Reconciling Agriculture and Stream Restoration in Europe

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All the corrections determined by the jury, and those alone, have been applied.

The jury's president,

Porto, _____/_____/_________

"Finished, Not Perfect."

Science is an expression of art.

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Abstract

In Europe and many other regions, agriculture has caused considerable impacts on freshwater ecosystems. To revert the degradation caused to streams and rivers, research and restoration efforts have been developed to recover ecosystem functions and services, with the European Water Framework Directive (WFD) implementation playing a significant role in strengthening the progress of freshwater ecosystem recovery.

In 2015, the first management cycle under the WFD has ended, and with it so did the deadline to achieve good ecological status on European water-bodies. With the transition to the second management cycle, restoring the freshwater ecosystems still in bad condition is crucial, given that in 2027 the WFD will meet its final deadline.

The present dissertation aims to explore the recent developments in reconciling the agricultural sector and the restoration of freshwater ecosystems in Europe. Furthermore, a practical restoration exercise was done, in order to comprehend the difficulties and barriers that basin managers must face when implementing basin-scale management plans.

The WFD allowed the scientific community to uncover several new topics in need of further investigation. Increasing our understanding of complex interactions, or of the full impact spectrum of pollution stressors may play an important role in improving future restoration techniques. Likewise, stakeholder engagement still needs further improvement. The dissemination of well structured environmental education may be crucial to homogenise perceptions amongst stakeholders.

Lastly, the lack of measures targeted at headwaters may jeopardise downstream restoration efforts. The relevance of these streams for the basin water quality must be further investigated.

Keywords: water framework directive, agricultural impact, land use, stakeholder management, climate change

Resumo

A agricultura tem impactes consideráveis em ecossistemas aquáticos, tanto na Europa como noutras regiões do globo. Com o objectivo de reverter os danos causados aos sistemas fluviais europeus, vários esforços de pesquisa e restauro foram desenvolvidos no âmbito de recuperar funções e serviços ecossistémicos. A implementação da Directiva Quadro da Água (DQA) teve um papel fulcral em fomentar o progresso no restauro dos ecossistemas fluviais.

Em 2015, o primeiro ciclo de gestão sob a DQA terminou, e com ele terminou também o prazo para atingir o bom estado ecológico nos ecossistemas fluviais Europeus. Com a transição para o segundo ciclo de gestão, é crucial restaurar estes ecossistemas fluviais, uma vez que a última meta da DQA será em 2027.

A presente dissertação tem como objectivo explorar os desenvolvimentos recentes no âmbito da reconciliação entre o sector agrícola e o restauro dos ecossistemas fluviais Europeus. Foi também desenvolvido um exercício prático de planeamento de restauro, com o objectivo de compreender quais as dificuldades e barreiras enfrentadas pelos gestores de bacia, aquando da implementação dos planos de gestão ao nível da bacia hidrográfica.

A DQA permitiu à comunidade cientifica desvendar diversos novos tópicos que necessitam de futura atenção. O aumento do nosso conhecimento sobre interações complexas, ou sobre o impacte total de várias pressões pode desempenhar um papel importante no desenvolvimento de melhores técnicas de restauro. De igual forma, são necessárias melhorias ao nível do envolvimento das várias partes interessadas (*stakeholders*). A disseminação de uma educação ambiental bem estruturada poderá revelar-se crucial na homogeneização de perceções entre *stakeholders*.

Por fim, a ausência de medidas que visem as massas de água de cabeceira poderá comprometer quaisquer esforços de restauro ecológico a jusante. A relevância destes cursos de água na qualidade da bacia hidrográfica necessita de investigação aprofundada.

Palavras-chave: directiva quadro da água, impacte agrícola, uso do solo, gestão de stakeholders, alterações climáticas

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Chapter 1

Introduction

1.1 Agriculture, the earliest human impact

Until humans discovered the ability to cultivate plants, anthropogenic impacts did not differ greatly from those of the remaining species (Barker, 2006). However, with the dawn of a reliable food source, the transition from a hunter-gatherer life-style to a sedentary one was to imply considerable changes (Clark, 1971; Nabil El Hadidi, 1985). By clearing land areas for the newly developed agricultural techniques, the human species stepped up in terms of landscape impacts. In their search for prosperous growth, our species soon understood the productivity potential of floodplain soils (Hassan, 1986). With the nutrients accumulated over the centuries and a supply of freshwater nearby, these areas have great potential to harbour agricultural fields (Bogucki, 1996).

Although the initial agricultural techniques were in balance with the natural cycles (e.g. the early Egyptian agricultural fields benefited from the Nile's seasonal floods; Macklin and Lewin, 2015), the technological development and the ability to further reshape the landscape continued to increase the agricultural impact's magnitude. With the growth of the human population and consequent need for larger crop yelds, the development of tile drainage systems and ever better plowing devices allowed to convert lands previously unfit for agriculture (such as bogs, swamps or clay soil areas) into drier, more suitable agricultural fields (Andersen et al., 2016). However, these changes were not to come without cost, and the increased draining turned out to be problematic downstream, so the rivers had to be deepened in order to accommodate the excessive water flow. Furthermore, the agricultural impacts were aggravated by the propagation of fertilisers and biocides, that were developed during the pursuit of the same original goal; a reliable food source for everyone. All in all, agriculture was the first significant human impact and, still today, is the major contributor to freshwater degradation around the globe (Davies et al., 2009).

1.2 Europe, a land carved by freshwater

The European territory is powdered with streams, ponds, rivers and other water bodies. Water has the ability to carve the landscape and multiply the habitats of a given space, for example by creating intricate below-ground galleries (CCOESP, 2010; Sharp, 1982). Europe has greatly benefited from this, as the combined force of water and tectonics created a complex abiotic structure, that greatly widened the niche possibilities. Not only does this create room for higher biodiversity levels but can also shelter the species from extreme events, such as the glaciations, allowing for a fast recovery (Sommer and Benecke, 2005; Taberlet and Bouvet, 1994). With a climatic context bound to the Atlantic ocean's mechanics (Knight et al., 2006; Qian et al., 2000; Sutton and Hodson, 2005), Europe's freshwater systems have thrived, and with them so did Europe's biodiversity.

1.2.1 The downfall of European streams

Since the early ages, the abundance of freshwater has made Europe a suitable home for flourishing human civilisations (Bogucki, 1996). A reliable source of water is indispensable for a growing community, both for direct consumption and other uses. However, the consistent rains and ever flowing streams give the illusion of an unending supply which, over the centuries, may have lessened human concern over this resource. As nature gave way to progress, streams have been constrained, swamps have been drained, lakes have been dredged and water sources have been polluted (Falkenmark and Rockström, 2004). The industrial and agricultural revolutions brought important changes to the hydrological cycles and freshwater ecosystems (Brunt, 2004; Kerridge, 1967, 1969); not only because of the contamination and excesses inherent to early factories' work-flow and the increase in fertiliser and biocide manufacturing, but also by the expanded human ability to spread agriculture to previously inapt terrains (e.g. by improved plowing; Andersen et al., 2016).

1.3 River restoration evolution in Europe

The negative effects of human interventions on rivers soon became apparent, as the simplified channels were unable to process pollution as efficiently as natural streams (Lefebvre et al., 2004). For example, in 1858, the British parliament had to be closed given the impossibility of standing near the river Thames' waters, such were the pollution levels (Halliday, 1999). Although some individual attempts to control riverine pollution have been recorded earlier, the degradation of freshwater systems was not properly addressed until the late 70's/80's (Brookes and Shields, 1996). By this time, new options for river management started being discussed, as it was clear that the traditional engineering methods were not sustainable (Darby and Sear, 2008). The river Skjern restoration, in Denmark, is a classic example of early integrated river management (Bregnballe et al., 2014).

1.3.1 Towards integrative legislation

The first freshwater ecosystems to receive detailed attention were the ones from which water was abstracted for human use. In 1975, European water legislation set out quality standards for these waterbodies (EC, 2016b).

In 1991, the Urban Waste Water Treatment Directive (EEC, 1991a) and the Nitrates Directive (EEC, 1991b) were adopted, focusing both urban and agricultural pollution sources. Industrial pollution was also targeted in 1996, with the Directive for Integrated Pollution and Prevention Control (EC, 1996). The quality standards for water abstraction for human consumption were also revised with a new Drinking Water Directive, in 1998 (EC, 1998). All these approaches were, however, mainly anthropocentric, requesting water quality standards whenever such water was necessary for human use. In the mean time, during the second half of the 90's, the European institutes started planning a new, integrative and coherent way of managing the European water bodies (Smith et al., 2014a). In 1996, after the Water Conference which was attended by close to 250 stakeholders, consensus was achieved on the need for a single Directive, providing a framework legislation for an integrative way of managing all the issues related to the European freshwater ecosystems. As a consequence, the Water Framework Directive was proposed by the European Comission (EC, 2000, 2016b).

Table 1.1: Timetable for some of the WFD crucial elements. Content adapted from EC (2016a).

Year	Objective	Reference
2000	Directive entered into force	Art. 25
2004	Characterisation of river basins	Art. 5
2006	Establishment of monitoring network	Art. 8
2009	RBMP is finalised and the first cycle starts	Art. 13 & 11
2015	First deadline to meet environmental objectives	Art.4
	Second RBMP cycle starts	
2021	Third RBMP cycle starts	Art 4 & 13
2027	Final RBMP cycle ends	Art 4 & 13
	Final deadline to meet environmental objectives	

1.3.2 The Water Framework Directive

The WFD is a benchmark in European legislation, focusing water management on the requirements of aquatic ecology. By taking into account the ecological effects of stressors (e.g. pollution) in it's management plans, the WFD allows the development of plans which fit the specificities of multiple ecosystems (Hering et al., 2010). Following this environmental line of thought, the WFD goal is to achieve good ecological condition for all European water bodies, while also guaranteeing a non-deteriorating status. The ecological condition is assessed based on 3 groups of elements: 1) biological, 2) hydromorphological and 3) physico-chemical (Kallis, 2001).

By implementing management plans at the basin level, the WFD implementation has proven a great opportunity to increase ecological knowledge of European freshwater ecosystems (Hering et al., 2010; Kallis, 2001).

These management plans are refered to as River Basin Management Plans (RBMPs) and are organised in “river basin districts", which correspond to the basin of major rivers and the respective tributaries' sub-basins. The WFD comprises a total of 3 planing cycles, of 6 years each (table 1.1). The RBMP's summarise the basin's pressures, present the current water bodies state and report restoration measures that must be implemented.

1.4 Objectives

Because agriculture is the human activity with higher impacts on freshwater ecosystems in Europe, this dissertation aims to explore how the relationships between this type of land use and riverine restoration have evolved in the last years. In the following chapter, a literature review was developed under the scope of this topic.

Upon the achievement of the first objective, one interesting conclusion was that, in recent years, the number of restoration projects published in peer-reviewed literature was low. This situation raised awareness to the possible difficulties that basin managers can encounter when designing restoration plans at basin scale. Therefore, on chapter 3, a practical approach to river restoration was made, with the development of a working plan that could be put in motion to restore the River Onda.

Chapter 2

Reconciling agriculture and stream restoration in Europe: a review relating to the EU Water Framework Directive

The present chapter corresponds to a paper that has been submitted to the Journal Science of the Total Environment. The paper has been peer-reviewed and revised according to the reviewers' reports, being currently under Editor appreciation.

Reconciling agriculture and stream restoration in Europe: a review relating to the EU Water Framework Directive

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Abstract

In Europe and many other regions, agriculture has caused considerable impacts on freshwater ecosystems. To revert the degradation caused to streams and rivers, research and restoration efforts have been developed to recover ecosystem functions and services, with the European Water Framework Directive (WFD) implementation playing a significant role in strengthening the progress. Following the recent closure of the WFD's first cycle, this review summarises recent European research (2010-2016) on river restoration efforts to mitigate agricultural pressures.

