freyhof, J. (2013) Forecasting fish distribution along stream networks: brown trout (Salmo trutta) in Europe. Diversity and Distributions 19, 1059-1071.

Giorgi, F. (2006) Climate change hot-spots. Geophysical Research Letters 33.

Haidvogl, G., Lajus, D., Pont, D., Schmid, M., Jungwirth, M., Lajus, J. (2013) Typology of historical sources and the reconstruction of long-term historical changes of riverine fish: a case study of the Austrian Danube and northern Russian rivers. Ecology of Freshwater Fish 23, 498–515.

Hayashida, F.M. (2005) Archaeology, Ecological History, and Conservation. Annual Review of Anthropology 34, 43-65.

Helfman, G.S. (2007) Fish conservation: a guide to understanding and restoring global aquatic biodiversity and fishery resources. Island Press, Washington, DC, USA.

Jepsen, N., Deacon, M., Koed, A. (2012) Decline of the North Sea Houting: and protective measures for an endangered anadromous fish. Endangered Species Research 16, 77-84.

Kettle, A.J., Asbjørn Vøllestad, L., Wibig, J. (2011) Where once the eel and the elephant were together: decline of the European eel because of changing hydrology in southwest Europe and northwest Africa? Fish and Fisheries 12, 380-411.

Larinier, M., (2001) Environmental issues, dams and fish migration, in: Marmulla, G. (Ed.), Dams, fish and fisheries. Opportunities, challenges and conflict resolution. FAO Fisheries Technical Paper, Rome, pp. 45-90.

Lassalle, G., Béguer, M., Beaulaton, L., Rochard, E. (2008) Diadromous fish conservation plans need to consider global warming issues: An approach using biogeographical models. Biological Conservation 141, 1105-1118.

Lassalle, G., Béguer, M., Beaulaton, L., Rochard, E., (2009a) Learning from the past to predict the future: responses of European diadromous fish to climate change, American Fisheries Society Symposium, pp. 175-193.

Lassalle, G., Crouzet, P., Rochard, E. (2009b) Modelling the current distribution of European diadromous fishes: an approach integrating regional anthropogenic pressures. Freshwater Biology 54, 587-606.

Lassalle, G., Rochard, E. (2009) Impact of twenty-first century climate change on diadromous fish spread over Europe, North Africa and the Middle East. Global Change Biology 15, 1072-1089.

Lenders, H.J., Chamuleau, T.P., Hendriks, A.J., Lauwerier, R.C., Leuven, R.S., Verberk, W.C. (2016) Historical rise of waterpower initiated the collapse of salmon stocks. Sci Rep 6, 29269.

Limburg, K.E., Waldman, J.R. (2009) Dramatic Declines in North Atlantic Diadromous Fishes. Bioscience 59, 955-965.

Logez, M., Bady, P., Pont, D. (2012) Modelling the habitat requirement of riverine fish species at the European scale: sensitivity to temperature and precipitation and associated uncertainty. Ecology of Freshwater Fish 21, 266-282.

Ludwig, A., Debus, L., Lieckfeldt, D., Wirgin, I., Benecke, N., Jenneckens, I., Williot, P., Waldman, J.R., Pitra, C. (2002) When the American sea sturgeon swam east. Nature 419, 447.

Maes, J., Stevens, M., Breine, J. (2008) Poor water quality constrains the distribution and movements of twaite shad Alosa fallax fallax (Lacépède, 1803) in the watershed of river Scheldt. Hydrobiologia 602, 129-143.

Magilligan, F.J., Graber, B.E., Nislow, K.H., Chipman, J.W., Sneddon, C.S., Fox, C.A. (2016) River restoration by dam removal: Enhancing connectivity at watershed scales. Elementa: Science of the Anthropocene 4, 000108.

McDowall, R.M. (1999) Different kinds of diadromy: Different kinds of conservation problems. ICES Journal of Marine Science 56, 410-413.

Nicola, G., Elvira, B., Almodóvar, A. (1996) Dams and fish passage facilities in the large rivers of Spain: effects on migratory species. Large Rivers 10, 375-379.

Phillips, S.J., Dudík, M., Elith, J., Graham, C.H., Lehmann, A., Leathwick, J., Ferrier, S. (2009) Sample selection bias and presence-only distribution models: implications for background and pseudo-absence data. Ecological Applications 19, 181-197.

Pourkazemi, M. (2006) Caspian Sea sturgeon Conservation and Fisheries: Past present and Future. Journal of Applied Ichthyology 22, 12-16.

Rackham, O., (1998) Implications of historical ecology for conservation, in: Sutherland, W.J. (Ed.), Conservation Science and Action, 1st ed. Blackwell Publishing Company, pp. 152-175.

Robalo, J.I., Almada, V.C., Levy, A., Doadrio, I. (2007) Re-examination and phylogeny of the genus Chondrostoma based on mitochondrial and nuclear data and the definition of 5 new genera. Molecular Phylogenetics and Evolution 42, 362-372.

Rojas, R., Feyen, L., Bianchi, A., Dosio, A. (2012) Assessment of future flood hazard in Europe using a large ensemble of bias-corrected regional climate simulations. Journal of Geophysical Research: Atmospheres 117, n/a-n/a.

Sandøy, S., Langåker, R.M. (2001) Atlantic salmon and Acidification in Southern Norway: A Disaster in the 20th Century, but a Hope for the Future? Water, Air, and Soil Pollution 130, 1343-1348.

Segurado, P., Branco, P., Avelar, A., Ferreira, M. (2014) Historical changes in the functional connectivity of rivers based on spatial network analysis and the past occurrences of diadromous species in Portugal. Aquatic Sciences, 1-14.

Swetnam, T.W., Allen, C.D., Betancourt, J.L. (1999) Applied Historical Ecology: using the past to manage for the future. Ecological Applications 9, 1189-1206.

Szabó, P. (2010) Why history matters in ecology: an interdisciplinary perspective. Environmental Conservation 37, 380-387.

UN – DESA, (2012) World urbanization prospects: the 2011 revision: highlights. United Nations - Department of Economic and Social Affairs, New York.

Veloz, S.D. (2009) Spatially autocorrelated sampling falsely inflates measures of accuracy for presence-only niche models. Journal of Biogeography 36, 2290-2299.

Vogt, J., Soille, P., Jager, A.d., Rimavičiūtė, E., Mehl, W., Foisneau, S., Bódis, K., Dusart, J., Paracchini, M.L., Haastrup, P., Bamps, C., (2007) A pan-European River and Catchment Database. European Commission - Joint Research Centre - Institute for Environment and Sustainability, Luxembourg, p. 120.

Williot, P., Arlati, G., Chebanov, M., Gulyas, T., Kasimov, R., Kirschbaum, F., Patriche, N., Pavlovskaya, L.P., Poliakova, L., Pourkazemi, M., Kim, Y., Zhuang, P., Zholdasova, I.M. (2002) Status and Management of Eurasian Sturgeon: An Overview. International Review of Hydrobiology 87, 483-506.

Zarfl, C., Lumsdon, A.E., Berlekamp, J., Tydecks, L., Tockner, K. (2015) A global boom in hydropower dam construction. Aquatic Sciences 77, 161-170.

8. Annexes

8.1 Supplementary material from Chapter 2

Table 8.1.7 – List of historical sources surveyed to create the PHish database.

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Almaça-Elvira_2000	Almaça C. & Elvira B.	Past and present distribution of *Acipenser sturio* L., 1758 on the Iberian Peninsula	2000	NA	Boletín. Instituto Español de Oceanografía, 16 (1-4): 11-16
Almeida_1866a	José Avelino d'Almeida	Dicionário abreviado de Corografia, Topografia e Arqueologia das Cidades, Vilas e Aldeias de Portugal (3 vol.)	1866a	1	Typographia de V. de Moraes, Valença
Almeida_1866b	José Avelino d'Almeida	Dicionário abreviado de Corografia, Topografia e Arqueologia das Cidades, Vilas e Aldeias de Portugal (3 vol.)	1866b	2	Typographia de V. de Moraes, Valença
Almeida_1866c	José Avelino d'Almeida	Dicionário abreviado de Corografia, Topografia e Arqueologia das Cidades, Vilas e Aldeias de Portugal (3 vol.)	1866c	3	Typographia de V. de Moraes, Valença
Amado_1861	José de Sousa Amado	Compendio de chorographia de Portugal. Seguido de Cartas chorographicas do reino e dos archipelagos dos Açores e da Madeira	1861	NA	Typographia de G. M. Martins, Lisboa
Amado_1874	José de Sousa Amado	Corografia da Lusitânia acompanhada de uma Carta Corográfica para uso dos alunos do 2º ano de Geografia e principalmente no exame final da disciplina	1874	NA	Typographia Universal, Lisboa
Andrade_1878a1	Agostinho Rodrigues de Andrade	Diccionario chorographico do reino de Portugal... seguido de dois pequenos diccionarios hydrographico e orographico do nosso paiz…	1878a1	NA	Imprensa da Universidade, Coimbra
Andrade_1878a2	Agostinho Rodrigues de Andrade	Pequeno Diccionario Hydrographico de Portugal	1878a2	NA	Imprensa da Universidade, Coimbra

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Andrade_1944	António Sampaio de Andrade	Dicionário corográfico de Portugal contemporâneo: (Continente, Ilhas Adjacentes e Colónias), elaborado de acordo com as actuais divisões	1944	NA	Livraria Figueirinhas, Porto
Anónimo_1817	Anónimo	Descripção de Portugal	1817	NA	-
Aranha_1871	Pedro Wenceslau de Brito Aranha	Memórias Histórico-Estatísticas de Algumas Villas e Povoações de Portugal	1871	NA	Livraria de A. M. Pereira – Editor, Lisboa
ARCL_1784	Academia Real das Ciências de Lisboa	Memorias económicas da academia real das sciencias de Lisboa, para o adiantamento da agricultura, das artes, e da industria em Portugal, e suas conquistas	1784	1	Na Officina da Academia Real das Sciencias, Lisboa
ARCL_1790	Academia Real das Ciências de Lisboa	Memorias económicas da academia real das sciencias de Lisboa, para o adiantamento da agricultura, das artes, e da industria em Portugal, e suas conquistas	1790	2	Na Officina da Academia Real das Sciencias, Lisboa
ARCL_1791	Academia Real das Ciências de Lisboa	Memorias económicas da academia real das sciencias de Lisboa, para o adiantamento da agricultura, das artes, e da industria em Portugal, e suas conquistas	1791	3	Na Officina da Academia Real das Sciencias, Lisboa
Azevedo_1906	Francisco Cardoso de Azevedo	Novo diccionario chorographico de Portugal Continental e Insular contendo as divisões administrativa, judicial, ecclesiastica e militar [...]	1906	NA	Typ. a Vapor de José da Silva Mendonça, Porto
Azevedo_1997	José Correia de Azevedo	Por terras e rios portugueses de trutas	1997	NA	Edições J. Correia, Braga
Baptista_1875a	João Maria Baptista	Chorographia Moderna do reino de Portugal (7 vol.)	1875a	2	Typographia da Academia real das Sciencias, Lisboa
Baptista_1875b	João Maria Baptista	Chorographia Moderna do reino de Portugal (7 vol.)	1875b	3	Typographia da Academia real das Sciencias, Lisboa
Baptista_1876a	João Maria Baptista	Chorographia Moderna do reino de Portugal (7 vol.)	1876a	4	Typographia da Academia real das Sciencias, Lisboa

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Baptista_1876b	João Maria Baptista	Chorographia Moderna do reino de Portugal (7 vol.)	1876b	5	Typographia da Academia real das Sciencias, Lisboa
Barbosa_1860a	Ignacio de Vilhena Barbosa	As cidades e villas da monarchia portugueza que teem brasão d'armas	1860a	1	Typographia do Panorama, Lisboa
Barbosa_1860b	Ignacio de Vilhena Barbosa	As cidades e villas da monarchia portugueza que teem brasão d'armas	1860b	2	Typographia do Panorama, Lisboa
Barbosa_1862	Ignacio de Vilhena Barbosa	As cidades e villas da monarchia portugueza que teem brasão d'armas	1862	3	Typographia do Panorama, Lisboa
Basto_1980	Artur de Magalhães Basto	Vereaçoens : anos de 1390-1395 : o mais antigo dos livros de Vereaçoes do Municipio do Porto existentes no seu Arquivo	1980	NA	Publicações da Câmara Municipal do Porto, Porto
Bastos_2006	Maria Rosário da Costa Bastos	O baixo Vouga em tempos medievos: do preâmbulo da Monarquia aos finais do reinado de D.Dinis	2006	NA	Tese de Doutoramento em Ciências Humanas e Sociais na especialidade de História apresentada à Universidade Aberta, Lisboa
Bettencourt_1874	Emiliano Augusto de Bettencourt	Diccionario chorographico de Portugal com as divisões administrativa, judicial, ecclesiastica e militar... precedido de um resumo de chorographia patria	1874	NA	Typographia Sousa & Filho, Lisboa
Bettencourt_1889	Emiliano Augusto de Bettencourt	Noções de chorographia de Portugal: seguidas da carta geographica do continente, e de um planispherio onde se indica a posição geographica das possessões portuguezas	1889	NA	A. Ferreira Machado & Cª, Lisboa
Bezerra_1785	Manuel Gomes de Lima Bezerra	Os estrangeiros no Lima, ou Conversaçoens eruditas sobre os varios pontos de historia ecclesiastica, civil, litteraria, natural, genealogica, antiguidades, geographia, agricultura, commercio, artes, e sciencias. Com huma descripção de todas a[...]	1785	NA	Real Officina da Universidade, Coimbra

