Universitat Autònoma de Barcelona

Assesing the effects of Global Change on ecological water quality of Mediterranean river basins

ANTONI MAS-PONCE

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Tutor: Esteve Corbera (ICTA-UAB)

In collaboration with
Consorci Besòs Tordera and Fundació Rivus

Besòs Tordera

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UAB Universitat Autònoma de Barcelona

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Abstract

Mediterranean river basins are exposed to a great water demand to meet the needs of the increasing population and other anthropogenic activities related such as the development of industry, intensive agriculture and tourism activities. In addition, these areas have strong inter-annual climatic variability mainly characterized by a dry period in summers, which represents an evident variability in rivers discharge annual regime, from permanent to temporal and a variation in the water quality status.

From this Global Change context, springs up the need to build new indicators to evaluate the impacts of Global Change in two Mediterranean river basins such as Tordera and Besòs river basins (North-East Iberian Peninsula). These two river basins are contiguous but have different hydrological regimes and population sizes, so pressures and impacts are diverse and are considered as two study cases which contributes to increase transferability to other Mediterranean river basins.

For that purpose, three main scopes are analysed three main scopes: the ecological through the evolution of the ecological quality status in both study areas; the anthropogenic, assessing the influence of wastewater treatment plants effluents on the ecological status and exploring the main Global Change effects through Land Use Land Cover (LULC) changes; and the social, exploring relationships between local perceptions and ecological quality status.

A model is run for developing the new approach, correlating water quality indicators stablished by the Water Framework Directive (2000/60/EC) such as biological indicators (macroinvertebrates, riparian vegetation and diatoms), physicochemical indicators (ammonium, nitrates, nitrites, phosphates and conductivity) to assess the ecological status of the water systems with the Land Use and Land Cover Changes Analysis (forest grassland and shrubs, urban, bare forested soil, crops and continental waters areas). In addition, climatic and topographic variables such as the slope, the altitude and the Water Availability Index (WAI) were added to this model as important explanatory variables to the variation of the water quality indicators.

The results show that this new and comprehensive assessment has the potential to assess the Global Change effects in a Mediterranean context. This tool could be profitable to provide a wider vision of a studied area and to detect the locations to focus future management plans and measures.

Resumen

Las cuencas fluviales mediterráneas están expuestas a una gran demanda hídrica con el fin de satisfacer las necesidades de una población en continuo crecimiento y de otras actividades antropogénicas relacionadas como la industrial, la agricultura intensiva y las actividades turísticas. Además, estas zonas presentan una fuerte variabilidad climática interanual, caracterizada principalmente por períodos de sequía en verano que, representa una evidente variabilidad en el régimen anual de caudales de los ríos, haciéndolos pasar de ríos permanentes a ríos temporales y, una variación en el estado de calidad del agua.

Desde una perspectiva de contexto de Cambio Global, surge la necesidad de construir nuevos indicadores para evaluar los efectos del Cambio Global en dos cuencas fluviales mediterráneas, como son las cuencas de los ríos Tordera y Besòs (Nordeste de la Península Ibérica). Estas dos cuencas hidrográficas son contiguas, pero tienen diferentes régimenes hidrológicos y tamaños poblacionales, por lo que las presiones e impactos son diversos y se consideran dos casos de estudio que contribuyen a demostrar la transversalidad en otras cuencas fluviales mediterráneos.

Para tal motivo, se analizan tres ámbitos principales: el ecológico a través de la evolución del estado de la calidad ecológica en ambas áreas de estudio; el antropogénico, evaluando la influencia de los efluentes de las plantas de tratamiento de aguas residuales sobre el estado ecológico y explorando los principales efectos del cambio global a través de los Cambios de Usos y Cubiertas del Suelo (LULC); y el social, explorando las relaciones entre las percepciones locales y el estado de la calidad ecológica.

Se ejecuta un modelo estadístico para desarrollar el nuevo enfoque, correlacionando indicadores del estado de calidad establecidos por la Directiva Marco del Agua (2000/60 / EC) con indicadores biológicos (macroinvertebrados, vegetación de ribera y algas) diatomeas) y fisicoquímicos (amonio, nitratos, nitritos, fosfatos y conductividad) para evaluar el estado ecológico de los sistemas fluviales con el análisis de cambios de usos y cubiertas del suelo (áreas forestales arboladas, forestales no arboladas, urbanas, suelo nudo forestal, agrícolas y aguas continentales). Además, se añadieron a este modelo, variables climáticas y topográficas como el índice de disponibilidad hídrica (WAI), la pendiente y la altitud, como variables explicativas relevantes de la variación de los indicadores de calidad del agua.

Los resultados muestran que esta nueva e integradora evaluación tiene el potencial para evaluar los efectos del Cambio Global en un contexto mediterráneo. Esta herramienta podría ser provechosa para tener una mayor visión de la zona de estudio y detectar los puntos sobre los cuales centrar esfuerzos en futuros planes y medidas de gestión fluvial.

Resum

Les conques fluvials mediterrànies estan subjectes a una gran demanda d'aigua per tal de satisfer les necessitats d'una població en continu creixement i d'altres activitats antropogèniques relacionades com la industrial, l'agricultura intensiva i les activitats turístiques. A més, aquestes zones presenten una forta variabilitat climàtica interanual, caracteritzada principalment per períodes de sequera a l'estiu que, representa una evident variabilitat en el règim anual de cabals dels rius, fent-los passar de ser rius permanents a rius temporals i, una variació en l'estat de qualitat de l'aigua.

Des d'una perspectiva de context de Canvi Global, sorgeix la necessitat de construir nous indicadors ecològics per avaluar els efectes del Canvi Global en dues conques fluvials mediterrànies, com són les conques dels rius Tordera i Besòs (Nord-est de la Península Ibèrica). Aquestes dues conques hidrogràfiques són contigües, però tenen diferents règims hidrològics i mides poblacionals, de manera que les pressions i impactes són diversos i es consideren dos casos d'estudi que contribueixen a demostrar la transversalitat en altres conques fluvials mediterrànies.

Per tal motiu, s'analitzen tres àmbits principals: l'ecològic a través de l'evolució de l'estat de la qualitat ecològica en les dues àrees d'estudi; l'antropogènic, avaluant la influència dels efluents dels sistemes de tractament d'aigües residuals sobre l'estat ecològic i explorant els principals efectes del canvi global a través dels Canvis d'Usos i Cobertes del Sòl (LULC); i el social, explorant les relacions entre les percepcions locals i l'estat de la qualitat ecològica.

S'executa un model estadístic per desenvolupar el nou enfocament, correlacionant indicadors de l'estat de qualitat establerts per la Directiva Marc de l'Aigua (2000/60/EC) com indicadors biològics (macroinvertebrats, vegetació de ribera i algues diatomees) i fisicoquímics (amoni, nitrats, nitrits, fosfats i conductivitat) per avaluar l'estat ecològic dels sistemes fluvials amb l'anàlisi de canvis d'usos i cobertes del sòl (LULC) (àrees forestals arbrades, forestals no arbrades, urbanes, sòl nu forestal, agrícoles i aigües continentals). A més, es van afegir a aquest model, variables climàtiques i topogràfiques com l'índex de disponibilitat hídrica (WAI), la pendent i l'altitud, com a variables explicatives rellevants de la variació dels indicadors de qualitat de l'aigua.

Els resultats mostren que aquesta nova i integradora avaluació té el potencial per avaluar els efectes del Canvi Global en un context mediterrani. Aquesta eina podria ser profitosa per tenir una major visió de la zona d'estudi i detectar els punts on centrar esforços en els següents plans i mesures de gestió fluvial.

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Créixer en un entorn familiar amb persones que s'han dedicat a la docència, ha estat el factor clau que m'ha permès arribar fins aquí. Tant els meus pares com la meva germana s'han dedicat i es dediquen a la seva professió amb entusiasme i ambició, superant tots els obstacles que dia a dia es troben en una professió tan dinàmica com és l'educació. Aquest entusiasme i ambició han estat aptituds que he tingut la sort d'adquirir al llarg de la meva vida personal i professional i que han fet que aquesta tesi doctoral hagi estat possible.

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Mentre estava cursant l'últim curs del grau de Ciències Ambientals, el Martí Boada em va donar la oportunitat de col·laborar en el projecte de, l'aleshores anomenat, Observatori de la Tordera com a educador ambiental en el Programa d'Educació Ambiental i Comunicació (PROECA). Aquella confiança dipositada, sense jo saber-ho, va suposar l'inici d'un llarg i profitós camí que m'ha portat moltes experiències i coneixements i aprendre a estimar els nostres rius. També vull aprofitar la oportunitat de donar les gràcies a l'Esteve, el qual no va dubtar en agafar el rol de tutor d'aquesta tesi quan el Martí va jubilar-se. Més enllà del seu paper, sempre agrairé la seva proximitat com a professional i persona.

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A finals de novembre del 2020 la meva vida professional va emprendre una altra via i vaig començar a treballar al departament de control d'abocaments del Consorci Besòs Tordera amb el Francesc, l'Andrea, la Núria, la Sonia, la Berta, l'Ivan i la Begoña i en general a tots als companys i companyes de l'entitat, que han fet que compaginar els últims mesos de la tesi amb la feina al Consorci hagi estat més fàcil. En especial també voldria mencionar a l'Albert i al Manel per la confiança i recolzament que sempre han mostrat i pel paper fonamental que van tenir per incorporar la conca del Besòs al projecte de L'Observatori i a la tesi.

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1. Introduction

This research is based on integrating an interdisciplinary and socioecological approach from disciplines such as ecology, geography and sociology through water in specific Mediterranean river basins located in the most populated areas of Catalonia.

1.1. Global Change effects on the Mediterranean basin context

Historically, water has always been priced as a resource, but during the last two decades a paradigm shift has occurred as water is considered as an indispensable element for life and the environment. As such, its social and ecological function must be assessed and as an asset to be protected and preserved.

During the decades of the 70's and the 80's, with the peak of the industrialization and the intensification of agricultural activities in Europe, the Mediterranean basin suffered a decrease in the freshwater quality and quantity (Vega et al., 1998; Hermoso, et al., 2011). In addition, another factor was the profound economic changes taking place in that region led to a process of land abandonment in rural areas, especially in headwaters (Otero, et al., 2011; Sànchez-Mateo, et al., 2011; Voza, et al., 2015), to middle and lower courses, due to the increase and the intensification of the human activity coupled with the reduced dilution capacity of this area (Benejam, et al., 2010; Navarro and Ortega, et al., 2014). This trend was intensified during the 90's and 00's when the effects of climate change were more stronger (MedECC, 2019) and with the afforestation processes due to rural abandonment in headwaters (Otero, et al., 2011).

The key role played by humans in the exploitation of natural resources provided by the different ecosystems has led to a series of environmental changes at a global scale which, in turn, modify the functioning of all layers of Earth such as hydrosphere, lithosphere or biosphere (Meyer and Turner, 1992; Boada and Sauri, 2002). These changes all play an important role as drivers of what is currently known as Global Change (Rosenzweig et al., 2008; Rabalais et al., 2009).

The Centro Andaluz para la Evaluación y Seguimiento del Cambio Global (CAESCG), such as most of the Global Change experts and institutions, defines the concept of Global Change to "the interference (causes) and disruptions (impacts) produced by human activity on the processes that determine the balance of the planet (Earth system). These changes are caused by the destruction, fragmentation and overexploitation of ecosystems, invasive species, the alteration of biogeochemical cycles, general pollution caused by nitrogen and phosphorus and above all, climate change, land use change and land abandonment. The impact generated by these agents of change also affects the essential ecological processes which support life on this planet and results in the loss of biodiversity, environmental goods and services and, finally, social welfare". All the cumulative local changes will be expressed globally too, and for that reason, the study of Global Change effects should start from the "local" to understand lately the "global".

It is important to highlight the influence that Global Change has on the fluvial dynamics and on biodiversity, which is intensified specifically by climate change. Dudgeon et al. (2005) reviewed the main five threats to freshwater biodiversity, namely overexploitation, water pollution, flow modification, degradation of habitat and invasion by exotic species. Thirteen years later, Reid et al. (2019) listed twelve new threats to freshwater biodiversity due to Global Change effects: changing climates, e-commerce and invasions, infectious diseases, harmful algal blooms, expanding hydropower, emerging contaminants, engineered nanomaterials, microplastic pollution, light and noise, freshwater salinization, declining calcium and cumulative stressors.

Furthermore, world biodiversity linked to freshwater has decreased 83% between 1970 to 2014, as referenced in the Living Planet Index (LPI) (Collen, et al., 2009; World Wildlife Fund, 2018).

Since 2002, Catalonia, experienced a decrease of the 54% of the biodiversity linked to fluvial systems. It is especially remarkable the decrease of the 92% of autochthonous fishes (Brotons, et al., 2020). This fact is explained, as many other Mediterranean river basins, by the limited resources of freshwater and the intensified human pressure.

These provoked multiple pressures including alteration of water quality flow regulation, water abstraction, pollution, changes in channel form, modification of riparian areas, and invasive exotic species (Navarro-Ortega, et al., 2008).

For all these reasons, the alteration of fluvial systems is considered as one of the major problems facing the world (European Environment Agency (EEA), 2008; United Nations, 2014; Rockström et al., 2009 Strayer and Dudgeon, 2010).

In addition, fluvial systems provide many essential ecosystem services for the general well-being of the society (Sweeney et al., 2004).

The Mediterranean basin is characterized by a strong inter-annual climatic variability, with a dry period in summers and driving rains in spring and autumn (Cuddennec, et al., 2007; Bonada and Resh, 2013; Skoulikidis, et al., 2017). Moreover, due to climate change, the average annual temperatures on these areas are now approximately 1.5ºC higher than the preindustrial period (1880-1899) and may be warmer in 2040 by 2.2ºC (MedECC, 2019). In addition, some climate models point to reduced rainfalls in coming decades (Saadi, et al.,2015) and the increase of the Atmospheric Evaporation Demand (AED) which is linked to the decrease of relative humidity and the increase of the maximum temperatures (Vicente-Serrano, et al., 2014). These phenomena could lead to a greater environmental aridity. In the specific case of Catalonia (North-East Spain), climatic models also indicate an upward temperature trend during the coming decades. From the period 1971-2000 to 2031-2050, models indicate that the annual average temperature in Catalonia will increase by 1.4ºC. There is a higher uncertainty about precipitations, but projections also show an annual rainfall decrease of 7% (Martin-Vide, et al., 2017).

In addition, climate change effects in this region are intensified due to an intense human activity mainly derived from a high population density but also for the intensive increasement of industrial settlements, especially in the middle and lower courses of the river basins. These factors provoked pronounced negative pressures and impacts on its environment (Ludwig, et al., 2009; Blondel, et al.,2010). The variability of the freshwater resources in the Mediterranean basin, considering a 2ºC warming, will determine the socioeconomic development of the area. In fact, this availability will decrease between 2% and 15%, being the largest freshwater decrease in the world (Mas-Pla, et al., 2016; Gudmundsson, et al., 2016; Gudmundsson, et al., 2017).

1.2. Towards good quality status

The quality of surface waters, considering biological, hydromorphologic and physicochemical parameters within a Global Change context, depends on the interaction of natural and anthropogenic factors (James, et al., 2006). The Water Framework Directive (2000/60/EC, WFD), established in 2000 to promote monitoring programs to assess the ecological status of the European rivers, aims to achieve a good water quality status and to prevent pollution of fluvial resources.

Furthermore, this Directive globally aims the protection of the environment and addresses to reach a) the conservation, protection and improvement of the fluvial ecosystems; b) protecting the human health; c) the correct of water uses; and d) promoting measures to prevent episodes of water pollution.

The first aspect which was implemented trough the WFD is the concept of "ecological status" which replaced the traditional concepts of physic, chemical and biological state. The ecological status is the measure of a freshwater ecosystem, considering the quality of the functionality and the hydromorphology of the studied area.

When the biological communities are equal or close to those that are under unchanged conditions is considered that the freshwater ecosystem presents a good ecological status. In addition, the hydromorphological and physicochemical conditions must be adequate for the correct development of these biological communities. Climate, orography, soil, vegetation and human activities determinate the aquatic ecosystems characteristics: hydrology, chemical composition and water temperature, light gradient, habitat structure, biotic interactions (competence, depredation, etc.) and trophic resources availability. In this sense, most of all the aquatic organisms can be used as fluvial systems indicators for being directly linked to human pressures and/or alterations and they provide ecosystems' information and for its capacity of integration.

Water quality started to be measured considering its conditions to proliferate life considering the indicators stablished in the Annex V of the WFD. However the situation is still far from ideal and further enforcement of environmental laws are required (Faure, 1995; Gherardi, et al., 2009).

Moreover, the WFD incorporated the principles for the sustainably management and uses of water. One of the main principles added were the public participation. In order to enrich the hydrological planning, citizen participation was promoted in the process of development, review and updating of the management plans. For this purpose, the aim is to improve the transparency and legitimacy in water management and offer dialogue to users and stakeholder of the river basin districts.

1.3. The interaction of the Land Use and Land Cover changes on the ecological quality status and dynamics of the fluvial systems

Surface water quality of the fluvial systems has a direct interaction with anthropogenic and natural factors (James, et al., 2006). In that sense, most of the research studies relate Global Change to water availability but, it is necessary to study the effects and consequences of these changes to the ecological water quality. Human-induced Land Use and Land Cover (LULC) changes, considered as one of the main Global Change drivers, are one of the main impacts on water quality and quantity (Khatri and Tyagi, 2015; Voza, et al., 2015). Land Cover is defined as the biophysical unit of the surface and, on the other hand, the concept of Land Use refers to the manipulation of the cover for taking some benefits (Meyer and Turner, 1996).

In the past, the effects of LULC changes on water resources were largely neglected but nowadays it is recognized that an evaluation of historical effects may be used to understand our current situation and predict consequences of future LULC change on water resources and the ecological functions of the fluvial ecosystems (Scanlon, et al, 2015). External factors that contributed to the shift in LULC change in the past continue to shape the direction of LULC change in the future.

For these reasons, it is relevant to perform research about the consequences of land use changes on freshwater ecosystems for describing current but also future Global Change impacts. Moreover, considering our study cases which present Mediterranean climate conditions that are characterized by strong inter-annual climatic variability (Cuddennec, et al, 2007), the influence on water quality (Vega, et al., 1998) and variability in annual rivers flow regime, from permanent to temporal (Navarro-Ortega, et al., 2014) is stronger.

1.4. The interaction between humans and nature: a conceptual framework of the socioecological systems

Historically most of the research studies considered natural and social sciences as separated two different fields of science that can never meet. This paradigm was replaced by a new one which emphasizes that societies (economy, politics and culture) directly interact with the biosphere shaping it from a local and/or global sense. Therefore, both worlds (nature and social) co-evolve. Socioecological systems arose from this new paradigm in which its components are conditioned constantly (Berkes, et al., 1998).

In recent decades, many studies have been conducted on the public perception of natural environments regarding aesthetic beauty, human well-being and restorative characteristics (Mosley, 1989; Tieskens, et al., 2018; Hermida, et al.,2019; Liu, et al.,2020). Since the knowledge obtained through perception is practical, this can therefore inform us about our environment and what it provides us (Ingold, 2000). As the field of using perception in environmental management develops, authors have been defining it in more quantitative terms. For example, Bennett (2016) outlined four categories of insights that local perception can contribute to conservation policy and practice: Social impacts of conservation, ecological outcomes of conservation, legitimacy of conservation governance and acceptability of conservation management. In the specific case of Tordera river basins there are some projects which relate conservation governance to citizen (FP7 Bewater and ISACC TorDelta). Bennett (2016) does not argue for the exclusive use of perception in policy making, but proposes its role in a better-informed, more holistic management approach involving public perception. Public perception can also be a useful source of information for policy makers regarding climate adaption and mitigation (Anthony et al., 2018). Stakeholder’s perception of risk is used to evaluate climate change effects with a view to assess relevant barriers to climate mitigation and prepare properly informed risk strategies. Where stakeholders do not perceive climate change as a significant risk, it is possible to adapt policy in order to improve education surrounding the subject and to disseminate information in a more optimal way (Martín, et al., 2017; Torres-Bagur, et al., 2019). In this way, if the public’s perception of a component or organism of their local environment is negative or even hostile, it is possible to explore the motivation behind that attitude.

2.

Research questions and objectives

The research questions of this research are:

- Which trend has followed the ecological quality status of Besòs and Tordera during the last twenty years? Which implication has had the implementation of a consolidated treatment system for both river basins?
- Is there a direct relation between LULC and the ecological quality status of Besòs and Tordera river basins? How do LULC affect the ecological quality status of these areas?
- How are the local perceptions of the fluvial systems correlated to its ecological status? Is there any correlation/connection between local perceptions and ecological status?

The general objective of this thesis is to improve and widen the existing knowledge of the impact of Global Change on Mediterranean fluvial systems. The Land Use and Land Cover (LULC) change, as presented in the introduction, is considered as the main driver that has influenced on the ecological quality status of Mediterranean river basins. This interaction requires an innovative and interdisciplinary tool to assess the Global Change effects on fluvial systems. This tool is proposed in the current research and it converges information related to LULC changes with climatic and topographic variables and ecological quality status.

As mentioned above, a wide vision of Mediterranean river basins is needed rather than the ecological but socioecological. For this reason, in this research an essay of local perceptions analysis has been also performed in order to provide new approaches for fluvial systems and society interactions. This section (explained in Research Chapter 3) is an overview to stablish a methodological framework, considering a specific case study that will allow to add the local perceptions to the tool.