Specifically, the following five questions are addressed: 1) Are recent restoration projects being reported in peer-reviewed literature? 2) Which topics are receiving attention and which are being left aside? 3) Which information gaps should future research thrive to close? 4) What progress has been achieved in reconciling agricultural stakeholders, managers and researchers? 5) Which WFD limitations have been reported in recent peer-reviewed literature?

This review reveals significant progress in restoration efforts, but it also demonstrates a need for more descriptions of restoration projects in the peer-reviewed literature. With the end of the first WFD management cycle, addressing reported limitations such as the importance of non Bodies of Surface Water or the unfitness of adopted Ecological Quality Standards is crucial. Likewise, further exploring topics such as nutrient and pesticide degradation pathways or the long term effects of restoration measures (e.g. wetland creation), as well as analysing recent developments on stakeholder management will provide invaluable insight for the next WFD planning cycle. Our recommendations are important for the second WFD cycle because they will 1) help securing the development and dissemination of science-based restoration strategies and 2) provide guidance for future research needs.

Keywords: land uses, freshwater ecosystem, agricultural impact, stakeholder management, water abstraction, climate change

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2.1 Introduction

Agriculture often has severe impacts on riverine systems (Allan, 2004; Grizzetti et al., 2012; Ormerod et al., 2010; Windolf et al., 2012). Agricultural ecosystems are highly dynamic and are usually under intensive use. This, in combination with the difficulties in controlling diffuse pollution sources (Collins et al., 2016), makes the prevention of ecosystem contamination a challenging task (Gonzales-Inca et al., 2015; Mitsch and Gosselink, 2007). Furthermore, the most suitable soils for agriculture tend to be on floodplains, which leads to an overuse of lands directly connected with the stream networks (Conroy et al., 2016; Holden et al., 2004). To further aggravate the problem, in many cases rivers have been subjected to high degrees of hydromorphological change, most of them directly or indirectly driven by agricultural needs of irrigation and drainage, with the breakdown of the longitudinal and lateral continuity that is characteristic of such ecosystems (Bolpagni and Piotti, 2015).

Throughout Europe, agriculture is the type of land use with the most significant impacts on freshwater ecosystems (e.g. Davies et al., 2009; Poole et al., 2013) and, with the growing recognition of these ecosystems' importance, there has been an increase in the awareness of the public opinion towards their restoration. Nowadays, it has become a political priority to provide the necessary conditions for freshwater ecosystems to recover from anthropogenic impacts.

The European Water Framework Directive (WFD; EC, 2000) is a mark in integrative European legislation, requiring active stakeholder engagement (Andersson et al., 2012; Blackstock et al., 2010; Richter et al., 2013). Aiming to have a significant role in increasing restoration efforts and integrative management plans, the WFD's first cycle of water resources management took place between 2009 and 2015 (EC, 2000). With the end of this planning cycle, the deadline to achieve good ecological status on the European freshwater ecosystems has been reached. However, many European water bodies have failed to achieve this condition (EEA, 2012) and member states must strive to increase ecological quality until 2027. With the second management cycle in place, it is important to evaluate if this legal framework helped to improve the way riverine restoration projects were designed and implemented, as well as to understand what lessons were learnt from this first cycle.

Freshwater ecosystems are known for their complexity, with cause-effect relationships extending beyond the set of functions and processes that take place on a given location (Allan, 2004; Culp and Baird, 2006). Stressors (e.g. pollution) are typically widespread and not simple to comprehend (Townsend et al., 2008). In light of this, it is necessary that research extends across multiple fields and scales. However, some research subjects may not receive the appropriate attention by researchers. Therefore, understanding which specific areas are receiving more attention and which are being left aside in the scientific world is important to secure optimal restoration efforts.

The aim of the present paper is to make a comprehensive review of the work that has been done on the relationships between agriculture impacts and restoration of lotic ecosystems, in Europe, from 2010 onward. Specifically, the authors examine the following issues:

1. Has the number of restoration projects reported in peer-reviewed literature increased since 2010?
2. Which novel topics are contributing to improved restoration efforts?
3. What knowledge gaps have been identified by recent works on riverine restoration?
4. What has been achieved to reconcile agricultural stakeholders, management and researchers?
5. Which WFD limitations have been reported during its first management cycle?

2.2 Methodology

This review followed the guidelines suggested by Pullin and Stewart (2006). A key search string was created which comprised keywords related to freshwater ecosystems, to ecological restoration and to agricultural stressors. The formulation was as follows: *(stream* OR river* OR watershed* OR catchment*) AND (restor* OR rehab* OR amend* OR interve*) AND (agricult* OR nitr* OR phosph* OR pesticide* OR herbicide*)*. This string was applied to four different databases to assure a wide coverage: B-On, DTU-Findit, WebofScience and Scopus. Analyses included the 2000 most relevant papers from each database (or the totality, whenever the total amount was lower than 2000), leading to a total of 7920 peer-reviewed papers examined (duplicates included).

During the exclusion process, the above mentioned 7920 papers underwent three levels of scrutiny: 1) title, 2) abstract and 3) content. On each level, the criteria presented in table 2.1 were examined. As Pullin and Stewart (2006) indicate, whenever there was uncertainty

Table 2.1: Admission/exclusion criteria.

Criteria	Include	Exclude
Peer-reviewing	Peer-reviewed	Everything else
Year	Y $\geq$ 2010	Y $<$ 2010
Geo-location[a]	European	Everything else
Ecosystem	Fresh-water and lotic[b]	Sea/Ocean and/or lentic
Stressors	Agricultural stressors are predominant	Agricultural stressors absent or playing a minor role

[a] On papers that had no physical representation (e.g. reviews), author's affiliation was used as a surrogate.
[b] Papers where artificial wetlands were targeted as part of the river continuum were included. Papers concerned with the terminal sections of rivers (e.g. estuaries) were included.

Table 2.2: Description of the four different types of papers considered.

Rest. Projects	Presents a given problematic situation and proposes a set of measures to be applied
Reviews	Systematises previous knowledge and develops new angles of thought
Monitoring [a]	Determines the condition of a given set of ecosystem elements or functions
Modeling	Focus on understanding/replicating a given cycle or pathway by mathematical means

[a] Papers where a restoration project was revisited any number of years past its conclusion were classified as monitoring works.

regarding the compliance to the inclusion criteria, the paper would be accepted for further scrutiny (e.g. if the title was ambiguous, the paper would proceed to abstract reading).

The chosen papers were then further catalogued in four main divisions: restoration projects, reviews, monitoring works and modelling works (table 2.2). Other aspects such as environmental variables or particular stressors were also recorded. The paper's results and insights were then summarised. An integrative vision of recent developments was then developed to answer the working topics.

2.3 Results and Discussion

During the literature scrutiny, 724 out of 7920 titles were selected for abstract reading. After reading the abstracts, a total of 235 papers qualified for full text reading. Upon reading the full text, 86 papers failed to comply with the inclusion criteria, leading to a total of 149 individual papers selected for review.

From the selected papers, 7% were classified as restoration projects, 15% as reviews, 58% as monitoring works and 20% as modelling works (table 2.3). Regarding spatial scales, most of the works were developed at a basin scale (35%), with papers both at the reach and broader scales represented similarly (21 and 18%, respectively; table 2.4).

Table 2.3: Number of papers included for review per year and topic. The total number of papers is 149. Brackets indicate the proportion of papers relative to the year's total.

	2010	2011	2012	2013	2014	2015	2016	Overall
Rest. Projects	2 (0.17)	0 (0)	1 (0.04)	2 (0.08)	2 (0.06)	2 (0.06)	1 (0.14)	10 (0.07)
Reviews	0 (0)	1 (0.07)	1 (0.04)	5 (0.21)	9 (0.25)	6 (0.19)	0 (0)	22 (0.15)
Monitoring	7 (0.58)	12 (0.86)	11 (0.46)	13 (0.54)	19 (0.53)	19 (0.59)	6 (0.86)	87 (0.58)
Modelling	3 (0.25)	1 (0.07)	11 (0.46)	4 (0.17)	6 (0.17)	5 (0.16)	0 (0)	30 (0.2)

The following subsections have been organised to answer the research questions. Firstly (subsection 2.3.1), the recent evolution on the number and structure of research projects is analysed, pointing out commonly applied measures and possible improvements reported in literature. Secondly (subsection 2.3.2), the topics related to riverine restoration are examined, underlining the need to diversify research foci and include multiple management options. Thirdly (subsection 2.3.3), recent information gaps are explored, including 1) the N_2O potential greenhouse effect, 2) the issue of phosphorus legacy, 3) excessive sediments, 4) pesticide pathways, 5) the effects of land use configuration, 6) water regulation and abstraction and finally 7) the implications of climate change. Fourthly (subsection 2.3.4), the evolving interaction with stakeholders is assessed and, lastly (subsection 2.3.5), recent limitations reported in the literature regarding the WFD are reviewed.

2.3.1 Has the number of restoration projects reported in peer-reviewed literature increased since 2010?

The number of papers describing restoration projects, in peer-reviewed literature, was low from 2010 to 2015, with the total amounts varying between 0 and 2 per year (table 2.3). This small number of reported projects may be the product of three different situations: 1) It is possible that there have been few restoration efforts during the studied time interval. However, such a scenario is unlikely given the current European context. 2) Despite being carried out, restoration projects are not prone to be published in peer-reviewed literature, as they do not tend to lead to major conclusions and apply to limited areas. Restoration projects can also be lacking a proper scientific coverage, therefore failing to be divulged to a wider public. 3) Lastly, recent restoration projects may have not yet been concluded and have still to be reported.

Although the number of recent restoration projects (sensu table 2.2) reported in peer-reviewed literature is low, several monitoring works have described ecosystem development in areas with previous restoration projects. In these monitoring works, a considerable diversity of restoration measures is reported, such as: unpiping (Grunewald et al., 2014), remeandering

Table 2.4: Working scale of papers included for review per year. Brackets indicate the proportion of papers relative to the year's total.

	2010	2011	2012	2013	2014	2015	2016	Overall
Reach S.	2 (0.17)	4 (0.29)	8 (0.33)	5 (0.21)	5 (0.14)	7 (0.22)	1 (0.14)	32 (0.21)
Basin S.	5 (0.42)	6 (0.43)	13 (0.54)	5 (0.21)	14 (0.39)	7 (0.22)	2 (0.29)	52 (0.35)
Broader S.[a]	3 (0.25)	2 (0.14)	2 (0.08)	4 (0.17)	5 (0.14)	8 (0.25)	3 (0.43)	27 (0.18)

[a] Papers which targeted multiple basins (e.g. on a national scale) were included on this group.
[*] Papers which had no physical representation (e.g. reviews) were not appointed a scale, explaining why the total number of papers is 111 and not 149 (table 2.3).

(Hoffmann et al., 2011), elevating the river bed, diverting tile drains and other waste waters (Audet et al., 2013), reinforcing shores with rocks or woody materials (live or dead), restricting livestock access (Horton et al., 2015; Muller et al., 2015), addition of boulders and riffles (Kail et al., 2015), unclogging the riverbed (Schirmer et al., 2014), implementing buffer strips (Bergfur et al., 2012; Passeport et al., 2013), changing farming practises (Braukmann et al., 2010; Kaspersen et al., 2016; Zhang et al., 2012), plant biomass harvesting (Audet et al., 2015; Hoffmann et al., 2012), sediment trapping to protect substrate for fish reproduction (e.g. gravel for salmonid spawning) or even egg planting to counter-act genetic drift (Skaala et al., 2014).