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Brito_1597	O. Cist. Bernardo de Brito	Geografia Antiga de Lusytania	1597	NA	António Alvarez, Impressor de Livros, Alcobaça
Cabreira-Cabral_1942	Estefânia Cabreira & Oliveira Cabral	Corografia de Portugal e seu Império	1942	NA	Editorial Domingos Barreira
Câmara_1850	Paulo Perestrello da Câmara	Diccionário geographico, histórico, político e litterário do reino de Portugal e seus domínios	1850	1	Typographia Universal E. e H. Laemmert, Rio de Janeiro
Cardoso_1832	Luís Cardoso (Ed.)	Memórias Paroquiais	1832	1	Arquivo Nacional da Torre do Tombo
Cardoso_1832a	Luís Cardoso (Ed.)	Memórias Paroquiais	1832a	2	Arquivo Nacional da Torre do Tombo
Cardoso_1832aa	Luís Cardoso (Ed.)	Memórias Paroquiais	1832aa	33	Arquivo Nacional da Torre do Tombo
Cardoso_1832ab	Luís Cardoso (Ed.)	Memórias Paroquiais	1832ab	34	Arquivo Nacional da Torre do Tombo
Cardoso_1832ac	Luís Cardoso (Ed.)	Memórias Paroquiais	1832ac	35	Arquivo Nacional da Torre do Tombo
Cardoso_1832ad	Luís Cardoso (Ed.)	Memórias Paroquiais	1832ad	36	Arquivo Nacional da Torre do Tombo
Cardoso_1832ae	Luís Cardoso (Ed.)	Memórias Paroquiais	1832ae	38	Arquivo Nacional da Torre do Tombo
Cardoso_1832af	Luís Cardoso (Ed.)	Memórias Paroquiais	1832af	39	Arquivo Nacional da Torre do Tombo
Cardoso_1832ag	Luís Cardoso (Ed.)	Memórias Paroquiais	1832ag	41	Arquivo Nacional da Torre do Tombo
Cardoso_1832b	Luís Cardoso (Ed.)	Memórias Paroquiais	1832b	3	Arquivo Nacional da Torre do Tombo
Cardoso_1832c	Luís Cardoso (Ed.)	Memórias Paroquiais	1832c	4	Arquivo Nacional da Torre do Tombo
Cardoso_1832d	Luís Cardoso (Ed.)	Memórias Paroquiais	1832d	5	Arquivo Nacional da Torre do Tombo
Cardoso_1832e	Luís Cardoso (Ed.)	Memórias Paroquiais	1832e	6	Arquivo Nacional da Torre do Tombo
Cardoso_1832f	Luís Cardoso (Ed.)	Memórias Paroquiais	1832f	7	Arquivo Nacional da Torre do Tombo

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Cardoso_1832g	Luís Cardoso (Ed.)	Memórias Paroquiais	1832g	8	Arquivo Nacional da Torre do Tombo
Cardoso_1832h	Luís Cardoso (Ed.)	Memórias Paroquiais	1832h	10	Arquivo Nacional da Torre do Tombo
Cardoso_1832i	Luís Cardoso (Ed.)	Memórias Paroquiais	1832i	11	Arquivo Nacional da Torre do Tombo
Cardoso_1832j	Luís Cardoso (Ed.)	Memórias Paroquiais	1832j	12	Arquivo Nacional da Torre do Tombo
Cardoso_1832k	Luís Cardoso (Ed.)	Memórias Paroquiais	1832k	13	Arquivo Nacional da Torre do Tombo
Cardoso_1832l	Luís Cardoso (Ed.)	Memórias Paroquiais	1832l	14	Arquivo Nacional da Torre do Tombo
Cardoso_1832m	Luís Cardoso (Ed.)	Memórias Paroquiais	1832m	15	Arquivo Nacional da Torre do Tombo
Cardoso_1832n	Luís Cardoso (Ed.)	Memórias Paroquiais	1832n	16	Arquivo Nacional da Torre do Tombo
Cardoso_1832o	Luís Cardoso (Ed.)	Memórias Paroquiais	1832o	18	Arquivo Nacional da Torre do Tombo
Cardoso_1832p	Luís Cardoso (Ed.)	Memórias Paroquiais	1832p	20	Arquivo Nacional da Torre do Tombo
Cardoso_1832q	Luís Cardoso (Ed.)	Memórias Paroquiais	1832q	21	Arquivo Nacional da Torre do Tombo
Cardoso_1832r	Luís Cardoso (Ed.)	Memórias Paroquiais	1832r	22	Arquivo Nacional da Torre do Tombo
Cardoso_1832s	Luís Cardoso (Ed.)	Memórias Paroquiais	1832s	23	Arquivo Nacional da Torre do Tombo
Cardoso_1832t	Luís Cardoso (Ed.)	Memórias Paroquiais	1832t	24	Arquivo Nacional da Torre do Tombo
Cardoso_1832u	Luís Cardoso (Ed.)	Memórias Paroquiais	1832u	25	Arquivo Nacional da Torre do Tombo
Cardoso_1832v	Luís Cardoso (Ed.)	Memórias Paroquiais	1832v	26	Arquivo Nacional da Torre do Tombo
Cardoso_1832w	Luís Cardoso (Ed.)	Memórias Paroquiais	1832w	27	Arquivo Nacional da Torre do Tombo
Cardoso_1832x	Luís Cardoso (Ed.)	Memórias Paroquiais	1832x	28	Arquivo Nacional da Torre do Tombo
Cardoso_1832y	Luís Cardoso (Ed.)	Memórias Paroquiais	1832y	29	Arquivo Nacional da Torre do Tombo

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Cardoso_1832z	Luís Cardoso (Ed.)	Memórias Paroquiais	1832z	32	Arquivo Nacional da Torre do Tombo
Carvalho_1765	José Monteiro de Carvalho	Diccionario Portuguez das Plantas, Arbustos, […]	1765	NA	Oficina de Miguel Manescal da Costa, Impressor do Santo Officio, Lisboa
Carvalho_1987	Rómulo de Carvalho	A História Natural em Portugal no Século XVIII	1987	NA	Oficinas Gráficas da Minerva do Comércio, Lisboa
Castro_1762	João Baptista de Castro	Mappa de Portugal Antigo e Moderno	1762	1	Officina Patriarcal de Francisco Luiz Ameno, Lisboa
Castro_1815	Lourenço da Mesquita Pimentel Sotto-Maior e Castr	Mappa Chronologico do reino de Portugal	1815	NA	Impressão de J. B. Morando, Lisboa
Castro_1966	Armando Castro	A evolução económica de Portugal dos séculos XII a XV	1966	4	Editora Portugália, Lisboa
Coelho_1990	Maria Helena da Cruz Coelho	Apontamentos sobre a comida e a bebida do campesinato coimbrão em tempos medievos. In: Homens, espaços e poderes (séculos XI a XVI)	1990	NA	Notas do viver social. Lisboa: Horizonte, 1990, p. 9-22
Coelho_1995	Maria Helena da Cruz Coelho	A pesca fluvial na economia e na sociedade medieval portuguesa	1995	NA	FLUC Secção de História - Artigos em Livros de Actas, Lisboa
Coroa_1258	Feitos da Coroa	Livro 5 de Inquirições de Dom Afonso III	1258	NA	Arquivo Nacional Torre do Tombo (PT/TT/FC/2/8)
Costa_1706	António Carvalho da Costa	Corografia Portuguesa e Descripçam Topográfica do famoso reyno de Portugal (3vol.)	1706	1	Officina de Valentim da Costa Deslandes impressor de Sua Magestade, & á sua custa impresso, Lisboa
Costa_1708	António Carvalho da Costa	Corografia Portuguesa e Descripçam Topográfica do famoso reyno de Portugal (3vol.)	1708	2	Officina de Valentim da Costa Deslandes impressor de Sua Magestade, & á sua custa impresso, Lisboa
Costa_1712	António Carvalho da Costa	Corografia Portuguesa e Descripçam Topográfica do famoso reyno de Portugal (3vol.)	1712	3	Oficina Real Deslandesiana, Lisboa

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Costa_1789	Agostinho Rebelo da Costa	Descripção Topographica e Historica da cidade do Porto. Que contém a sua origem, situaçaõ, e antiguidades: a magnificencia dos seus templos, mosteiros, hospitaes, ruas, praças, edificios, e fontes...	1789	NA	Na Officina de Antonio Alvarez Ribeiro, Porto
Costa_1929	Américo Costa	Diccionario Chorographico de Portugal Continental e Insular: Hydrographico, Historico, Orographico, Biographico, Archeologico, Heraldico, Etymologico	1929	1	Livraria Civilização, Porto
Costa_1930	Américo Costa	Diccionario Chorographico de Portugal Continental e Insular: Hydrographico, Historico, Orographico, Biographico, Archeologico, Heraldico, Etymologico	1930	2	Livraria Civilização, Porto
Costa_1932	Américo Costa	Diccionario Chorographico de Portugal Continental e Insular: Hydrographico, Historico, Orographico, Biographico, Archeologico, Heraldico, Etymologico	1932	3	Livraria Civilização, Porto
Costa_1934	Américo Costa	Diccionario Chorographico de Portugal Continental e Insular: Hydrographico, Historico, Orographico, Biographico, Archeologico, Heraldico, Etymologico	1934	4	Livraria Civilização, Porto
Costa_1936	Américo Costa	Diccionario Chorographico de Portugal Continental e Insular: Hydrographico, Historico, Orographico, Biographico, Archeologico, Heraldico, Etymologico	1936	5	Livraria Civilização, Porto
Costa_1938	Américo Costa	Diccionario Chorographico de Portugal Continental e Insular: Hydrographico, Historico, Orographico, Biographico, Archeologico, Heraldico, Etymologico	1938	6	Livraria Civilização, Porto

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Costa_1940	Américo Costa	Diccionario Chorographico de Portugal Continental e Insular: Hydrographico, Historico, Orographico, Biographico, Archeologico, Heraldico, Etymologico	1940	7	Livraria Civilização, Porto
Costa_1943	Américo Costa	Diccionario Chorographico de Portugal Continental e Insular: Hydrographico, Historico, Orographico, Biographico, Archeologico, Heraldico, Etymologico	1943	8	Livraria Civilização, Porto
Costa_1947	Américo Costa	Diccionario Chorographico de Portugal Continental e Insular: Hydrographico, Historico, Orographico, Biographico, Archeologico, Heraldico, Etymologico	1947	9	Livraria Civilização, Porto
Costa_1948a	Américo Costa	Diccionario Chorographico de Portugal Continental e Insular: Hydrographico, Historico, Orographico, Biographico, Archeologico, Heraldico, Etymologico	1948a	10	Livraria Civilização, Porto
Costa_1948b	Américo Costa	Diccionario Chorographico de Portugal Continental e Insular: Hydrographico, Historico, Orographico, Biographico, Archeologico, Heraldico, Etymologico	1948b	11	Livraria Civilização, Porto
Costa_1949	Américo Costa	Diccionario Chorographico de Portugal Continental e Insular: Hydrographico, Historico, Orographico, Biographico, Archeologico, Heraldico, Etymologico	1949	12	Livraria Civilização, Porto
Denis_1846a	M. Fernando Denis	Portugal pittoresco ou Descripção historica d'este reino	1846a	1	Typografia de L.C. da Cunha, Lisboa
Denis_1846b	M. Fernando Denis	Portugal pittoresco ou Descripção historica d'este reino	1846b	2	Uma Sociedade, Typografia de L.C. da Cunha, Lisboa
Denis_1847	M. Fernando Denis	Portugal pittoresco ou Descripção historica d'este reino	1847	3	Uma Sociedade, Typografia de L.C. da Cunha, Lisboa

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Denis_1849	M. Fernando Denis	Portugal pittoresco, ou, Descripção historica d'este reino	1849	4	Uma Sociedade, Typografia de L.C. da Cunha, Lisboa
Deusdado_1893	Manuel António Ferreira Deusdado	Chorographia de Portugal illustrada [com] 50 gravuras [e] 20 mappas a cores	1893	NA	Guillard, Aillaud & Cª, Lisboa
DGSFA_1965	Direcção-Geral dos Serviços Florestais e Aquícolas	Portaria nº21295 - Aprova o Regulamento Especial para a Zona de Pesca da Lagoa Comprida	1965	NA	Ministério da Economia, Lisboa
DGSFA_1966	Direcção-Geral dos Serviços Florestais e Aquícolas	Portaria nº22040 - Aprova o Regulamento Especial para a Zona de Pesca Reservada que se designa por «Grupo das pequenas lagoas da Serra da Estrela»	1966	NA	Ministério da Economia, Lisboa
Dinis_1960	Dias Dinis	Estudos Henriquinos	1960	1	Acta Universitatis Conimbrigensis, Coimbra
DPAI_1999	Direcção-Geral das Florestas (DGF) – Divisão de Pe	Gestão dos recursos aquícolas em Portugal	1999	NA	Direcção-Geral das Florestas, Lisboa
Eça_1877	Bento Fortunato de Moura Coutinho de Almeida d'Eça	Memorias ácerca do regimen do Tejo e outros rios	1877	NA	Imprensa Nacional, Lisboa
Faria_1655	Manuel Severim de Faria	Noticias de Portugal: offerecidas a El Rey N.S. Dom João o IV	1655	NA	Na Officina Craesbeeckiana, Lisboa
Fernandes_1937	Manuel Fernandes	Memorial da corografia de Portugal	1937	2	-
Ferreira_1608	José Martins Ferreira	Breve Compendio, ou summario das grandezas, e cousas notaveis da comarca entre Douro, e Minho, com a lista dos condestaveis de Portugal, e Vice-Reis da India	1608	NA	-
Figueiredo-Lima_1817	Manuel de Figueiredo & Henrique de	Descripção de Portugal : apontamentos e notas da sua historia antiga, e moderna, ecclesiastica, civil, e militar	1817	NA	Tipografia Lacerdina, Lisboa

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
	Campos Ferreira				
Franclim_1999	Francisco Nunes Franclim	Terras portuguesas: arquivo histórico-corográfico ou corografia histórica portuguesa	1999	NA	Oficinas gráficas Copi-Pronto; EDINOVA, Lisboa
Frazão_1952	António César Amaral Frazão	Novo Dicionário Corográfico de Portugal (Continente, Ilhas Adjacentes e Colónias)	1952	NA	Domingos Barreira, Porto
Frazão_1981	António César Amaral Frazão	Novo dicionário corográfico de Portugal: Continente e Ilhas Adjacentes	1981	NA	Domingos Barreira, Porto
Freire_1739	António de Oliveira Freire	Descripçam Corografica do reyno de Portugal que contem huma exacta relaçam de suas Provincias, Comarcas, Cidades, Villas, Freguezias, montes, rios, portos […]	1739	NA	Officina de Miguel Rodrigues, Lisboa
Freire_1870	Henrique Augusto da Cunha Soares Freire	Compendio de chorographia de Portugal	1870	-	-
Frias_1886	David Correia Sanches de Frias	Notas a lápis, passeios e digressões peninsulares	1886	NA	Edição António Maria Pereira, Lisboa
Geraldes_1999	Ana Maria Geraldes	Peixes de água doce	1999	NA	João Azevedo Editores, Mirandela
Gomes_2011	Sandra Rute Fonseca Gomes	Territórios Medievais do Pescado do Reino de Portugal	2011	NA	Dissertação de mestrado em Alimentação - Fontes, Cultura e Sociedade, apresentada à Faculdade de Letras da Universidade de Coimbra
Gonçalves_2012	Iria Gonçalves	Por terras de entre-Douro-e-Minho com as inquirições de Dom Afonso III	2012	NA	Edições Afrontamento Lda., Porto
Guerra_1861	Manuel José Júlio Guerra	Estudos chorographicos, phisicos e hidrographicos da bacia do Tejo comprehendida no Reino de Portugal	1861	NA	Imprensa Nacional, Lisboa