Our research is focused on the study areas of the Besòs and Tordera river basins which are in North-East of Spain. These two areas, which share Mediterranean climatic and hydromorphological characteristics, are adjacent and have similar areas but different historical, socio-economic and ecological context (see Study Areas section).

In that sense, this tool will be used by river basin managers to apply measures which can be used to prevent and correct Global Change effects and consequences.

The specific objectives of this study are the following:

- To evaluate the evolution of the ecological quality status in both study areas.
- To assess the influence of wastewater treatment plants effluents on the ecological status of Besòs river basin.
- To explore the main Global Change effects on both study areas Tordera and Besòs river basins through LULC analysis (1993 – 2016).
- To explore relationships between local perceptions and ecological quality status.
- To build an interdisciplinary tool to assess Global Change effects on Mediterranean River Basins.

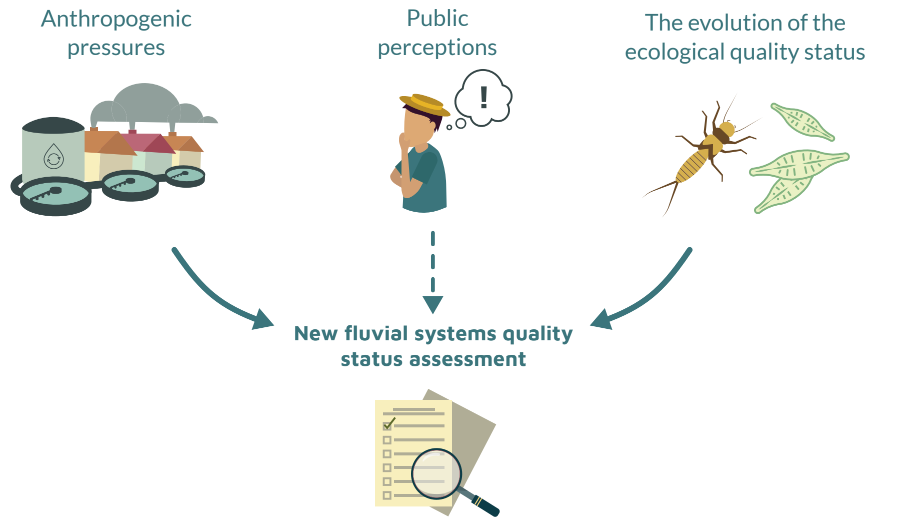

Figure 1. Representation of the main concepts that compose the basis for the methodological framework of the research.

3. Study areas

Our research is focused on the study areas of the Besòs and Tordera river basins which are in North-East of Spain. These two areas, which share Mediterranean climatic and hydromorphological characteristics, are adjacent and have similar areas but different historical, socio-economic and ecological context. These rivers have suffered changes in streamflow regimes in the last decades due mainly to water abstraction (Benejam, et al., 2010). In Tordera, since the 1960s, a significant decrease in the streamflow is reported (nearly 50% in the middle course). In the case of Besòs, it receives part of the water abstracted from the Ter river (river basin located in the North of Catalonia which supply water to Barcelona Metropolitan Area), and thus now has more flow and fewer dry days than expected. Beyond these differences in flow regimes, streamflow projections under climate change scenarios suggest future reductions for coastal river basins in Catalonia (Mas-Pla, et al., 2016) at the end of the century. In the case of the Tordera, Pascual et al. (2015) projects a reduction of 34% for 2076-2100 period in the worst scenario and increase in the frequency of streamflows below ecological flows.

The selection of these areas is explained first of all for its Mediterranean representative vision which allows that the tool built could be performed in other Mediterranean river basins. In addition, these areas are not regulated river basins. Other relevant aspect of these areas is that in contrast of being its reduced surface comparing to other European river basins, they present an elevated heterogeneity of uses. In both cases, their fluvial courses (headwaters, middle and lower course) are great differentiated. Generally, headwaters are characterized by the presence of natural protected areas and with less anthropogenic pressures and middle and lower courses present more human settlements such as industrial and urban activities.

Finally, both areas are studied since the 90's which allows to have large data series that help to know how the basins evolved during a considerable period.

3.1. Besòs river basin

The Besòs river basin has a total drainage surface of 1,038km² is located between the province of Barcelona in the counties of Barcelonès, Vallès Occidental, Vallès Oriental and a sector of Osona and an annual mean flow of 2.9 m³/s. It includes six main sub-basins with their own characteristics: 1) Mogent, 2) Congost, 3) Tenes, 4) Caldes and 5) Ripoll, which all drain to 6) Besòs (Table 2). The Besòs river basin, subjected to a Mediterranean climate, is within the province of Barcelona and includes part of its Metropolitan Area (Figure 2). The population within the river basin has increased tenfold during the last 50 years, and it currently amounts to almost 2 million inhabitants (Sànchez-Mateo, et al., 2017, Institut d'Estadística de Catalunya (IDESCAT), 2019).

The mean temperature in the Besòs river basin is around the 15ºC. In the middle and lower courses of most of the subbasins the mean temperature could exceed the 15ºC between May and October. On the other hand, headwaters during winter reach soft temperatures with a minimum temperature of 6ºC. The mean precipitation in this basin is variable through the years for its Mediterranean conditions but it is around the 500 mm.

Table 1. Mean temperature (Tmean), minimum temperature (Tmin) and maximum temperature (Tmax) by the year 2016 and seasons through the Atles Climàtic Digital de Catalunya.

	Winter	Spring	Summer	Autumn	Annual
CONGOST					
Tmean (°C)	8.4	12.93	21.33	14.4	14.27
Tmax (°C)	10	16	24	20	24
Tmin (°C)	6	10	18	8	6
MOGENT					
Tmean (°C)	9.17	13.67	21.5	15.17	14.88
Tmax (°C)	10	16	24	20	24
Tmin (°C)	6	10	18	8	6
TENES					
Tmean (°C)	8.67	13.5	21.83	15	14.75
Tmax (°C)	10	18	24	22	24
Tmin (°C)	6	8	18	8	6
CALDES					
Tmean (°C)	9.47	13.33	21.73	15.2	14.93
Tmax (°C)	12	18	24	22	24
Tmin (°C)	6	10	18	8	6
RIPOLL					
Tmean (°C)	9.55	14.11	22.11	15.55	15.33
Tmax (°C)	12	18	24	22	24
Tmin (°C)	6	10	18	8	6
BESÒS					
Tmean (°C)	11	15	22.67	17	16.41
Tmax (°C)	8	12	20	22	24
Tmin (°C)	12	18	24	12	8

During the 60's the main activity was the agriculture which occupied most of the available territory. Even though, this activity was substituted by industrial activities which occupy most of the agricultural soils, especially around rivers.

The industry in this area is very diversified with special emphasis to chemistry, metals, plastic, among others. In total, there are almost 10,000 potential pollutant establishments in the basin.

Headwaters are characterized by the presence of different Natural Protected Areas (NPA's) with high socio-ecological values, e.g. the Montseny Biosphere Reserve. The mid and lower courses of the Besòs rivers have suffered an evident transformation in the last decades provoked by increasing industrial activity and population growth.

Table 2. Main characteristic of the six sub-basins of the Besòs river basin. Source: Consorci Besòs Tordera.

▽

	Besòs sub-basins					
River/Stream	**Congost**	**Mogent**	**Tenes**	**Caldes**	**Ripoll**	**Besòs**
Source and municipality (altitude)	Font de Cant Regàs - Hostalets (920 m)	Pi Novell - Tagamanent (620 m)	La Collada Collsuspina (935 m)	Sant Sadurní - Gallifa (951 m)	Sot Galí - Sant Llorenç Savall (640 m)	Congost - Mogent - Montmeló (72 m)
Surface (km²)	210.04	180.68	154.46	111.57	243.3	138.26
Longitude of the main course (km)	43	31.4	28	22.6	39.2	17.7

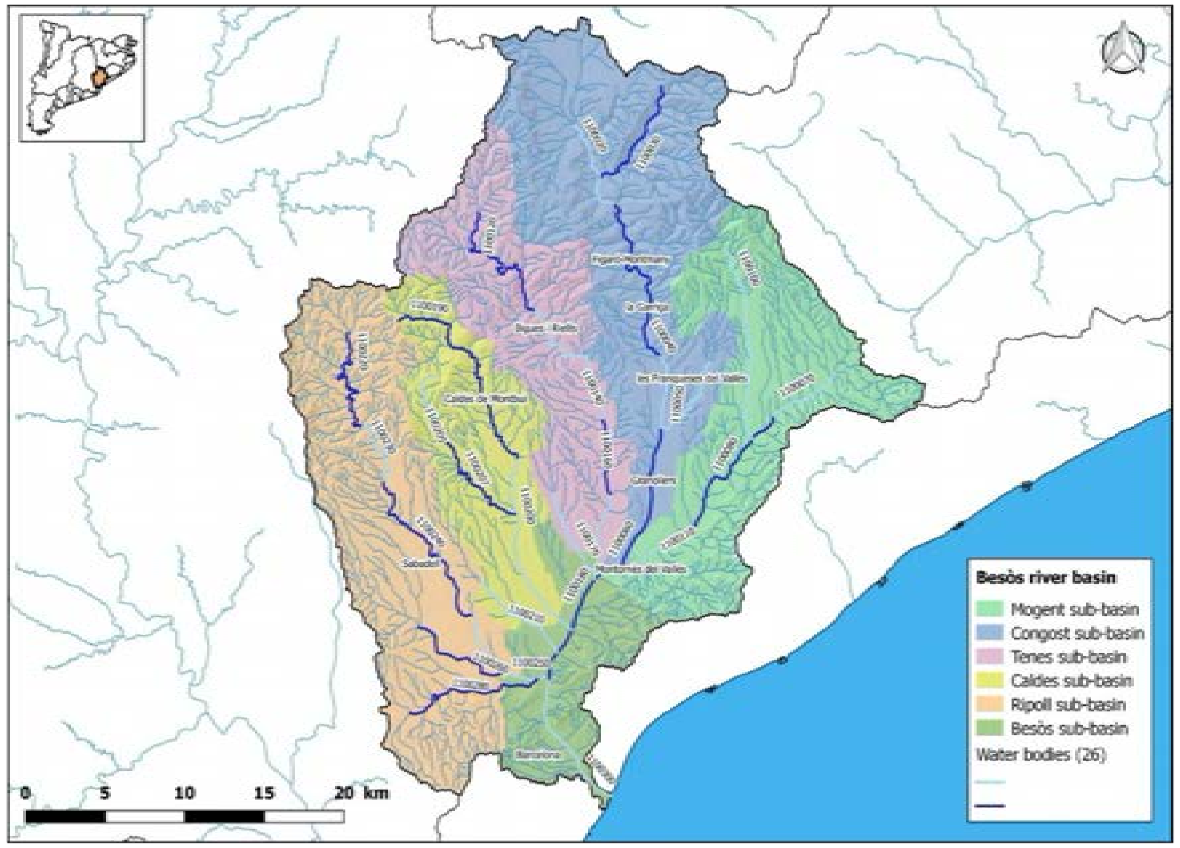

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Figure 2. Besòs river basin, subbasins and water bodies. Source: Agència Catalana de l'Aigua (ACA) and Consorci Besòs Tordera (CBT).

3.2. Tordera river basin

The Tordera basin, with a total surface of 898 km², is located between the provinces of Barcelona and Girona, in the counties of Vallès Oriental, La Selva, Maresme and a sector of Osona and an annual mean flow of 4.86 m³/s registered in the lower course (L'Observatori de la Tordera, 2018). The main course of the Tordera river, with 61 km of length, springs up in the massif of the Montseny between the Turó de l'Home (1,712 m) and Matagalls (1,696 m). The area that delimits the basin is formed by a set of different sub-basins, among which the Arbúcies stream stands out, with an area of 99.89 ha; and the Santa Coloma stream, which occupies a total area of 56 ha.

The Tordera river is considered a river clearly influenced by the rains, geological structure and its hydrology. The Mediterranean chracteristics of this area condition dry periods during summer and intense rains during spring and autumn, provoking flood episodes.

The mean temperature in the Tordera river basin is around the 13ºC. In the middle and lower courses of most of the areas the mean annual temperature could exceed the 15ºC. The mean precipitation in this basin is variable through the years for its Mediterranean conditions but it is around the 800 mm.

Table 3. Mean temperature (Tmean), minimum temperature (Tmin) and maximum temperature (Tmax) by the year 2016 and seasons through the Atles Climàtic Digital de Catalunya.

▽

	Winter	Spring	Summer	Autumn	Global
Tmean	7	11.9	20.9	14.7	13.6
Tmax	12	17.3	26.7	19.8	18.9
Tmin	2	6.5	15.2	9.6	8.3

At its headwaters, it drains the waters of the south-eastern slope of Montseny and Les Guilleries (Catalan Prelitoral mountain range) and of the northern slopes of the Montnegre massifs and the Selva Marítima (Catalan Coastal mountain range). The surface of the basin also occupies, in its middle course, part of the Catalan Prelitoral Depression and the Selva Depression. Tordera reaches the Mediterranean Sea between the municipalities of Blanes and Malgrat, forming a small arched delta of approximately 8 km² which was amplified due to big seasonal storm (Storm Gloria from 20th January to 23rd January).

Historically and nowadays, Tordera is considered as a driving force for socio-economic activity, as well as the different uses that take place there. The river becomes the main axe of the territory, from which the main population settlements and socio-economic activities are stablished. Currently, the population of the basin is 282,513 (2017) and is mainly concentrated in the Tordera plain (middle course) and especially in the coastal areas near the mouth.

The Tordera river basin includes protected natural areas in its geographical area. In the case of the upper course, the Montseny Natural Park and Biosphere Reserve favours the conservation of the environment and the preservation of the biodiversity associated with the river area. In its middle course, the Tordera crosses longitudinally the corridor located between the Montnegre and Montseny massifs, where important road and railway infrastructures converge, including the C-35, the AP7, the TGV and the Barcelona-Barcelona railway line. Already at its mouth, the agricultural activities of the delta and an important tourism area associated with the north coast of the Maresme and the south of La Selva converge.

Other transformations of the territory in the area of the alluvial plain, essentially motivated by the extraction of sediments, the increase of the industrial soil and infrastructures, have restricted the fluvial systems to a narrow and very artificial fringe. Although there are no dams or reservoirs in the main course, has led to the morphological modification of the channel, affecting both the development of river dynamics and the relationship between river and aquifer. The hydrological parameters of the Tordera basin are highly conditioned by the strong demand to which they are subjected.

Table 4. Main characteristic of the tributaries of the Tordera river basin. Source: Consorci Besòs Tordera.
▽

Tordera tributaries		
	Stream	**Length (km)**
Left side	Pertegàs	3
	Riera de Gualba	12
	Riera de Breda	8.6
	Riera d'Arbúcies	31.6
	Riera de Santa Coloma	30.2
Right side	Riera de Vallgorguina	6.7
	Riera d'Olzinelles	7
	Riera de Fuirosos	7

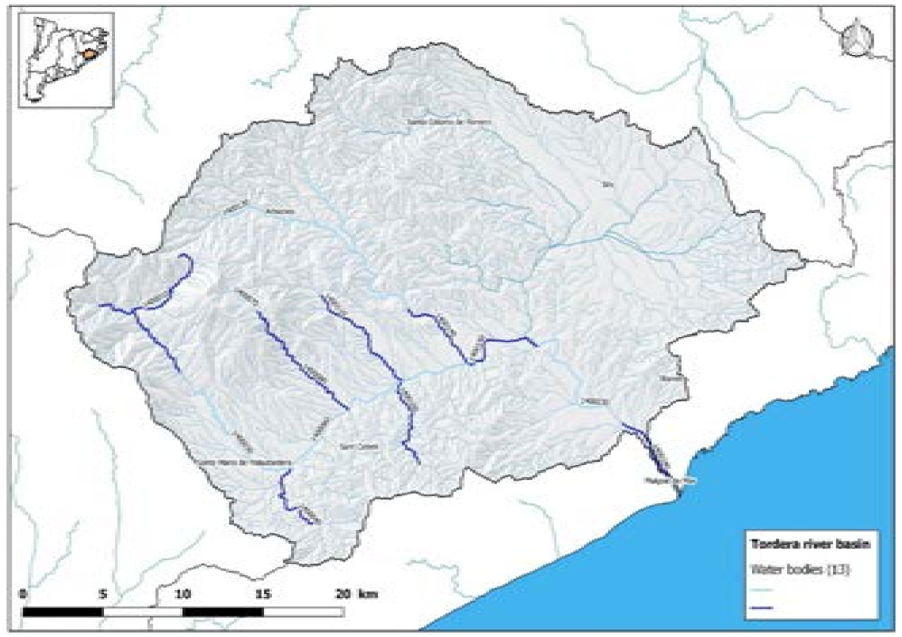

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Figure 3. Tordera river basin, subbasins and water bodies.

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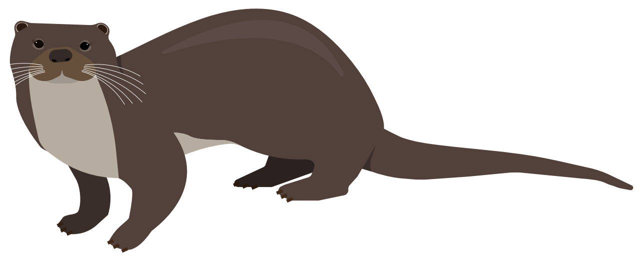
Research chapter 1

The evolution of the ecological quality status of the Besòs and Tordera river basins (1997 – 2017)

Part of this Research Chapter is published in Environtmental Processes journal as "Assessing the Effects of Wastewater Treatment Plant Eff uents on the Ecological Quality Status in a Mediterranean River Basin. Accepted 14 February 2021"



1. Introduction

During the 90's and as part of their International duties such as Agenda 21 and OECD reviews, many countries developed different strategies for the assessment of the ecological quality status of freshwater ecosystems. Most of the countries focused on direct chemical analysis of the fluvial systems, which are normally more accurate but do not reflect the current ecological status of the area. Consequently, this led to the enforcement of strict environmental laws and policies such as the Water Framework Directive (WFD, 2000/60/EC, 2000).

In the European context, the Water Framework Directive (2000/60/EC, WFD) was implemented in 2000 to promote monitoring programs to assess the ecological status of the European rivers. Its main goal was to achieve a good water quality status and to prevent pollution of fluvial resources. The imposition of sanctions, which depends on each national legislation, has also limited pollution discharges to fluvial systems, although the situation is still far from ideal and further enforcement of environmental laws is required (Faure, 1995; Gherardi, et al., 2009). Direct assessment of water quality in rivers and other sources can be carried out by monitoring their chemical (e.g., pH, presence of heavy metals, organic compounds or pesticides), physical (e.g., turbidity) and microbiological (e.g., presence of harmful bacteria) status. Indirect assessment, on the other hand, can be done by evaluating its biological and hydromorphological quality, which is reflected by the presence or absence of different groups of organisms that act as proxies for not only water quality but also habitat quality or hidromorphological conditions (Poff, et al., 1997). It is relevant to highlight the importance of both strategies in long-term monitoring programs, which are valid and complementary in the ecological assessment. These programs provide robust and long-time series data about the ecological status of the freshwater ecosystems, which becomes more relevant under a climate change context (Angeler, et al., 2014). Different examples of procedures for the prevention, control and treatment of water pollution to guarantee the good ecological quality status of fluvial systems can be found in previous studies (see e.g., Ene, et al., 2010; Gatica, et al., 2012; Griffiths, et al., 2017; Su, et al., 2017).

The main goal of this research chapter is to assess the evolution of the ecological quality and the applicability of the WFD, from a biological and hydromorphological point of view, in the fluvial systems of Besòs and Tordera river basins from 1997 to 2017. For that purpose, we will use the experience gained at the Observatori Rivus project (Sànchez-Mateo, et al., 2021), which has conducted long-term monitoring programs at the Tordera (since 1996) and Besòs (since 2018) basins to assess their ecological status. The analysis has been carried out at three spatial scales (Headwater, Middle and Lower courses), and employs two biological indicators (IBMWP, for macroinvertebrates, and IPS for diatom algae) and one hydromorphological indicator (QBR, for riparian forest) that are included in the WFD.

2. Methods

2.1. Data compilation

To analyse the evolution of the ecological quality status of Besòs and Tordera river basins, a compilation data of the indicators used for the assessment was performed. The data compilation was mainly focused on the research project of *Observatori Rivus*. This long-term monitoring program, which started in 1996, has as main goal the monitoring of biological, hydromorphological and physicochemical indicators to obtain long-time data series. Those datasets, in turn, allow the assessment of the ecological context of Tordera river basin and in 2000, considering the transposition of the WFD. In particular, the biological and hydromorphological indicators data of the Besòs river basin from 1997 to 2017 were collected in Carceller et al. (1999) and Sànchez-Mateo et al. (2017).

In addition, this project also assesses the biological communities of other taxonomic groups which are not included in the WFD but that bring information about the ecological status of the fluvial systems, such as amphibians, aquatic reptiles, birds and aquatic mammals (e.g. otter) (Table 5).

For this study, we only consider the water quality indicators of IBMWP, IPS and QBR.

The qualitative analysis is performed considering the three main river sections: Headwaters, Middle and Lower courses for Besòs and Tordera river basins.

Table 5. Research areas, indices, indicators and evaluated parameters of Observatori Rivus project.