Outcomes of individual measures do not always turn out as expected (Bergfur et al., 2012; Hoffmann et al., 2011; Muller et al., 2015; Schirmer et al., 2014), either by design constraints or considerable side effects. However, bundling restoration measures (i.e. simultaneously applying multiple actions on different ecosystem compartments and/or targeting multiple anthropogenic stressors) often provides better results (Simaika et al., 2015). Simaika et al. (2015) concluded that restoration projects should always include measures targeted at the stream banks (e.g. wall removal, planting), since those measures tend to yield most positive results when bundled together, indicating a need for holistic approaches (Rasmussen et al., 2013). Restoration projects need to scale up to the catchment level to ensure that a better integration of ecosystem functional connections is achieved (Grossmann, 2012; Merseburger et al., 2011; Milledge et al., 2012). However, care must be taken to ensure that project managers do not lose sight of small scale relationships (e.g. between critical source areas and the river). Harris and Heathwaite (2012) pointed out that interactions based on small scale relationships tend to yield identifiable ecological outcomes and are essential in providing insights regarding the ecosystem's state and evolution.

Recently, concerns have been raised regarding the time scales of restoration projects. After years of anthropogenic exploration, the rebalancing of ecosystem cycles can take several decades (Audet et al., 2015; Glendell et al., 2014; Smith et al., 2014b). This can hinder the success of restoration plans either directly due to insufficient monitoring periods (too short to detect environmental changes; Braukmann et al., 2010), or indirectly by lowering stakeholder interest or creating conflicts with legal deadlines.

2.3.2 Which novel topics are contributing to improved restoration efforts?

The most targeted topics were nitrogen (40%), phosphorus (34%), pesticides (13%) and sediments (9%). During the first two years (2010-2011), nitrogen and phosphorous were the main research subjects. However, from 2013 onwards, the number of papers on these two topics decreased, as research focus shifted to other themes such as pesticides or ecosystem services (figure 2.1). The most targeted biological elements were macroinvertebrates (15%), macrophytes and riparian plants (10%) and fish communities (7%; figure 2.2). Chemicals (other than pesticides), amphibian communities and potentially harmful bacteria were amongst the less studied subjects.

Ensuring that different topics are being studied, and that researchers continue to search for new stressors and ways to mitigate them is crucial. However, stressors might have different impacts depending on the land management of each specific agricultural field. For example, it is expected that excessive nutrient inputs will lead to higher impacts for streams in intensive, non buffered monocultures than on extensive mixed culture fields. Thus, it is also necessary to assure that research is spreading across multiple management options. For this reason, management options (e.g. intensive/extensive, mixed/monoculture) were included in the analyses. However, on 51% of the papers, the agricultural management was either not specified or not applicable (data not shown). Additionally, in many cases, only a general description of the practices was provided. Therefore, it was not possible to establish a relation between study topics and the types of agricultural use. Future studies should strive to describe management options being applied on the study areas to allow the integration of such information with other variables.

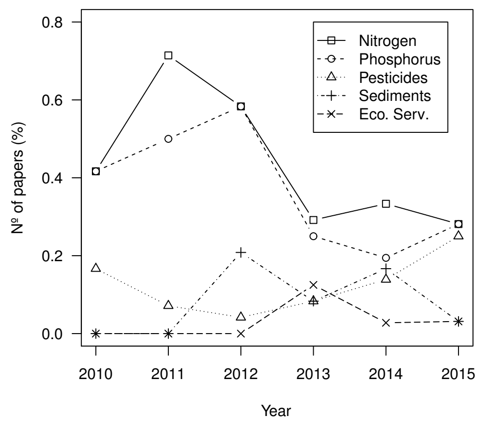

Figure 2.1: Evolution of the principal research topics from 2010 to 2015 (top y = 0.8).

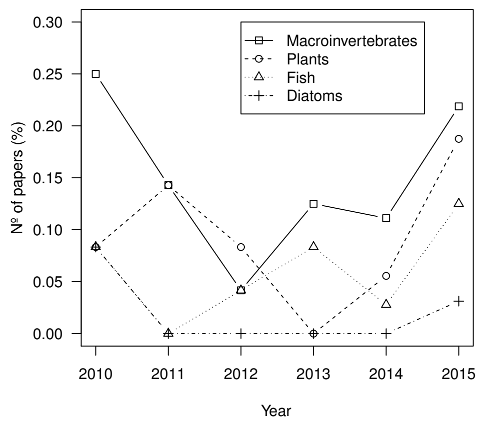

Figure 2.2: Evolution of the principal biotic elements from 2010 to 2015 (top y = 0.3).

2.3.3 What knowledge gaps have been identified by recent works on riverine restoration?

2.3.3.1 The N_2O potential greenhouse effect

Given the complexity of the N cycle, NO_3^- can intervene in various biological pathways (figure 2.3; Arce et al., 2015; Audet et al., 2013; Vilain et al., 2012), possibly leading to the formation of N_2, N_2O, NO or NH_4^+. Although any process that transforms NO_3^- into a less mobile form might have a positive effect on the ecosystem (Arce et al., 2015), the greenhouse effects of N_2O could prove to be a potential problem, should its atmospheric concentration increase.

As stated by Garnier et al. (2014), "caution must be taken to limit a shift from nitric to N_2O pollution", especially because the concentrations of N_2O found in streams might not always be a result of local production, but rather come from saturated ground water (e.g. on the Orgeval watershed, in the Seine basin, France; Garnier et al., 2014).

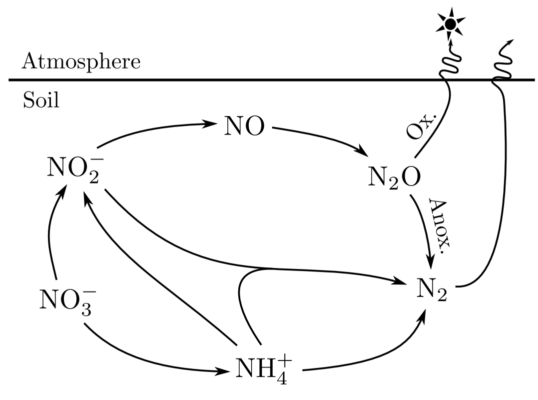

Figure 2.3: Simplified representation of the pathways that lead to NO_3^- removal from the environment, evidencing the possibility of N_2O release under oxic conditions and consequent greenhouse effects.

As the N_2O production is negatively correlated to the moisture content in the soil (Cannavo et al., 2002; Garnier et al., 2010; Vilain et al., 2012) and restoration efforts often rise groundwater tables, it is expected that the propagation of anoxic conditions may ensure complete denitrification (Arce et al., 2015). This is corroborated by the positive performance of wetland creation in increasing N removal from the soil and water (Moreno-Mateos et al., 2010; Veraart et al., 2014).

Wetlands connected to the main water courses tend to perform better (i.e. remove higher amounts of N from the water; Racchetti et al., 2011), as the water flow supplies N to the area and diffusion mechanisms further distribute it through the soil (Pinay et al., 2015), preventing nitrogen availability from becoming a limiting factor. Furthermore, increasing wetland areas on a given catchment improves water residence times, an important factor specially during high flows, because nitrogen uptake efficacy often drops as the discharge increases (Hoffmann et al., 2012). However, a common management intervention is the removal of plant biomass from streams and wetlands. Hoffmann et al. (2012) highlights the need to further investigate the potential impacts that plant removal can have on denitrification, as the organic matter bio-availability can be greatly reduced.

2.3.3.2 Phosphorus legacy, an inherited problem

Besides the current emissions of P to the environment, the issue of P legacy is a major constraint to ecosystem restoration. This legacy is the result of past practices and has led to the saturation of ecosystem compartments such as soil particles in many areas (Jarvie et al., 2013; Moreno-Mateos et al., 2010). This leads to an unstable equilibrium where a shift in environmental conditions can cause the release of high amounts of P (e.g. by active soil erosion or changes in redox conditions; Hoffmann et al., 2012; Meissner et al., 2010; Prem et al., 2015; Surridge et al., 2012).

Actual restoration efforts tend to produce few results whenever there is a pool of legacy P present, and might even worsen the ecological state due to the fact that restoring involves disturbing the existing ecosystem balance (Jarvie et al., 2013; Moreno-Mateos et al., 2010). To tackle this problem, several efforts have been made to understand how P interacts with the environment (Baattrup-Pedersen et al., 2011; Jaakkola et al., 2012; Klaus et al., 2011; Poulsen et al., 2014), how to make P less bioavailable (Ekholm et al., 2012; Uusitalo et al., 2015) and how to remove P from the ecosystem (Audet et al., 2015; Hoffmann et al., 2012). However, depleting the legacy P pool by sustainable means (e.g. phytoremediation) can take anywhere between 15 to 60 years (Audet et al., 2015; Hoffmann et al., 2012; Schulte et al., 2010), a time interval that is not easily accepted by decision makers and public demands.

Recently there has been a shift in the P paradigm from coping with the excesses to making stored P useful once more (Cordell et al., 2011; Quilliam et al., 2015). This is driven not only by the possibility of solving the legacy P problem in a more eco-friendly way, but also by the increasing costs and difficulty of extracting phosphate rock (Cordell et al., 2011). For instance, P can be recovered before it builds up in the system by diverting effluents (e.g. agricultural tillage waters or waste waters) through filtering materials; or P that is already in excess can also be harvested by plants that are then used to produce fertilisers (Quilliam et al., 2015). Future studies should strive to improve P recovery techniques, to ensure an effective reduction of impacts.

2.3.3.3 Excessive sediments: effects on riverbed and living organisms

Excess sediments can have a great impact on freshwater systems, as these small particles may directly interfere with the fractal nature of the riverbed. By clogging the interstitial spaces, fine sediments can hinder the hyporheic exchanges (Teufl et al., 2013) and prevent the formation of microhabitats that are essential for the stream fauna (Stockan et al., 2014). Sediments may also increase water turbidity, hinder photosynthetic activity (Bolpagni and Piotti, 2015), reduce fish survival through gill clogging (Rickson, 2014) and limit fish egg and larval fitness and gravel nest area (Louhi et al., 2011). Likewise, various crayfish species may be negatively effected by sediment (Rosewarne et al., 2014).

On some European basins, agriculture can account for over 70% of the sediment load (Rickson, 2014). Recent modelling efforts have been applied to better understand sediment deposition patterns (Poulsen et al., 2014) and to prioritise restoration targets. Based on knowledge about geochemical behaviours (both in the soil and water), recent sediment source fingerprinting techniques have been applied to trace impacts back to their source (Stockan et al., 2014).

To solve the excess sediment problem, measures must be considered at the basin scale, bringing together source minimisation efforts and in-stream pathway changes. Future works must provide guidance on how to integrate these two types of efforts, to guarantee that future restoration measures do not accidentally deteriorate the current conditions (Teufl et al., 2013).

2.3.3.4 The pesticide knowledge gap

Pesticides lead to changes in fish behaviour and cognitive capacity (Shinn et al., 2015), cause drops in photosynthetic capacity and efficiency (Ricart et al., 2010), induce macroinvertebrate taxa loss (Berger et al., 2016) and may be bio-accumulable (Belenguer et al., 2014). Contrary to nutrients such as nitrogen or phosphorous, which are beneficial in moderate concentrations, pesticides can lead to negative impacts even in minimal concentrations (McKnight et al., 2015; Shinn et al., 2015; Tournebize et al., 2013). Furthermore, pesticides tend to be released in mixtures rather than singular compounds, often with synergistic negative effects (Berger et al., 2016; Passeport et al., 2013) that are difficult to investigate and predict.