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
HFAC_1980	História Florestal, Aquícola e Cinegética	Colectânea de Documentos existentes no Arquivo Nacional da Torre do Tombo. Chancelarias Reais (1208-1483), direcção e selecção de C.M.L. Baeta Neves, transcrição e revisão de provas de Maria Teresa Barbosa Acabado, compilação, sumários e índices de Maria	1980	1	Ministério da Agricultura e Pescas, Direcção-Geral do Ordenamento e Gestão Florestal
HFAC_1982a	História Florestal, Aquícola e Cinegética	Colectânea de Documentos existentes no Arquivo Nacional da Torre do Tombo. Chancelarias Reais (1439-1481), direcção e selecção de C.M.L. Baeta Neves, transcrição e revisão de provas de Maria Teresa Barbosa Acabado, compilação, sumários e índices de Maria	1982a	2	Ministério da Agricultura e Pescas, Direcção-Geral do Ordenamento e Gestão Florestal
HFAC_1982b	História Florestal, Aquícola e Cinegética	Colectânea de Documentos existentes no Arquivo Nacional da Torre do Tombo. Chancelarias Reais (1481-1493), direcção e selecção de C.M.L. Baeta Neves, transcrição e revisão de provas de Maria Teresa Barbosa Acabado, compilação, sumários e índices de Maria	1982b	3	Ministério da Agricultura e Pescas, Direcção-Geral do Ordenamento e Gestão Florestal
HFAC_1983	História Florestal, Aquícola e Cinegética	Colectânea de Documentos existentes no Arquivo Nacional da Torre do Tombo. Chancelarias Reais (1495-1521), direcção e selecção de C.M.L. Baeta Neves, transcrição e revisão de provas de Maria Teresa Barbosa Acabado, compilação, sumários e índices de Maria	1983	4	Ministério da Agricultura e Pescas, Direcção-Geral do Ordenamento e Gestão Florestal
HFAC_1988	História Florestal, Aquícola e Cinegética	Colectânea de Documentos existentes no Arquivo Nacional da Torre do Tombo. Chancelarias Reais (1521-1527), direcção e selecção de C.M.L. Baeta Neves, transcrição e revisão de provas de Maria Teresa Barbosa	1988	5.1	Ministério da Agricultura e Pescas, Direcção-Geral do Ordenamento e Gestão Florestal

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
		Acabado, compilação, sumários e índices de Maria			
HFAC_1990	História Florestal, Aquícola e Cinegética	Colectânea de Documentos existentes no Arquivo Nacional da Torre do Tombo. Chancelarias Reais (1528-1564), direcção e selecção de C.M.L. Baeta Neves, transcrição e revisão de provas de Maria Teresa Barbosa Acabado, compilação, sumários e índices de Maria	1990	5.2	Ministério da Agricultura e Pescas, Direcção-Geral do Ordenamento e Gestão Florestal
HFAC_1993	História Florestal, Aquícola e Cinegética	Colectânea de Documentos existentes no Arquivo Nacional da Torre do Tombo. Chancelarias Reais (1553-1583), direcção e selecção de C.M.L. Baeta Neves, transcrição e revisão de provas de Maria Teresa Barbosa Acabado, compilação, sumários e índices de Maria	1993	6	Ministério da Agricultura e Pescas, Direcção-Geral do Ordenamento e Gestão Florestal
Ilharco_1947	João Ilharco	Corografia de Portugal e do império colonial português	1947	NA	Domingos Barreira, Porto
Júnior_1968	José Bragança Gil Júnior	Dicionário corográfico administrativo e judicial: Portugal Continental e Insular	1968	NA	Editoria Portugália, Lisboa
Lage_1897	José Gonçalves Lage	Elementos de chronologia, de geographia e de corographia de Portugal	1897	NA	-
Leal_1873	Augusto Soares de Azevedo Barbosa Pinho Leal	Portugal Antigo e Moderno - Diccionário Geográphico, Estatístico, Chorográphico; Heráldico, Archeologico; Histórico, Biographico e Etymologico de todas as Cidades, Villas e Freguezias de Portugal e grande número de Aldeias (12 vol.)	1873	1	Livraria Editora de Mattos Moreira & Companhia, Lisboa

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Leal_1874a	Augusto Soares de Azevedo Barbosa Pinho Leal	Portugal Antigo e Moderno - Diccionário Geográphico, Estatístico, Chorográphico; Heráldico, Archeologico; Histórico, Biographico e Etymologico de todas as Cidades, Villas e Freguezias de Portugal e grande número de Aldeias (12 vol.)	1874a	2	Livraria Editora de Mattos Moreira & Companhia, Lisboa
Leal_1874b	Augusto Soares de Azevedo Barbosa Pinho Leal	Portugal Antigo e Moderno - Diccionário Geográphico, Estatístico, Chorográphico; Heráldico, Archeologico; Histórico, Biographico e Etymologico de todas as Cidades, Villas e Freguezias de Portugal e grande número de Aldeias (12 vol.)	1874b	3	Livraria Editora de Mattos Moreira & Companhia, Lisboa
Leal_1874c	Augusto Soares de Azevedo Barbosa Pinho Leal	Portugal Antigo e Moderno - Diccionário Geográphico, Estatístico, Chorográphico; Heráldico, Archeologico; Histórico, Biographico e Etymologico de todas as Cidades, Villas e Freguezias de Portugal e grande número de Aldeias (12 vol.)	1874c	4	Livraria Editora de Mattos Moreira & Companhia, Lisboa
Leal_1875a	Augusto Soares de Azevedo Barbosa Pinho Leal	Portugal Antigo e Moderno - Diccionário Geográphico, Estatístico, Chorográphico; Heráldico, Archeologico; Histórico, Biographico e Etymologico de todas as Cidades, Villas e Freguezias de Portugal e grande número de Aldeias (12 vol.)	1875a	5	Livraria Editora de Mattos Moreira & Companhia, Lisboa
Leal_1875b	Augusto Soares de Azevedo Barbosa Pinho Leal	Portugal Antigo e Moderno - Diccionário Geográphico, Estatístico, Chorográphico; Heráldico, Archeologico; Histórico, Biographico e Etymologico de todas as Cidades, Villas e Freguezias de	1875b	6	Livraria Editora de Mattos Moreira & Companhia, Lisboa

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
		Portugal e grande número de Aldeias (12 vol.)			
Leal_1876	Augusto Soares de Azevedo Barbosa Pinho Leal	Portugal Antigo e Moderno - Diccionário Geográphico, Estatístico, Chorográphico; Heráldico, Archeologico; Histórico, Biographico e Etymologico de todas as Cidades, Villas e Freguezias de Portugal e grande número de Aldeias (12 vol.)	1876	7	Livraria Editora de Mattos Moreira & Companhia, Lisboa
Leal_1878	Augusto Soares de Azevedo Barbosa Pinho Leal	Portugal Antigo e Moderno - Diccionário Geográphico, Estatístico, Chorográphico; Heráldico, Archeologico; Histórico, Biographico e Etymologico de todas as Cidades, Villas e Freguezias de Portugal e grande número de Aldeias (12 vol.)	1878	8	Livraria Editora de Mattos Moreira & Companhia, Lisboa
Leal_1880	Augusto Soares de Azevedo Barbosa Pinho Leal	Portugal Antigo e Moderno - Diccionário Geográphico, Estatístico, Chorográphico; Heráldico, Archeologico; Histórico, Biographico e Etymologico de todas as Cidades, Villas e Freguezias de Portugal e grande número de Aldeias (12 vol.)	1880	9	Livraria Editora de Mattos Moreira & Companhia, Lisboa
Leal_1882	Augusto Soares de Azevedo Barbosa Pinho Leal	Portugal Antigo e Moderno - Diccionário Geográphico, Estatístico, Chorográphico; Heráldico, Archeologico; Histórico, Biographico e Etymologico de todas as Cidades, Villas e Freguezias de Portugal e grande número de Aldeias (12 vol.)	1882	10	Livraria Editora de Mattos Moreira, Lisboa

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Leal_1886	Augusto Soares de Azevedo Barbosa Pinho Leal	Portugal Antigo e Moderno - Diccionário Geográphico, Estatístico, Chorográphico; Heráldico, Archeologico; Histórico, Biographico e Etymologico de todas as Cidades, Villas e Freguezias de Portugal e grande número de Aldeias (12 vol.)	1886	11	Livraria Editora de Tavares Cardoso & Irmão, Lisboa
Leal_1890	Augusto Soares de Azevedo Barbosa Pinho Leal	Portugal Antigo e Moderno - Diccionário Geográphico, Estatístico, Chorográphico; Heráldico, Archeologico; Histórico, Biographico e Etymologico de todas as Cidades, Villas e Freguezias de Portugal e grande número de Aldeias (12 vol.)	1890	12	Livraria Editora de Tavares Cardoso & Irmão, Lisboa
Leão_1610	Duarte Nunez do Leão	Descripção do reino de Portugal	1610	NA	Jorge Rodriguez, Lisboa
Lima_1935	Baptista de Lima	Terras Portuguesas: arquivo histórico-corográfico ou corografia histórica portuguesa	1935	3	Camões, Póvoa-de-Varzim
Lopes_1841	João Baptista da Silva Lopes	Corografia, ou Memoria economica, estadistica, e topografica do reino do Algarve	1841	NA	Typographia da Academia das Sciências de Lisboa, Lisboa
Lopes_1891	João Baptista da Silva Lopes	Diccionario postal e chorographico do Reino de Portugal comprehendendo a divisão administrativa, judicial e ecclesiastica do Continente do Reino e dos archipelagos dos Açores e Madeira	1891	1	Imprensa Nacional, Lisboa
Lopes_1893	João Baptista da Silva Lopes	Diccionario postal e chorographico do Reino de Portugal comprehendendo a divisão administrativa, judicial e ecclesiastica do Continente do Reino e dos archipelagos dos Açores e Madeira	1893	2	Imprensa Nacional, Lisboa

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Lopes_1894	João Baptista da Silva Lopes	Diccionario postal e chorographico do Reino de Portugal comprehendendo a divisão administrativa, judicial e ecclesiastica do Continente do Reino e dos archipelagos dos Açores e Madeira	1894	3	Imprensa Nacional, Lisboa
Loureiro_1882	Adolfo Ferreira de Loureiro	Memória sobre o porto e a barra da Figueira e as obras para o seu melhoramento	1882	NA	Imprensa Nacional, Lisboa
Machado_1980	Fernando Falcão Machado	Corografia lusíada	1980	-	-
Maranhão_1852	Francisco dos Prazeres Maranhão	Diccionario geographico abreviado de Portugal e suas possessões ultramarinas […]	1852	NA	Typographia de Sebastião José Pereira, Porto
Marnay_1883	C. Marnay	Projecto do porto e melhoramento da barra do Douro, do Lima e do Mondego: considerações geraes, apreciações e descripção summaria d'este projecto com a demonstração da exequividade e das vantagens do systema adopta do e r	1883	NA	Typographia Occidental, Porto
Marques_1992	A. H. de Oliveira Marques (ccord.)	Chancelarias Portuguesas : D. Afonso IV, vol. II, 1336-1340	1992	2	Instituto Nacional de Investigação Científica / Centro de Estudos Históricos da Universidade Nova de Lisboa, Lisboa
Marques-Iria_1944	João Martins da Silva Marques & Alberto Iria	Descobrimentos Portugueses: Documentos para a sua História (1147-1460).	1944	1	Instituto para a Alta Cultura, Lisboa
Marques-Rodrigues_1992	A. H. de Oliveira Marques & Teresa Ferreira Rodrig	Chancelarias Portuguesas : D. João I, vol. III, tomo 3, 1410-1418	1992	3	Instituto Nacional de Investigação Científica / Centro de Estudos Históricos da Universidade Nova de Lisboa, Lisboa

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Mascarenhas-Abreu_1879	Joaquim Augusto de Oliveira Mascarenhas & R Clemen	Portugal: diccionario chorographico, historico, heraldico, ethologico, biographico, estatistico, archeologico e bibliographico	1879	1	Pomar, Lisboa
Mascarenhas-Lima_1884	Joaquim Augusto d'Oliveira Mascarenhas & Henrique	Portugal e possessões: novíssimo diccionario chorographico, historico, biographico, archeologico, numismatico, estatistico e heraldino	1883	NA	Manoel Salvador Vieira, Viseu
Mattos_1889	Francisco António de Mattos	Diccionario chorographico de Portugal: parte Continental e Insular	1889	NA	Deposito, Lisboa
Monteiro_1850	José Maria de Souza Monteiro	Diccionario Geographico das Provincias e Possessões Portuguezas no Ultramar; […]	1850	-	Typographia Lisbonense, Lisboa
NA_!!!!	NA	NA	NA	NA	NA
Neves_1961	Carlos Manuel Leitão Baeta Neves	Peixes das águas doces de Portugal	1961	NA	Gazeta das Aldeias, Porto
Neves_1976	Carlos Manuel Leitão Baeta Neves	D. Dinis e um esturjão célebre	1976	NA	Gazeta das Aldeias, Porto
Nobre_1909	Augusto Pereira Nobre	Fauna aquicola de Portugal: peixes, batrachios	1909	-	Imprensa Nacional, Lisboa
NOname_1987	NO NAME	Novo dicionário corográfico de Portugal: actualização	1987	-	-
Pereira_1841a	Agostinho José Pereira	Diccionario geografico do districto administrativo de Lisboa	1841a	1	-
Pereira_1841b	Agostinho José Pereira	Diccionario geografico do districto administrativo de Lisboa	1841b	2	-
Pereira_1861	João Teles Pereira	Compendio de corografia portuguesa	1861	NA	-
Pereira-Rodrigues_1904	Esteves Pereira & Guilherme Rodrigues	Portugal - Diccionario Historico, Chorografico, Heraldico, Biographico, Bibliographico, Numismatico e Artistico (7 Volumes)	1904	1	João Romano Torres - Editor, Lisboa