Research area	Indices and evaluated parameters
Research areas included in the WFD	
Biological indicators	
Diatoms	• IPS index • Monitoring of the allochthonous species • Richness and relative abundance of each taxon, Distribution trends and seasonal difference
Macroinvertebrates	• IBMWP index • BMWPC index • Richness and relative abundance of each taxon, Distribution trends and seasonal difference
Hydromorporhological indicators	
Riparian vegetation	• Hydrochemistry • Assessment of the hydrological regime and the river-aquifer relation • Analysis of the rain and Flow data
Research areas not included in the WFD	
Amphibians and aquatic reptiles	• Richness and abundance of the species
Birds	• Richness and indicator value: checklists and classification of the species in categories for its habitat • Evolution of the species density for categories • Monitoring specific bioindicator species
Aquatic Mammals (Otter)	• Population size • Seasonal distribution • Ecological requirements • Diet analysis

The selection of the three quality indicators was chosen for the availability of long-time series data and for its relevance within the WFD.

Biological indicators

IBMWP

Macroinvertebrates communities occupy different micro-habitats along the river, in the benthic habitat of freshwater systems, and are considered as the most reliable biological indicators for the ecological water quality assessment (Rosenberg and Resh, 1993). Due to their wide range of tolerance to water pollution, the presence or absence of concrete macroinvertebrates at a site can act as a proxy of water quality and so, the alteration and pollution stress of a fluvial course which can be provoked by high physicochemical concentration levels (Mayo, et al., 2008). The Catalan Water Agency (ACA) determined that the IBMWP index (Alba-Tercedor, et al., 2002; ACA, 2006) in the Catalan river basins was the most relevant macroinvertebrate indicator. The IBMWP acquires different quality ranges due to the fluvial typology of the river stretch assessed. The IBMWP is a sum of the indicator values of the macroinvertebrate taxa sampled in the study site. Each taxon has an indicator value ranging from 1 (the lowest indicator value) to 10 (the highest indicator value) depending on the ecological requirements of all the species of the group. Generally, the IBMWP index can be classified into five categories, see Table 6 (Alba-Tercedor, et al., 2002; ACA, 2006; Munné, et al., 2009).

IPS

Diatoms are the most studied microalgae and are widely used as bioindicators. Due to its tolerance to pollution, they are useful as proxies for pointing out the pressures caused by eutrophication and for identifying increments in organic matter and salinity. Moreover, diatoms represent the 80% of the total species of fluvial algae community.

The Catalan Water Agency (ACA) has also recommended the use of the Pollution Sensitive Index (IPS - Cemagref, 1982; Descy and Coste, 1991) in Catalonia. The IPS is calculated considering the averages of sensitivity and tolerance to pollution and the relative abundance of each species, once the fieldwork has been performed and the different species have been identified in the laboratory.

The result is a qualitative value of the ecological status and it is determined by five categories (see Table 6).

Hydromorphological indicators

QBR

Riparian habitats are a key element for the river dynamics (Tabacchi et al., 1998). They hold a high percentage of the freshwater biodiversity, maintain the fluvial channel of temporary alterations and provide food and shelter for wildlife.

There are several methodologies that can be used to assess river habitat conditions (Turak et al., 1999) and to determine the health status of rivers (Meyer, 1997). However, very few have focused specifically on the characterization of rivers. In that sense, the Riparian Forest Quality index (QBR) was developed to assess the quality of riparian habitats and the degree of alteration of the riparian zone (Munné et al., 1998). The calculation of this index is carried out in the field using easily identifiable measures in relatively short stretches of river between 100 and 200 m: degree of coverage of the riverbank, structure of the vegetation, quality of the cover and naturalness of the river channel. The result is a value between 0 and 100, which we have further differentiated for practical purposes into 5 ordered categories (see Table 6).

Table 6. Quality ranges stablished by IBMWP, IPs and QBR indicators. Source: Manual BIORI and HIDRI de l'Agència Catalana de l'Aigua (ACA).

▽

Ecological quality ranges					
Indicator	High	Good	Moderate	Poor	Bad
IBMWP	>90	75-90	55-70	30-50	<25
IPS	>16	13-16	9-12	5-8	<5
QBR	>90	75-90	55-70	30-50	<25

2.2. Statistical analysis

To determine whether water quality had improved across the Besòs and Tordera river basins (i.e. headwaters, middle and lower courses), as measured by the IBMWP, QBR and IPS water quality indicators, we applied an ANCOVA model with the "lm" function of the "stats" R package.

We checked the temporal trends in the three selected quality status indicators (IBMWP, QBR and IPS) across the Besòs and Tordera river basins between 1997 and 2017. Those indices were expected to steadily improve from their low (i.e. poor) initial values at all locations. For the analysis in the Besòs river basin, we used the data of the 26 water bodies which composes the study area. In the case of Tordera river basin, we considered 13 water surface bodies which refers to the entire fluvial system of Tordera river, in this river basin was not considered Arbúcies and Santa Coloma subbasins for not having enough and robust long-term data.

The temporal behavior of each index separately will be modelled by assuming a linear trend, where time (in years) will be the quantitative predictor variable. It is not known a priori whether the data sets fulfill the main assumptions of a regression analysis, i.e. whether there is a) homogeneity of the slopes (i.e. the slopes of the trends are different for different river courses), b) normality of the residuals (i.e. the residuals of the fits follow a Gaussian distribution), c) homogeneity of the variances of the residuals (i.e. variances of residuals are not different between levels of factor), and d) homoscedasticity of the residuals (i.e. variance does not vary with expected value).

3. Results

3.1. Besòs river basin

Figure 4 shows the results of the ANCOVA that analyze the water quality evolution through three different water quality indexes such as IBMWP (macroinvertebrates), IPS (diatoms) and QBR (riparian vegetation) in the Besòs river basin from headwaters to lower courses and over the period 1997-2017. The regression model results indicate a general improvement of the ecological quality status of the three main river sections (headwaters, middle and lower courses) of the Besòs river basin during this period.

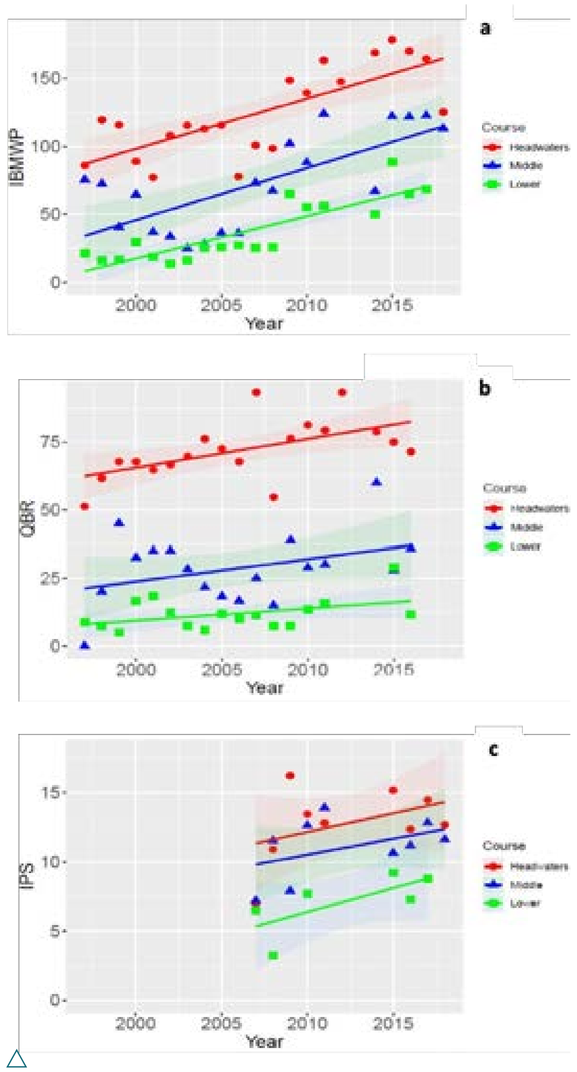


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Figure 4. Results of the ordinal regression (lines) with a cumulative link model and the observations (points) for IBMWP (a), QBR (b) and IPS indices (c), from 1997 to 2017 for the different river courses (Headwater in red; Middle course in blue; and Lower course in green) of the Besòs river basin. See Supplementary Material 1, page 115 for details. Source: Own elaboration in R v. 3.1.2 through the water quality data compiled.

The increasing trend shown in the three plots is always statistically significant (significance of slope coefficients p<0.05, see Supplementary material 1, page 115), demonstrating a general improvement in the water quality of the different river courses and indices.

In general terms, there is an increase of the qualitative values in Headwater, except in QBR which maintains a Moderate range. All the indices in the Middle courses improved their qualitative levels but only the IBMWP shows a correct quality status (Good and/or High). Finally, the indices of the Lower courses present incorrect quality status (Moderate, Poor and/or Bad) but there is a general improvement except for the QBR.

3.2. Tordera river basin

Unlike the Besòs river basin, the Tordera river basin do not show a clear improvement in water quality. In the specific case of IBMWP there is some visible improvement for each of the river sections, but results for the QBR and IPS indices both show a decrease in quality status in the middle course.

In general, the linear models for both study areas seem to satisfactorily explain the observed trend, although some wiggling around the model can be seen in some of the datasets. In addition, post-hoc tests (Supplementary material 1, page 115) show that there are significant differences between river courses, controlling for the time (in years) covariate.

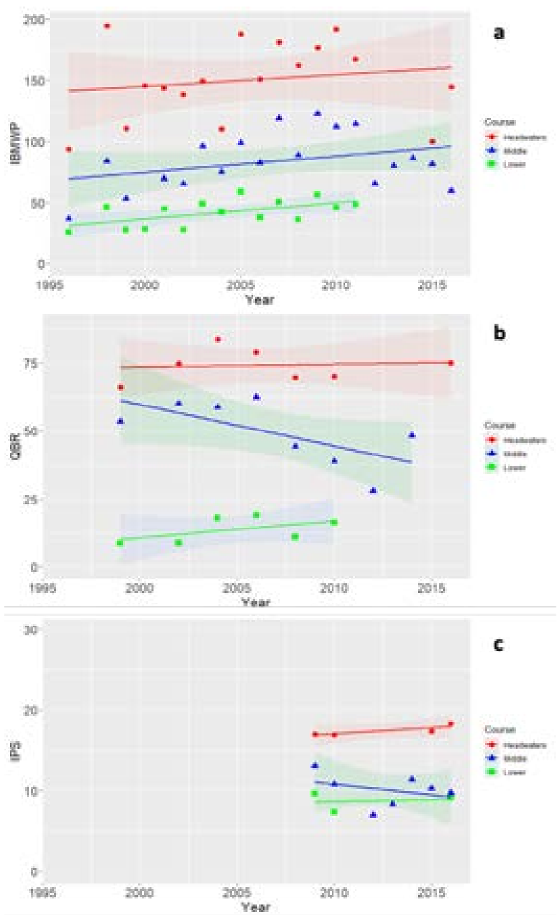

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Figure 5. Results of the ordinal regression (lines) with a cumulative link model and the observations (points) for IBMWP (a), QBR (b) and IPS indices (c), from 1997 to 2017 for the different river courses (Headwater in red; Middle course in blue; and Lower course in green) of the Tordera river basin. See Supplementary material 1, page 115 for details. Source: Own elaboration in R v. 3.1.2 through the water quality data compiled.

4. Discussion

Our research results distinctly show that the three main river courses of the Besòs river basin (headwaters, middle and lower course) underwent a considerable water quality improvement from 1997 to 2017. There is a spatial distribution of the ecosystem services provided by a river basin. Generally, in headwaters is generated the resource which lately will be used in the middle and lowers courses for industrial and/or agricultural activities. The improvement of water quality in headwater has consequences on the middle and lower courses (Brauman, et al., 2007).

Although indices differ in absolute value, temporal trends in IBMWP, QBR and IPS show a similar relative upward trend in time across all river courses (Figure 4 and 5).

The results in Tordera river basin are, however, somehow different. In general terms, there is a qualitative improvement of all the indices studies but not for all the rivers sections. Middle courses of Tordera river basin showed a decrease of QBR and IPS values (Figure 5). This could be explained for the alteration of the fluvial habitat. The middle course of the Tordera river presents some industrial and urban settlements which can modify the local habitat. A more extended and detailed justification of these factors is developed in the Research Chapter 2, where changes in Land Use and Land Cover are discussed for each river basin.

Generally, we conclude that the implementation of environmental laws is likely the main factor that could explain this general quality improvement (Faure, 1995). This is more relevant in a Mediterranean climate conditions area with flow variabilities, which is more emphasized in a climate change scenario. Both areas do not present any dams which implies that these rivers are not regulated, and its river flow depends directly on the meteorology, the water abstractions and the flow provided by the Wastewater Treatment Plants (WWTPs).

Our results also confirm the impact of implementing the WFD in 2000. Moreover, this assessment reinforced the need and the importance of implementing long-term monitoring programs. Through these programs it is possible to know how the quality status of the freshwater systems in the EU state members are, and on which river sections or water bodies management strategies need to focus. However, in some cases a reinforcement of these laws is required to finally reach a correct quality status in all EU state members.

To sum up, there is a general improvement of the ecological status of both river basins expressed in the three indicators analyzed but also, a considerable decrease if we consider the spatial scale where the quality status decreases from headwater to middle and lower courses.

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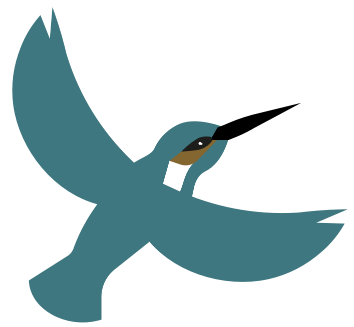
Research chapter 2

Assesing the anthropogenic effects on the ecological quality status

Part of this Research Chapter is published in Environtmental Processes journal as “Assessing the Effects of Wastewater Treatment Plant Eff uents on the Ecological Quality Status in a Mediterranean River Basin. Accepted 14 February 2021”



1. Introduction

The main objective of the present study is the assessment of two of the main anthropogenic drivers which alter the ecological quality status of the fluvial systems: i) the effects of the WWTPs and ii) the Land Use and Land Cover (LULC) changes.

1.1. The influence of WWTPs on fluvial system quality: the case of Besòs river basin

Wastewater, including domestic, industrial and storm water, must receive an adequate treatment before being discharged in order to reduce its impact on the fluvial ecosystem. During the 1970's, most of the cities in Catalonia did not have any urban wastewater treatment system. In addition, the increase of the industrial settlements in the territory with uncontrolled discharges provoked significant pollution episodes in most of the Catalan rivers. In this context, in 1995 the Catalan government approved the Catalan Treatment Plan (Generalitat de Catalunya, 1995) to accomplish the Council Directive 91/371 (European Commission, 1991) with the main purpose of reducing and eliminating the present pollutants in Catalan fluvial systems.

Later, in 2000, the European Commission and Parliament approved the WFD. The WFD defines a normative tool where all the member states of the European Union must specify their own public management plans to improve the water quality status of European rivers. In Catalonia, the Catalan Water Agency (ACA in its Catalan acronym) is the public administration responsible for the transposition and implementation of the WFD. Finally, during the years up to 2019, twenty-four years after the Treatment Plan of Catalonia was approved, water treatment systems in Catalonia experimented a considerable change, both in the WWTP number and in treatment processes. At present, 514 WWTPs are installed in the Catalan region to treat the wastewater generated by the population, including economic and industrial activities, which produce discharges similar to the urban waters. Therefore, the water discharges of approximately 97% of the population are currently processed by a nearby water treatment plant (ACA, 2017).

The Besòs river basin (North-East Iberian Peninsula, Figure 6) is a paradigmatic case study. During the 60's and 70's, the Besòs basin underwent great water demand in order to meet the needs of an increasing population of the Barcelona metropolitan region, which brought about a rise in anthropogenic activities such as intensive farming and livestock production, industrial development and tourism. During this period, the Besòs river basin suffered the continuous discharge of untreated residual water of industrial, domestic and farming origin, being the Besòs river basin considered as the most polluted in Europe (Gordi, 2005). After WWTPs started to be implemented, in accordance with the WFD, it was essential to promote long-term monitoring programs for assessing and measuring the ecological status of the Besòs fluvial system.

1.2. LULC and water quality

Land Use and Land Cover (LULC) changes are considered as one of the main Global Change effects. Land Cover is defined as the biophysical unit of the surface and, on the other hand, the concept of Land Use refers to the manipulation of the cover for taking some benefits (Meyer and Turner, 1997). This phenomenon has several consequences on geomorphology, soil properties, biodiversity, worldwide habitat loss and/or fragmentation, climatic trends (Pitman et al., 2004) and water quality and availability (Sala, et al., 2000; Chapin, et al., 2001; Miserendino, et al., 2011), at global, regional and local scales.

LULC changes have various impacts on the water quality of a watercourse, as they lead to both increases and declines in the concentration of water quality variables.

In general, most studies focus on large rivers in temperature areas, which causes a shortage in scientific literature for Mediterranean river basins. For that reason, there are few management strategies that focus directly on the prevention of Global Change effects in Mediterranean rivers for a long-term period.

Currently, the change in water quality provoked by anthropogenic activities is one of the main global concerns our society must face (Abbot, et al., 2019; Garg, et al., 2019). In that sense, it is estimated that in 2050 the world water demand will increase by 20-30% (UNESCO,2019) which will become a serious challenge in order to guarantee the needs of the society. Moreover, this factor also will have an interaction with the quality status of the fluvial systems provoking an alteration of their hydromorphological functions.

Moreover, LULC changes directly interact with climate through the changes in the energetic model and the alteration of the water balance (Kalnay and Cai, 2003).

Human population and activities growth are one of the main drivers which altered freshwater systems over the globe (Vörösmarty, et al., 2010). Globally, in the last 50 years, the pressures of human activities on river systems have been accelerated (Meybeck, 2003; Vörösmatry, et al., 2000).

These effects are highlighted in the Mediterranean basin, being historically one of the most impacted areas by human activities (Ludwig, et al., 2009), mainly agricultural and urban activities and uses (Osborne and Wiley, 1988; Sliva and Williams, 2001), which are more intensified by climate change effects (MedECC, 2019). Moreover, past and present pressures in the region made the Mediterranean basin, one of the most vulnerable regions to projected Global Change events.

Human population density and urban area have increased 13% during the 90's and 00's in most of the Mediterranean regions. The current proportion of the urban farm and pasture lands covering this area ranges from 15% to 69% (Cooper, et al., 2013).

One of the main effects of past and current land-use changes is the replacement of autochthonous vegetation by infrastructures such as roads and/or buildings as well as its substitution by allochthonous vegetation and the hydromorphological structure of this ecosystems are altered. Native vegetation, soils and cultivation of open monocultures are some of many examples of the fluvial systems disturbances. In addition, the projected land uses, and climate changes indicates that the Mediterranean ecosystems will be negatively affected by the deterioration of the environmental conditions (Kiesel, et al., 2019; Sala, et al., 2000). In South and East Mediterranean countries, the main environmental problems on the water quality are influenced by the lack and/or poor urban water treatment systems. On the other hand, in North Mediterranean countries, particularly ones included in the EU, invest efforts in wastewater treatment measures. Moreover, the disturbances such as urban and industrial development and deforestation are more highlighted than in North countries of the Mediterranean basin (Plan Bleu, 2019).

Many research studies investigating the relationship between LULC and stream water quality have concluded that a significant relationship exists between land use and water quality parameters at a catchment level (see e.g. Soy-Massoni, et al., 2014; Kibena et al., 2014). Other studies, on the other hand, have shown the existence of complex relationships, varying from one region in the world to another and which are dependent on the depth of analysis (Miserendino et al., 2011). It was highlighted the importance of temporal, spatial and scale variations, and noted that upstream river reaches are subject to fewer impacts, compared to those downstream. Fewer impacts in steeper areas, compared to flatter areas, have also been reported, and LULC impacts in large streams differ greatly from those in small streams.

1.3. Scope and goals

Firstly, this research aims to evaluate the interaction between the ammonia concentration [NH_4^+] (mg/l) and the conductivity (EC) (µS/cm) discharged by 13 selected WWTPs (Supplementary material 2, page 119) and the Iberian Biological Monitoring Working Party index (IBMWP) which measures the ecological quality status using families of macroinvertebrates as biological indicators (Alba-Tercedor et al., 2002; ACA, 2006; Munné, et al., 2009) from 2000 to 2018 in the Besòs river basin. This research proposes a novel method to assess the effects of WWTPs on Mediterranean river systems, considering that most of the studies published so far have not focused on biological quality indicators such as the IBMWP index. Two research questions are aimed to be answered:

- How are the temporal evolutions of [NH_4^+] (mg/l) and EC (µS/cm) discharges from the selected WWTPs and their future scenarios?
- What is the observed relationship between the IBMWP index and [NH_4^+] and EC in the Besòs fluvial systems?

Secondly, the interaction between LULC and ecological quality status in the Besòs and the Tordera river basins between 1997 and 2017 has been explored. This research highlights the importance of these land use changes and their possible effects on the freshwater quality status in these two case studies. Finally, the analysis is performed considering the temporal (1997, 2000 and 2009) and spatial scale (headwater, middle and lower courses).