Pesticides may use various pathways to flow into a stream, such as surface run-off, groundwater movement or even atmospheric deposition (McKnight et al., 2015; Reichenberger et al., 2007; Vymazal and Březinová, 2015). In particular, tile drains may function as direct channels that transfer pesticides from agricultural fields to streams without allowing for any buffering mitigation (Muller et al., 2015). Relocating tile drainage openings away from the stream allows the adsorption of pesticides into organic matter deposited on buffer strips (Rasmussen et al., 2011). This, alongside a general reduction of run-off speed, allows buffer strips to decrease the magnitude of pesticide peaks (Passeport et al., 2013). One other option for pesticides' mitigation, as they appear to be highly degraded in hyporheic processes (Schirmer et al., 2014), is the creation of wetlands, because these ecosystems directly increase the ground/water interface area.

Multiple studies have reported the need to deepen our understanding of ecologically relevant endpoints for pesticide concentrations and consequently adjust Ecological Quality Standards (EQS; Ricart et al., 2010; Shinn et al., 2015; Silva et al., 2015b). More information regarding chronic exposure impacts and thresholds is also needed (McKnight et al., 2015) . Finally, new knowledge regarding pesticide degradation pathways and synergistic relationships may guide future restoration efforts.

2.3.3.5 The effects of land use and configuration

The effect of landscape use on freshwater ecosystems is well known (Glendell et al., 2014; Grunewald et al., 2014; Kail et al., 2015). The present review considered three dominant land uses: 1) urbanised areas, 2) agricultural fields and 3) natural/forested areas. These areas have different dynamics, with lands more intensively used by humans typically being more prone to equilibrium shifts and natural areas having well established and stabilised pathways (Glendell et al., 2014; Harris and Heathwaite, 2012; Kovacs et al., 2012; Looy et al., 2013; Mossman et al., 2015; Poole et al., 2013).

As the human population of a given area increases, the landscape's land uses tend to shift (i.e. previously peri-urban agricultural areas are used for urban expansion and previously forested areas are cleared to accommodate new agricultural fields; Cooper et al., 2013). Land use changes can have profound impacts on the ecosystems, such as increasing runoff speed and reduce native vegetation cover (Allan, 2004; Cooper et al., 2013). Furthermore, these changes can lead to multiple stakeholder disputes (e.g. over uncommon resources or property rights; Brown and Raymond, 2014) and also conflicts between land use and land aptitude (Pacheco and Sanches Fernandes, 2016). For example, agricultural fields may be implemented on soils which are prone to erosion, leading to an increase in nutrient leaching and soil loss (Pacheco and Sanches Fernandes, 2016; Valle Junior et al., 2015).

One common environmental land use conflict is the placement of agricultural fields on floodplain soils. Although these lands could be used to implement forested buffers (Walsh and Kunapo, 2009), their productivity may lead to the clearance of the riparian vegetation in order to establish more productive agricultural fields (Looy et al., 2013). This situation tends to be aggravated by the discrepancy between legally required buffer widths and the widths considered necessary for an effective pollution mitigation (Rasmussen et al., 2011). For instance, while in some European countries legislation seems to encourage the establishment of narrow, fixed width buffer zones (e.g. 10-30m; AR, 2005), Weissteiner et al. (2013) suggests a cautious (i.e. assuming 75% efficiency) width of 115m for complete abatement of both excessive N and P, while also pointing out that most riparian areas tend to under-perform due to the presence of concentrated flow paths (i.e. the water does not distribute equally throughout the riparian area as it flows through it).

The configuration of different land uses in the landscape has also proven likely to affect freshwater ecosystems (Davies et al., 2009; Ding et al., 2016; Teels et al., 2006). However, as the impacts on a given land are determined by a multitude of factors (e.g. management options, abiotic conditions; Glendell et al., 2014; Mossman et al., 2015; Theodoropoulos et al., 2015; Wasson et al., 2010), linking ecosystem responses with the landscape use may prove challenging (Ding et al., 2016; Thackway and Specht, 2015). For example, Uuemaa et al. (2005) indicate that landscapes with a higher edge density (i.e. multiple land use patches) present lower nutrient and organic material losses, while Lee et al. (2009) suggests that landscapes with larger, aggregated land uses (i.e. lower edge density) may perform better at retaining pollutants.

These complex landscape interactions make the task of managing catchment land uses challenging. In order to provide decision-makers with strategies to minimise land use conflicts and, at the same time, maximise configuration potential, researchers should continue exploring these interactions and reporting on the effects of multiple management options (Thackway and Specht, 2015). Assessing the impact of different land use patterns on the ecosystem services provision may prove useful to develop integrative management options.

2.3.3.6 Water regulation and abstraction: the effects of balancing agriculture with ecosystem needs.

Water regulation and abstraction are well known factors severely impacting lotic ecosystems. However, a controlled water supply is also crucial for many food producing industries, creating a basis for conflict (Davis et al., 2015; Lange et al., 2014). For example, agricultural activities may include water abstraction for irrigation and damming to provide pools for irrigation (Brummett et al., 2013). Indeed, stream-flow change and associated water scarcity are key stressors in freshwater ecosystems (Arenas-Sánchez et al., 2016; Pyne and Poff, 2016). Damming creates lentic areas that change the ecosystem profoundly and often block access to spawning, nursery and foraging habitats of many migratory species (Abril et al., 2015; Duponchelle et al., 2016; Pelicice et al., 2015; Piper et al., 2015; Svendsen et al., 2010). Research on fish passes has made substantial progress in recent years (e.g. Alexandre et al., 2013; Silva et al., 2015a), but several important questions remain (Cooke and Hinch, 2013) and technical solutions rarely ensure that all migrating individuals pass the obstacle (Forty et al., 2016; Noonan et al., 2012; Pereira et al., 2016; Tummers et al., 2016).

Interestingly, restoration projects may include restoring or creating wetlands within lotic ecosystems (Jensen et al., 2015; Koed et al., 2006; Poulsen et al., 2012), which may have effects similar to agricultural water damming. When restoration is not planned at a catchment scale, migratory barriers can be created, which may block the recovery of fish populations (Braukmann et al., 2010). Importantly, to avoid the accidental creation of migratory barriers, caution is needed when implementing wetlands as a restoration measure. For example, Koed et al. (2006) found that new wetlands may have detrimental effects on migrating juvenile Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*). Passy et al. (2012) suggested that wetlands, and other restoration projects interfering with fish migration, should be placed in first order streams, where minimal impact may be caused on migratory fish species. Placing restoration projects in first order streams implies that fish migrating further downstream are not directly affected. However, lentic wetlands may still influence water quality further downstream (e.g. water temperature; Bae et al., 2016) and may reduce the availability of spawning substrates. For example, in many cases, brown trout uses first order streams for spawning (Harshbarger and Porter, 1982) where eggs are deposited in reds made of gravel and cobble. Indeed, wetlands flooding gravel and cobble beds, and transforming habitats from lotic to lentic, reduce the availability of substrates for spawning. There is rarely a technical solution eliminating all ecosystem effects of transforming a lotic habitat into a lentic habitat (Pelicice et al., 2015), but some of the effects may be mitigated if water is allowed to bypass the wetland in a channel mimicking the river.

2.3.3.7 Adapting to climate change

Climate change is clearly accepted by today's European society (Eurobarometer, 2014a). This change in climatic conditions appears as a long term trend of warming temperature which impacts multiple events, such as rainfall patterns (Dono et al., 2016). Nowadays, it is recognised that European agriculture will be considerably affected by climatic change (Kahil et al., 2015; Long et al., 2016), with Dono et al. (2016) indicating that, as soon as in the next decade (2020-2030), adapting agricultural management to face new climatic conditions will be necessary.

The effects of climate variation on agricultural production have been widely studied (e.g. Dono et al., 2016; Olesen et al., 2011; Pulatov et al., 2015). In a recent review, Iglesias and Garrote (2015) indicate that climate change will have considerable impacts in European agriculture, pointing out that these shifts in climatic conditions will lead to decreases in water availability and quality, an increase in irrigation requirements (particularly in areas already prone to water scarcity) and to a shift in farming conditions that might result in reduced crop productivity and land abandonment. Pulatov et al. (2015) also points out the possibility of increased pressure by biotic elements (e.g. pests). To further aggravate these concerns, with the rising human population, food production will have to increase considerably in years to come (Elliott et al., 2014; Kahil et al., 2015; Long et al., 2016). Climate change can also impact agriculture by increasing the number and intensity of wildfires. Such events can directly lead to crop destruction and, indirectly, might hinder farming practicability by severely changing soil N and

P contents and polluting freshwater reservoirs (i.e. due to leaching on subsequent rainfalls; Santos et al., 2015a,b). Ultimately, such changes can lead to stakeholder conflicts that should be carefully addressed.

Adapting to climate change will likely require efforts both at policy and local levels, including measures such as improving integrative water management or increasing the number of water reservoirs (Iglesias and Garrote, 2015). Increasing intra-regional farming diversity can also play an important role in guaranteeing farming resilience and complementarity (Dono et al., 2016; Kahil et al., 2015; Leclère et al., 2013). An interesting initiative to prepare agriculture for changing climate conditions is the “Climate-Smart Agriculture" (CSA), from the Food and Agriculture Organization of the United Nations (FAO), which aims to sustainably increase productivity and incomes, adapt to climate change and reduce greenhouse gas emissions where possible (FAO, 2013; Long et al., 2016). However, in their work on the adoption of CSA-related technologies in some European countries, Long et al. (2016) found that a lack of consumer demand for products with lower environmental impacts, together with policy and cost barriers reported by technology producers and potential users, could reduce the uptake of measures by farmers considerably.

Climate change will likely lead to a need to tighten water use priorities and optimise control of resources allocation (Iglesias and Garrote, 2015). One way to do so is the implementation of water markets, that would increase water resource monitoring and allow supply to areas more severely affected by drought (Gohar and Ward, 2010; Kahil et al., 2015). Nevertheless, this solution can lead to reduction of environmental water flows, as it leads to the trade of previously unused water reservoirs (Kahil et al., 2015). Continuing to develop knowledge on the impacts associated to the adoption of novel strategies, designed to cope with climate change under multiple management scenarios, might prove essential to backup management decisions. Moreover, further refining international and regional policies may also allow a broader adoption of more resilient agricultural practices. Importantly, it is necessary to assure that, with the growing pressures for an increased agricultural production, managers do not loose sight of the need to preserve and restore Europe’s freshwater ecosystems.

2.3.4 What has been achieved to reconcile agricultural stakeholders, management and researchers?

Historically, it has frequently been a struggle to develop agricultural environmental regulation that could achieve the desired outcomes (Collins et al., 2016; Doole et al., 2013). For example, during an inspection of Scottish watercourses, breaches to formal regulations which aim to prevent diffuse pollution were commonly found (Christen et al., 2015). Farmers are many times unaware of existing regulation or simply choose not to comply with regulations (Collins et al., 2016), as these landowners have grown sceptic of conflicting policy messages (Christen et al., 2015). Furthermore, farmers often appear to consider their role on freshwater pollution as insignificant, thus failing to acknowledge that there is indeed a problem in need of solving (Barnes et al., 2013b; Blackstock et al., 2010; Gachango et al., 2015). Even when farmers acknowledge their role in freshwater diffuse pollution, there are often several barriers that keep them from uptaking mitigation measures, such as 1) the costs of application and impacts on revenue, 2) the bureaucracy related to accessing available funds (Christen et al., 2015) or 3) a lack of guidance on how to best apply such measures and on the effectiveness of these improved practises (Del Corso et al., 2015; Guillem and Barnes, 2013).

The frequent aversive reaction to imposed regulations (Barnes et al., 2013a,b), alongside the fact that farmers would rather face prosecution than change agricultural practices (Posthumus et al., 2011), has demonstrated the need to rethink the way to approach agricultural landowners. It is necessary to find improved ways to convince farmers that their role in freshwater pollution is significant and that their help is needed to solve the problem (Howarth, 2011). Likewise, increasing knowledge of non-farming stakeholders may also prove important, because Europeans often have limited knowledge about farming (Eurobarometer, 2014b) and the impacts of the activity on surrounding ecosystems.