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Pereira-Rodrigues_1906	Esteves Pereira & Guilherme Rodrigues	Portugal - Diccionario Historico, Chorografico, Heraldico, Biographico, Bibliographico, Numismatico e Artistico (7 Volumes)	1906	2	João Romano Torres - Editor, Lisboa
Pereira-Rodrigues_1907	Esteves Pereira & Guilherme Rodrigues	Portugal - Diccionario Historico, Chorografico, Heraldico, Biographico, Bibliographico, Numismatico e Artistico (7 Volumes)	1907	3	João Romano Torres - Editor, Lisboa
Regalla_1888	Francisco Augusto da Fonseca Regalla	Relatorio sobre a Pesca no Rio Minho em 1884	1888	NA	Imprensa Nacional, Lisboa
Rego_1816	José António da Silva Rego	Geographia Moderna de Portugal e Hespanha	1816	NA	Officina de J. F. M. de Campos, Lisboa
Reguart_1791a	António Sañez Reguart	Diccionario Historico de los Artes de la pesca nacional	1791a	1	Imprenta de la Viuda de Don Joaquin Ibarra, Madrid
Reguart_1791b	António Sañez Reguart	Diccionario Historico de los Artes de la pesca nacional	1791b	2	Imprenta de la Viuda de Don Joaquin Ibarra, Madrid
Reguart_1792	António Sañez Reguart	Diccionario Historico de los Artes de la pesca nacional	1792	3	Imprenta de la Viuda de Don Joaquin Ibarra, Madrid
Reguart_1793	António Sañez Reguart	Diccionario Historico de los Artes de la pesca nacional	1793	4	Imprenta de la Viuda de Don Joaquin Ibarra, Madrid
Reguart_1795	António Sañez Reguart	Diccionario Historico de los Artes de la pesca nacional	1795	5	Imprenta de la Viuda de Don Joaquin Ibarra, Madrid
Rodrigues_1844a	António Patrício Pinto Rodrigues	Diccionario Geografico ou Noticia Historica de todas as Cidades, Villas, Rios, Ribeiras, Serras e Portos de Mar dos Reinos de Portugal e Algarve, 10 vols.	1844a	1	Lisboa
Rodrigues_1844b	António Patrício Pinto Rodrigues	Diccionario Geografico ou Noticia Historica de todas as Cidades, Villas, Rios, Ribeiras, Serras e Portos de Mar dos Reinos de Portugal e Algarve, 10 vols.	1844b	2	Lisboa
Rodrigues_1844c	António Patrício Pinto Rodrigues	Diccionario Geografico ou Noticia Historica de todas as Cidades, Villas, Rios, Ribeiras, Serras e Portos de Mar dos Reinos de Portugal e Algarve, 10 vols.	1844c	3	Lisboa

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Rodrigues_1844d	António Patrício Pinto Rodrigues	Diccionario Geografico ou Noticia Historica de todas as Cidades, Villas, Rios, Ribeiras, Serras e Portos de Mar dos Reinos de Portugal e Algarve, 10 vols.	1844d	4	Lisboa
Rodrigues_1844e	António Patrício Pinto Rodrigues	Diccionario Geografico ou Noticia Historica de todas as Cidades, Villas, Rios, Ribeiras, Serras e Portos de Mar dos Reinos de Portugal e Algarve, 10 vols.	1844e	5	Lisboa
Rodrigues_1844f	António Patrício Pinto Rodrigues	Diccionario Geografico ou Noticia Historica de todas as Cidades, Villas, Rios, Ribeiras, Serras e Portos de Mar dos Reinos de Portugal e Algarve, 10 vols.	1844f	6	Lisboa
Rodrigues_1844g	António Patrício Pinto Rodrigues	Diccionario Geografico ou Noticia Historica de todas as Cidades, Villas, Rios, Ribeiras, Serras e Portos de Mar dos Reinos de Portugal e Algarve, 10 vols.	1844g	7	Lisboa
Rodrigues_1844h	António Patrício Pinto Rodrigues	Diccionario Geografico ou Noticia Historica de todas as Cidades, Villas, Rios, Ribeiras, Serras e Portos de Mar dos Reinos de Portugal e Algarve, 10 vols.	1844h	8	Lisboa
Rodrigues_1844i	António Patrício Pinto Rodrigues	Diccionario Geografico ou Noticia Historica de todas as Cidades, Villas, Rios, Ribeiras, Serras e Portos de Mar dos Reinos de Portugal e Algarve, 10 vols.	1844i	9	Lisboa
Rodrigues_1844j	António Patrício Pinto Rodrigues	Diccionario Geografico ou Noticia Historica de todas as Cidades, Villas, Rios, Ribeiras, Serras e Portos de Mar dos Reinos de Portugal e Algarve, 10 vols.	1844j	10	Lisboa
Rodriguez-Garcia_1982	Francisco Cantelar Rodríguez & António Garcia y G	Synodicon Hispanum. II, Portugal	1982	2	Biblioteca de autores cristianos, Madrid
Sampaio_1940	M Sampaio	Dicionário corográfico de Portugal	1940	NA	Editoria Portugália, Lisboa

ID_Doc	Authors	Title	Doc_date	Volume	Publisher place
Secco_1853	António Luiz de Sousa Henriques Secco	Memoria historico-chorographica dos diversos concelhos do districto administrativo de Coimbra	1853	NA	Imprensa da Universidade de Coimbra, Coimbra
Serra_1824	José Correia da Serra	Collecção de livros ineditos da historia portuguesa dos reinados de D. Affonso V, a D. João II (5 vol.)	1824	5	Typographia da Academia Real das Sciencias, Lisboa
Silva_1891a	António Artur Baldaque da Silva	Estado Actual das Pescas em Portugal: comprehendendo a pesca maritima, fluvial e lacustre em todo o continente do reino, refreido ao anno de 1886	1891a	1	Imprensa Nacional, Lisboa
Silva_1891b	António Artur Baldaque da Silva	Estado Actual das Pescas em Portugal	1891b	2	Imprensa Nacional, Lisboa
Silveira_1804	Francisco do Nascimento Silveira	Mappa breve da Lusitania antiga, e Galliza bracarense	1804	1	Oficina de Simão Thaddeo Ferreira, Lisboa
Tavares_2009	Maria José Ferro Tavares	As pescas: uma riqueza em extinção?	2009	NA	Caleidoscópio, Lisboa
Teles_1914	Bruno Teles	Sinopse de corografia de Portugal	1914	-	-
Vasconcelos_1884	José Leite de Vasconcelos	Diccionario da chorographia de Portugal contendo a indicação de todas as cidades, villas e freguesias	1884	NA	Livraria Portuense de Clavel & C.ª editores, Porto
Vasconcelos_1926	Augusto de Vasconcelos	Corografia de Portugal	1926	-	-
Vieira_1886a	José Augusto Vieira	Minho Pittoresco	1886a	1	Livraria Antonio Maria Pereira, Lisboa
Vieira_1886b	José Augusto Vieira	Minho Pittoresco	1886b	2	Livraria Antonio Maria Pereira, Lisboa
Visconde_1876	2º Visconde de Vila Maior	O Douro Illustrado: album do rio Douro e paiz vinhateiro	1876	NA	Livraria Universal de Magalhães & Moniz, Porto

Table 8.1.8 – Fields and respective description contained in each table of the Portuguese Historical Fish Database.

Table	Field	Field description
Basins	WSO_ID	ID of the basin
	Basin Name	Name of the Basin
	B_MidPoint_X	X coordinate of the midpoint of the basin mouth segment
	B_MidPoint_Y	Y coordinate of the midpoint of the basin mouth segment
	Area_B	Area of the Basin
	Perimeter_B	Perimeter of the Basin
Sub-basins	subWSO_ID	ID of the sub-basin
	WSO_ID	ID of the basin
	Sub-basin Name	Name of the sub-basin
	SB_MidPoint X	X coordinate of the midpoint of the sub-basin mouth segment
	SB_MidPoint Y	Y coordinate of the midpoint of the sub-basin mouth segment
	Area_SB	Area of the sub-basin
	Perimeter_SB	Perimeter of the sub-basin
Segments	WSO1_ID	ID of the Segment
	subWSO_ID	ID of the sub-basin
	WSO_ID	ID of the basin
	River	Name of the river
	S_MidPoint_X	X coordinate of the midpoint of the segment
	S_MidPoint_Y	Y coordinate of the midpoint of the segment
	Area_S	Drainage area of the segment
	Length_S	Length of the segment

Table	Field	Field description
Taxonomical Groups	Group Name	Name of the taxonomical group
	Sub-group Name	Sub-division or detailed identification within the taxonomical group
	English Name	Common English name
	Portuguese Name	Common Portuguese name
	Other PT Names	Old Portuguese names used
	Phenology	Phenology of the animals in this group
	PT Red List	Portuguese Red List status
	UICN Red List	UICN Red List status
Historical Documents	ID_Doc	ID of the historical document
	Author	Name of the Author of the historical document
	Title	Title of the historical document
	Doc_date	Date or period of the historical document
	Volume	Volume of the historical document
	Publisher_place	Publisher and place of the historical document
	Investigator Name	Name of the investigator that scanned the historical document
	Doc_URL	Hyperlink to the digital document
	Doc_PDF	PDF of the document
	Notes	Notes about the historical document
Historical Records	ID_key	ID of the historical record
	Scale_item	Scale at which to consider the record
	WSO_ID	ID of the basin
	subWSO_ID	ID of the sub-basin
	WSO1_ID	ID of the segment
	Extract Name	Species extract name

Table	Field	Field description
	Group Name	Name of the taxonomical group
	Sub-group Name	Sub-division or detailed identification within the taxonomical group
	Village	Historical location of the record
	Basin Name PT	Portuguese name of the basin
	Sub-basin Name	Name of the sub-basin
	River	Name of the river
	Record Date	Date of the historical record
	Century	Century of the historical record
	ID_Doc	ID of the historical document
	Researcher Name	Name of the researcher that scanned this historical document
	Notes	Notes of the historical record

8.2 Supplementary material from Chapter 4

River Network Toolkit Manual

January 19

Introduction

RivTool is an innovative software that integrates river network information with environmental data. Designed to be a straightforward and user-friendly software it facilitates: (1) obtaining information that characterises the network based only on its topographic structure; and (2) by linking environmental data to freshwater networks acquire new data through mathematical calculations that account for the hierarchical nature of these systems. The software is table driven and was developed to work with two distinct basic units: segment and sub-basin.

Disclaimer – Terms & Conditions

The current version is continuously under testing and improvement. Also, we are continuously improving existing features and correcting minor details, please make sure you have the latest version.

The River Network Toolkit is a free software, provided "as-is" and does not come with any warranty or guarantee of any kind. It may be used at your own risk and authors will not be held responsible for its incorrect installation and/or use.

All comments, suggestions and questions may be sent to info@rivtoolkit.com.

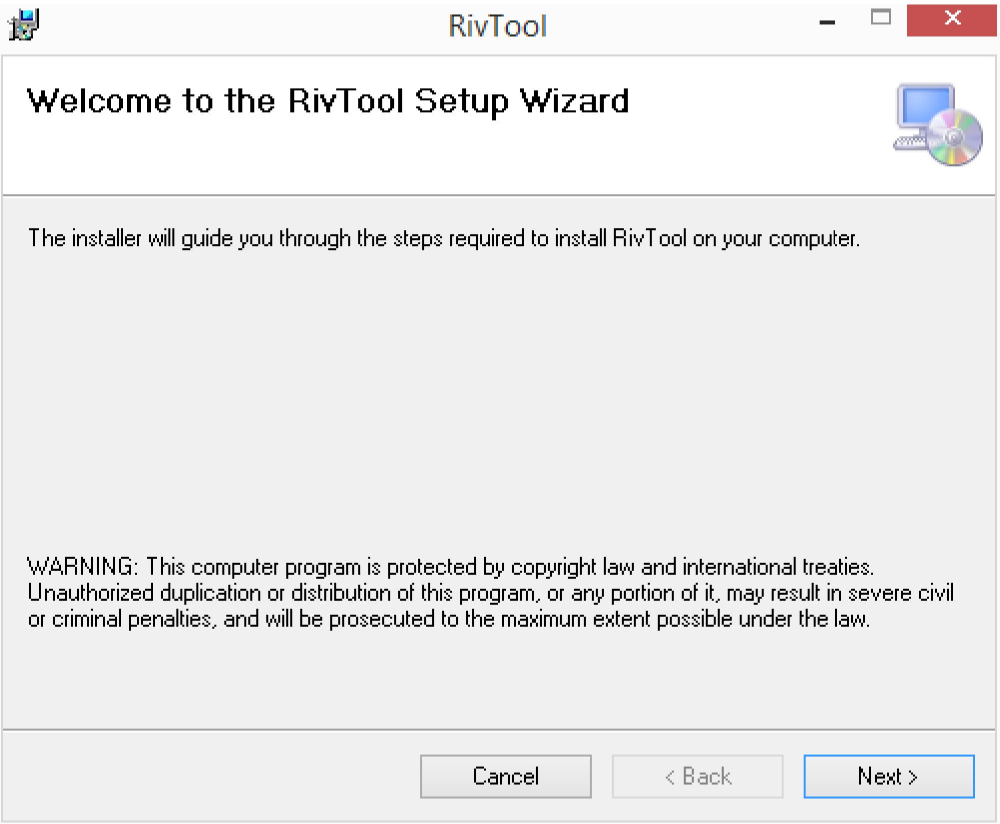
System

Requirements

- RivTool runs under Microsoft .NET framework 4.5.2. If you don't have this installed, the setup will download and install it automatically.
- It has a version for 32-bit systems and another for 64-bit systems. We recommend using a 64-bit system due to the increased memory addressability. Users with 32-bit systems might run into out-of-memory problems when using large input files.
- We recommend 4GB RAM or higher. Be aware that a 32-bit system only uses a maximum of 3GB RAM.
- To achieve a faster calculation, the tool uses parallel processing. This type of processing uses all available processor resources. With this in mind, we recommend a 2-core computer or higher.