In general, most of the research published so far, proving the linkages between LULC and freshwater quality status, has employed physicochemical indicators such as Nitrogen and Phosphorus compounds, which are the main pollutants derived by industrial and agricultural activities. For this study three typologies of water quality indicators were considered: 1) two biological indicators, such as IBMWP (macroinvertebrates) and IPS (diatoms algae); 2) one hydromorphological indicator, such as QBR (riparian forest); and 3) five physicochemical indicators (Conductivity, Ammonia, Nitrates, Nitrites and Phosphates), included in the Water Framework Directive (2000/60/EC) (European Commission, 2000).

In this sense, both river basins have been subject to a significant diversity of land uses and covers, and the industrial, farming and agricultural activities may represent the main sources of N-compounds and P-compounds discharges, which can alter the water quality.

The socioeconomic panorama specific for these areas, and in general for most of the Mediterranean mountain ranges, can be characterized by the energetic model change suffered during the 1960's an1970's decades, which led to a land abandonment process in rural areas (especially in headwaters) due to an industrialization process, which is mainly located nearby fluvial areas (Otero, et al., 2011). In that sense, during the 1990's decade, the urban area in the Mediterranean basin increased a 17% (Cooper, et al., 2013).

2. Methods

2.1. Wastewater treatment system at the Besòs river basin

Before the Treatment Plan of Catalonia was approved in 1995, only two WWTP were installed in the Besòs river basin: Besòs WWTP, located at the mouth of the Besòs river (1 in Supplementary material 2, page 119), and Bigues i Riells WWTP (16 in Supplementary material 2, page 119), located in the upper-middle course of the Tenes river. Currently, there are 26 WWTP distributed across the 6 sub-basins: 4 in Mogent, 7 in Congost, 4 in Tenes, 3 in Caldes, 4 in Ripoll and 4 in Besòs (Figure 6). Apart from increasing the number of plants, WWTP treatments were also improved to cope with the increase of demographical and industrial activities in the Besòs river basin, especially downstream. At present, the main wastewater treatments carried out in the river basin are physicochemical and biological (Supplementary material 2, page 119). In most cases, the biological treatment represents the last treatment stage before the discharge to the fluvial course; but in others, there is an additional stage for nutrient elimination of Phosphorus and/or Nitrogen compounds, which mainly derive from urban waters. The nutrient elimination treatment is the most efficient, but it is not yet available in all the WWTP that implement a biological treatment. The Bigues i Riells WWTP is the unique plant that is still implementing the physicochemical treatment system. The other 25 WWTPs have different biological treatment processes (Supplementary material 2, page 119). In addition, 6 WWTPs do not implement nutrient elimination; 2 of them include phosphorus elimination; another 2 incorporate nitrogen elimination and 15 combine nitrogen and phosphorus elimination. This means that the 96% of the WWTPs in Besòs river basin are functioning with biological treatment system, and 71% of these (that is, 0.96*0.71*100=68.2% of all WWTPs plants) have a nutrient elimination system (Supplementary material 2, page 119). As has been mentioned above, 13 WWTPs were chosen for analysis because they were the only WWTPs managed by the Consorci Besòs Tordera (CBT) that provided robust and long series data. In addition, these 13-selected WWTPs are representative of the different sub-basins of the study area (data provided by CBT, WWTPs management body).

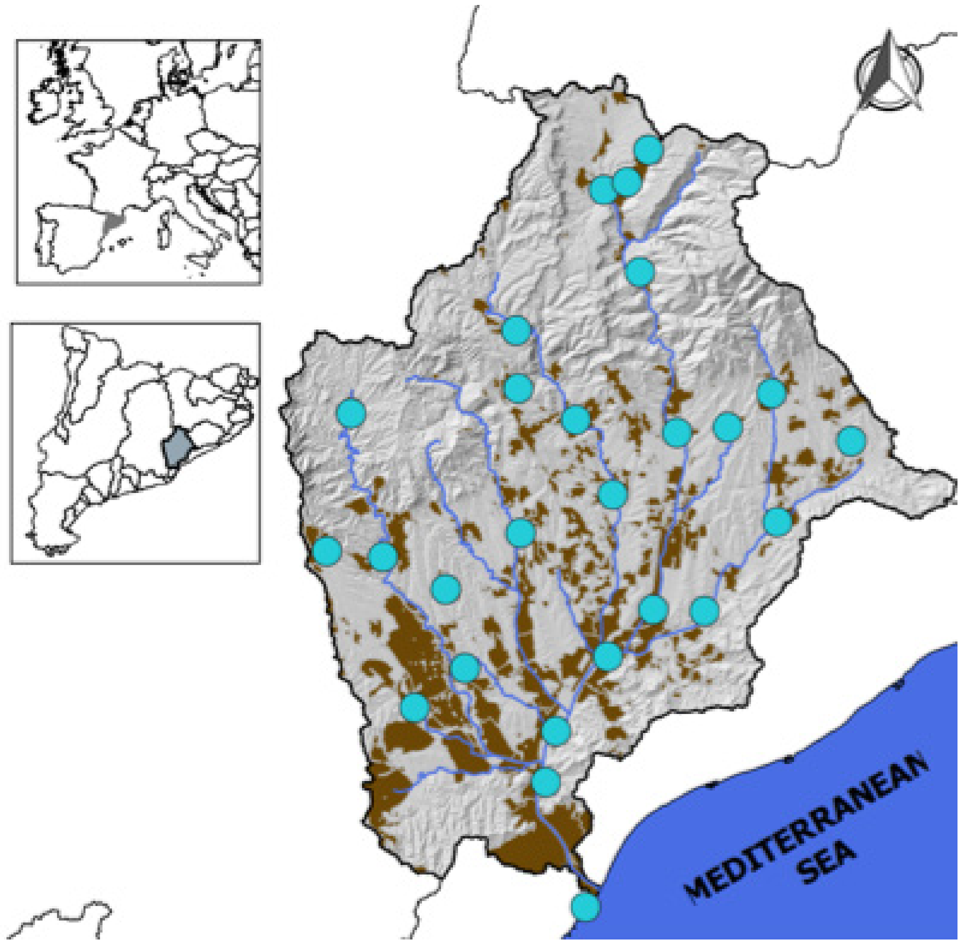


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Figure 6. The Besòs river basin and the location of the 26 WWTPs. See Supplementary material 2, page 119 for details of the Besòs river basin WWTPs. Source: Own elaboration in QGIS v.2.18.20 through the data obtained from the Catalan Water Agency (ACA).

2.2. Thematic literature review

Before setting out to respond to the main research objectives, a search of relevant scholarly literature has been performed through a thematic literature review method (Snyder, 2019). This method was selected to discuss about literature based on theorical concepts, in this case, to show the lack of research which assesses the effects of WWTPs relating biological indicators in Mediterranean river basins. All the searches were conducted through the Web of Science (WOS) database considering the keywords "macroinvertebrates", "IBMWP", "wastewater treatment", "WWTP", "Mediterranean", "south Europe" and "southern Europe".

2.3. Data compilation

2.3.1. Water quality

To assess the effects of the WWTPs on the water quality status of the Besòs river basin, the interaction between IBMWP index and WWTPs discharges of [NH_4^+] (mg/l), and EC (μS/cm) were considered. Generally, the concentration variability of these physicochemical parameters directly affects freshwater biodiversity, especially macroinvertebrates (Monda, et al., 1995).

Moreover, the water quality indicators data to correlate with the LULC changes follows the same method which is explained in Research Chapter 1.

2.3.2. Land Use and Land Cover analysis

The land use data were generated from the Land Cover Map of Catalonia (LCMC) for the years 1997, 2000 and 2009, as well as from interpreting aerial photographs for 2016. A LULC change analysis of the Besòs and Tordera river basins from 1997, 2000 and 2009 was performed to assess the main changes occurred in the study areas. The LULC map was elaborated considering a 100 m "buffers" (i.e., zones influenced by land use) were set measuring the monitoring site by 100 m at both sides of each water body as reference and the LCMC interpretation and categorization convers analysis (Ibáñez, et al., 2010) (See Supplementary material 3, page 120). Working with small-scale buffers demonstrate a more direct interrelation of the effects of land uses in different basins and produce useful information to apply in statistical models (Shani and Dudley, 2001). Miramon v. 8.1 and QGIS v. 2.18.20 software's were used for carrying out the photointerpretation based on the 1997 LULC map (Carceller, et al., 1999) and the satellite orthophotomaps of the Institut Cartogràfic i Geològic de Catalunya (ICGC).

In addition, for the photointerpretation, we considered the Level 2 of the legend of MCSC methodology, which was categorized to six LULC categories for being comparable to the 1993 LULC map: forested, shrubs and grasslands, forested bare soil, built-up, crops and continental waters (See Supplementary material 3, page 120).

2.4. Statistical analysis

2.4.1. The assessment of the effects of the WWTP on the ecological quality status

Different statistical analyses were performed using R v. 3.1.2. (R Development Core Team, 2014), depending on the question aimed to answer. All the statistical analyses are detailed explained in the Supplementary material 4, page 124: 1. To determine whether water quality had improved across the Besòs basin (i.e. headwaters, middle and lower courses), as measured by the IBMWP, QBR and IPS water quality indicators, we applied an ANCOVA model with the "lm" function of the "stats" R package. 2. To model the temporal evolution of [NH_4^+] and EC, as well as the relationship between IBMWP and [NH_4^+] or EC, we employed generalized linear ("glm" function of the "stats" R package) and non-linear ("gnm" function of the "gnm" R package) models.

2.4.2. Correlation between the Land Use and Land Cover (LULC) changes and the ecological quality status of the Besòs and Tordera river basins

Many statistical models could be used to perform the correlation between LULC changes and the ecological quality status of both study areas. In that sense, first different suitable models are analysed through the package MASS of R software to find out the model which can be more explicative. Five models were considered, the OLS (Ordinary Least Square), the Akaike OLS which considered the same model structure but with the step AIC, the Random Forest, other version of the Random Forest with a smaller error and Null Model which considered all the variables as a constant.

Later, it is analysed the importance of each water quality indicator considering the LULC category using the function "vip" and the method firm.

First, five different statistical models were applied to the LULC datasets, namely: Ordinary Least Squares (OLS) with the full set of predictor variables; OLS with Akaike predictor variable selection; Random Forest (RF, "randomForest" R package); RF with selection of best mtry parameters; and a Null Model (Null) with a constant value. Akaike model selection was carried out with the "MASS" R package (Venable et al., 2002). Then, variable importance was calculated for all models with the "vip" R package (Dongyu et al., 2011).

3. Results

3.1. Literature review of previous works

As a preliminary step in our study, we carried out a search of any previous article or report in the scientific literature that dealt with the assessment of the effects of the WWTPs in Mediterranean river basins. Our thematic search turned up 10 research papers (Supplementary material 5, page 138) whose study area included at least one Mediterranean river. Specifically, 7 articles dealt with WWTPs along rivers in Spain (of which 5 are in Catalonia) and 3 articles dealt with WWTPs along rivers in Portugal, Israel and United States, one per country. In that set of 10 articles only one paper focused explicitly on the interaction between the IBMWP index and WWTPs physicochemical discharges (Pinto, et al., 2010), although those authors used a statistical analysis different from what is performed here. Moreover, the other 9 articles focused only on how the anthropogenic activities (in some cases derived by WWTPs discharges) altered the macroinvertebrates habitat structure and communities, but without the use of the IBMWP index (Supplementary material 5, page 138).

3.2. Evolution of the WWTPs discharges (2000 – 2008)

For this study, the [NH_4^+] and EC values were obtained from the data available and provided by the CBT from the selected WWTPs (Supplementary material 2, page 119) from 2000 to 2018. The [NH_4^+] and EC values for discharged effluents have decreased through time, a fact that is mainly explained by the improvement of the treatment systems from physicochemical to biological with elimination of nutrients (N and P compounds). High N and P concentration levels derived from the WWTPs have significant consequences for the water quality status of the Besòs river basin so they are one of the main factors which alter the fluvial ecosystem and the biodiversity linked to it (Monda, et al., 1995).

Figure 7a shows results for ammonia. From 2000 to 2005, most of the WWTP discharged high levels of [NH_4^+] ranged between 30 mg/l to 48 mg/l, which means a reliable impact to the water quality status of the fluvial systems. During 2005 and 2008, concentrations started to suffer a considerable decrease because of the implementation of the denitrification plants, except for La Llagosta WWTP, which currently does not have a denitrification process and its [NH_4^+] discharge is still in the range of the 30 mg/l. In general, in 2018 the concentrations are relatively low, between 0.34 mg/l to 2 mg/l. Figure 7b, in turn, shows results for EC values. Like the case for ammonia, the drop in [NH_4^+] is also noticeable. From 1999 to 2005, there were high levels of EC, but water-water treatment made these concentrations decrease from 2005 to 2018 (Figure 7b).

Models accounting for an exponential decrease of [NH_4^+] and EC explain satisfactorily the observed trends. In those models we have included a basal level that is reached when time tends to infinite, which is apparent in Figure 7a and 7b and is statistically significant (Table 7).

The predictions performed through the application of a Generalized Nonlinear Model (GNM) for both [NH_4^+] and EC showed a 1.13 mg/l and 1,110 µS/cm estimation in future projections considering the discharges of the 13-selected WWTPs of the Besòs river basin (Table 7 and 8).

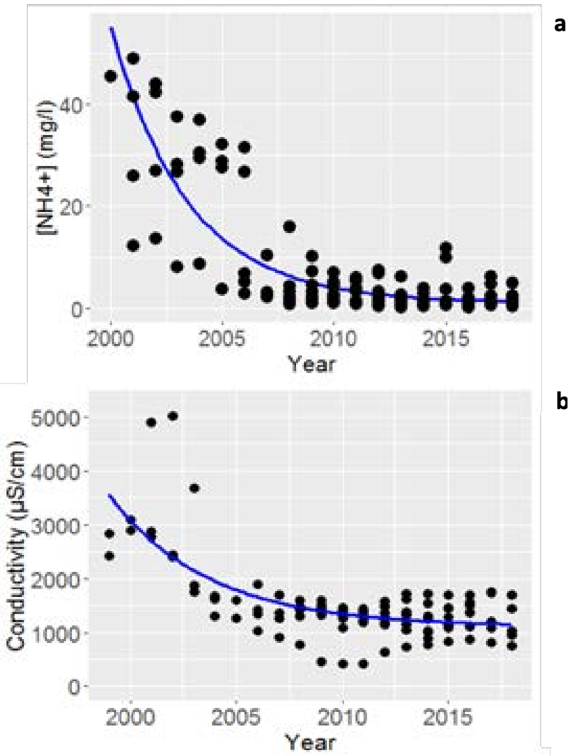

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Figure 7. 7a. Evolution of the [NH_4^+] (mg/l) and 7b. EC (µS/cm) discharged by the 13-selected WWTPs between 1997 to 2018. See Supplementary material 4, page 124 for details.

Table 7. Regression coefficients for the [NH_4^+] (mg/l) vs. Year model. See Supplementary material 4, page 124 for details. Source: Own elaboration in R v. 3.1.2 through the data provided by CBT.

▽

	Estimate	Std. Error	t value	Pr(>|t|)
a	1.1309	0.5012	2.2563	0.0256
b	53.9569	6.4957	8.3065	2.2x10^-16
c	0.2924	0.0332	8.8007	2.2x10^-16

Table 8. Regression coefficients for the EC (µS/cm) vs. Year model. See Supplementary material 4, page 124 for details. Source: Own elaboration in R v. 3.1.2 through the data provided by CBT.

▽

	Estimate	Std. Error	t value	Pr(>|t|)
A	1110.0283	107.9791	10.2800	2.2x10^-16
B	1977.9528	187.0510	10.5744	2.2x10^-16
C	0.2139	0.0462	4.6264	2.2x10^-16

3.3. Influence between WWTPs discharges and biological water quality status (IBMWP).

Our results show that there is a significant relationship between the IBMWP index and [NH_4^+] (Figure 8a), as well as between IBMWP and conductivity (Figure 8b; see also Table 9 and 10). In general, lower values of [NH_4^+] and EC imply higher IBMWP values. In that sense, the model shows that when there are discharges of ammonium concentrations between 0 and 1 mg/l, which correspond to a correct water quality status, the IBMWP values ranges from 100 to 250 showing a correct water quality status (European Commission, 2000; Alba- Tercedor, et al., 2002). On the other hand, the model also indicates that when the ammonium concentrations increase (a situation which would correspond, in our context, to a lack of water treatment), IBMWP values tend to zero (Figure 8a). In relation to the interaction between IBMWP index and conductivity, when conductivity is between 500 µS/cm and 2,000 µS/cm, the IBMWP index also presents a good water quality status. In addition, when the conductivity increases to elevate concentrations the IBMWP index values tend to zero (Figure 8b).

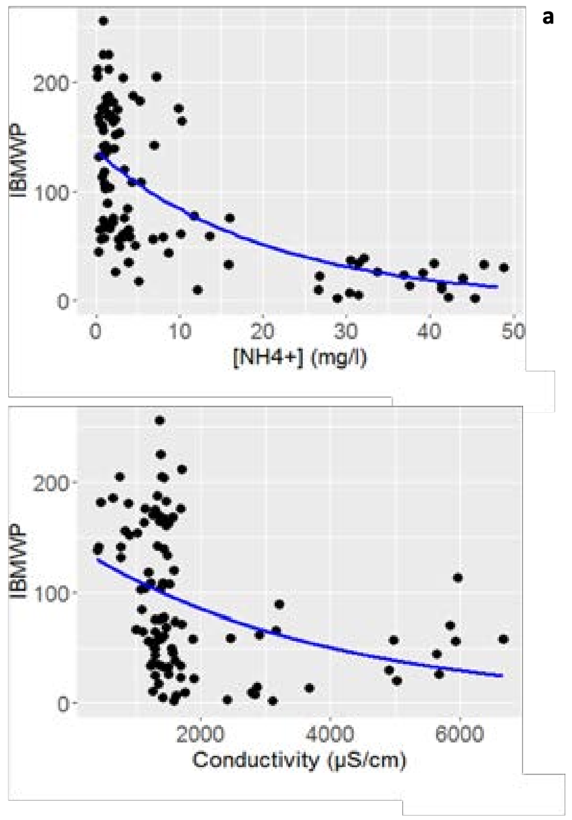

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Figure 8. 8a. GLM results for the interaction between [NH_4^+] (mg/l) and 8b. EC (µS/cm) and the IBMWP indices. See Supplementary material 4, page 124 for details. Source: Own elaboration in R v. 3.1.2 through the data provided by CBT and obtained in Sànchez-Mateo, et al., 2017 and Fortuño, et al., 2018.

Table 9. Regression coefficients for the IBMWP vs. [NH_4^+] (mg/l) model. See Supplementary material 4, page 124 for details. Source: Own elaboration in R v. 3.1.2 through the data provided by CBT and obtained in Sànchez-Mateo, et al., 2017 and Fortuño, et al., 2018.

▽

	Estimate	Std. Error	t value	Pr(>|t|)
b	137.2653	9.0642	15.1437	0
c	0.0493	0.0038	12.9154	0

Table 10. Regression coefficients for the IBMWP vs. EC (µS/cm) model. See Supplementary material 4, page 124 for details. Source: Own elaboration in R v.3.1.2. through the data provided by CBT and obtained in Sànchez-Mateo, et al., 2017) and Fortuño, et al., 2018.

▽

	Estimate	Std. Error	t value	Pr(>|t|)
b	144.1966	18.6196	7.7443	0
c	0.0003	0.0001	3.6538	4e-04

3.4. LULC change analysis of the Besòs and Tordera basins

The LULC analysis performed has consided three different spatial scales: river basin, fluvial courses and water bodies. The fluvial courses and water bodies analysis was performed considering the LULC of Besòs and Tordera maps of 1997, 2000, 2009 and 2016 from a 100 meters buffer of each of the water body.

Besòs

In 1997, the most predominant cover in the Besòs basin was that of forested area (47.69% or total area), followed by crops (26.36%) and urban (16.34%). With a lower percentage were grassland and shrub (8.09%), bare forest soil (1.45%) and continental waters (0.08%) covers.

The analysis of land cover for the year 2000 shows a similar trend as in 1997, being the category of forested area that maintains the highest percentage with 45.83%, despite suffering a small decline. On the other hand, there was a considerable increase in urban area (19.29%) and grassland and shrubs (12.45%) and, to a lesser extent, continental waters (0.26%). Finally, crops (21.25%) and bare forest soil (0.82) decreased compared to 1997.

The land cover map in 2009 continues to illustrate the dominance of forested area in the Besòs basin (46.48%) with a slight increase compared to 2000. On the other hand, the second land cover with highest percentage is urban area (23.12%) to the detriment of crops (18.48%). With regard to the grassland and shrubs, it has suffered a decrease in its surface (10.81%), however, the bare forest soil and continental waters have remained in the same trend with respect to the year 2000, with a 0.83 % and 0.27% respectively.