In order to achieve a greater cooperation, getting farmers, managers and researchers to work together is crucial (Collins et al., 2016; Gumiero et al., 2013; Spiller et al., 2013a,b). Christen et al. (2015) have demonstrated that farmers and non-farmers tend to have different perceptions of key factors such as biodiversity or causality. For example, while non-farming stakeholders consider biodiversity as a positive factor, farmers tend to view biodiversity as a negative factor due to a perception of increased bureaucracy and time requirements (Christen et al., 2015). Understanding these different perspectives and how they influence the final opinions of multiple stakeholders is crucial to assure integrative river management (Aggestam, 2014; Nainggolan et al., 2013). Targeting information channels which are more often used by farmers and structuring message contents in a credible and constructive way may increase farmer awareness of their freshwater impacts and increase their willingness to adopt new practices (Blackstock et al., 2010; Kay et al., 2012; Whitmarsh, 2011). Farmers and researchers must work together, interchanging knowledge and allowing for the development of restoration strategies that specifically target the difficulties faced by each agricultural sector (Blackstock et al., 2010; Guillem et al., 2015).

The WFD implementation had a considerable impact on stakeholder engagement, as it requires their active involvement (Blackstock et al., 2010; EC, 2000). However, it is still important to uncover how to achieve an optimal balance between obligatory measures (which might provoke a negative stakeholder reaction) and voluntary ones (which farmers might choose to ignore; Barnes et al., 2013b). Closely addressing different farmer groups within a catchment, as well as carefully targeting funds to sub-catchment critical zones may have an important impact in achieving the desired reduction in freshwater pollution load (Barnes et al., 2013b; Davies et al., 2009; Kay et al., 2012).

During the coming WFD management cycles, basin managers should continue to improve the communication and understanding between local communities, decision makers and researchers in order to produce and implement integrative management plans (Aggestam, 2014; Buckley et al., 2012). Environmental education may play an important role in sensitising stakeholders (Iglesias and Garrote, 2015; Long et al., 2016) and the use of decision support systems and models can help in facilitating management programs' acceptance (Meissner et al., 2010).

2.3.5 Which WFD limitations have been reported during its first management cycle?

The WFD's first cycle was a major milestone in increasing overall care for European freshwater ecosystems. With it's closure at the end of 2015, some limitations have been reported. Addressing these issues is important to guide the development of the second planning cycle.

Across Europe, many water bodies have not reached the goal of good ecological state by 2015, as established by the WFD (Hirt et al., 2012; McMellor and Underwood, 2014). As described by previous studies, the importance of non-BSW's (non Bodies of Surface Water, sensu WFD) was not properly addressed (Lassaletta et al., 2010; Rasmussen et al., 2011). The WFD does not consider these waterbodies as targets for quality improvement and, as in some situations they provide a large part of the water and are also relevant as biodiversity refugee and recolonisation spots, failing to protect them might hinder the recovery capacity of the watershed as a whole (figure 2.4). In some cases, this might even block restoration efforts downstream from producing satisfactory results (Dodds and Oakes, 2008; Lassaletta et al., 2010).

A second reported limitation is the use of general quality and restoration measures to highly variable watersheds (Kaspersen et al., 2016). For example, Bouleau and Pont (2015) indicates that the concept of reference condition can often be problematic, as ecosystems are ever evolving, particularly when considering the effects of past human actions or changing climatic conditions. In several European watersheds, management plans were designed by external agencies, lacking connections to local communities and problems (Benson et al., 2014; Kaspersen et al., 2016). This calls for a better incorporation of the stakeholders' interests in management plans, as well as enhanced information and communication with local communities.

A limitation also remains in understanding, specifically, when is it that restoring a freshwater body to achieve the good ecological state might be considered “infeasible or disproportionately expensive" (Del Saz-Salazar et al., 2009; EC, 2000; Klauer et al., 2016; Martin-Ortega et al., 2014). The ambiguity associated to the word “disproportionately" has been a subject of interest for multiple studies, which attempt to find a specific and reproducible way to apply

Figure 2.4: The Water Framework Directive's measures apply only to Bodies of Surface Water (BSW's). However, non-BSW's can correspond to a large part of the hydrographic net, draining water from lands impacted by human activities. Restoration efforts targeted only at BSW's can be ineffective if stressors exist further upstream, on non-BSW's. The river Onda (Portugal) is shown as an example. Notice non-BSW's cross through areas used for agriculture and urbanisation.

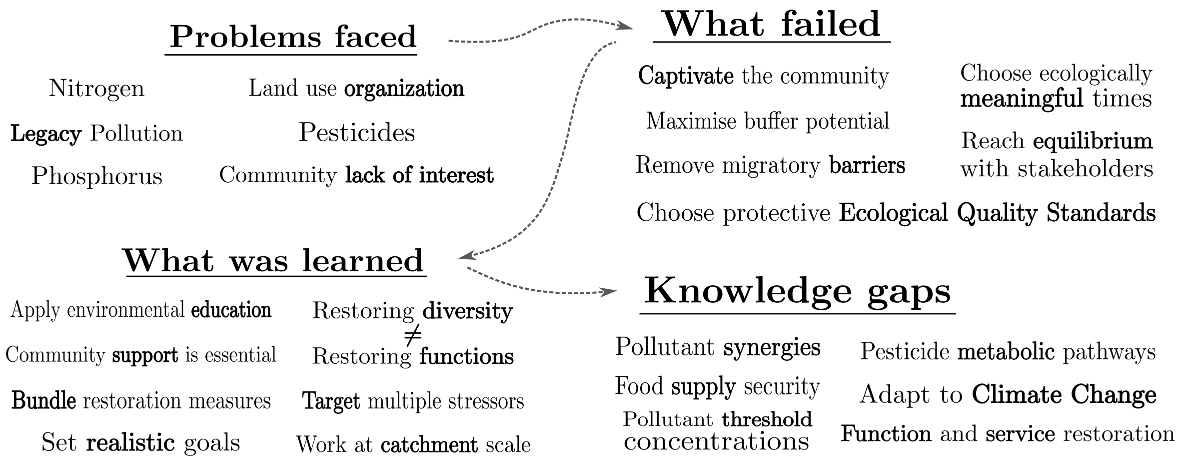

Figure 2.5: Summary of the main developments on restoration of agriculture impacted rivers and streams in Europe during the past 6 years (2010-2015; both years included).

this legal exception (e.g. Feuillette et al., 2016; Jensen et al., 2013; Klauer et al., 2016; Vinten et al., 2012). Nevertheless, with the closure of the first WFD deadline for good water ecological quality, and the need to determine on which water bodies it will be necessary to aim for “less stringent environmental objectives", continuing to explore this issue is crucial.

Lastly, the particular thresholds (i.e. EQS) and measures aiming to control specific substances (such as nitrates or pesticides) have raised concerns. Recent literature reports that the options considered might be insufficient to achieve a meaningful pollution reduction and rebalancing of freshwater ecosystems (Howden et al., 2010; Lava et al., 2014; Thieu et al., 2010).

2.4 Conclusion

Recent research developments have increasingly 1) encompassed the effects of multiple stressors, 2) pointed out where and why restoration projects failed, 3) reported what could be done to improve results and 4) identified knowledge gaps that must be filled regarding various subjects (figure 2.5).

Although a considerable amount of restoration reports would be expected during the implementation of the WFD’s first cycle, only a limited amount is present in recent scientific peer-reviewed literature. The availability of multiple restoration project reports on peer-reviewed literature is crucial to explore new methodologies and assure the future development and dissemination of well-informed, science-based restoration strategies and management decisions. This is important because restoration efforts often have direct consequences on species extinctions and provision of ecosystem services, as highlighted by Diefenderfer et al.

(2016). A multidisciplinary approach often provides a better understanding of the ecosystem and helps preventing less desirable outcomes due to unforeseen constraints (e.g. migratory barriers).

To date, most works have focused on monitoring the environment (human community included), either to better understand cycles or to document the ecological progression of older restoration projects. Such works are essential both in terms of 1) developing a better understanding of the temporal and spatial scales of ecological processes and 2) allowing researchers to pinpoint potential new fields in need of attention. For example, understanding that increasing species diversity does not necessarily improve the functions of the ecosystem (Muller et al., 2015) uncovered the need to understand which other possibilities exist to restore ecosystem functions and services. Likewise, finding that pesticides can be quickly degraded in the hyporheic zone raised attention to the lack of information regarding the by-products (and consequent effects) of the associated metabolic pathways.

Stakeholder management is a central topic in recent European literature. Nevertheless, there is still a considerable difficulty in consensualising concepts, perceptions and decisions and amongst stakeholders, as well as involving the local community. This is reflected in the difficulty to restructure catchment land uses, setting viable restoration goals and guaranteeing long-term application of eco-friendly practices. Land owners often consider their negative contribution insignificant and therefore believe that a change of agricultural practices (e.g. better control of fertiliser or pesticide application) is unnecessary. Balancing different land uses and carefully manage their relative arrangement in the landscape could be essential to assure ecological stability and control negative effects of anthropogenic activities. Basin managers must continue providing environmental education so that all stakeholders can receive information on themes such as 1) how ecological relationships develop at catchment scales, 2) how the natural dynamics of freshwater systems are necessary to assure the health of these ecosystems and 3) the benefits that such healthy ecosystems have for the community. Such education efforts may go a long way in resolving stakeholder conflicts, greatly increasing restoration efforts' probability of success.

The WFD has been a major milestone in raising awareness to the need of restoring Europe's rivers, but its application during the first management cycle was not without limitations. The deadline to have all rivers in good ecological state by 2015 failed. Expecting unrealistic restoration speeds, setting unprotective concentration thresholds or the difficulty to connect with the local communities were some of the reasons given to explain this failure. However, the WFD also opened way for a new mentality and, during future management cycles, working towards achieving a good ecological status for Europe's freshwater systems remains a priority. Successful restoration cases highlight the possibility to restore European streams and rivers to natural or semi-natural conditions, allowing the provision of enhanced ecosystem services throughout the territory.

2.5 Acknowledgements

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Chapter 3

Practicing restoration at basin scale: The Onda river proposal.

After undergoing a review of existing literature on the restoration of agriculturally impacted rivers, a practical approach was developed to plan the restoration procedures that would have to be followed to restore a particular river. As it is highly impacted by agriculture and failed to achieve a good ecological status by 2015 (therefore failing to comply with the WFD), the river Onda was chosen as study subject.

Therefore, this chapter is not meant to provide the specific restoration measures that each reach would have to undergo, but rather provide an integrative basin scale plan that would need to be concretised for each specific reach upon implementation.