Installation procedure

RivTool is very easy to install. After you download the setup file – RivTool.msi – please execute and proceed with the installation.

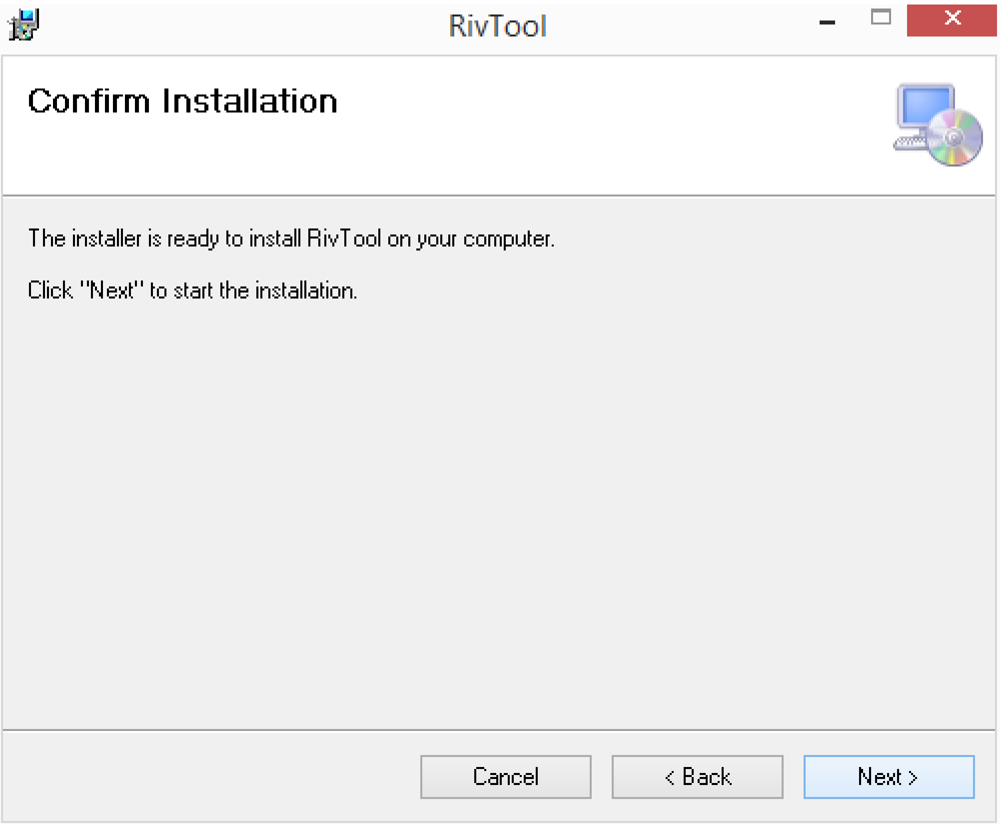


Welcome to the RivTool Setup Wizard

The installer will guide you through the steps required to install RivTool on your computer.

WARNING: This computer program is protected by copyright law and international treaties. Unauthorized duplication or distribution of this program, or any portion of it, may result in severe civil or criminal penalties, and will be prosecuted to the maximum extent possible under the law.

Click Next > button to proceed with the setup.

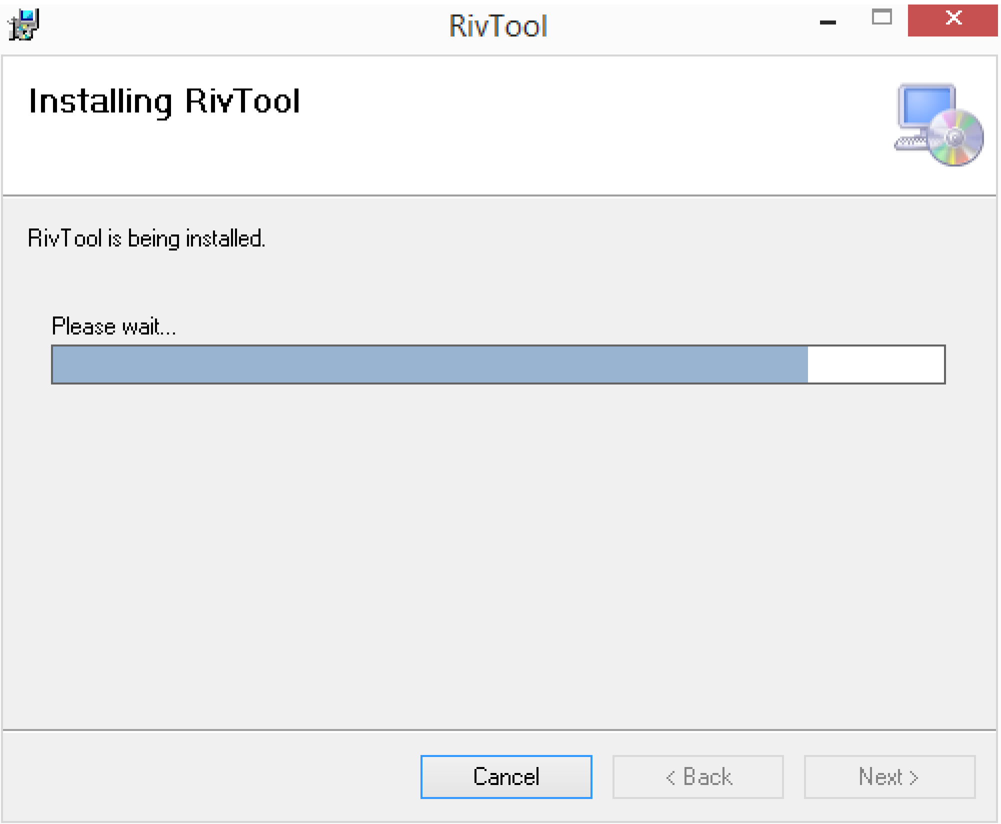


Confirm Installation

The installer is ready to install RivTool on your computer.

Click "Next" to start the installation.

Click Next > button to confirm the installation process and the setup will finish.



RivTool

Installing RivTool

RivTool is being installed.

Please wait...

When the installation finishes, a desktop icon will be created as well as a shortcut folder in your Windows start menu.

Upgrading procedure

After downloading the new version of RivTool and before installing it please uninstall the previous release.

❗ The workspace folder will not be erased, but just for safe keeping please backup your workspace environment.

Folder structure

RivTool

- fns *(functions images)*
- Help *(help documents)*
- Images *(images used in the application)*
- Library *(library files folder)*
    - Data *(data files)*

    - CCM *(CCM data files)*
      - Segments *(CCM data files)*
      - Sub-basins *(CCM data files)*
    - ECRINS *(ECRINS data files)*
      - Segments *(CCM data files)*
  - Label *(label files)*
    - CCM *(CCM label files)*
      - Segments *(CCM label files)*
      - Sub-basins *(CCM label files)*
    - ECRINS *(ECRINS label files)*
      - Segments *(CCM label files)*
  - Main Rivers *(main river source files)*
    - CCM *(CCM network files)*
    - ECRINS *(ECRINS network files)*
  - Networks *(network files)*
    - Segments *(CCM network files)*
      - CCM *(CCM network files)*
        - Basins *(CCM network files)*
        - Countries *(CCM network files)*
          - Portugal *(CCM network files)*
      - ECRINS *(ECRINS network files)*
        - Basins *(ECRINS network files)*
    - Sub-basins *(ECRINS network files)*
      - CCM *(CCM network files)*
        - Main River segments excluded from sub-basins *(CCM network files)*
          - Basins *(CCM network files)*
        - Main River segments included in sub-basins *(CCM network files)*
          - Basins *(CCM network files)*
      - ECRINS *(ECRINS network files)*
        - Main River segments excluded from sub-basins *(ECRINS network files)*

        - Basins *(ECRINS network files)*
      - Main River segments included in sub-basins *(ECRINS network files)*
        - Basins *(ECRINS network files)*
- Templates *(templates folder containing examples)*
- Workspaces *(workspaces folder)*
  - Default *(default workspace folder – all exports and saved data will be sent to this folder)*

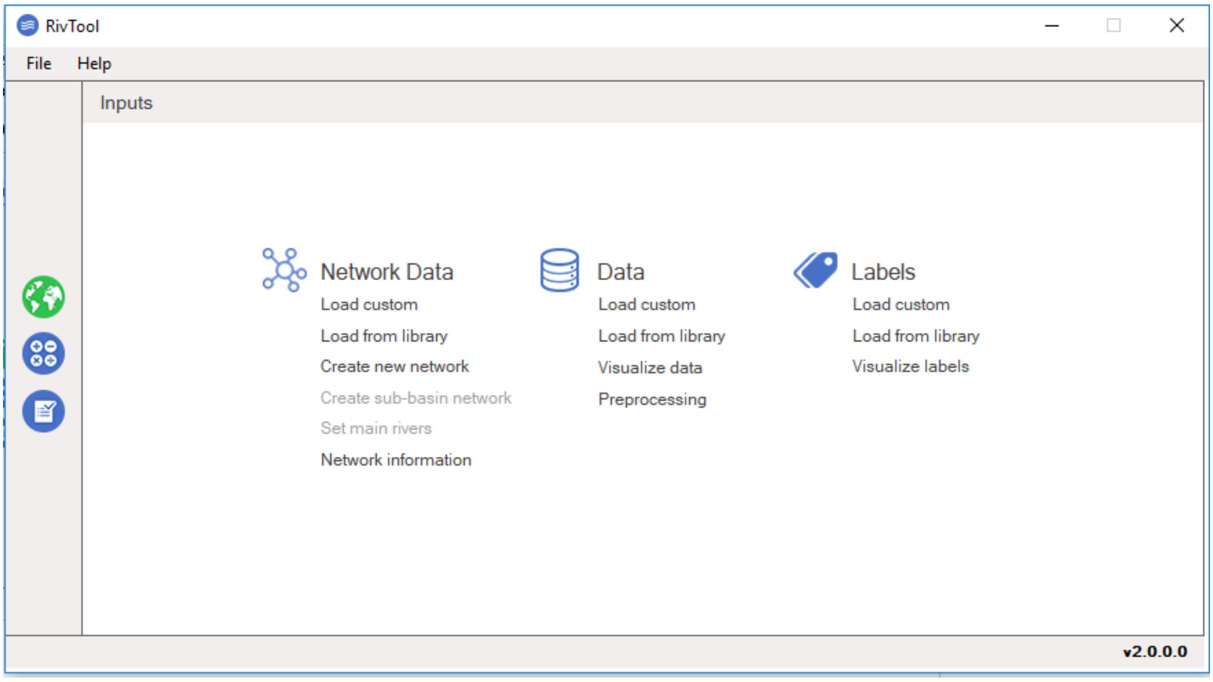
RivTool Interface

There are 5 main interfaces for the software:

1. **Inputs**

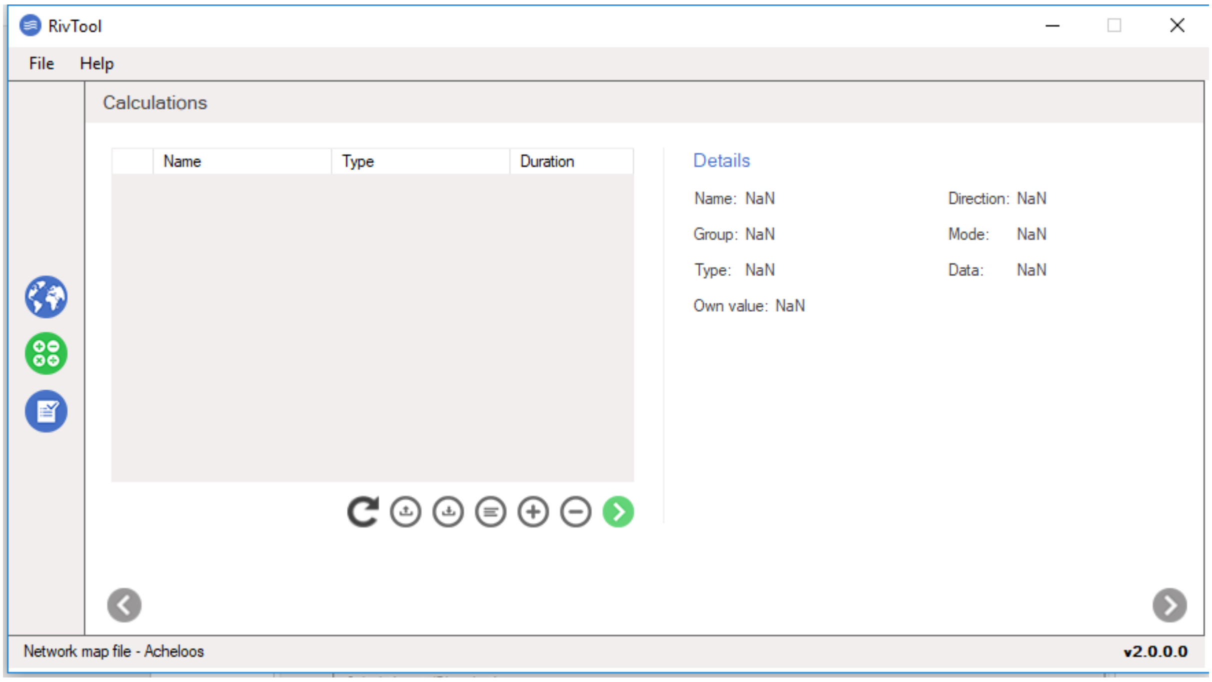
   This area is for inputting network, network settings, data variables and label variables. Here you can choose the network(s), set the main river(s), pre-process landscape/environmental data to comply with RivTool data input requirements, load data and labels that you want to use in the calculations.

   You can also create your custom map, segments or sub-basins, based on a custom segments file (check *Help -> Templates* for the map file template).