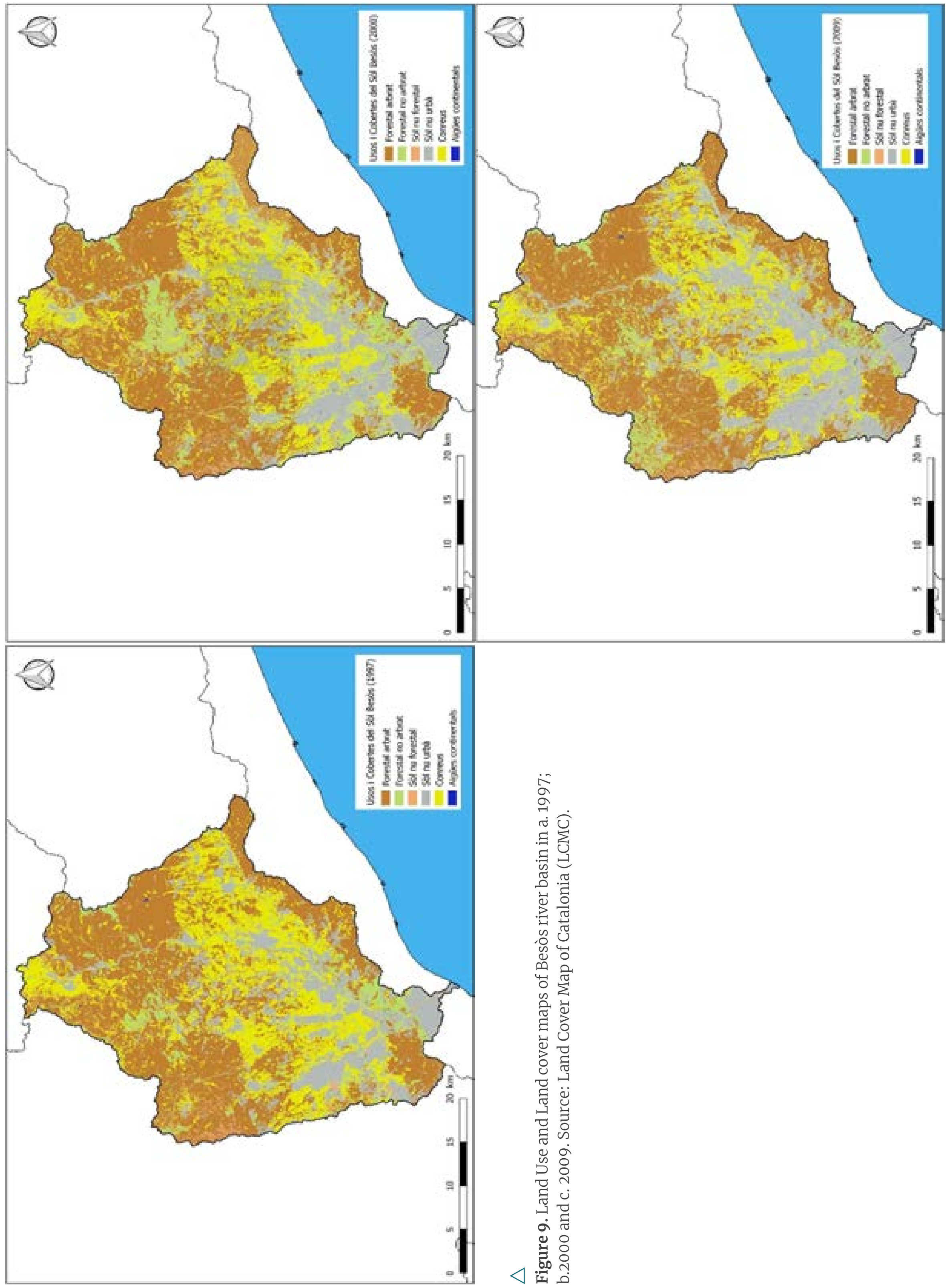
The analysis of land cover changes between 2009 and 1997 shows very similar percentages between the periods studied with respect to the forested area. There was a considerable increase of 6.78% in the area of urban and 2.72% in grassland and shrubs.

By contrast, there was a decrease in the percentage of crops of 7.88%, 0.62% of forest bare soil and 0.19% of continental waters

Tabla 11. The Land Use and Land Cover results in 1997, 2000 and 2009 and the differences for Besòs river basin.

▽

	Forested		G&S		Bare soil		Urban		Crops		Continental waters	
	Ha	%	ha	%	ha	%	ha	%	ha	%	ha	%
1997	48,822.39	47.69	8,282.10	8.09	1,484.43	1.45	16,727.99	16.34	26,985.91	26.36	71.66	0.08
2000	46,918.23	45.83	12,837.76	12.54	839.47	0.82	19,748.04	19.29	21,754.58	21.25	266.17	0.26
2009	47,583.66	46.48	11,066.68	10.81	849.71	0.83	23,668.98	23.12	18,918.80	18.48	276.41	0.27
2009-1997	-1,238.73	-1.21	2,784.58	2.72	-634.72	-0.62	6,940.99	6.78	-8,067.11	-7.88	204,75	0.19



◁ **Figure 9.** Land Use and Land cover maps of Besòs river basin in a. 1997; b.2000 and c. 2009. Source: Land Cover Map of Catalonia (LCMC).

Tordera

In 1997, the most predominant cover in the Tordera basin was that of forested area with 74.92%, followed by crops (16.07%) and urban (4.64%). With a lower percentage are the categories of grassland and shrubs (3.55%), bare forest soil (0.77%) and continental waters (0.04%).

The analysis of land cover for the year 2000 continues to show the predominance of forested area, despite its decrease of 67.92%. On the other hand, there has been a considerable increase in urban area (6.96%) and grassland and shrubs (9.69%) and, to a lesser extent, continental waters (0.15%), compared to the 1997 analysis. On the other hand, crops (15.05%) and the bare forest soil (0.24%) have been the covers that have suffered a certain decrease, although not very noticeable.

Finally, the analysis of 2009 shows a recovery of the still predominant cover of the forested area (71.96%). On the other hand, the urban area follows the upward trend (8.81%), in the same way, although not in a less pronounced way, the continental waters (0.32%). Crops, grassland and shrubs and bare forest soils are the three areas that have suffered a decrease in their percentage compared to 2000 with a final percentage cover of 10.76%, 7.94% and 0.21%, respectively.

The analysis of land cover changes between 2009 and 1997 shows a slight decrease in the most predominant cover in the basin, the forested area, with a decrease of 2.96%. It should be noted that the surface area of urban area has increased by 4.17% compared to 1997, the grassland and shrubs and the continental waters have also increased by 4.39% and 0.28%, respectively. On the other hand, there was a decrease in the percentage of crops of 5.31% and 0.56% of bare forest soil.

Tabla 12. The Land Use and Land Cover results in 1997, 2000 and 2009 and the differences for Tordera river basin.

	Forested		G&S		Bare soil		Urban		Crops		Continental waters	
	Ha	%	ha	%	ha	%	ha	%	ha	%	ha	%
1997	64782.65	74.92	3069.65	3.55	665.81	0.77	4012.17	4.64	13895.59	16.07	43.23	0.05
2000	58686.58	67.92	8361.56	9.69	242.11	0.24	6035.54	6.96	13013.60	15.05	129.70	0.15
2009	62223.17	71.96	6865.65	7.94	181.59	0.21	7617.93	8.81	9304.08	10.76	276.70	0.32
2009-1997	-2559.48	-2.96	3799	4.39	-484.22	-0.56	3605.76	4.17	-4591.51	-5.31	233.47	0.28

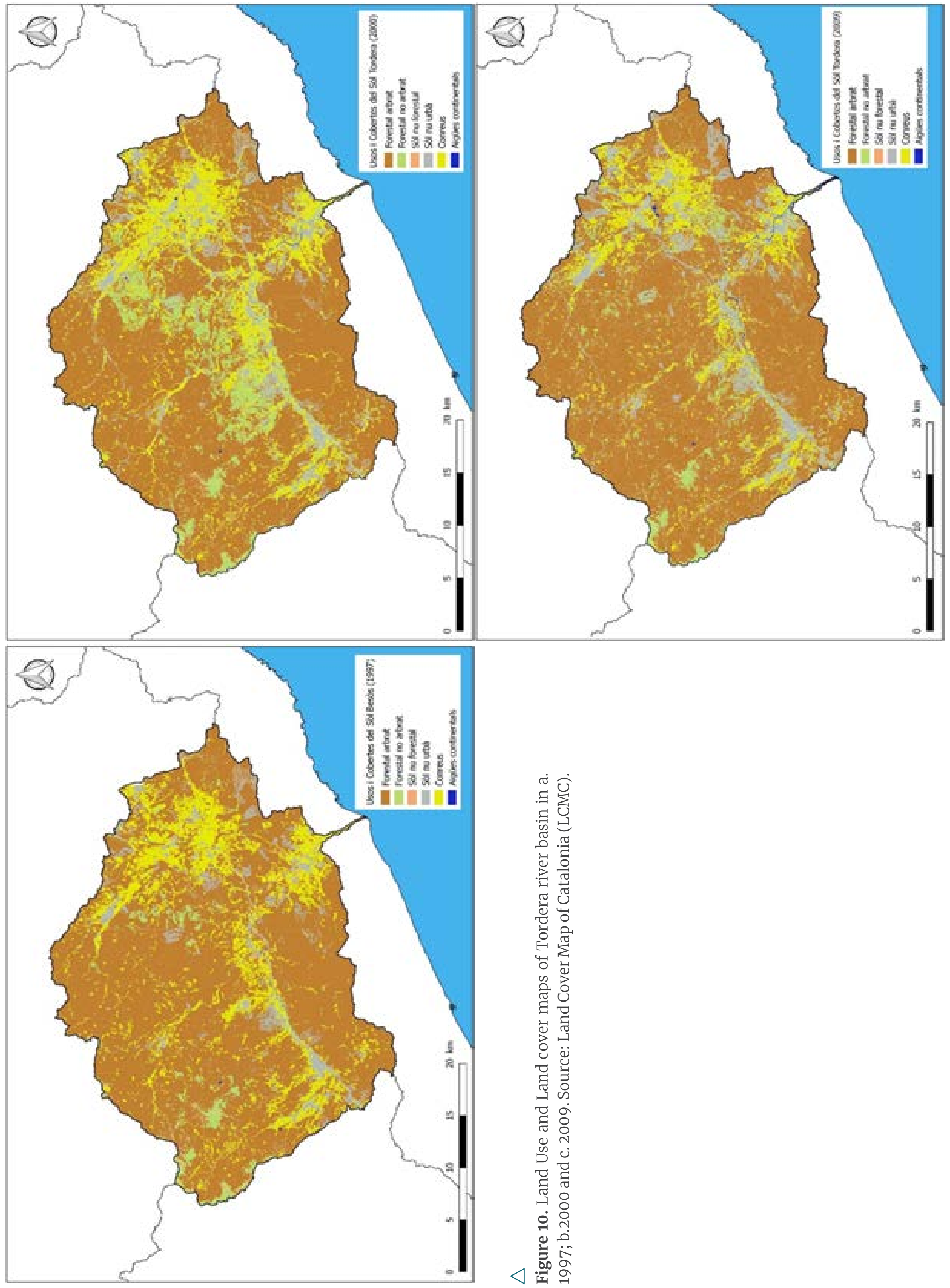


Figure 10. Land Use and Land cover maps of Tordera river basin in a. 1997; b.2000 and c. 2009. Source: Land Cover Map of Catalonia (LCMC).

3.5. Variable importance of LULC on ecologic quality indicators

The analysis to find out which land cover has most importance on the ecological quality status was taken considering the LULC analysis of the 100 meters of buffer of the water bodies of both study areas.

Firstly, we applied two different statistical models to study the relationship between LULC changes and water quality indices: Ordinary Least Square and Random Forest. For all the water quality indicators and for each case study, we analyzed the performance of both statistical models and selected Random forest as the most accurate model to perform this analysis.

Secondly, the model to explore the importance of each land cover on water quality indicators was applied through the different periods' studies. The (+) and (-) symbols refer to the trend which followed the water quality indicator with the increase of land cover percentage (see Supplementary material 6, page 139 for detailed results).

Besòs river basin

As it is seen in Table 13, in 1997 and in 2000, the most influential cover was the urban area. On the other hand, in 2009 and 2016, the influence of the urban area decreases, and forested area has the higher cover importance on the ecological quality status with a positive relation.

In 2009 and 2016, Forested area is the cover with higher importance for the IPS and followed by Grassland and Shrubs and Urban area but with a negative correlation.

Several LULC categories influenced the QBR, but it is mainly influenced by areas with vegetation (forested and grassland and shrubs).

The physicochemical indicators (ammonia, conductivity, nitrates and nitrites) also present different influences from LULC variables but in general terms the relation led to a positive trend to urban areas. On the other way round, there are negative trends to natural areas such as Forested and Grasslands and shrubs areas. However, it is to highlight that in 2016 the main influenced LULC category for ammonia and conductivity is grassland and shrubs areas with a positive trend in 2016, this could be explained by the increase of American cane (Arundo donax) in the lower course of the river basin.

Table 13. Results of the variable importance of LULC categories on water quality indicators in Besòs river basin during 1997, 2000, 2009 and 2016. The (+) and (-) refers to the trend.

▽

Besòs river basin					
Indicator	**LULC category**	**1997**	**2000**	**2009**	**2016**
IBMWP	Forested	(+) 81.94	(+) 54.19	(+) 100	(+) 100
	Grassland and shrubs	(-) 63.12	(-) 28.50	(-) 59.91	(-) 96.81
	Bare forested soil	(+) 61.34	(+) 28.32	(+) 15.17	(-) 14.21
	Urban	(-) 100	(-) 100	(-) 69.21	(-) 70.5
	Crops	(+) 39.49	(+) 74.05	(+) 13.21	(-) 20.23
IPS	Forested	NA	NA	(+) 100	(+) 100
	Grassland and shrubs	NA	NA	(-) 48.92	(-) 72.57
	Bare forested soil	NA	NA	(-) 30.48	(-) 16.04
	Urban	NA	NA	(-) 63.13	(-) 60.61
	Crops	NA	NA	(-) 25.91	(-) 25.01
QBR	Forested	(-) 75.56	(-) 100	(-) 100	(-) 37.72
	Grassland and shrubs	(+) 100	(+) 66.05	(+) 71.57	(+) 100
	Bare forested soil	(-) 40.07	(+) 22.07	(+) 31.84	(+) 17.54
	Urban	(+) 93.21	(+) 92.81	(+) 87.05	(+) 15.11
	Crops	(-) 48.21	(-) 10.20	(-) 79.84	(-) 46.38
Ammonia	Forested	(-) 75.56	(-) 100	(-) 100	(-) 37.72
	Grassland and shrubs	(+) 100	(+) 66.05	(+) 71.57	(+) 100
	Bare forested soil	(-) 40.07	(+) 22.07	(+) 31.84	(+) 17.54
	Urban	(+) 93.21	(+) 92.81	(+) 87.05	(+) 15.11
	Crops	(-) 48.21	(-) 10.20	(-) 79.84	(-) 46.38
Conductivity	Forested	NA	(-) 74.80	(-) 100	(-) 63.65
	Grassland and shrubs	NA	(+) 60.27	(-) 87.12	(+) 100
	Bare forested soil	NA	(+) 31.45	(+) 42.23	(+) 69.42
	Urban	NA	(+) 100	(+) 70.84	(-) 27.67
	Crops	NA	(-) 45.64	(-) 22.77	(+) 65.20
Nitrites	Forested	(-) 67.67	(-) 69.09	(-) 100	(-) 83.69
	Grassland and shrubs	(+) 37.78	(+) 46.18	(+) 68.19	(+) 100
	Bare forested soil	(-) 40.55	(+) 25.61	(+) 37.34	(+) 22.34
	Urban	(+) 100	(+) 100	(+) 70.19	(+) 53.94
	Crops	(+) 45.42	(-) 29.62	(-) 56.53	(-) 29.41
Nitrates	Forested	(-) 48.56	(+) 100	(-) 67.55	(-) 56.28
	Grassland and shrubs	(+) 35.53	(-) 71.32	(+) 29.23	(+) 14.88
	Bare forested soil	(+) 100	(-) 38.41	(+) 24.48	(+) 15.17
	Urban	(+) 50.67	(-) 35.57	(+) 100	(+) 57.92
	Crops	(+) 46.69	(+) 30.98	(+) 35.40	(+) 100
QBR	Forested	(+) 100	(+) 89.01	(+) 100	(+) 100
	Grassland and shrubs	(-) 23.90	(-) 64.13	(-) 95.74	(-) 40.56
	Bare forested soil	(-) 54.50	(+) 55.64	(+) 67.56	(+) 32.61
	Urban	(-) 63.08	(-) 36.26	(-) 51.17	(-) 65.48
	Crops	(-) 52.40	(-) 100	(+) 10.55	(-) 24.37
Ammonia	Forested	(-) 100	(-) 78.97	(+) 58.87	(+) 100
	Grassland and shrubs	(-) 31.06	(+) 82.77	(-) 95.98	(-) 70.92
	Bare forested soil	(-) 71.13	(+) 100	(-) 47.24	(+) 47.27
	Urban	(+) 100	(+) 40.49	(-) 87.48	(-) 46.92
	Crops	(+) 52.57	(-) 46.76	(+) 100	(-) 60.58
Conductivity	Forested	(-) 100	(-) 100	(-) 100	(-) 100
	Grassland and shrubs	(+) 50.75	(+) 33.68	(+) 63.20	(+) 40.56
	Bare forested soil	(+) 53.22	(+) 34.22	(-) 42.49	(-) 32.61
	Urban	(+) 56.46	(+) 63.88	(+) 62.49	(+) 65.48
	Crops	(+) 70.23	(+) 52.47	(+) 28.82	(+) 24.37
Nitrites	Forested	(-) 89.59	(-) 100	(-) 29.69	(-) 75.89
	Grassland and shrubs	(+) 100	(-) 61.09	(-) 41.07	(+) 20.82
	Bare forested soil	(+) 62.84	(+) 39.41	(-) 28.08	(+) 27.16
	Urban	(+) 92.84	(+) 41.38	(+) 100	(+) 100
	Crops	(-) 9.36	(+) 79.68	(+) 28.12	(+) 31.86
Nitrates	Forested	(-) 100	(+) 17.27	(-) 56.12	(-) 100
	Grassland and shrubs	(+) 51.70	(-) 100	(+) 9.97	(+) 48.47
	Bare forested soil	(-) 70.91	(-) 38.26	(-) 33.06	(+) 20.44
	Urban	(+) 79.58	(-) 49.13	(+) 100	(+) 85.04
	Crops	(+) 47.77	(+) 57.73	(+) 29.28	(+) 34.98

Tordera river basin

In this case, as it is seen in table 14, Forested areas become the most explicative cover to the alteration of the ecological quality status with a positive trend for the biological indicators (IBMWP and IPS) in most of studied periods. But in 2016 for the IBMWP, Crops spring up as the most influenced cover for this indicator but with a negative trend.

The QBR is completely dependent on forested covers with a positive relation except in 2000, so Crops become the most influenced cover with negative trend.

Nitrates and nitrites are very dependent on Urban areas and with a positive trend but in some periods the forested areas appear as the most relevant cover but with negative trend. The ammonia presents different influences on LULC variables and it is difficult to stablish a clear influenced cover for this specific case. On the other way round, we found the conductivity that for all the periods presents a strong negative relation to forested covers.