3.1 Basin characterisation

The Onda is a coastal river situated in the 2^{nd} Portuguese Hydrographic Region (figure 3.1), with a basin of approximately 47km^2. The potential hydrographic net (i.e. extrapolated from the terrain's elevation profile) consists mainly of first and second order streams (approximately 73.7%), with third order streams accounting for 18.7%. The remaining 7.6% correspond to fourth order streams, leading to a total extension of approximately 87km. Of these, only 10.5km are considered for WFD implementation. The Onda river and it's tributaries cross lands used for agriculture and urbanisation, as well as natural/forested areas (see figure 2.4, from the previous chapter). From these, the most common land use on the basin is

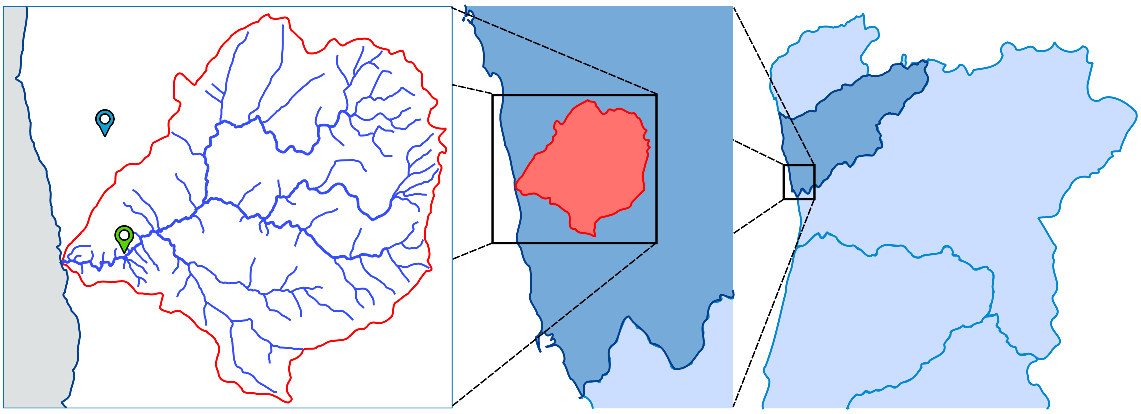


Figure 3.1: The Onda river is situated on the 2^{nd} Portuguese hydrographic region's southwestern edge (region marked with a darker blue on the right image). The blue marker indicates the weather station 06E/03UG and the green marker the water quality station 06/01SED, from which information was gathered to draw figures 3.2 and 3.3.

agriculture, which accounts for 48.8% of the terrain. Forested areas and urban areas occupy a considerable lower share: 28.8% and 23.4%, respectively (information extracted from the Soil Uses Map[1]). The current agricultural extent reflects the long usage of this river's lands for agricultural purposes, which have greatly impacted and reshaped the stream network.

According to the first cycle Hydrographic Region Management Plan, the Onda river is impacted mostly by agriculture and industry effluents, with the former contributing with close to 75% and 60% of the excessive N and P input, respectively. From amongst the excessive N, the most abundant form are nitrates (NO_3^-, figure 3.2). These stressors have considerable impacts on the biotic community, which led to the attribution of the lowest ecological classification (Bad) to the river. Furthermore, the river was not expected to achieve a good ecological state before the WFD deadline closure.

From a different point of view, the local population reports that flooding events with damaging effects to lands and infrastructures have been frequent in the past years. The same can also be seen from various pieces of news regarding the river on past years (table 3.1). Such can be a consequence of 1) increasing soil immobilisation and straightening of stream beds associated with 2) a increasing discrepancy between wet and dry years, which leads to unstable and hardly predictable high flows despite the overall tendency for less precipitation (figure 3.3).

The local population also reported that fisheries undergone at sea nearby the river mouth tend to produce lesser results after pesticides application on agricultural fields. The effects of pesticides on fish behaviour are well known. For example, in their meta-analysis, Shuman-

[1]From the portuguese: "Carta de Ocupação do Solo (COS)".

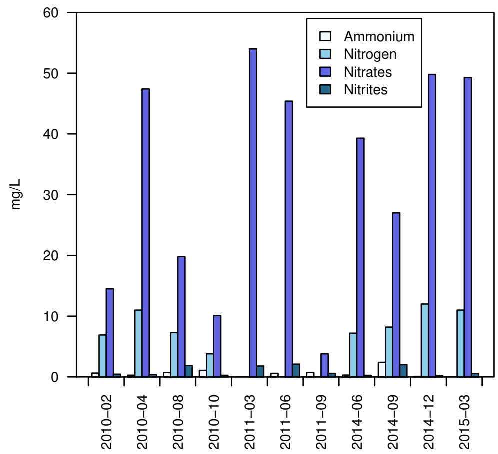


Figure 3.2: Concentration of various nitrogen forms in the water from the station 06E/01SED (APA, 2016), from 2010 to 2015.

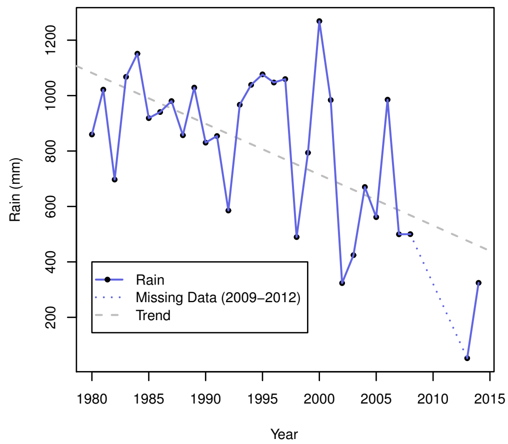


Figure 3.3: Precipitation records from the station 06E/03UG (APA, 2016), from 1980 to 2014 (data from 2009-2012, inclusive, unavailable).

Goodier and Propper (2016) concluded that pesticide concentrations consistently reduced swim speed (up to 35%) and activity levels (up to 72%) of exposed fish and amphibians in experimental studies.

3.1.1 Current stream conditions

Currently, most of the stream's network has been modified to fit human demands (appendix A). Agriculture has been widely implemented on upper reaches. On extreme cases, the river spring has been burrowed to allow for wider fields, forcing the river to surface further downstream (figure 3.4). On other situations, industrial expansion has led to a disregard for upper reaches, with the destruction of former riverbeds (figure 3.5). Agricultural fields such as the one depicted on figure 3.4 have an extremely high contamination potential, as they drain directly over the hydrographic net. Therefore, mitigating the impacts of these fields is of high priority.

On mid reaches, channel deepening, straightening and concrete walling of the riverbed are common features both on agricultural lands and on roads/urbanisation (figures 3.6 and 3.7), with some extreme cases of riverbed relocation or burrowing under infrastructures (figure 3.8). The lower reaches have a strong flow and therefore avoided heavy hydromorphological changes. However, on these situations the riverbanks have been widely suppressed.

Across the river basin there are still some meandering reaches with a semi-natural riparian forest. These tend to result mostly of seemingly abandoned agricultural fields.

Table 3.1: Examples of pieces of news regarding the struggles suffered at the Onda basin provoked both by flooding events and by punctual pollution discharges.

"the Onda river's water invaded the road and dragged a vehicle, which had 2 people inside, by Labruge's church. ... the bridge that connects Labruge to Angeiras .. was closed to traffic, given the risk of collapse. ... The flood occurrence led to a partial cut of the Metro line."   From: TVI24 on 2011-10-26
"Hundreds of fish appeared dead today by the Onda river mouth in Angeiras, Matosinhos, with the county having already alerted the National Maritime Authority to a sewer discharge. ... The county reminded that, in 2010, due to a similar discharge, Angeiras' beach lost its Blue Flag."   From: Porto Canal on 2013-08-30
"...the river Onda, in Labruge, Vila do Conde, wrose up from it's regular path and pushed water and mud against a nearby house with 3 people inside, blocking all the exits."   From: Radio OndaViva on 2015-11-03

3.2 Restoration plan

3.2.1 The vision

When planning the river's restoration, the recovery of several ecosystem services was taken into account. Specifically, the plan aims to increase the regulation services' potential for 1) flood minimisation/attenuation and 2) nutrient/pollution depuration, as well as the support services of 3) providing riverine ecotones, which have high biodiversity potential. Furthermore, restoring the river would have a potential impact on production services such as agricultural output (due to less damage provoked by flooding) as well as, ex loci, increase the fisheries captures by reducing pollutant output to the nearby sea.

3.2.2 Setting priorities

The river basin was subdivided into 4 head-water groups (orange, purple, teal and green), one mid-reach group (blue) and one lower reach group (red; Appendix B). The project compartmentalisation would allow to better cope with possible monetary constraints, while also allowing to have a greater control of the measures' impacts.

The first priority is to decrease flood impacts in order to obtain community support for the restoration plan. To accomplish this goal, it is imperative to increase water residence times.

(a) 2003-01-13

(b) 2013-11-05

Figure 3.4: Agricultural field on top of one of the basin's springs. Red arrows show areas where the surface flow still marks the probable historical position of the stream. The river surfaces at the end of the field (light-blue arrow). Black arrow indicates flow direction. Images from Google Earth.

(a) Spring

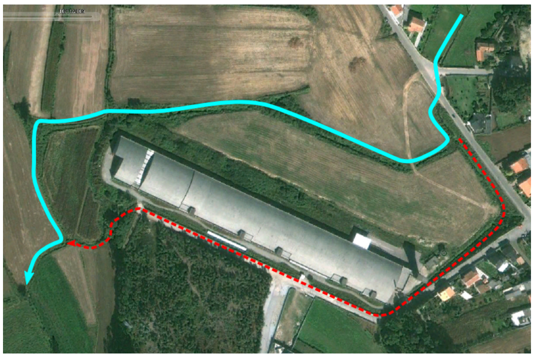
(b) First stream meters

Figure 3.5: Spring located inside an industrial complex (red arrow). The stream runs on the street's side until the complex ends. Black arrows indicate flow direction.

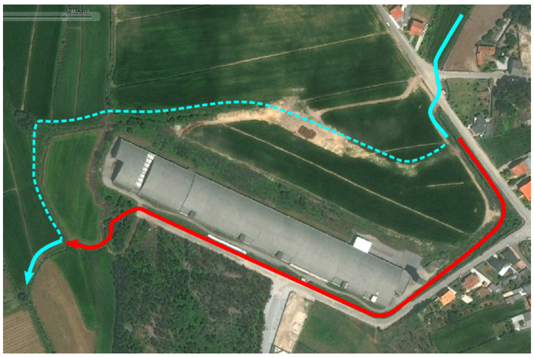
Figure 3.6: Section where the river has been walled and deepened as it crosses agricultural fields.

Figure 3.7: Section where the river was straightened and runs side by side with a road on an urbanised zone.

Removing tile draining is an efficient way of raising the water level and, therefore, increase the water residence times (Audet et al., 2013). However, in this particular network, doing so would have considerable impacts on nearby agricultural fields. Therefore, the best option is to widen the river section (through unchanneling) and increase the surface roughness to decrease the flow speed (Hoffmann et al., 2011; Rutherfurd et al., 2000a).



(a) 2009-10-11: Most of the water flows through the blue path. The red path is already present, but secondary.



(b) 2010-07-18: The blue path is buried. The possible presence of underground piping is unknown.

(c) 2013-11-05: The previous riverbed is now nonexistent.

Figure 3.8: Section of the river that was displaced due to the expansion of industry and agriculture. Light blue line indicates the pre-disturbance path. Red line indicates the modified path. Water flows from right to left. Images from Google Earth.

As measures to unchannel and/or undeepen reaches get increasingly costly and time-consuming with increasing river dimension, the upper reaches should be the first ones targeted for restoration. This would allow increasing the water residence time on these reaches, giving the lower channels more time to deal with the increased water input during high flows. Furthermore, these measures would also indirectly increase the nutrient retention and pollutant depuration capacity of the upstream zones, reducing the pressure on downstream reaches.

To determine which of the head-water groups should be targeted first, pollutant concentrations and water outflow should be measured at the end of each group, with the group responsible for a higher total input of pollutants to the lower reaches (i.e. *pollutant concentration * water volume passed downstream*) being targeted first. This would allow to prioritise streams that have a greater role on both hydrological impacts (i.e. floods) and pollution stressors (e.g. nutrients).