2. Calculations

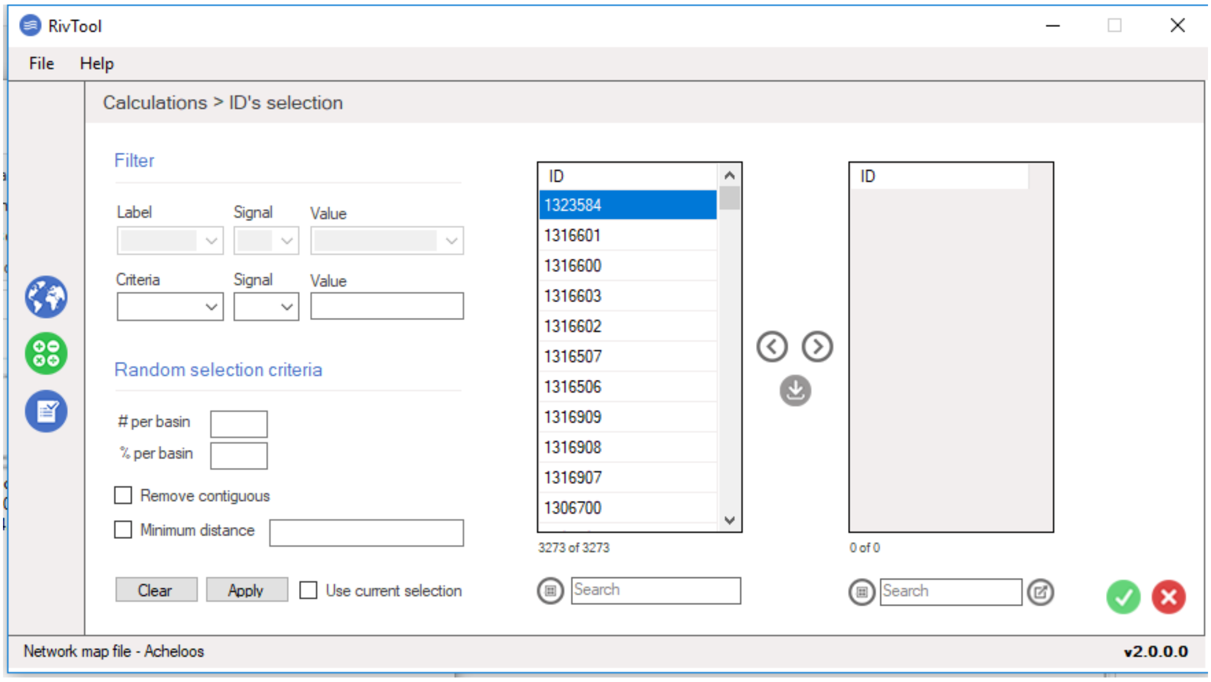
This area gives access to the interface of the calculations' editor and the interface of selection of segments. Also, in this window, after choosing and defining the calculations, it is possible to visualise the calculations chosen and their specifications.



Name: NaN
Group: NaN
Type: NaN
Own value: NaN
Direction: NaN
Mode: NaN
Data: NaN

3. Segments selection

This area is for the selection of the unit of analysis ID's. Here you can choose which ID's you want to use in your calculations. Several methods for segment selection are available and, by default, all segments will be used.



ID
1323584
1316601
1316600
1316603
1316602
1316507
1316506
1316909
1316908
1316907
1306700

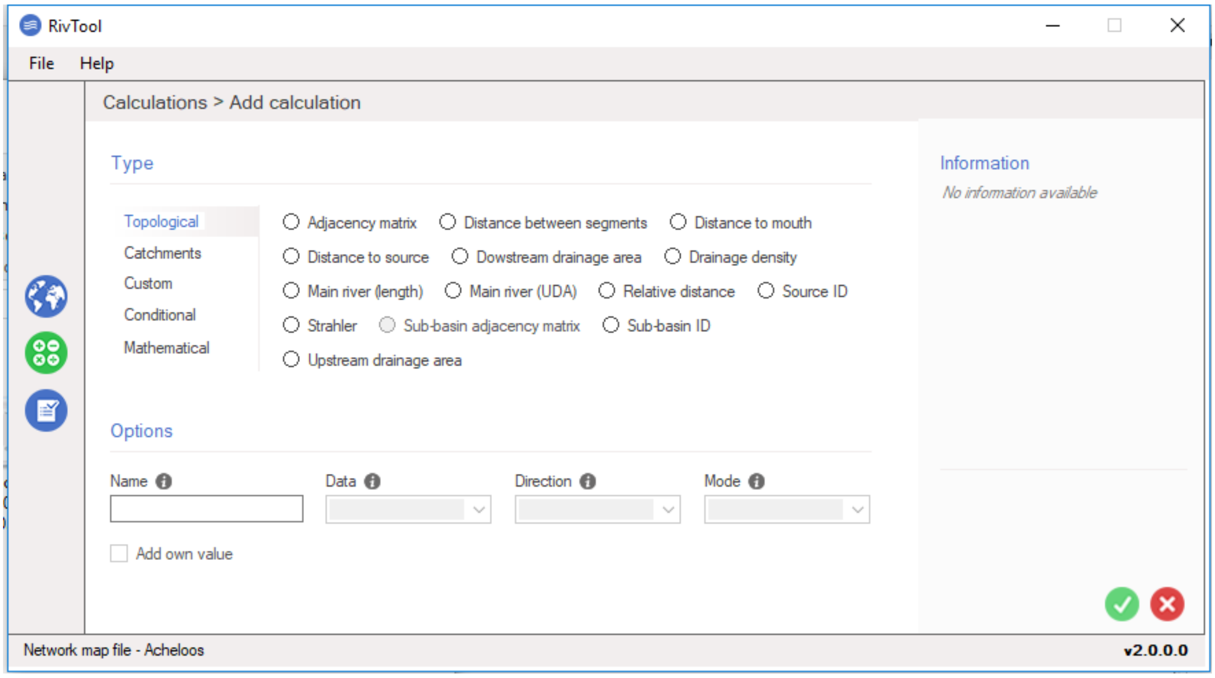
3273 of 3273

0 of 0

Network map file - Acheloos

4. Calculations editor

Here you can add and edit calculations that will be executed using the selected units of analysis of the network.

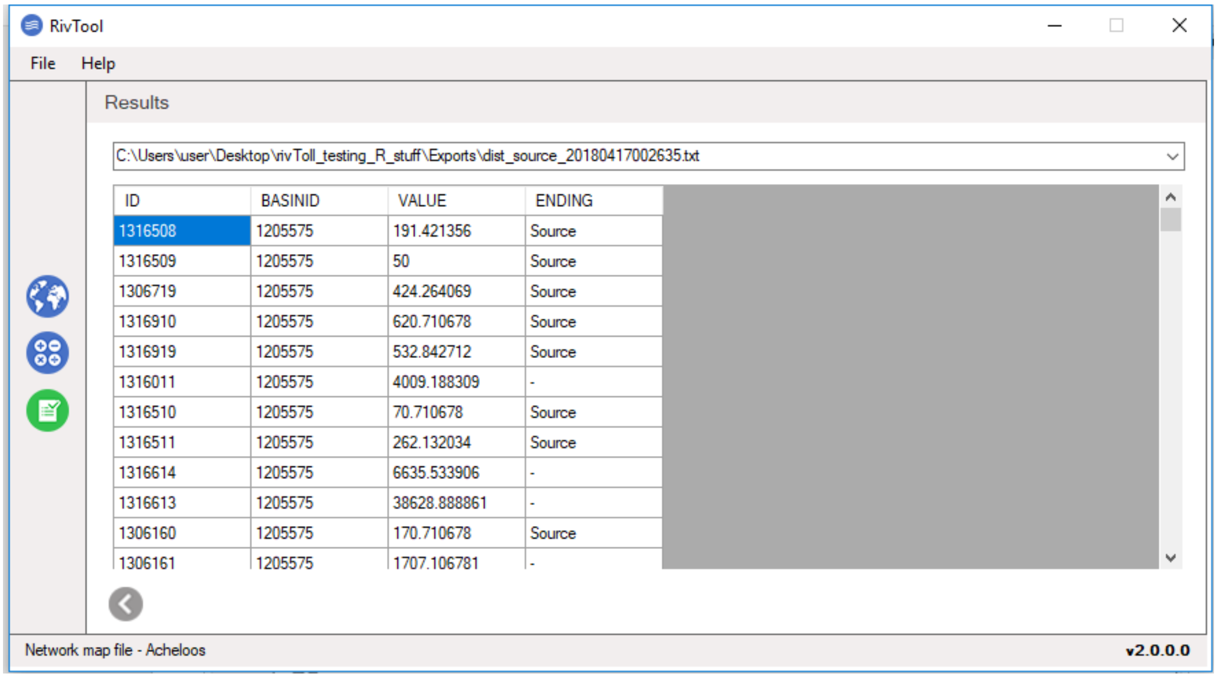


No information available

Network map file - Acheloos

5. **Results**

This area is for results display purposes. Here you will find all calculation results. You can then analyse and export the results into separate files or all in one export file.



C:\Users\user\Desktop\rivToll_testing_R_stuff\Exports\dist_source_20180417002635.txt

ID	BASINID	VALUE	ENDING
1316508	1205575	191.421356	Source
1316509	1205575	50	Source
1306719	1205575	424.264069	Source
1316910	1205575	620.710678	Source
1316919	1205575	532.842712	Source
1316011	1205575	4009.188309	-
1316510	1205575	70.710678	Source
1316511	1205575	262.132034	Source
1316614	1205575	6635.533906	-
1316613	1205575	38628.888861	-
1306160	1205575	170.710678	Source
1306161	1205575	1707.106781	-

Templates

Map creation input file

The software provides the possibility of creating a custom network from a user-provided file. The file should contain 4 fields:

1. The ID of the segment or the sub-basin
2. The ID of the Basin where it belongs
3. The ID of the downstream adjacent segment or sub-basin (also called the nextdown ID)
4. Primary catchment area of the segment or sub-basin area
5. The length of each segment or the sum of the length of all segments in a sub-basin
6. The Name of the River (optional)

Fields should be separated by a comma (,) while decimal values are indicated by using a dot (.) Finally, in this file, all fields should have a header.

Example:

Segment_ID,Basin_ID,Next_down_ID,Area,Length
30844,4,30843,20000,300.00

```
30845,4,30925,1200.56,1589.94
30842,4,30866,10000,665.68
30843,4,30912,50000,1972.79
52870,2,52966,150000.42,1189.9
```

Main River Sources

The software allows the user to define the source of the main river for every basin. By default, it will consider the source of the main river as the most distant from the river mouth. In this setting, a library file can be used or a user-provided file. It should contain 2 fields:

1. The ID of the Basin
2. The ID of the main river source segment for the respective basin. Obligatorily this has to be a source segment.

Fields should be separated by a comma (,). In this file, all fields should have a header.

Example:

```
Basin_ID,Main_river_source_ID
130749,255566
129537,250975
129742,252129
130834,267432
129778,270310
```

Data file

The user can provide custom data for any network but this file must provide information for every segment/sub-basin present in the network map it intends to use.

The file has 1 mandatory field, after which data fields intended to be used in RivTool can be added:

1. The ID of the segment or the sub-basin
2. Data for variable 1
3. Data for variable 2

N. Data for variable N

Fields should be separated by a comma (,) while decimal values are indicated by using a dot (.). Finally, in this file, all fields should have a header.

Example:

```
Segment_ID,Strahler,Temperature,Precipitation,slope,Forest
30844,4,21,300.00,1.0,35
30845,4,10,1589.94,1.6,65
52875,6,20,300.00,2.9,25
52873,7,21,1065.68,1.8,90
52870,2,27,1189.94,3.0,10
```

Label file

The user can provide custom label data for any network but this file must provide information for every segment/sub-basin present in the network map it intends to use. Label should be text fields.

The file has 1 mandatory field, after which data fields intended to be used in RivTool can be added:

1. The ID of the segment or the sub-basin
2. Label 1
3. Label 2

N. Label N

Fields should be separated by a comma (,) while decimal values are indicated by using a dot (.). Finally, in this file, all fields should have a header.

Example:

```
Segment_ID,Basin,Sub-basin,Ocean,Land_use,Climate_type
30844,Nemunas,Neris,Baltic,Pasture,Continental
30845,Danube,Inn,Black,Forest,Alpine
52877,Tagus,Jarama,Atlantic,Urban,Mediterranean
52875,Nemunas,Shchara,Baltic,Urban,Continental
52870,Tagus,Zezere,Atlantic,Forest,Mediterranean
```

Segment list file

When choosing the segments or sub-basin IDs to be used in the calculation the user can provide a file with these IDs. The file should be a simple list of the IDs of the segments/sub-basins to be used in the calculation.

Example:

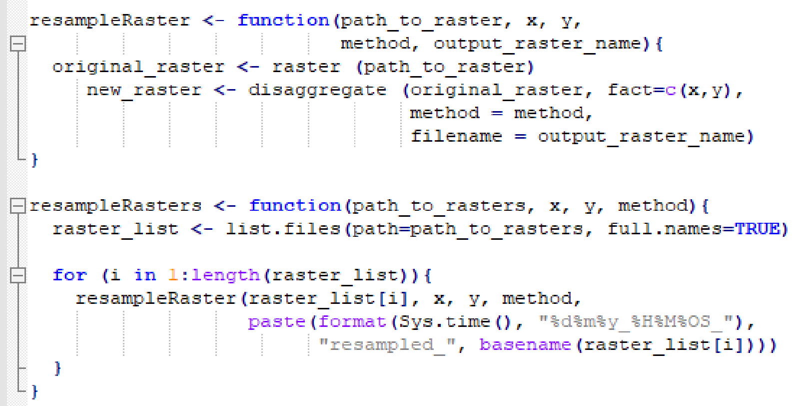
30844
30845
52875
52873
52870

Data Preprocessing

Users can create data inputs tables from raster information using the preprocessing option of the Data Inputs. There are 4 functionalities available: Resample, Calculation using multiple rasters, Zonal Statistics and Missing Data Patch. The first 3 options use internal R software computation.