Table 14. Results of the variable importance of LULC categories on water quality indicators in Tordera river basin during 1997, 2000, 2009 and 2016. The (+) and (-) refers to the trend.
▽

Tordera river basin					
Indicator	**LULC category**	**1997**	**2000**	**2009**	**2016**
IBMWP	Forested	(+) 100	(+) 100	(+) 100	(+) 71.16
	Grassland and shrubs	(-) 39.57	(-) 27.39	(-) 87.08	(-) 39.57
	Bare forested soil	(+) 43.65	(+) 69.92	(+) 77.77	(-) 23.40
	Urban	(-) 63.99	(-) 35.92	(-) 51.48	(-) 62.80
	Crops	(-) 60.57	(-) 84.98	(+) 29.47	(-) 100
IPS	Forested	NA	NA	(+) 100	(+) 100
	Grassland and shrubs	NA	NA	(-) 87.68	(-) 87.32
	Bare forested soil	NA	NA	(+) 28.17	(+) 24.44
	Urban	NA	NA	(-) 39.89	(-) 31.15
	Crops	NA	NA	(+) 12.91	(-) 40.15
QBR	Forested	(+) 100	(+) 89.01	(+) 100	(+) 100
	Grassland and shrubs	(-) 23.90	(-) 64.13	(-) 95.74	(-) 40.56
	Bare forested soil	(-) 54.50	(+) 55.64	(+) 67.56	(+) 32.61
	Urban	(-) 63.08	(-) 36.26	(-) 51.17	(-) 65.48
	Crops	(-) 52.40	(-) 100	(+) 10.55	(-) 24.37
Ammonia	Forested	(-) 100	(-) 78.97	(+) 58.87	(+) 100
	Grassland and shrubs	(-) 31.06	(+) 82.77	(-) 95.98	(-) 70.92
	Bare forested soil	(-) 71.13	(+) 100	(-) 47.24	(+) 47.27
	Urban	(+) 100	(+) 40.49	(-) 87.48	(-) 46.92
	Crops	(+) 52.57	(-) 46.76	(+) 100	(-) 60.58
Conductivity	Forested	(-) 100	(-) 100	(-) 100	(-) 100
	Grassland and shrubs	(+) 50.75	(+) 33.68	(+) 63.20	(+) 40.56
	Bare forested soil	(+) 53.22	(+) 34.22	(-) 42.49	(-) 32.61
	Urban	(+) 56.46	(+) 63.88	(+) 62.49	(+) 65.48
	Crops	(+) 70.23	(+) 52.47	(+) 28.82	(+) 24.37
Nitrites	Forested	(-) 89.59	(-) 100	(-) 29.69	(-) 75.89
	Grassland and shrubs	(+) 100	(-) 61.09	(-) 41.07	(+) 20.82
	Bare forested soil	(+) 62.84	(+) 39.41	(-) 28.08	(+) 27.16
	Urban	(+) 92.84	(+) 41.38	(+) 100	(+) 100
	Crops	(-) 9.36	(+) 79.68	(+) 28.12	(+) 31.86
Nitrates	Forested	(-) 48.56	(+) 100	(-) 67.55	(-) 56.28
	Grassland and shrubs	(+) 35.53	(-) 71.32	(+) 29.23	(+) 14.88
	Bare forested soil	(+) 100	(-) 38.41	(+) 24.48	(+) 15.17
	Urban	(+) 50.67	(-) 35.57	(+) 100	(+) 57.92
	Crops	(+) 46.69	(+) 30.98	(+) 35.40	(+) 100
QBR	Forested	(+) 100	(+) 89.01	(+) 100	(+) 100
	Grassland and shrubs	(-) 23.90	(-) 64.13	(-) 95.74	(-) 40.56
	Bare forested soil	(-) 54.50	(+) 55.64	(+) 67.56	(+) 32.61
	Urban	(-) 63.08	(-) 36.26	(-) 51.17	(-) 65.48
	Crops	(-) 52.40	(-) 100	(+) 10.55	(-) 24.37
Ammonia	Forested	(-) 100	(-) 78.97	(+) 58.87	(+) 100
	Grassland and shrubs	(-) 31.06	(+) 82.77	(-) 95.98	(-) 70.92
	Bare forested soil	(-) 71.13	(+) 100	(-) 47.24	(+) 47.27
	Urban	(+) 100	(+) 40.49	(-) 87.48	(-) 46.92
	Crops	(+) 52.57	(-) 46.76	(+) 100	(-) 60.58
Conductivity	Forested	(-) 100	(-) 100	(-) 100	(-) 100
	Grassland and shrubs	(+) 50.75	(+) 33.68	(+) 63.20	(+) 40.56
	Bare forested soil	(+) 53.22	(+) 34.22	(-) 42.49	(-) 32.61
	Urban	(+) 56.46	(+) 63.88	(+) 62.49	(+) 65.48
	Crops	(+) 70.23	(+) 52.47	(+) 28.82	(+) 24.37
Nitrites	Forested	(-) 89.59	(-) 100	(-) 29.69	(-) 75.89
	Grassland and shrubs	(+) 100	(-) 61.09	(-) 41.07	(+) 20.82
	Bare forested soil	(+) 62.84	(+) 39.41	(-) 28.08	(+) 27.16
	Urban	(+) 92.84	(+) 41.38	(+) 100	(+) 100
	Crops	(-) 9.36	(+) 79.68	(+) 28.12	(+) 31.86
Nitrates	Forested	(-) 100	(+) 17.27	(-) 56.12	(-) 100
	Grassland and shrubs	(+) 51.70	(-) 100	(+) 9.97	(+) 48.47
	Bare forested soil	(-) 70.91	(-) 38.26	(-) 33.06	(+) 20.44
	Urban	(+) 79.58	(-) 49.13	(+) 100	(+) 85.04
	Crops	(+) 47.77	(+) 57.73	(+) 29.28	(+) 34.98

4. Discussion

4.1. The relevance on the implementation of WWTPs on the Besòs river basin

The installation of the treatment systems plays an important role on the water quality status of the Mediterranean river basins. In the specific case of Catalonia, the implementation of the Catalan Treatment Plan during the 90's led to important investments for building WWTPs. Furthermore, the amount of water that flows in the Besòs river basin is mostly dependent to the WWTPs discharges. In fact, 70% of the water that flows in the Besòs rivers comes from WWTPs discharges and the other 30% comes from natural sources (Consorci Besòs Tordera, 2019). For these reasons, it is urgent that we implement minimum ecological flows to tackle the reduced dilution capacity of Mediterranean freshwater ecosystems, an action that would reduce the risk of transforming from permanent to temporal rivers, thus helping to keep or improve the ecological status of river basins. The annual river flow in some Mediterranean fluvial systems is altered due to human population growth and the pressure on water availability derived (Benejam, et al., 2010).

Generally, the discharges derived by industrial and agricultural activities are one of the main pollution sources that modify the ecological quality status of the fluvial systems (Voza et al., 2015). The inappropriate and excessive use of inorganic and organic fertilizers are considered as one of the main pollution sources. In fact, surface waters and groundwater are most affected by intensive livestock farming and intensive agriculture (Food and Agriculture Organization (FAO) of the United Nations, 2017). In Catalonia, 64.2% of groundwater, 6.7% of rivers and 2.9% of coastal waters are affected by industrial discharges. Agricultural activities affected the 69.8% of groundwater, 57% of rivers, 44.1% of coastal waters, 25% of wetlands and 13.3% of reservoirs (ACA, 2008). For instance, the Besòs river basin receives some of the most important industrial pollution discharges of Catalonia, a fact that is demonstrated by the presence of metals, organic compounds and organochlorides in its fluvial systems (ACA, 2008).

High concentration levels of wastewater contaminants such as ammonia (NH_4^+) and chlorines (EC) have significant consequences as to the ecological quality status, which are mostly apparent when a threshold is exceeded (Momba, et al., 2006; Osode, et al., 2009). The statistical analysis conducted in this research highlights the importance of investing in N and P compounds elimination treatment processes for all the WWTPs of the study areas. In fact, some of the WWTPs that did not have N- compounds elimination treatment system (2 and 2b in Supplementary material 2, page 119), discharged high amounts of [NH_4^+] to the fluvial system (main outliers of Figure 5 in Supplementary material 4, page 124) which could be the main factor behind the lack of improvement of the general quality status of the river basin (WFD, 2000). In that sense, future projections for all the WWTPs discharges of ammonia and chlorines considered in this study were performed to show whether these physicochemical parameters would be under a correct water quality status threshold (between 0.1 and 0.4 mg/l for [NH_4^+] and < 100 µS/cm of EC; Fortuño et al., 2018). In both cases, the [NH_4^+] and EC will present levels (1.13 mg/l and 1,110 µS/cm, respectively: Tables 7 and 8) higher than the values of a correct water quality status. Therefore, these future scenarios show that there is still a need for promoting new investments in treatment systems to reach acceptable levels in water quality.

4.2. How this assessment could be profitable for the river basin management?

The approach proposed in the present work to study the impact of WWTPs on water quality could be used as an integrative procedure that could be added as a tool to the 3rd round of the River Basin Management Plan (RBMP) for the 2022-2027, considering the importance of the climate change in Mediterranean river basins. The WMP is a legislative tool for integrating a set of proposals, which is being currently prepared by the Catalan Water Agency (ACA), in accordance with the principles of the WFD. It is aimed at storing and rationalizing the use of water, as well as ensuring the good condition of the aquatic systems. In that sense, to respond the Directive 91/271/EC for the treatment of urban wastewater, and to achieve the environmental goals of the WFD (2000/60/EC), some investments are done to improve the treatment systems to guarantee a greater environmental and health security.

The results shown in the present study corroborate the positive influence of the WWTPs on the Besòs river basin. Statistically significant positive trends could be seen in the three IBMWP, QBR and IPS indices. As we have mentioned above, the results for the IBMWP index are most relevant from an ecological point of view because that index is considered one the most suitable biological indicators for quality status assessment (Alba-Tercedor, et al., 2002). Despite this, future assessments could incorporate other biological and hydromorphological quality indicators established in WFD, such as IPS, IBICAT2010 index and QBR index, if the data availability is robust enough and continuous over the studied period, for a better ecological assessment of the river ecosystem (Pinto, et al., 2010). In addition, similar statistical techniques could be applied to other Mediterranean fluvial systems.

4.3. The LULC changes on Besòs and Tordera river basins

Generally, the LULC analysis performed showed down the difference between both case studies, from the point of view of their land uses and covers but in general terms both areas followed the same trend. In 2009, the main land cover of the Besòs river basin is the Forested area (46.48%) like in the case of Tordera river basin but with a higher percentage (71.96%). This factor may indicate that the impact of anthropogenic modification is lower in Tordera river basin than Besòs river basin.

Otherwise, what is most relevant to compare is whether all the land covers categories analysed, in both cases, followed similar trends. In all the cases, there is a considerable decrease in Crops and Forested covers and slightly one in Bare Soil and, also a remarkable increase in Grassland and Shrubs and Urban covers and, with less impact, the Continental waters.

The difference between both analyses could be explained from a sociodemographic point of view. Besòs river basin holds more than 2 million of inhabitants, which englobes a third part of Barcelona. In addition, the middle and lower courses of this area comprise a great number of industrial and urban settlements. On the other hand, Tordera river basin also holds the same pattern than Besòs with the middle and lower courses mainly occupied by anthropogenic activities but the main difference is that population in this area is approximately 300,000 people and the anthropogenic influence is less pronounced.

4.4. Impact of LULC on ecological quality status

The statistical model proposed used a 100-metre buffer of the water bodies which encompasses both study areas (26 in Besòs and 13 in Tordera). The selection of a 100-metre buffer was taken for being a remarkable influence area to explore the LULC changes but, other studies reflected that this could be replicated by larger influence areas such as 300m, 500 m and/or 1 km. For this first exploration, we focused on focus the 100-metre buffer as it is the most related influence area.

Moreover, the analysis allows to know which land cover has more influence on the different water quality indicator. Generally, it is seen that in both river basins, the forested area is the most relevant cover and has a positive influence on the biological indicators in 2009 and 2016. The hydromorphological indicator (QBR) also shows the influence of the Forested area in most of the periods but, it is to highlight that in 1997 and in 2009 in Besòs, the cover which best explained the QBR results is the urban area and with a negative correlation. This reinforces the hypothesis of the anthropogenic interaction with the river. The interaction to the physicochemical indicators is more variable but, in general terms, the influence of the urban and forested areas are well correlated with positive and negative trends, respectively.

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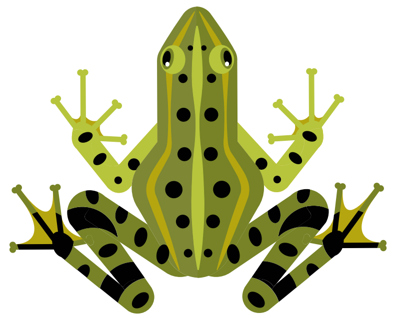
Research chapter 3

Exploring the connections between public perceptions and quality status in mediterranean river basins



1. Introduction

Society and ecosystems are intrinsically linked. Humans have shaped and formed their landscape to directly influence biological processes for centuries. Therefore, anthropogenic influence must be accounted for in environmental management practice (Albuquerque et al., 2019). There have been many studies in recent decades on public perception of natural environments regarding aesthetic beauty, human well-being and restorative properties (Mosley, 1989; Tieskens et al., 2018; Hermida et al., 2019; Liu et al., 2020). Since the knowledge obtained through perception is practical, this can therefore serve to inform us about our environment and what it affords us (Ingold, 2000). As the field of using public perception in environmental management emerges, authors have been defining it in more quantitative terms. For example, Bennett (2016) outlines four categories of insights that local perception can contribute to conservation policy and practice: (1) social impacts of conservation, (2) ecological outcomes of conservation, (3) legitimacy of conservation governance and (4) acceptability of conservation management. Bennett does not argue for the exclusive use of perception in policy making, but proposes its role in a better-informed, more holistic management approach involving public perception. Public perception can also be a useful source of information for policy makers regarding climate adaption and mitigation (Anthony et al., 2018). In this vain, if the public's perception of a component or organism of their local environment is negative or even hostile, it is possible to explore the motivation behind this perception and correct it, if necessary, through increased education or management strategy (Kellert, 1993). Spaces which are perceived negatively can be associated with danger or risk. An example of this is seen in literature regarding riparian landscape in the Mediterranean, where people perceive a connection between lack of management with fires or floods (Garcia, Benages-Albert and Vall-Casas, 2018; Ruiz-Villanueva et al., 2018). Similarly, positive perception of local environment can elicit a sense of connection to the landscape, evoking a positive feedback loop of better management and even better connection (Raatikainen and Barron, 2017). However, there is also evidence that the negative perception of landscapes which are associated with anti-social behaviour, for example illegal dumping, can act as a catalyst to mobilise community to clean and restore the environment for the common good (Benages-Albert et al., 2015). Public perception entails an understanding of the local environment based on traditional ecological and heritage knowledge that can promote intuitive stewardship (Lindholm and Ekblom, 2019).

In sum, two main aspects explain the importance of involving public perception for a better-informed river management: 1) public perception may provide valuable knowledge of river landscapes, and 2) public perception may support stewardship. Both aspects are of particular interest in urban rivers where impacts on river quality are complex and the contribution of local communities in their identification and mitigation potentially relevant. This study focuses on the first aspect (the link between public perception and river landscape assessment) while considering its implications on the second one. We analyzed 12 articles focused on the relationship between social perceptions and rivers ecological quality status. Special attention was paid on the variables of public perception and the methods thorough which public perceptions were elicited.

2. Methodology

2.1. Case Study

Caldes Stream is a tributary stream that flows to the right of the Besòs. It is 22.6 km long, its basin surface is 111 km², and has average flow rate of 0.25 m³/s. The stream flows through four municipalities; Caldes de Montbui, Palau-solità i Plegamans, Santa Perpètua de Mogoda and la Llagosta whose population totals about 60,000 inhabitants (Figure 11). The headwaters of the Caldes Stream are dominated by mountainous, forested land. Further downstream, this changes to encompass shrubs and grassland and urban landscape, more typical of an urban river (Garcia et al., 2017; Garcia, Benages-Albert and Vall-Casas, 2018).

Although it was traditionally an agricultural area, from the 1960's to the 1980's, the area surrounding the Caldes Stream basin suffered the effects of rampant urbanisation and industrialisation, characterised by pollution and degradation (Garcia et al., 2017). The movement of economically prioritising industrialisation over agriculture combined with ensuing pollution led to the subsequent abandonment of river banks and further degradation of areas (Rius, 2018). The stream became heavily polluted with sewer water and industrial run-off and this, coupled with out-of-control vegetation on the degraded river banks (Moya-Angeler, 2019). Since the 1980's there have been significant efforts over improving the ecological quality status of the river, take flood prevention measures and revitalising the area as a social focal point. The implementation of the Catalan wastewater treatment plan (Generalitat de Catalunya, 1991) which, was stablish to guarantee the correct treatment of this waters for all the Catalan territory, can also be credited with improving the water quality of the basin over all, as there has been a demonstrable increase in quality since the mid-nineties (Sànchez-Mateo et al., 2018).

Moreover, in the twentieth century, Mediterranean river basins experienced a shift in population density towards urban centres. This was largely motivated by primary sector crisis, industrialisation, economic necessity and an energetic societal shift (Badia et al., 2019; Cervera et al., 2019; Sànchez-Mateo et al.,2018). This was particularly relevant in Catalonia (North-East Spain) where led to rural abandonment to the Metropolitan Area of Barcelona (MBA) and subsequently changes in land use and land cover which has a considerable influence on water quality. This factor is considered as one of the main Global Change impacts (Meyfroidt, 2013; Risal et al., 2020). This means that population density shifted from rural areas where headwaters are located, to urban areas around the mid and lower river courses, focusing an increasingly industrialising stress on these areas. The headwaters forests which were traditionally managed to harvest firewood and produce charcoal in rural areas, were left unmanaged due to this rural abandonment. This resulted in afforestation processes which created implications for water discharge due to increased vegetative evapotranspiration (Otero et al., 2011; Vila Subirós, et al., 2016). These factors, coupled with increased on water demands (domestic, agricultural and industrial consumption) further downstream, have directly contributed to lower flows and prolonged dry periods in Mediterranean rivers.

These areas are further stressed by climate change in the form of increased temperatures and increased precipitation outside of summer months and historic and modern activity which serves to restrict, pollute and extract river flow (MedECC, 2019). Mediterranean river-basins are characterised by high variability and seasonal flow (Navarro Ortega, Sabater and Barceló, 2014). This variability is represented in the dichotomy of droughts and floods, with streams periodically expanding and contracting hydrologically. Summer brings long dry periods with Autumn and Spring often bringing floods (Gaudes, Artigas and Muñoz, 2010). Climate change is projected to add further stress to Mediterranean river basins.

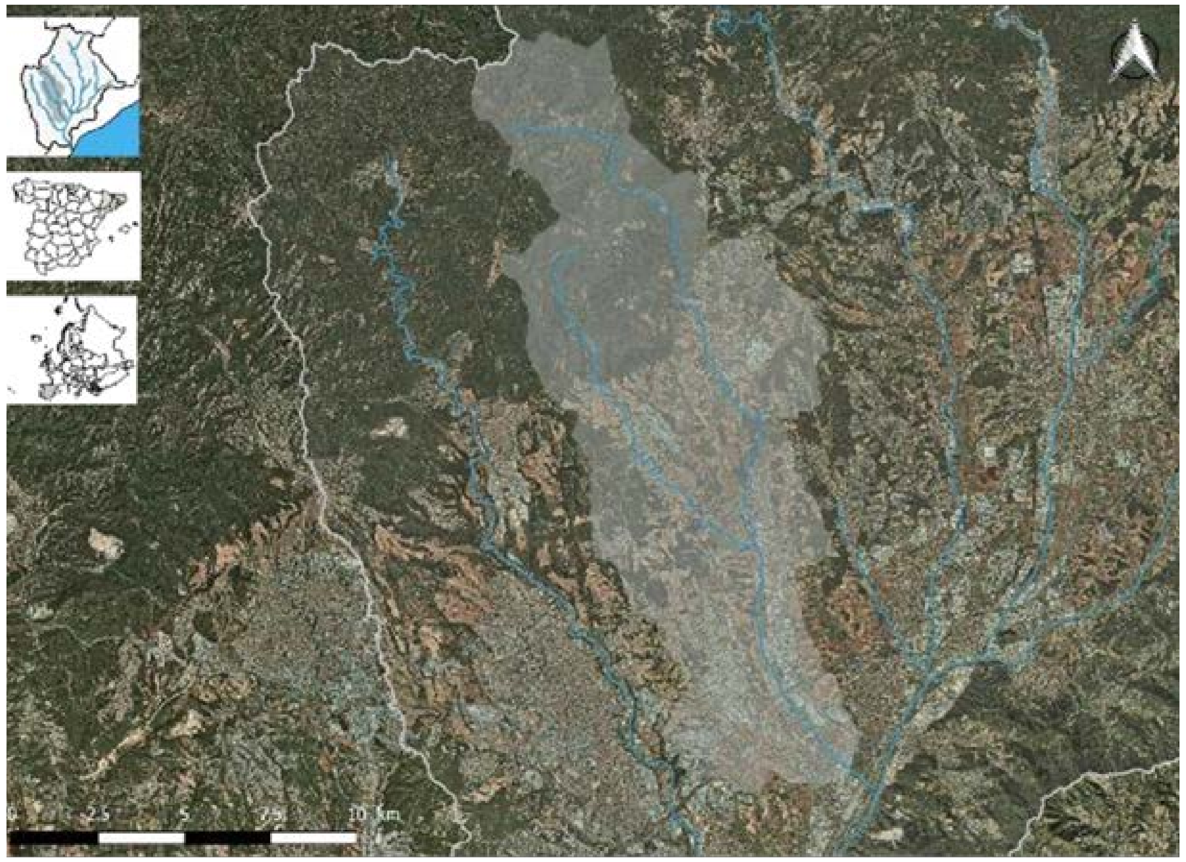


Figure 11. Caldes river basin location in the Besòs river basin. Source: Own elaboration in QGIS v.2.18.20 through the data obtained from the Catalan Water Agency (ACA).

2.2. Data compilation

Using two sources of compiled data, this study will attempt to explore the connections and relationships between quality status and public perception of the sub-basin of the Caldes Stream. The public perceptions gathered by The Viu La Riera! project provide a sociological perspective by registering public perception of positive and negative elements of the Caldes Stream (Vall-Casas, et al., 2021). The ecological quality status data provided by the Observatori Rivus project gives insight on the actual quality status of the river based on the biological and hydromorphological indicators of macroinvertebrates (IBMWP), riparian vegetation (QBR) and diatoms (IPS). These two projects have independent goals but for this research, its data was analysed from an integrative vision as a first step for building an holistic methodological framework. In this specific case, the data was focused on the two water bodies which composes the subbasin. Water bodies are the units stablished by the Catalan Water Agency (the Catalan abbreviation is ACA) to accomplish the WFD goals in the Catalan fluvial systems.

2.2.1. Ecological quality status

The quality status data used in this study are provided by the Observatori Rivus, an interdisciplinary project coordinated at the Institute of Environmental Science and Technology of the Autonomous University of Barcelona and Fundació Rivus (assigned to Besòs Tordera Consortium). The main function of the project is to ascertain the ecological status indicators of the Besòs and Tordera river basins and use these indicators to carry out medium- and long-term monitoring. The project focuses on biological, hydrological and physiochemical status and five main objectives. The project uses three main parameters; biological indicators (diatoms, macroinvertebrates, fish, birds, riparian vegetation, amphibians and mammals (specifically, the study of otter), hydrological indicators (river continuity, morphological conditions, groundwater supply, hydrological regime, and drought or flood risk) and physiochemical indicators (temperature conditions, salinity, oxygenation conditions, nutrient conditions and acidification status) (Boada et al., 2018). These parameters provide a comprehensive overview that permits researchers to assess the overall ecological status of the basin. Where data is available, indicators are divided into five categories indicating quality status: high, good, moderate, poor and bad.