Additionally, areas where there are historical traces of swamps and bogs should be given special attention (Rutherfurd et al., 2000b). If possible, these ecosystems should be re-

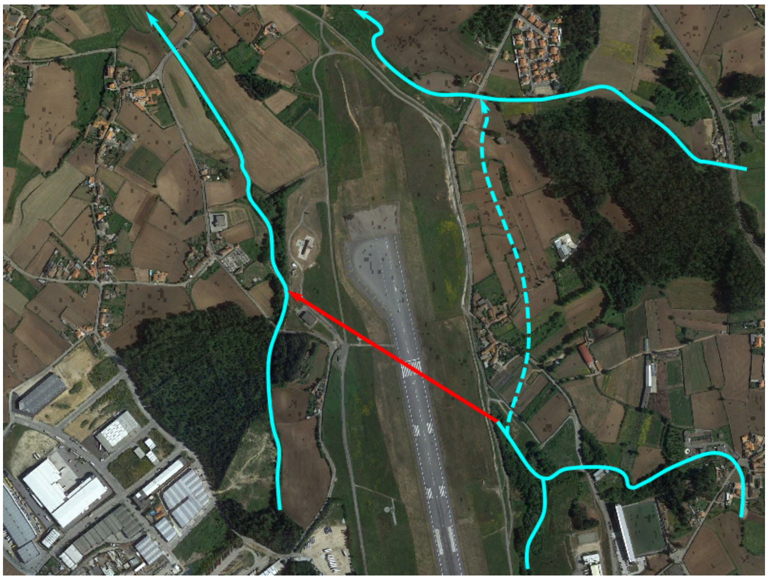


Figure 3.9: Riverbed shift proposal on the Sá Carneiro airport's runways. Red line indicates the current, burrowed channel. Light blue lines indicate the close-by hydrological net. The dashed line shows the potential new riverbed, which would allow the water to flow at the surface. The underground channels beneath the airport could be kept as a protection against eventual flooding events.

established. This measure would have positive impacts on the local biotic communities, on the hydrography downstream and on the overall water quality.

Detailed field studies are needed on 1) the exact positioning of burrowed reaches and 2) the condition of walled reaches, as these tend to be under/through constructions that cannot be displaced. On this situations, evaluating alternative riverbed paths is a possibility, while keeping the walled/burrowed channel present as a safety measure against peak flows. The most noticeable example is the Sá Carneiro airport, where the riverbed could be shifted north to meet the remaining tributaries before going under the runways (figure 3.9).

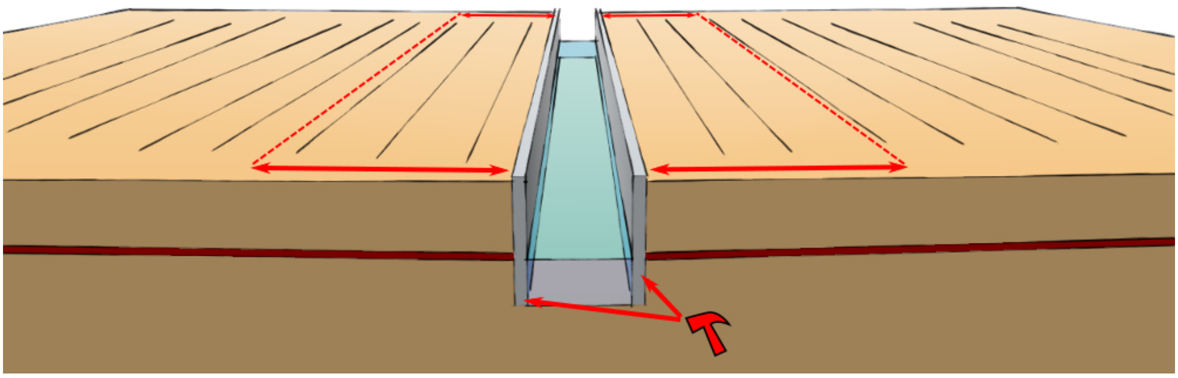
3.2.3 Measures

Upon defining which target group will be handled first, a set of measures should be put in motion. In order to establish the physical boundaries of the project, it is necessary to request information regarding which terrains belong to the Public Hydric Domain (PHD) to the Portuguese Environmental Agency. This request could be done for each sub-catchment group or for the whole basin, depending on convenience. Where the PHD does not apply, a consensus should be reached with land owners regarding either the possibility to lawn the terrains for project implementation or the possibility to acquire such terrains. Additionally, where agricultural fields border the stream, information regarding tile drains positioning should be gathered.

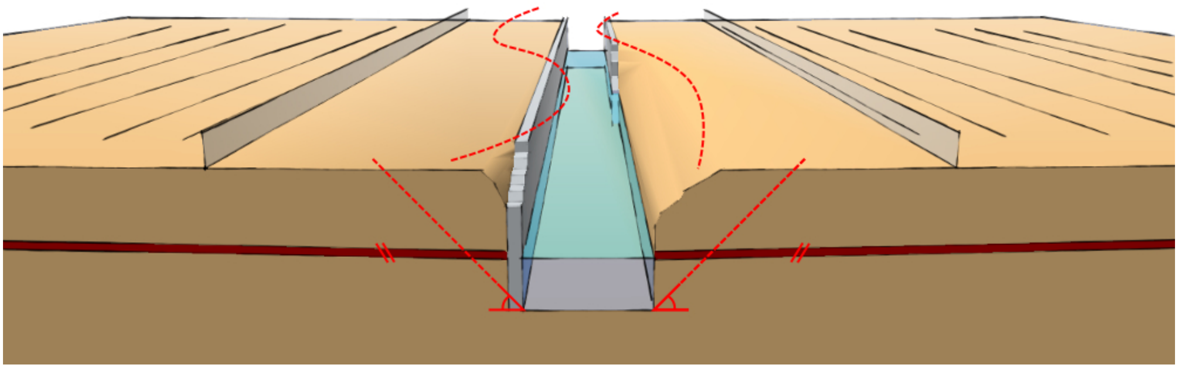
After having gathered all the preliminary information, fulfilling the goal of increasing the water residence time on the reaches would require multiple steps, starting with clearing a buffer-strip along the stream course. Buffer-strip widths are still a controversial subject (e.g.; Rasmussen et al., 2011; Weissteiner et al., 2013). Given the project's location, achieving a 10m radius buffer-strip, in accordance to the PHD (AR, 2005) would allow a considerable improvement of the stream's ecological quality (figure 3.10a). Having secured the buffer area, it would be necessary to run Phosphorus Saturation Index texts (PSI) on the soil. If the soil happens to be saturated with phosphorus, further mobilisation should be avoided, and non invasive remediation techniques should be applied. However, if the soil is not saturated, then the process may continue. The next step would be to unpipe or remove walls from the stream channel (figure 3.10b) and start developing the vision for the restored stream bed. It is then possible to readjust the terrain slope and restructure the riverbanks to allow for meanders. The ideal bank slope depends on multiple factors such as bank height or soil composition. Nevertheless, keeping the slope close to 45° seems to ensure a resistant structure (Lindow et al., 2009). During this step, it is also important to retreat tile drainage openings away from the stream. Finally, it is necessary to promote the occurrence of ponds and increase channel complexity (e.g. by reintroducing riffle-pool sequences), as well as ensure future bank stability by, for example, promoting vegetation growth. Following these steps would improve the stream's hydromorphology (figure 3.10c; Gilvear et al., 2013).

Some of these measures (e.g. remeandering) are expected to greatly increase sediment transport over short periods of time, potentially causing damaging effects to the stream ecosystem (Gilvear et al., 2013). Before the intervention, it is necessary to identify critical sedimentation spots downstream that must be monitored during/after the upstream interventions. Setting up these monitoring points downstream is essential to avoid channel failure. Upon completion of the hydromorphological changes, the development of a healthy riparian structure must be overseen. Such is essential given that during high flow events, although widened, the riverbanks will have to endure high erosion forces. Having a well developed riparian flora not only allows to hold the riverbank in place but also plays an important role in decreasing flow speed.

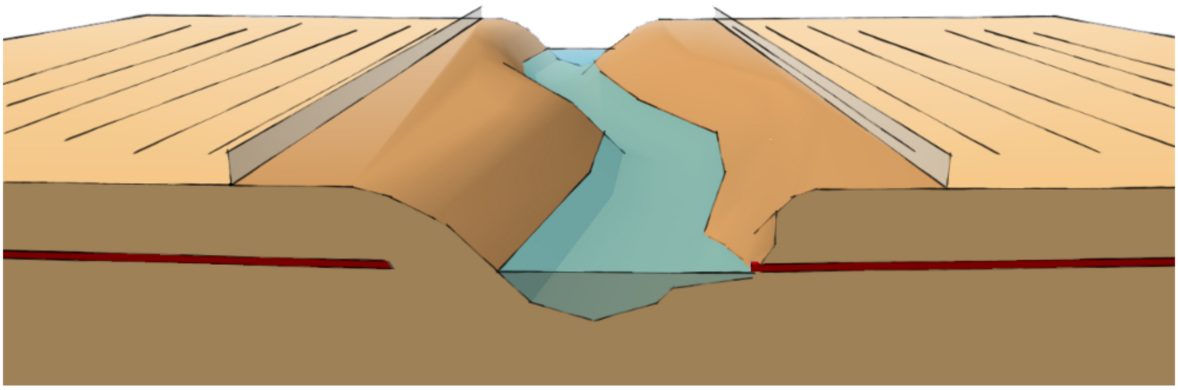
After restoring the 4 head-water groups, the restoration project would move to the mid-reaches, by following the same steps as before. The same applies to the downstream areas.



(a) Start by clearing a 10m ratius bufferstrip (or the ratius available) and then remove the reach walls.



(b) Proceed to rethinking the riverbed, allowing for the presence of meanders. Adjust the bank slope to at most 45 degrees. Retreat tile drainage so the drained water is not passed directly to the stream.



(c) Additional pools can be created to accommodate tile drainage flows. The resulting reach has improved pollution depuration capacity and water residence times.

Figure 3.10: Steps to restore the hydromorphology of a walled reach heavily impacted by agriculture.

3.2.4 Goals

With the aim of addressing the project's efficiency and objectively determine when would the project be considered successful, a set of measurable objectives was devised:

1. Decrease pollutant concentrations to legally accepted levels (e.g. thresholds of the Nitrates Directive, Integrated Pollution Prevention Directive, Dangerous Substances Directive and ultimately Water Framework Directive).
2. Restore macroinvertebrate, fish and plant community status to an ecological condition of good or higher.
3. Reduce the number and magnitude of flood events by at least 50%.
4. Reduce the percentage of reaches with a highly impacted hydromorphology (e.g. straightened, walled, burrowed) by 50%.

3.3 Discussion

Developing this practical exercise of basin scale restoration planning provided invaluable insight regarding the multiple difficulties faced by basin managers. The long history of human use on this basin has lead to an almost complete disassociation of the stream and the surrounding landscape. The Water Framework Directive was implemented 16 years ago, but there is still a long way to go in terms of river restoration. For example, during the WFD period, the river suffered interventions that ideologically still resemble the initial concrete engineering interventions, such as bridge reconstruction techniques that lead to stream bed bottlenecks (with consequent flow speed increase) or the burrowing of reaches (e.g. the striking example from figure 3.8). The fact that such situations are still occurring underline one of the greatest challenges of future policies, that is to sensitise local stakeholders about the importance of healthy freshwater ecosystems and successfully integrate them in management decisions. Furthermore, river basins usually cross multiple administrative zones, thus making the task of achieving consensus even harder.

Despite the PHD, a limitation that became clear was the difficulty associated with restructuring land uses to provide space for the river to flow naturally. The channelised or burrowed reaches throughout the basin often pass through urban or industrial areas. Displacing these infrastructures would have "disproportionate" costs, but displacing the riverbed is not always possible, which leaves the basin manager with a unsolvable situation that can greatly impact the remaining stream network (e.g. by changing water flow patterns or creating barriers for animal migration).