Resample rasters

Allows users to resample one or a set of raster using the following functions:



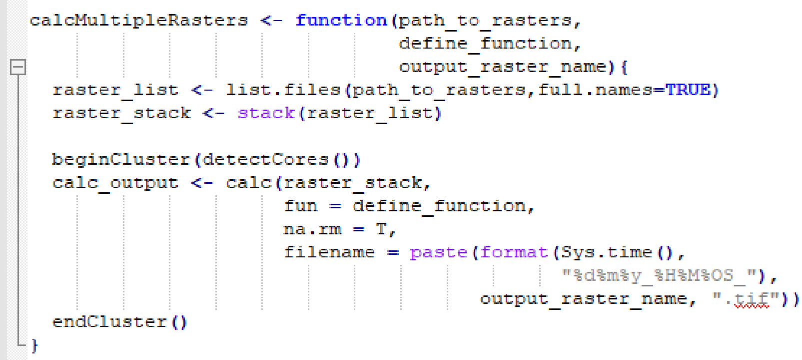
```
resampleRaster <- function(path_to_raster, x, y,
                           method, output_raster_name){
  original_raster <- raster (path_to_raster)
     new_raster <- disaggregate (original_raster, fact=c(x,y),
                                 method = method,
                                 filename = output_raster_name)
}

resampleRasters <- function(path_to_rasters, x, y, method){
  raster_list <- list.files(path=path_to_rasters, full.names=TRUE)

  for (i in 1:length(raster_list)){
    resampleRaster(raster_list[i], x, y, method,
                   paste(format(Sys.time(), "%d%m%y_%H%M%OS_"),
                         "resampled_", basename(raster_list[i])))
  }
}
```

Calculation using multiple rasters

Allows users to perform mathematical calculations using multiple rasters using the following function:

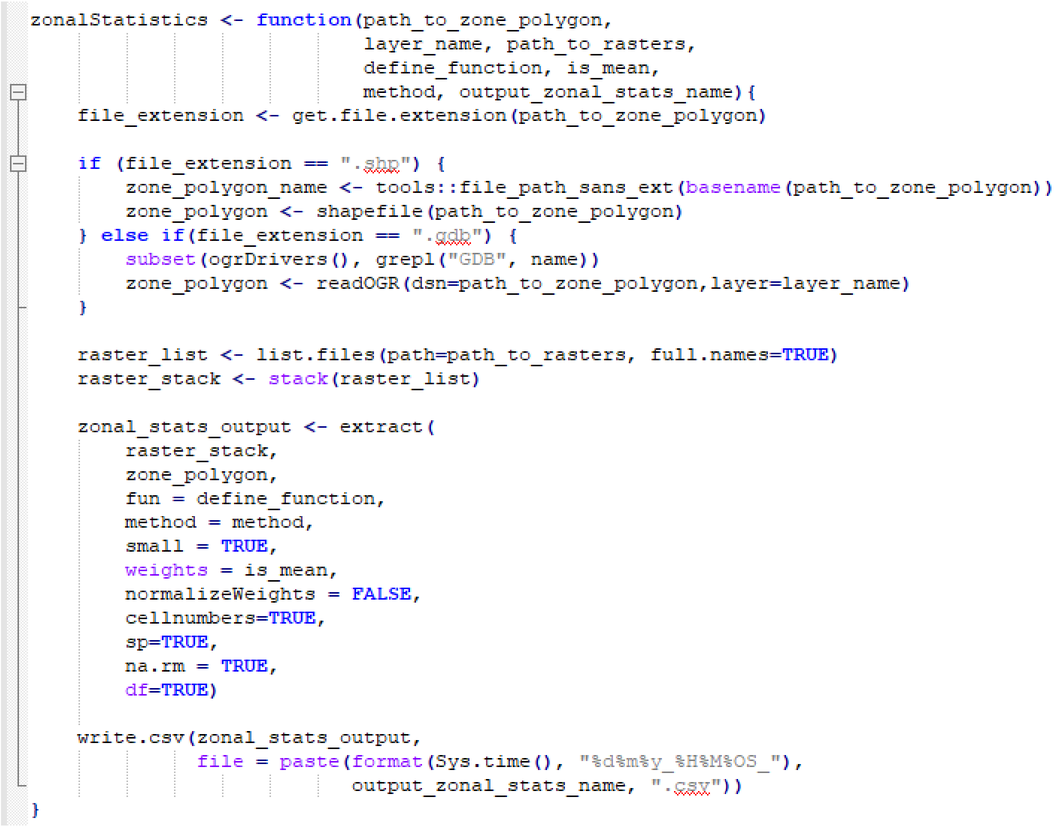


```
calcMultipleRasters <- function(path_to_rasters,
                                define_function,
                                output_raster_name){
  raster_list <- list.files(path_to_rasters,full.names=TRUE)
  raster_stack <- stack(raster_list)

  beginCluster(detectCores())
  calc_output <- calc(raster_stack,
                      fun = define_function,
                      na.rm = T,
                      filename = paste(format(Sys.time(),
                                              "%d%m%y_%H%M%OS_"),
                                       output_raster_name, ".tif"))
  endCluster()
}
```

Zonal Statistics

Allows users to perform zonal statistics using one or several rasters and polygon shapefile using the following function:



```
zonalStatistics <- function(path_to_zone_polygon,
                            layer_name, path_to_rasters,
                            define_function, is_mean,
                            method, output_zonal_stats_name){
    file_extension <- get.file.extension(path_to_zone_polygon)

    if (file_extension == ".shp") {
        zone_polygon_name <- tools::file_path_sans_ext(basename(path_to_zone_polygon))
        zone_polygon <- shapefile(path_to_zone_polygon)
    } else if(file_extension == ".gdb") {
        subset(ogrDrivers(), grepl("GDB", name))
        zone_polygon <- readOGR(dsn=path_to_zone_polygon,layer=layer_name)
    }

    raster_list <- list.files(path=path_to_rasters, full.names=TRUE)
    raster_stack <- stack(raster_list)

    zonal_stats_output <- extract(
        raster_stack,
        zone_polygon,
        fun = define_function,
        method = method,
        small = TRUE,
        weights = is_mean,
        normalizeWeights = FALSE,
        cellnumbers=TRUE,
        sp=TRUE,
        na.rm = TRUE,
        df=TRUE)

    write.csv(zonal_stats_output,
              file = paste(format(Sys.time(), "%d%m%y_%H%M%OS_"),
                           output_zonal_stats_name, ".csv"))
}
```

Missing Data Patch

Geographic differences between shapefiles and raster files will lead to missing values in the zonal statistics procedure (eg, small differences between coastal limits in the shapefiles and the last pixel of the raster with information in the coastal area often leads to zones with no information). This means that the produced table from the zonal statistics procedure will lack some data and thus possibly preventing the rivtool from using it as a data input. This functionality will fill these information gaps using data from adjacent river segments. For each segment with missing data, rivtool will perform the weighted average using the data from the adjacent segments. Because this problem may affect multiple adjacent segments, rivtool will start the calculation for those segments with a higher number of adjacent segments with pre-existing information.

Functions

All functions require the completing of the field "*Name*". The alphanumeric characters introduced in this field will be used to name the output table to be created after performing the calculation. Nearly all functions also require the user to choose, in the "*Data*" dropdown box which variable from the environmental data will be used to perform the calculation. The "add own value" checkbox gives the user the possibility of choosing if they want to consider the segment/sub-basin for which the calculation is being performed as part of this calculation.

Type

Topological

Functions that only depend on the topological structure of the network data.

Catchments

Functions that retrieve descriptive information about basins or sub-basins.

Custom

Ready-to-use functions mostly without the need for configuration. Most of these retrieve common relevant information searched when dealing with freshwater systems.

Conditional

Functions where a condition before calculation has to be imposed.

Mathematical

Ordinary mathematical calculations that are performed using both network and environmental data. These functions require the specification of a few options:

- **Direction**: Establishes the direction to indicate which segments or sub-basins will be included in the calculations. Downstream will use segments/sub-basins that are downstream of a considered segment/sub-basin. Upstream will use segment/sub-basin that is upstream of a considered segment/sub-basin.
- **Mode:** Given a direction, this option will establish which of these segments/sub-basins will be used to perform the calculations. Path establishes that only segments/sub-basins in the shortest path towards mouth (when the direction is downstream) or towards the respective source (when the direction is upstream) will be used in calculations. Relatives establish that all segments/sub-basins downstream or upstream (depending on the established direction) of a given segment/sub-basin will be used in calculations.

Function Descriptions

Type	Function	Description	Unit of Analysis	Units
Topological	Adjacency matrix	Identifies the IDs of contiguous units of analysis of a given unit.	Segment and sub-basin	-
Topological	Distance between segments	Distance along the river between the midpoints of a given set of segments.	Segment	meters (m)
Topological	Distance to mouth	Distance from the midpoint of a given segment to the mouth of the river.	Segment	m
Topological	Distance to source	Distance from the midpoint of a given segment to its correspondent river source.	Segment	m
Topological	Downstream drainage area (DDA)	Downstream drainage area of a given unit.	Segment and sub-basin	m^2
Topological	Drainage density	Ratio between the length and the primary catchment of a unit, when using segments. Ration between the sum of the units lengths and the sum of primary catchments' area when using sub-basins.	Segment and sub-basin	-
Topological	Main river (length)	Identifies the segments that belong to the main river course of a basin based on the longest path between source and mouth.	Segment	-
Topological	Main river (UDA)	Identifies the segments that belong to the main river course of a basin based on the largest upstream drainage area.	Segment	-
Topological	Relative distance	Indicates the relative distance of a segment to the mouth considering the full distance between the mouth and the correspondent river source for that segment. For more information about the application of this descriptor see Imbert, H. et al. (2008).	Segment	Proportion
Topological	Source ID	Identifies the ID of the correspondent source for a given unit.	Segment and sub-basin	-
Topological	Strahler	Calculates the Strahler stream order for every segment. For more information see Strahler, A. N. (1952) and Strahler, A. N. (1957).	Segment	-
Topological	Sub-basin ID	Considering the main river course established, identifies the natural sub-basins to which a given segment belongs. It establishes the ID of the sub-basin using the ID of the first main river segment after the mouth of the tributary. The maximum Strahler number of the sub-basin is equal to the one from the last segment of the sub-basin river.	Segment	-
Topological	Upstream drainage area (UDA)	Upstream drainage area of a given unit.	Segment and sub-basin	Km^2
Catchments	Basin drainage density	Ratio between the sum of the length of all segments and the drainage area of a basin.	Basin (inputs: Segment or sub-basin)	Km^{-1}
Catchments	Basin stats	Summary statistics about each basin using segments as an analysis unit (check the manual for more detail).	Basin (inputs: segments)	several
Catchments	Basin stats (sub-basins)	Summary statistics about each basin using sub-basins as an analysis unit (check the manual for more detail).	Basin (inputs: sub-basins)	several

Type	Function	Description	Unit of Analysis	Units
Catchments	Bifurcation ratio	Average of the ratios between the number of segments of one Strahler order (n) and those of the next-higher Strahler order (n+1) in a basin.	Basin (inputs: segments)	-
Catchments	Total mouth segments	Number of mouth segments per basin.	Basin (inputs: segments)	-
Catchments	Total source segments	Number of source segments per basin.	Basin (inputs: segments)	-
Custom (also in Topological)	Drainage density	Ratio between the length and the primary catchment of a unit, when using segments. Ration between the sum of the units lengths and the sum of primary catchments' area when using sub-basins (same as in the Topological type).	Segment and sub-basin	-
Custom	Occupancy in DDA	Area covered by the chosen variable (e.g. forest, crop) in the downstream drainage area of a given unit.	Segment and sub-basin	dependent on selected variable
Custom	Occupancy in UDA	Area covered by the chosen variable (e.g. forest, crop) in the upstream drainage area of a given unit.	Segment and sub-basin	dependent on selected variable
Custom (also in Topological)	Relative distance	Indicates the relative distance of a specific ID to the mouth considering the full distance between the mouth and the correspondent river source for that ID. For more information about the application of this descriptor see Imbert, H. et al. (2008) (same as in the Topological type).	Segment	proportion
Custom	Relative occupancy in DDA	Area covered by the chosen variable (e.g. forest, crop) in the DDA of a given unit divided by the total area of the DDA.	Segment and sub-basin	proportion
Custom	Relative occupancy in primary catchment	Area covered by the chosen variable (e.g. forest, crop) in the primary catchment of a given unit divided by the total area of primary drainage catchment.	Segment and sub-basin	proportion
Custom (also in Topological)	Strahler	Calculates the Strahler stream order for every segment. For more information see Strahler, A. N. (1952) and Strahler, A. N. (1957) (same as in the Topological type).	Segment	-
Custom	Stream Power	Calculates for each segment the rate of potential energy expenditure over a reach (Gordon, N. D. et al. 2004), i.e., Stream Power per river segment. Calculation according to Gordon, N. D. et al. (2004) and using the computation formulas described in Logez, M. et al. (2012).	Segment	kg m^2 s^{-3} km
Custom (also in Topological)	UDA	Upstream drainage area of a given unit (same as in the Topological type).	Segment and sub-basin	Km^2
Conditional	Conditional sub-basin Strahler	Starting from the output of the "Sub-basin ID" function, aggregates the segments for which the Strahler number is lower than the established threshold to the one immediately downstream that fulfils this condition. If there is no sub-basin below that matches the condition, it will look for one immediately upstream. If no sub-basin has a Strahler number equal or larger than the threshold, then all units of analysis of the basin are considered to be in the same sub-basin (in this case the sub-basin corresponds to the total basin).	Segment	-

Type	Function	Description	Unit of Analysis	Units
Mathematical	Average	Arithmetic mean considering the values of a given variable for all considered units in the calculation.	Segment and sub-basin	dependent on selected variable
Mathematical	Count	Number of units given the direction and mode chosen.	Segment and sub-basin	
Mathematical	Max	Maximum value of a given variable for all considered units in the calculation.	Segment and sub-basin	dependent on selected variable
Mathematical	Min	Minimum value of a given variable for all considered units in the calculation.	Segment and sub-basin	dependent on selected variable
Mathematical	Range	Range of values of a given variable for all considered units in the calculation.	Segment and sub-basin	dependent on selected variable
Mathematical	Standard deviation	Standard deviation considering the values of a given variable for all considered units in the calculation.	Segment and sub-basin	dependent on selected variable
Mathematical	Standard error	Standard error considering the values of a given variable for all considered units in the calculation.	Segment and sub-basin	dependent on selected variable
Mathematical	Sum	Retrieves the sum of all the values of a given variable for all considered units in the calculation.	Segment and sub-basin	dependent on selected variable
Mathematical	Variance	Variance considering the values of a given variable for all considered units in the calculation.	Segment and sub-basin	dependent on selected variable
Mathematical	Weighted Average	Area or length weighted arithmetic mean considering the values of a given variable for all considered units in the calculation.	Segment and sub-basin	dependent on selected variable

Formulas and detailed Functions

Basin Stats

The calculations performed by this function using a network of segments includes:

- Total segments
- Total sources
- Total mouths
- Total major river segments
- Total minor river segments

- Total sub-basins
- Maximum segment length
- Minimum segment length
- Main river length
- Drainage density
- Bifurcation ratio