Three main indices were used from the Observatori data: the QBR index as a hydromorphological status indicator, and the IBMWP and IPS as biological status indices. The analysis of the evolution of the biological quality status was performed considering the water bodies as study units, defined by the Catalan Water Agency (ACA) to assess the ecological quality status of the different river basins in Catalonia and to accomplish with the goals stablished in the WFD (ACA, 2006). The study case is composed by two water bodies: a) headwater to the Caldes de Montbui WWTP and b) from the Caldes de Montbui WWTP to the Besòs river.

2.2.2 Public Perception

The Viu La Riera! (Experience the River) project is the result of the collaboration of The Universitat Internacional de Catalunya (UIC) and the Institute of The Environment at the University of Girona. The project aimed to support public participation in the improvement of rivers and streams. With this purpose, Viu La Riera! designed a bottom-up participatory framework and deployed it by means of conducting some on-site and on-line activities though three main participatory phases (Vall-Casas, et al., 2021). One such on-line activities was using a web-based Public Participation Geographic Information System GIS (PPGIS) tool called "We comment!" (Garcia et al., 2020). PPGIS refers to the use of Geographic Information System (GIS) methods and technologies to engage the public in spatial decision-making (Sieber 2006). We comment! web-based PPGIS enables users to identify, and obtain spatially explicit information about places they are familiar with along the river basin and comment about what characteristics they like (positive aspects), dislike (negative aspects). Previous to the implementation of the We comment! web-based PPGIS, 53 semi-structured in-person interviews with stakeholders of the Caldes Stream were conducted, to conduct a qualitative-based PPGIS process, which was subsequently used as a model for the design of We comment!. Concretely, these interviews were based on a set of open-ended questions which invited participants to identify, sketch and describe places with positive and negative aspects of river landscapes, and then to describe the reason for identifying this place. Based on a set of predefined categories, and the qualitative content analysis of these information, this positive and negative perceptions were classified and mapped (Figure 12).

This study is based on the public perception of the responses logged by users of this web-based PPGIS tool, and those provided by the participants in the qualitative-based PPGIS study. For more details about the We comment! web-based PPGIS implementation, refer to Garcia et al. (2020) and Vall-Casas, et al. (2021). Garcia et al. (2017; 2018) for the case of the qualitative-based PPGIS process.

In both cases, information about improvement preferences was also gathered. However, this last category of information was not used in this study because it cannot be considered perceptions, or at least not as much as the previous ones. Since both studies are interlinked, positive and negative perceptions categories are assimilable. Together, 1370 point based (positive/negative) perceptions that are spatially distributed along the Caldes Stream under study and are classified under the following categories.

2.3. Literature Search Method

A literature review has been performed to emphasize the importance to study the relation between social perceptions and ecological quality status and, to explore the main social perception methodologies used for these studies and which have more relevance and suitability to relate to the quality status. While there have been many studies on the connection between public perception and river water quality, few researchers have taken into account the necessity to create a universal set of parameters of perception which would correspond into a more universal tool. The object of this search was to identify studies in which both public perception and river basin quality were considered. This review focused on 12 peer reviewed research articles directly focused on correlations between ecological status and public perception in rivers. In order to establish which articles would be used, a systematic literature search was conducted. The platforms ScienceDirect and Researchgate were selected for the search due to their quantity of high quality, peer-reviewed material. Searches were conducted through these databases using the keywords “public perception” “Mediterranean river basin” “river management” “Mediterranean river” “perception of river”, “ecological status”, “water quality” and “environmental status”. keywords were directly derived from the research objective of this paper. The key study area considered was the Mediterranean region, however this was later broadened to consider other areas due to difficulty in finding material. One possible reason for this was that research for writing this paper was conducted almost exclusively in English. Papers were saved to be included in the literature review if they directly pertained to the relationship between public perception and the ecological status of rivers.

2.4. Frequency analysis

Combining public perception data from The Viu La Riera project and maps of the water body areas provided by the Observatori Rivus project, a frequency analysis using QGIS software was performed in order to contextualise the data set in a quantitative manner. A map of the area divided into fourteen buffers was obtained using data kindly provided by UIC and the University of Girona. The geographic position of where a perception subcategory, for example “sport/leisure” was recorded is depicted as a coloured point on the map. the points were then counted across the map buffers in the study area where five buffers corresponded to the headwaters, and the following nine buffers corresponded to the downstream area. Beyond the fourteen buffers, there were also outlying variables, perceptions which occurred beyond the water bodies but were also recorded. The resulting number of recorded perceptions in each area give insight into popularity or frequency of the subcategory and also where it is likely or unlikely to be recorded. Overall a total of 584 perceptions were recorded in the headwaters, 721 perceptions were recorded in the downstream body and 65 perceptions were recorded outside of the buffer areas but are considered in the analysis.

These perceptions will be related to the ecological quality status of 2016 of both water bodies and considering the three quality indicators mentioned above (IBMWP, IPS and QBR).

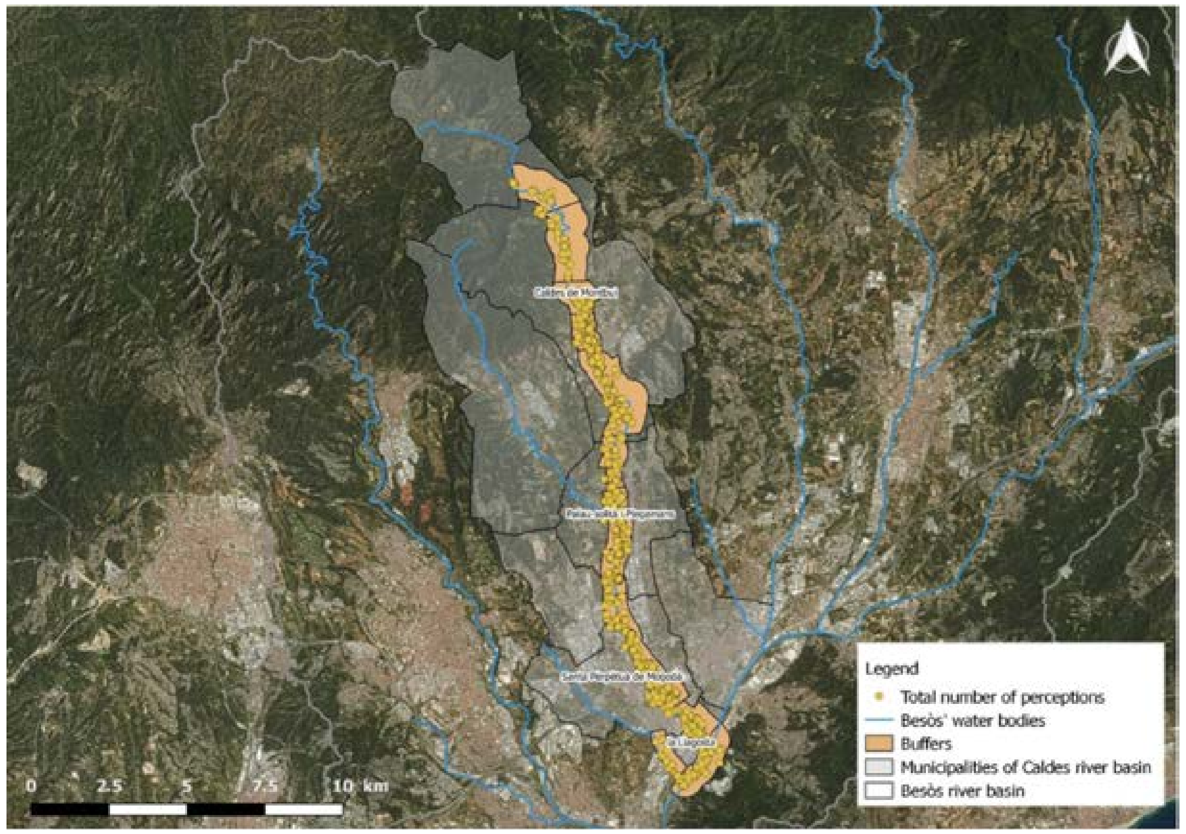


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Figure 12. Distribution of perceptions in the buffers of public perceptions in study area using QGIS software (Mas Ponce, 2020).

3. Results

3.1. Evolution of the biological quality status of the Caldes' stream sub-basin

In some instances, there are gaps in the knowledge of the quality status of the study area as it was not possible to recover findings for a particular indicator during season. Over time there has been an overall improvement trend in the biological quality status of the Caldes stream sub-basin.

IBMWP

In the headwaters (1100190), the IBWMP indicator increased significantly in quality by 194 between 1997 and 2016, bringing the quality from moderate to high, with the occasional dip in quality but an overall improvement trend. Within the downstream water body (1100200), there is less data available regarding the IBMWP indicator. Among the available data the evolution of ecological status is more variable. The IBMWP indicator has undergone an increase in status, improving by 46 and jumping in quality from poor to good.

IPS

There is a lack of data in the headwaters (1100190), however it also shows improvement from the year 2008 to the year 2016, increasing by 5.3 and changing from moderate to good in status. Downstream (1100200), the IPS indicator notes a significant decline, from moderate in 2007 to poor in 2016, it is notable that the IPS downstream is the only one that trends downwards towards declining quality status. Overall, the ecological status data would suggest that the Riera de Caldes stream is healthier up stream in the headwaters. This would be a logical conclusion as anthropogenic and territorial pressure is much higher downstream in the metropolitan area.

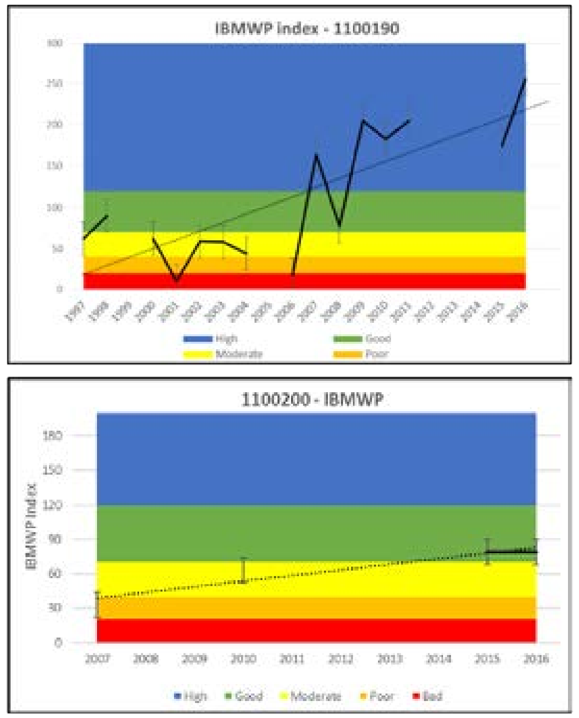

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Figure 13. IBMWP index trends in headwaters and downstream of the Riera de Caldes stream (Sànchez Mateo, 2018c).

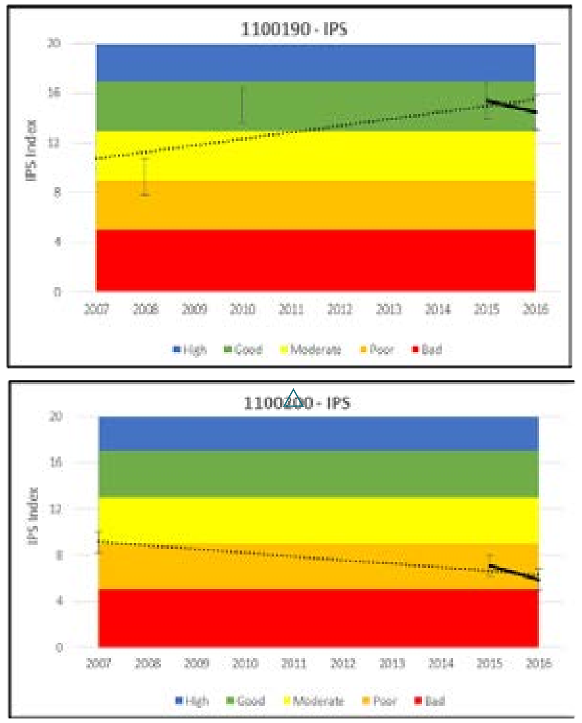

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Figure 14. IPS index trends in headwaters and downstream of the Riera de Caldes stream (Sànchez Mateo, 2018c).

QBR

In the headwaters (1100190), QBR index increased by 50 between 1997 and 2016 and was reclassified from bad to good, the most notable improvement in the buffer despite some fluctuation. Within the downstream water body (1100200), the QBR indicator increases slightly in quality before quickly experiencing decline again, changing status from bad to poor to bad again.

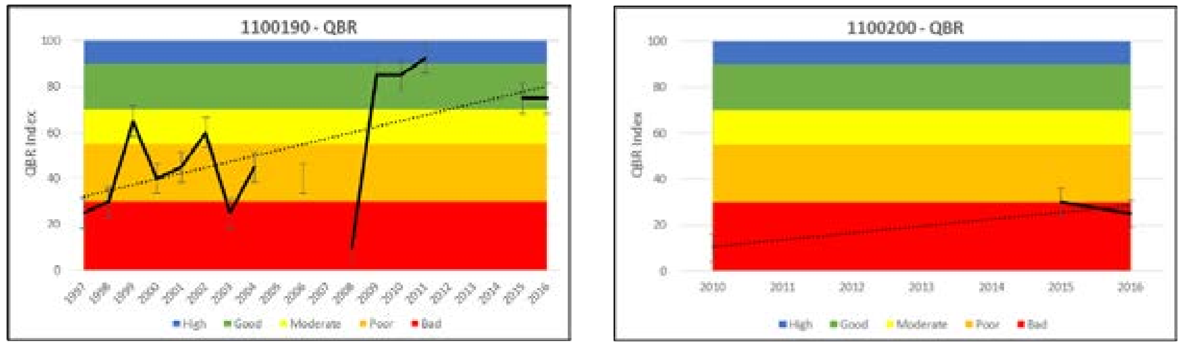

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Figure 15. QBR index trends in headwaters and downstream of the Riera de Caldes stream (Sànchez Mateo, 2018c).

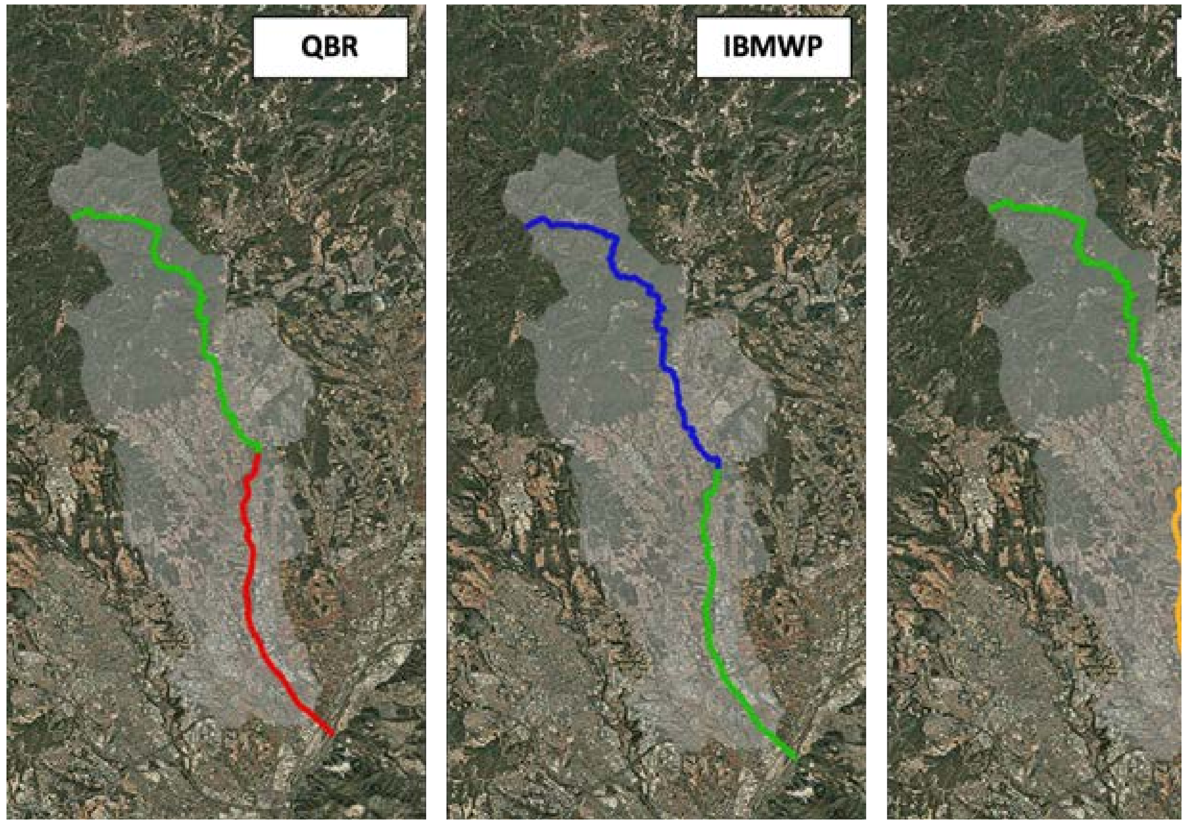

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Figure 16. Results of the QBR, IBMWP and IPS indices of the Riera de Caldes stream in 2016 (L'observatori, 2018).

3.2. Public perceptions

The data utilised in this section was provided by the Viu La Riera project through the means of the SiGPP survey tool. As demonstrated in the literature review, there is a clear necessity to create universal categories in order to categorically measure public perception. For the purposes of this research, four categories of perception are considered: socio-cultural, well-being, environment/biodiversity and environmental impact. These four categories provide a broad outlook through which to consider perception, they encompass negativity and positivity, physical and intangible perception. Within the four categories exist subcategories, which must be well defined in order to succinctly characterise the perception being expressed. In order to define these subcategories, relevant literature was reviewed in order to provide a succinct definition and corresponding keywords. This information can be reviewed in the table below.

3.3.1. Categories

Positive categories:

Table 15. Positive perception categories

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Category	Variables	Definition	Keyword
Socio-cultural	1.Sport/Leisure	Sites with recreational activities such as fishing, bathing and walking (Vidal-Abarca et al., 2014)	Sport, health, bathing, walking
	2.Culture and heritage	Sites containing memories in the form of stories, place names and collective practices creating generational identity construction Invalid source specified.	Culture, memories, stories, practices
	3.Promoting social relations	Sites which play a key role in every day social integration. (Garcia et al., 2017)	Integration, recreation, social interaction
	4.Educational/research	Sites which play a role as agents of integrated pedagogy. (Whitbread, 2015)	Education, knowledge transfer, research
	5.Resources/materials/food	Sites which supply natural resources such as food, game, water or wood. (Garcia et al., 2017)	Water, food, wood, game
Well-being	1.Scenic/Landscape beauty	Well-maintained, picturesque, aesthetically pleasing sites. (Nassauer, 2004)	Wildlife, open terrain, picturesque, well-maintained
	2.Emotional Link	Sites which evoke place attachment and have restorative properties. (Liu et al., 2020)	Emotion, attachment, restorative properties
	3.Connection with other places	Sites evoking a personal or cultural landscape connection. (Liu et al., 2020)	Connection, wonder, emotion
Environment/ biodiversity	1.Ecological habitat/ restoration	Sites used by species for reproduction, food or shelter. (Duflot et al., 2018)	Habitat, species, wildlife

Negative categories:

Table 16. Negative perception categories

▽

Category	Variables	Definition	Keyword
Environmental Impact	1.Contamination of any source	Sites which contain stressors such as toxic chemicals, pollutants or pesticides. (von der Ohe et al., 2011)	Toxin, chemical, pollutant, pesticide
	2.Flood and fire risk	Sites at risk of flood or fire due to poor management or neglect.(Garcia, Benages-Albert and Vall-Casas, 2018)	Flood, fire, management, risk
	3.Landscape impact	Unpleasant Sites with slight or bad smell. (Zhao et al., 2019)	Impact, urban, industry
	4.Bad smells	Sites which are littered. (Weber and Ringold, 2015)	Odour, disgust, unpleasant
	5.Waste accumulation	Sites where antisocial behaviour occurs. (Garcia et al., 2017)	Trash, litter, garbage
	6.Anti-social behaviour	Sites which are not connected by longitudinal pathways or sidewalks. (Kondolf and Pinto, 2016)	Alcohol, graffiti, crime
	7.No people pathways	Sites containing unmaintained vegetation. (Özgüner, Eraslan and Yilmaz, 2012)	Pathway, footpath, walkway
	8.Invasive Species	Sites containing non-native species, subspecies or lower taxon, Provoking alterations in the ecosystem. (Boon, Clarke and Copp, 2020)	Invasive, allochthonous, exotic
	9.Uncontrolled vegetation	Sites containing unmaintained vegetation. (Özgüner, Eraslan and Yilmaz, 2012)	Risk, decontrol, unmaintained

3.3. Literature review

As seen in the table 17, different parameters of perception are used across different literature in order to consider the divergence or connection between public perception and river status. These parameters of perception can be contextualised as being positive, negative or neutral. Of these 31 parameters, 10 were mentioned across than more than one study. The most frequently used parameter was categorized as "pollution", which occurred in five of the eleven papers. McDaniels et al. regard pollution as the measure of whether or not the water quality of the river is adequate for sustaining flora and fauna and thus recorded the publics assessment of water quality. Le Lay et al. also measured the parameter or pollution in terms of water quality, and noted that respondents used water colour and smoothness – or absence of wood – to understand this parameter. Cockerill considers the parameter of pollution within a wider scope, taking into consideration thermal pollution, pet waste, street run-off and chemical contamination. Marshall and Duran also consider the parameter of pollution under a broader scope, taking into consideration solid waste especially plastic, industrial and organic pollutants and garbage. In their study, Gao et al ask respondents to define what they believe are main sources of pollution in their area, and over a two year period find that improper disposal of lawn waste, oils and chemicals into storm drains as well as littering and illegal dumping of trash are perceived as measures of pollution. Clarity and colour – intrinsically linked- are the second most often occurring parameters found in the literature review, occurring four times and both occurring in the same studies throughout. Moser indicates the inconsistency in the parameter of colour, noting that the water is always judged to be clean if it has a clear colour. Conversely, absence of clarity was not found to be an indicator of poor water quality in Moser's study. Cottet et al. point to colour and clarity as key parameters of river perception, noting a strong aesthetic preference for clear, transparent waters and overall rejection of brown coloured waters. West et al. found that clarity was frequently a more important parameter than colour, after asking respondents to rank photos by what criteria they deemed meaningful. Morales et al. correlated this information, finding that the public are more likely to perceive clear, colourless flowing water as healthy and yellow or red-tinged water as poorer in quality. Aesthetic, flooding, recreation and vegetation are the third most commonly occurring parameters. Le Lay et al considered the parameter of aesthetic in terms of naturalness- with conflicting results about whether more natural or less natural riverscapes are more aesthetically pleasing, Cockerill found that the public is likely to relate aesthetic value with naturalness. Ruiz-Villanueva et al. found that riverscapes containing wood- although less natural – were consistently perceived as being less aesthetically pleasing by the public. The parameter of flooding is utilised within the Cockerill in the context of measuring the perceived need for river basin management. Marshall and Duram find that the perception of flooding can vary between groups – depending on level of environmental education and familiarity with local environmental policy. Ruiz-Villanueva et al. conclude that communities effected by flooding are more likely to perceive the presence of wood in a riverscape negatively. Ruiz-Villanueva et al. link the parameter of recreation to the community's sense of connection or ownership of the riverscape. McDaniels et al. conceptualise the parameter of recreation through the likeliness the public would have to swim in the river body – depending on perceived ecological status.