Moreover, under the current changing climatic conditions, the outcome uncertainty associated with restoring freshwater ecosystems is amplified and can hinder the successful achievement of the proposed objectives. For example, the increasing amplitude of yearly rainfall patterns (figure 3.3) may increase the magnitude of flood events. Likewise, higher temperatures and (possibly) extended periods of drought may significantly decrease stream flow volume, indirectly leading to an increase in pollution concentration. This deviations may render restoration positive effects imperceptible. Nevertheless, climate change must be pointed out as a crucial motive for riverine restoration, since this process makes freshwater ecosystems more resilient and, thus, more able to cope with uncertainty.

Chapter 4

Conclusion

The role of agriculture in freshwater degradation throughout Europe is nowadays indisputable. There is a need to guide policies towards mitigating this sector's impacts, but legislation to control agricultural impacts often fails to provide the desired results. The Water Framework Directive marks a new paradigm of European legislation, focusing on the ecological role of water and appealing to the integration of multiple stakeholders.

The first River Basin Management Plan is now over. As the second cycle entries to force, exploring recent developments on the area of restoring agriculturally impacted freshwater ecosystems is crucial. During the development of the first cycle, the number of reported restoration projects in peer-reviewed literature was limited. This outcome can partly result from the definition of “restoration project" adopted in this work (see table 2.2 in Chapter 2), but it also may be tied to the difficulty in publishing such works in peer-reviewed journals, as well as the time it may take for such projects to be concluded and then be reported. The availability of such reports is crucial to assure the dissemination of science-based restoration strategies.

Although the WFD has provided an important opportunity to further explore European freshwater ecosystems, the development of this knowledge has uncovered several new topics in need of further investigation. Increasing our understanding of complex interactions that take place in interfaces such as the hyporheic zone, or the full impact spectrum of pollution stressors such has pesticides or nutrients may play an important role in improving future restoration techniques.

On a broader scale, land use management is probably one of the greatest challenges of future policies. Finding how to maximise the benefits of managing both land use conflicts and land use configuration is challenging, but also has the potential for preventing pollution at its source. These interactions can be integrated in a framework of ecosystem services, in an attempt to quantify the effects of multiple management options.

The potential effects of climate change on agriculture are also a concern. The increasing pressure on this sector to produce greater quantities of food, coupled with the increasing struggle to nurture cultures in changing climatic conditions, may lead to a lessening of care for freshwater ecosystems, which would hinder their restoration. Basin managers must not loose sight of the need to preserve and restore Europe's freshwater ecosystems. To assure this continued effort, achieving consensus with stakeholders is crucial.

Some European member states have a history in stakeholder management (e.g. the anglosaxonic countries), and have gone a long way in implementing integrative plans. However, on countries like Portugal, where engaging stakeholders and develop integrative management plans is relatively new, stakeholder engagement still needs further improvement, and the dissemination of well structured environmental education may be crucial to homogenise perceptions amongst stakeholders.

However, there is one WFD limitation that might render all efforts valueless: the lack of measures targeted at non-BSW's. This issue is very relevant for future management plans, as these water bodies may hold the key for integrated and successful basin management and restoration. On the practical exercise realised, the importance of non-BSW's and their potential impact became very clear. These outcast streams and their relevance for the basin water quality must be further investigated in years to come, so that policies can be adapted and integrate measures at the head-water level.

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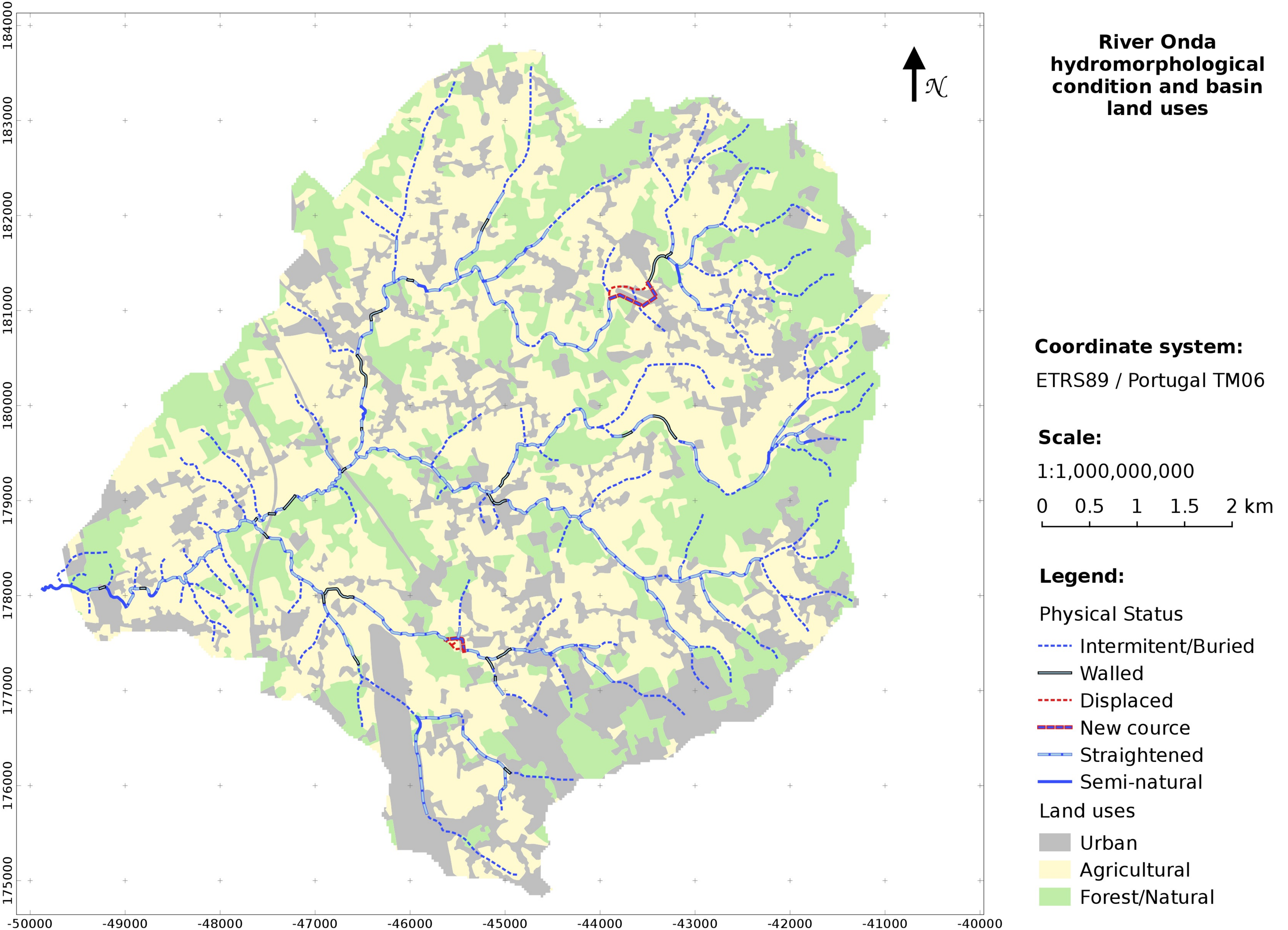
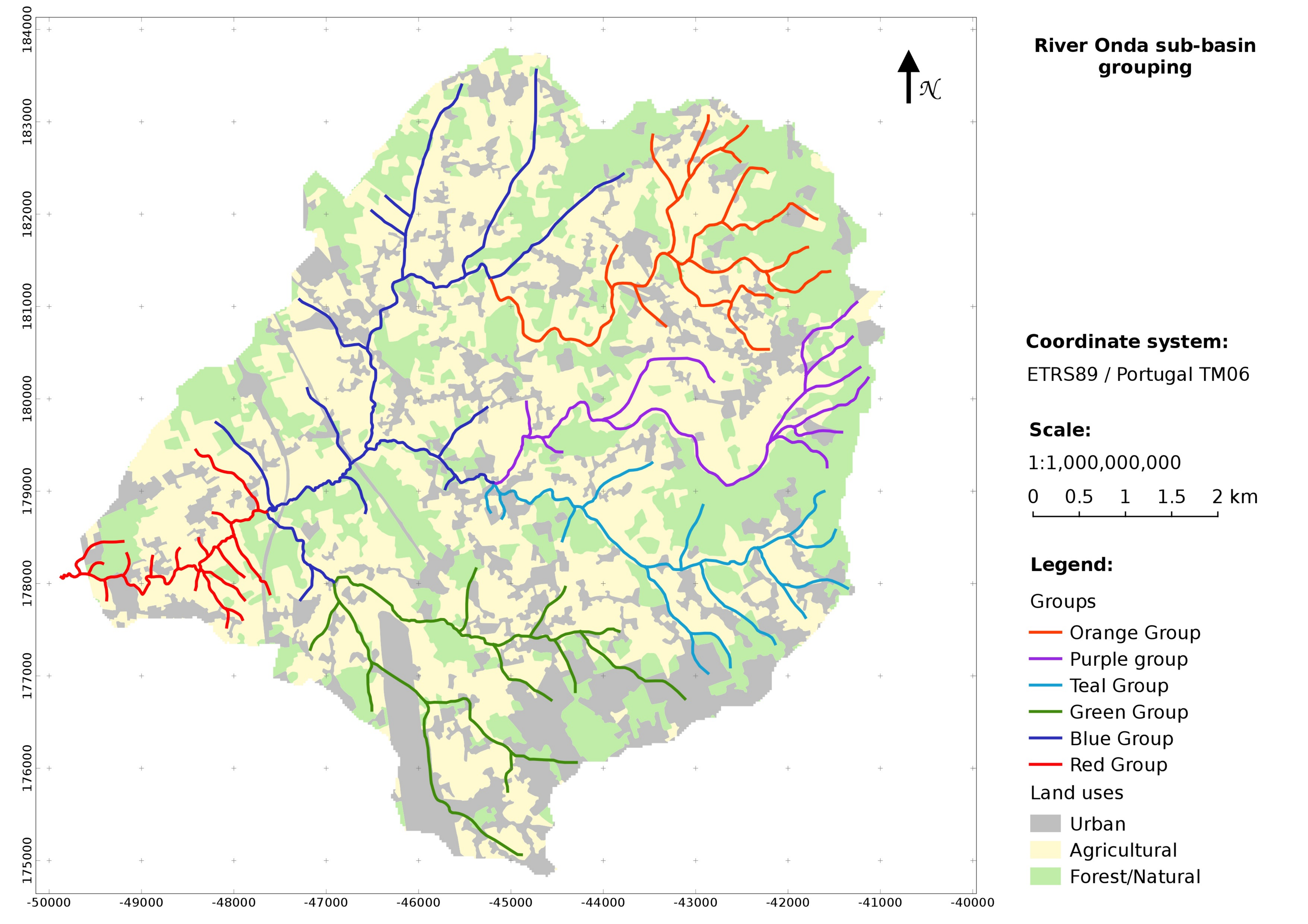
Appendix A


River Onda hydromorphological condition and basin land uses
Coordinate system:
ETRS89 / Portugal TM06
Scale:
1:1,000,000,000
0 0.5 1 1.5 2 km
Legend:
Physical Status
Intermitent/Buried
Walled
Displaced
New cource
Straightened
Semi-natural
Land uses
Urban
Agricultural
Forest/Natural
-50000 -49000 -48000 -47000 -46000 -45000 -44000 -43000 -42000 -41000 -40000
175000 176000 177000 178000 179000 180000 181000 182000 183000 184000

Appendix B


River Onda sub-basin grouping
Coordinate system:
ETRS89 / Portugal TM06
Scale:
1:1,000,000,000
0 0.5 1 1.5 2 km
Legend:
Groups
Orange Group
Purple group
Teal Group
Green Group
Blue Group
Red Group
Land uses
Urban
Agricultural
Forest/Natural
184000
183000
182000
181000
180000
179000
178000
177000
176000
175000
-50000
-49000
-48000
-47000
-46000
-45000
-44000
-43000
-42000
-41000
-40000