The calculations performed by this function using a network of sub-basins includes:

- Total number of sub-basins
- Maximum water courses length
- Minimum water courses length
- Average water courses length
- Maximum sub-basins area
- Minimum sub-basins area
- Average sub-basins area
- Drainage density

Bifurcation Ratio

Average of the ratios between the number of segments of one strahler order (n) and those of the next-higher strahler order (n+1) in a basin.

$$Bifurcation\,ratio = \sum_{n}^{i} \frac{strahler\ order_n}{strahler\ order_{n-1}}$$

Drainage Density

Ratio between the length and the primary catchment of a unit, when using segments. Ratio between the sum of the units lengths and the sum of primary catchments' area when using sub-basins.

$$Drainage\ Density\ = \frac{length}{area}$$

Relative Distance

Indicates the relative distance of a segment to the mouth considering the full distance between the mouth and the correspondent river source for that segment. For more information about the application of this descriptor see Imbert et al. (2008).

$$RelativeDist = \frac{Distance\ to\ mouth}{Distance\ to\ Mouth + Distance\ to\ respective\ source}$$

Stream Power

Calculates for each segment the rate of potential energy expenditure over a reach (Gordon, N. D. et al. 2004), i.e., Stream Power per river segment. Calculation according to Gordon, N. D. et al. (2004) and using the computation formulas described in Logez, M. et al. (2012).

$$STP = \rho\, g\, Q\, S$$

P – density of water g – gravitational acceleration

Q – annual discharge S – slope

$$Q = \frac{MAR \times UDA}{31536}$$

MAR – Mean annual run-off UDA – Upstream drainage area

$$MAR = P - PET$$

P – Mean annual precipitation PET – Annual potential evapotranspiration

$$PET = \frac{P}{\sqrt{0.9 + (\frac{P}{L})^2}}$$

$$L = 300 + 25T + 0.05T^2$$

L – Temperature factor derived from mean annual temperature

The software allows you to perform this function using the temperature, precipitation and drainage values calculated for the segment drainage area (SDA) or the upstream drainage area (UDA). These work independently, i.e., you may have temperature data for the UDA and precipitation data for SDA. If you have discharge values for every segment you may directly calculate the Stream Power of the segment without using the UDA or SDA drop-down boxes.

Libraries

Networks

Catchment Characterisation and Modelling v2.1 (CCM2)

All basins included in the CCM2 have a network data file, and there is one file that includes all basins. Please check Vogt, J. et al. (2007) for more information.

European Catchments and Rivers Network System – ECRINS/ Managing Aquatic Ecosystems and Resources under Multiple Stress (MARS)

Only basins with more than 50 km2 were included. There is one file for each basin and a file that includes all basins. Please check EEC (2012) and MARS (2015) for more information.

Main River Sources

CCM2

Main river sources for CCM2 were established for 794 basins using the "MAINRIVERS" and the "NAMEDRIVERS" CCM2 layers. We also cross-checked these layers with ArcBruTile v0.7 layers to verify and/or confirm river sources. Please check Vogt, J. et al. (2007) for more information about the CCM2 layers used. For ECRINS (666 basins) we used the information created for CCM2 and cross-checked again with ArcBruTile v0.7 layers to verify and/or confirm river sources.

Variables

CCM2

All data variables included in the segments and primary catchment layers of the CCM2 are available. Please check Vogt, J. et al. (2007) for more information and detail about the aforementioned variables.

ECRINS/MARS

Two label files are included, one with labels related to the biogeographic regions and other with the Corine Land Cover information present in the MARS geodatabase. Please check MARS (2015) for more information.

Labels

CCM2

The basin name and the field “Sea_CD” were included as label data. For those basins where the name was not available, the basin ID was used concatenated with the word “Basin”. For the “Sea_CD” field we concatenated every value with the letter “a” to make it a text field. Please check Vogt, J. et al. (2007) for more information and detail about the aforementioned fields.

ECRINS/MARS

Two data files are included, one with variables characterising the segments and respective drainage areas and other related with the River Basin Districts (RBDs) and their subunits (RBDSUs) (EEA 2017). Please check MARS (2015), EEA (2017) and EEA (2016) for more information.

Troubleshooting

Please make sure to read the manual and check the template files to correctly use the River Network Toolkit. Since we are continuously improving and correcting minor details, please make sure you have the latest version.

All comments, suggestions and questions may be sent to river.network.toolkit@gmail.com.

How to reference RivTool

For this please contact the authors via the email info@rivtoolkit.com.

References

EEA. 2016. WISE GIS Guidance - Guidance on the reporting of spatial data to WISE. cdr.eionet.europa.eu.

EEA. 2017. WISE WFD reference spatial data sets. https://www.eea.europa.eu/data-and-maps/data/wise-wfd-spatial.

EEC. 2012. Catchments and Rivers Network System ECRINS v1.1 - Rationales, building and improving for widening uses to water Accounts and WISE applications. 7/2012, European Environment Agency, European Union, Copenhagen.

Gordon, N. D., B. L. Finlayson, T. A. McMahon, C. J. Gippel, and R. J. Nathan. 2004. Stream hydrology: an introduction for ecologists. 2nd Edition edition. John Wiley and Sons LTd., New York.

Imbert, H., S. De Lavergne, F. Gayou, C. Rigaud, and P. Lambert. 2008. Evaluation of relative distance as new descriptor of yellow European eel spatial distribution. Ecology of Freshwater Fish 17:520-527.

Logez, M., P. Bady, and D. Pont. 2012. Modelling the habitat requirement of riverine fish species at the European scale: sensitivity to temperature and precipitation and associated uncertainty. Ecology of Freshwater Fish 21:266-282.

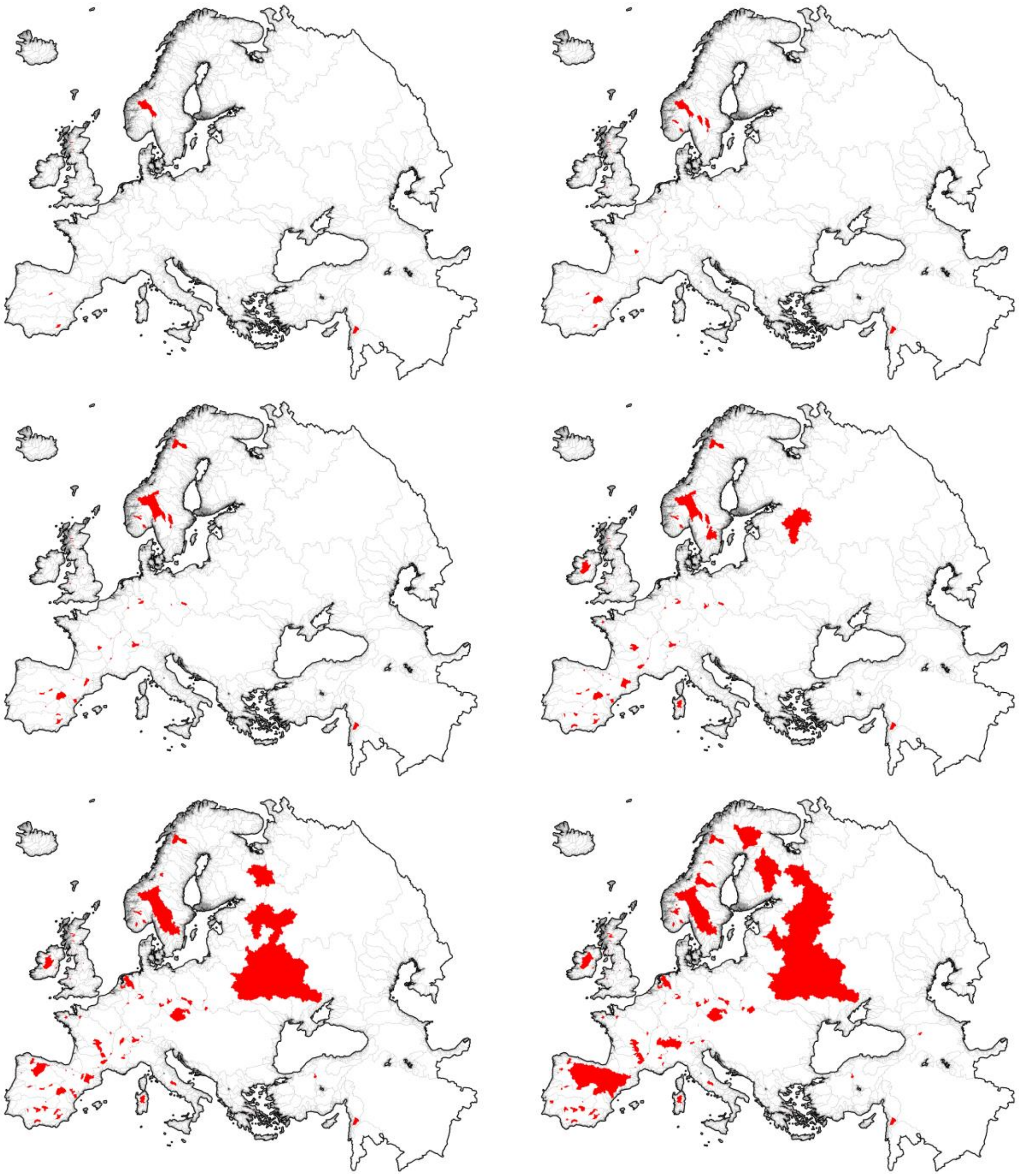
MARS. 2015. Managing Aquatic ecosystems and water Resources under multiple Stressors (MARS) Geodatabase. http://www3.fgg.uni-lj.si/~/mars/MARS_Geodatabase_20150930/.

Strahler, A. N. 1952. Hypsometric (Area-Altitude) Analysis of Erosional Topography. Geological Society of America Bulletin 63:1117.

Strahler, A. N. 1957. Quantitative analysis of watershed geomorphology. Eos, Transactions American Geophysical Union 38:913-920.

Vogt, J., P. Soille, A. d. Jager, E. Rimavičiūtė, W. Mehl, S. Foisneau, K. Bódis, J. Dusart, M. L. Paracchini, P. Haastrup, and C. Bamps. 2007. A pan-European River and Catchment Database. European Commission - Joint Research Centre - Institute for Environment and Sustainability, Luxembourg.

8.3 Supplementary material from Chapter 5



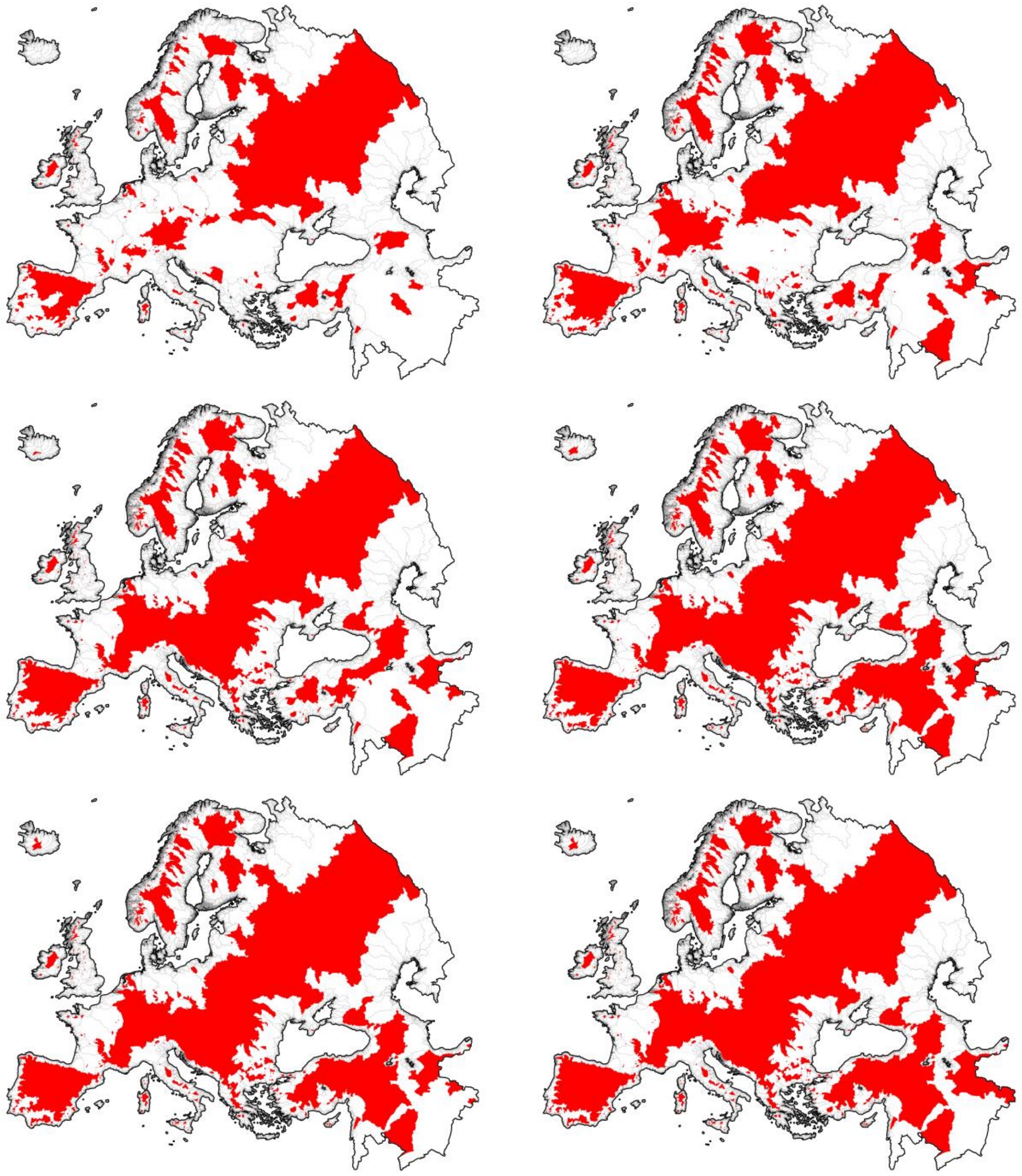


Figure 8.3.20 – Evolution of the potential inaccessible areas of European freshwater basins for diadromous fish species considering the construction of large dams throughout the 20th century. The first map represents the situation at the beginning of the 20th-century, the following 10 are the perspective at the end of each decade, and the last map is the current situation.