In the Cottet et al. study, water with floating aquatic vegetation and water with vegetation growing underneath the surface serve as visual parameters. Water with floating aquatic vegetation was found to be perceived as having fair aesthetic value, while water with submerged vegetation was perceived as having higher aesthetic value. Cockerill also found that respondents perceived high levels of vegetation favourably. Moser on the other hand found that in the absence of visible debris, visible vegetation in the water was a factor in the public perceiving water quality as bad.

Moser comments that floating debris is a key factor in leading the public to perceive the water body as polluted to some extent. Ruiz-Villanueva et al. find that the public perceive debris in the channel such as wood as un-aesthetically pleasing, hazardous and in need of cleaning. Regarding the parameter of habitat/conservation, Gao et al speak about this parameter within the context of practices to improve water quality, Cottet et al. performed a multiple correspondence analysis about the cumulated occurrence of 57 classes of words, notably including "high biodiversity" and "low biodiversity". In a cross cultural analysis, LeLay et al. found that the parameter of "naturalness" is perceived both in conjunction with beauty and degree of management. Naturalness is also connected to aesthetically pleasing riverscapes containing wood according to Ruiz-Villanueva et al. On the other hand, naturalness is also perceived within the context of lack of management and danger.

The remaining 21 parameters were mentioned in only one of the studies featured in the literature review, firstly we can consider the positive parameters of perception. Starting with the parameter of river ecosystem-servicer. Iona-Toroimac et al. describes this parameter as having tangible outputs to the community. However, their study showed that the public recognised few varieties of river ecosystem-services. McDaniels et al. describes the public perception parameters of river water drinking quality and edibility of fish as being relative to high levels of treatment. Regarding the more subjective parameters of emotion, idealness, identity and sensory, Cottet et al. write about the diversity of the parameter of emotion, finding that river landscapes evoked a wide variety of emotions such as lightness, cheerfulness and beauty. The parameter of idealness on the other hand was less subjective. Cockerill et al. found a strong correlation with the parameter of idealness and high quality of habitat. Gao et al. examined the parameter of identity within the context of the community identifying their local riverscape as important to them as well as being a symbol of the region. Cottet et al. records that the sensory parameter is related to visual, olfactory or tactile experiences related to the riverscape. On the subject of less subjective parameters, Morales et al. describe the parameter of flavour as being organoleptic that can therefore vary between groups, examined within the context of being salty or sweet, as well as the context of appreciation of taste.

Negative parameters were of course also considered in the literature review. LeLay et al. considered the parameter of danger and found that people perceived both presence and absence of wood in river channels to be associated with danger depending on the cultural context of the group. They also perceived wide rivers and turbulent flows to be dangerous. Marshall & Duram record that the public perceive the parameters deforestation in river headwaters, traffic and development in the river basin to be significant concerns. In the same study, the parameter of lack of regulation was found to be the second most frequently perceived concern while the parameter of invasive species also a perceived threat – and one that was most recorded amongst their public service respondents. Overfishing was also a negative parameter recorded as causing concern among the public. The studies took parameters directly influenced by anti-social activity into account, for example Gao et al. found that the parameter of illegal dumping was more likely to disconnect the public from the riverscape, making them feel apathetic towards its stewardship. Cockerill et al. found that the parameter of erosion was associated with need for management or intervention in riverscapes and evoked a strong reaction from the public most likely because it is a visible parameter associated with flooding. The parameter of sediment was also negatively perceived by the public, Cottet et al. found it associated with an unnatural riverscape which is not aesthetically pleasing. Odour was found to be the most influential parameter in the Moser study, with the public immediately perceiving the water body to be of poor ecological quality when it had a strong odour. Finally, the most 'neutral' parameter – neither positive nor negative - with respondents at times perceiving a water body to be of poor ecological quality but with good movement.

Table 17. Results of the literature review.

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Authors and date	Title	Geographic Location	Method	Sample Size	Parameters of Perception
Moser (1984)	Water Quality Perception, A Dynamic Evaluation	The River Loing, France	Semi-directive interviews	(n=85)	Vegetation Clarity Colour Movement Debris Odour
McDaniels et al. (1998)	Public perceptions regarding water quality and attitudes toward water conservation in the Lower Fraser Basin	British Colombia, Canada	Survey Technical summary	(n=183)	Drinking quality Recreation Edibility of fish Pollution
Le Lay et al. (2008)	Variations in cross-cultural perception of riverscapes in relation to in-channel wood	International: Germany, Sweden, United States	Photo-questionnaire	(n=2250)	Aesthetics Pollution Naturalness Danger
Cottet et al. (2013)	Does human perception of wetland aesthetics and healthiness relate to ecological functioning?	The Ain River, France	Photo-questionnaire survey	(n=403)	Recreation Sediment Clarity Vegetation Sensory Colour Emotions Habitat/ Conservation
Cockerill (2016)	Public Perception of a High-Quality River: Mixed Messages	North Carolina, United States of America	Survey	(n=122)	Vegetation Flooding Erosion Aesthetic Pollution Idealness
West et al. (2016)	Optical water quality and human perceptions of rivers: an ethnohydrology study	Ozarks of Arkansas, United States of America	Interview Pile sort Cluster Analysis Geological Survey	(n=151)	Clarity Colour
Marshall and Duram (2017)	Factors influencing local stakeholders' perceptions of Tisza River Basin management: The role of employment sector and education	The Tiza River Basin (covering Ukraine, Romania, Serbia, Hungary, Slovakia)	Survey	(n=86)	Pollution Deforestation Traffic Flooding Overfishing Invasive species Lack of regulation Development
Gao et al. (2018)	Public perception towards river and water conservation practices: Opportunities for implementing urban stormwater management practices	Indiana, United States of America	Survey	Survey1 (n=352) Survey2 (n=309) Survey3(n=278) Survey 4 (n=255)	Recreation Pollution Illegal dumping Identity Habitat/ Conservation
Ruiz-Villanueva et al. (2018)	Does the public's negative perception towards wood in rivers relate to recent impact of flooding experiencing?	Central and North-East Spain	Questionnaire Online Survey Field survey	Questionnaire (n=388) Online survey (n=135)	Debris Aesthetic Naturalness Flooding
Ioana-Toroimac et al. (2020)	Translating a river's ecological quality in ecosystem services: An example of public perception in Romania	Bucharest, Romania	Survey	(n=254)	Ecosystem Services
Morales et al. (2020)	An interdisciplinary approach to perception of water quality for human consumption in a Mapuche community of arid Patagonia, Argentina	Patagonia, Argentina	Semi-structured interviews Tours guided by informants Physicochemical and microbiological analysis of water sources.	(n=3600)	Temperature Colour Flavour Clarity

3.4. Frequency Analysis: Social perceptions categories

The frequency analysis accounts for all perceptions logged in each variable across the headwaters and downstream. Perceptions were also logged further away from the water bodies outside of the buffer zones. These perceptions appear in the tables below as "area outside water body".

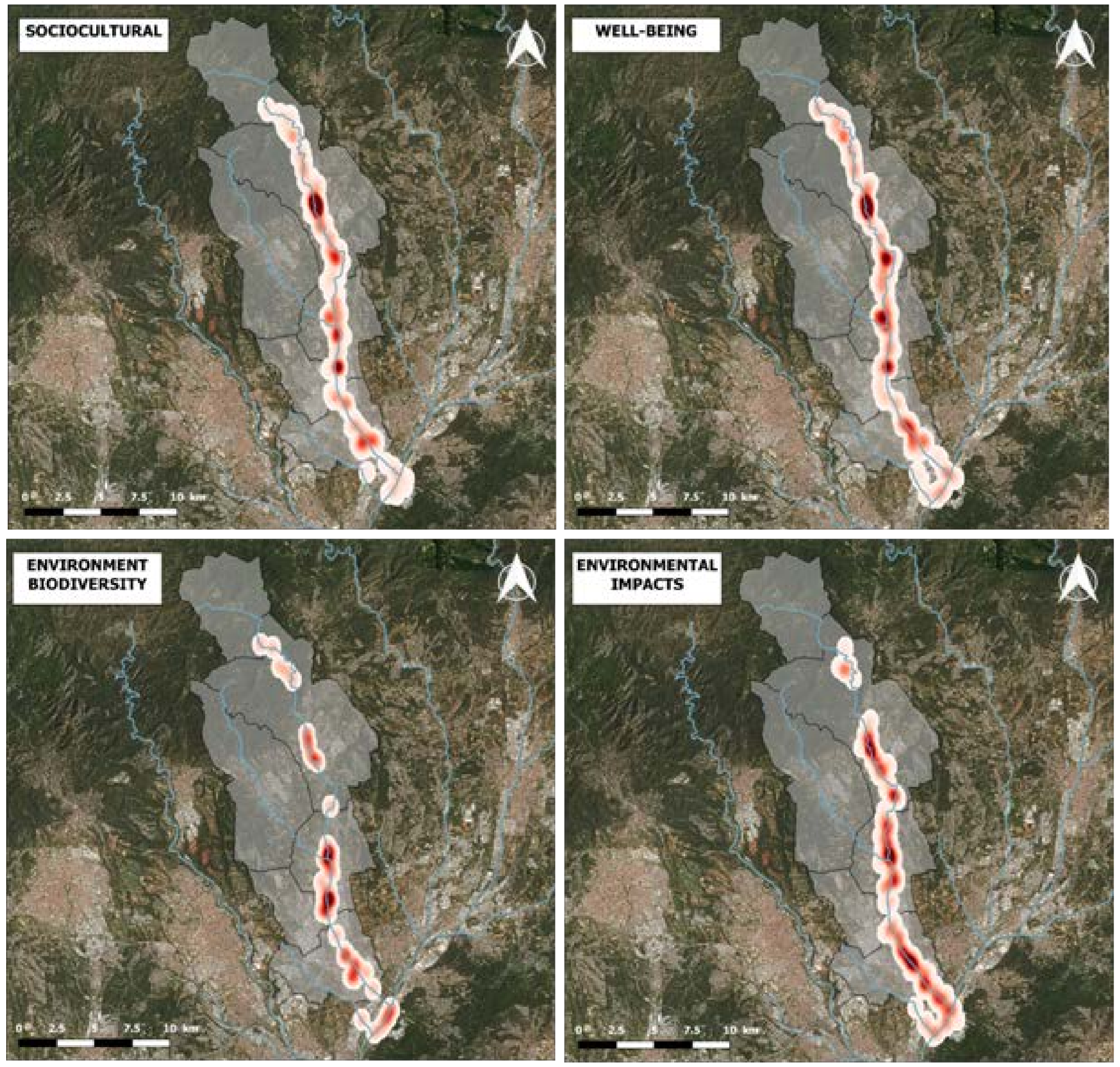

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Figure 17. Heatmap showing sociocultural, well-being, environment/biodiversity and environmental impacts frequency analysis. (Mas Ponce, 2020d)

Table 18. Frequency analysis results.

Category	Variables	Total perceptions: Headwaters (1100190)	Downstream (1100200)	Area outside water body
Sociocultural (583)	Sport/Leisure	100 (17.15%)	110 (18.87%)	9 (1.54%)
	Culture/heritage	114 (19.55%)	60 (10.29%)	5 (0.86%)
	Promoting social relations	45 (7.72%)	59 (10.12%)	4 (0.69%)
	(583)	50 (8.58%)	17 (2.92%)	0 (0%)
	Resources/Materials/Food	5 (0.86%)	5 (0.86%)	0 (0%)
Well-being (383)	Scenic/landscape beauty	125 (32.64%)	124 (32.38%)	16 (4.18%)
	Emotional link	35 (9.14%)	47 (12.27%)	2 (0.52%)
	Connection with other places	12 (3.13%)	18 (4.70%)	4 (1.04%)
Ecology/Habitat/Conservation (58)		12 (20.69%)	43 (74.14%)	3 (5.17%)
Environmental impact (346)	Contamination of any source	10 (2.89%)	28 (8.09%)	1 (0.29%)
	Flood and Fire risks	3 (0.87%)	29 (8.38%)	7 (2.02%)
	Landscape impacts	12 (3.47%)	50 (14.45%)	7 (2.02%)
	Bad smells	15 (4.34%)	18 (5.20%)	1 (0.29%)
	Waste accumulation	22 (6.36%)	46 (13.29%)	0 (0%)
	Antisocial behaviour	8 (2.31%)	24 (6.94%)	0 (0%)
	No people pathways	2 (0.58%)	24 (6.29%)	4 (1.16%)
	Invasive species	7 (2.02%)	4 (1.16%)	0 (0%)
	Uncontrolled Vegetation	7 (2.02%)	15 (4.34%)	2 (0.58%)

Trends or correlations were searched for when comparing public perception and quality status. Taking the most recent quality status data from 2016, there seems to be some indications supporting the main thesis of this study as well as evidence to the contrary, reflecting the literature reviewed. As discussed previously, the headwaters can be considered of good ecological quality, whereas downstream can be considered of predominantly poor ecological quality.

Within the Sociocultural category, both water bodies registered a similar perception among the public, 53.86% in headwaters and 43.05% in downstream, with the data suggesting that there was not a big difference in sociocultural value between them. The exception to this was the subcategory of Educational/research where three times more impressions where registered in the headwaters (50) than downstream (17), and in Culture/heritage with 114 perceptions in headwaters and 60 in downstream.

In the Well-being category, downstream registered overall more impressions from the public (189, 49.35%) than the headwaters (172, 44.91%). The Ecology/Habitat/Conservation category also presents the same trend with a 74.14% of the perceptions located in the downstream areas and a 20.69% in headwaters. In the negative category of Environmental impact, downstream registered a significantly higher number of perceptions than the headwaters, except for the subcategory of Invasive species, where almost 65% of all impressions were registered in the headwaters.

Overall, the downstream body registered more impressions from the public (721) than the headwaters (584).

The majority of the public perception categories analysed shows that downstream received more attention rather headwaters, except the Sociocultural category. It is quite remarkable the number of perceptions focused on the Environmental impacts in downstream (238) which can be correlated to the water quality. In the downstream the quality status is correct considering the IBMWP but poor and bad considering the IPS and QBR, respectively. In the headwaters on the other hand, the IPS and QBR indicators are classified as good and the IBMWP as excellent. These results would therefore suggest a disconnection between public perception and quality status assessment, at least when it comes to 'positive categories' but a possible connection between the 'negative' category and ecological quality status.

3.5. Frequency Analysis: Social perceptions variables

Furthermore, the literature review performed, showed different researches which main goal is to relate the social perceptions to quality status of fluvial systems with several methodological approaches. Besides, the results of the literature review also provide the main social perceptions where the studies focus on. In that sense, from the 11 papers reviewed a total amount of 28 variables were considered. These parameters were transformed to the social perceptions' variables used in this study to be related to the ecological quality status.

In general terms, the variables related to environmental impacts category such as Contamination of any source, Flood and Fire risks, No people pathways and Uncontrolled vegetation, have a higher number of perceptions in the downstream than in headwaters. On the other hand, it is seen that Sociocultural category has similar number of perceptions in both areas, but it is remarkable the variable Culture/Heritage which presents a greater number of perceptions in the headwaters.

4. Discussion

River basin management encompasses not only the quality status of the river, but also the needs of its stakeholders across the economic, political and ecological spectrum. In order to avoid fractured management practices, it is necessary to integrate processes to reflect this. When united under a common goal, more integrated approaches to management can lead to more sustainable development practices that reflect societal values and use interdisciplinary knowledge in an optimised way (Cardwell et al., 2009). It is needed to impulse and reinforce the social perceptions and opinions as a tool in the management plans and decision-making processes. In that sense, this research aims to perform a first data exploration through the frequency analysis.

The frequency analysis shows the complex interplay, strongly mediated by the existing land use conditions in the stream corridor, between public perception and ecological quality. Headwaters more natural, less populated and less accessible, and downstream strongly urbanized, populated, more accessible (paths, parks, allotments).

To sum up, the analysis shows up two main learning: 1) citizen science experiences linked to ecological quality status could affect the changes in their perceptions. 2) social-oriented variables inform on the rich array of ecosystem services beyond biodiversity, etc, thus facilitating a holistic assessment of the river quality.

Moreover, this research could be considered as the first steps to build a methodological framework to study the relations between public perceptions and ecological quality status. The Literature review also provides the available tools which could be used to perform this sort of study. Moreover, following steps could interpretated the Land Use and Land Cover Changes (LULC) analysis, which can also provide illustrative evidence of the Global Change effects in the area and how they have influenced the Riera de Caldes or other specific Mediterranean river basins.

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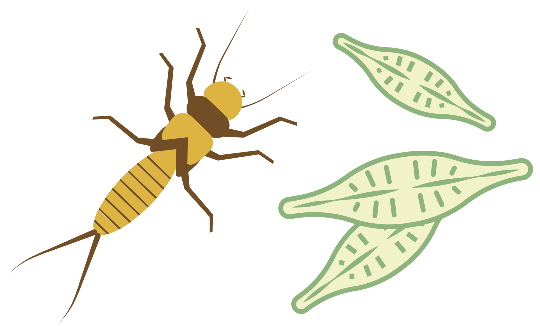
Research chapter 4

Modelling a multidisciplinary tool to evaluate Global Change effects on mediterranean river basins



1. Introduction

To achieve and guarantee a correct quality status of the freshwater ecosystems, in 2000 was stablished the Water Framework Directive (WFD) (2000/60/EC, European Commission 2000). This Directive is the milestone of all water policies and management plans to all surface waters such as rivers, lakes, transitional and coastal waters of European Union states which, moreover, promotes the sustainable use of the water resources. The principal basis of the WFD is to enhance the value of water and its responsible management and to not consider the water just a "commercial product but rather a heritage which must be protected, defended and treated as such" (European Commission, 2000).

Furthermore, to accomplish the goals stablished in the Directive, many improved monitoring and ecological assessment methods have been implemented in long-term monitoring programs (Birk, et al., 2012). These improvements provide us with a broader knowledge of the ecological status of the water bodies which, in turn, furnish us with the tools to build resolutive and multitude restoration measures (Voulvoulis et al., 2019). Although the WFD means a big step in the European water policy, the EU member states have not reached the objective to achieve a good quality status in all European water bodies. The European Environment Agency (EEA) reported that after the 2nd River Basin Management Plans (RBMP), the 69% of the surface water bodies had reached a good status. Year 2015 was the deadline proposed in the WFD to reach the good status level in all water bodies, but this was extended in two cycles of 6 years up to 2027.

In 2021 the 2nd 6-year cycle of the RBMP will finish. Currently, a round of consultation has been performed among EU members to highlight the need to improve the integration of the WFD goals in the respective water policies and management strategies.

Moreover, since the time WFD was presented, some new perspectives were included such as the recognition of specific pressures on water bodies, new environmental management perspectives, the inclusion of the UN Sustainable Development Goals and other EU policies on biodiversity renewable energy and floods management (Table 19).

Table 19. New perspectives included in the WFD and the topics included.

New WFD perspectives	Topics
Recognition of pressures	Climate Change (floods and drought risks) (Quevauviller 2011)
	Invasive species (Cardoso and Free 2008)
	Emerging pollutants (von der Ohe et al., 2011)
New Environmental Management Perspectives	Ecosystem services
	Natural-based solution (NBS)
	Adaptive and resilience-based approaches (Spears et al., 2015
UN Sustainable Development Goals (SDGs)	Targets related to water
Other EU policies	Biodiversity
	Renewable energies
	Floods management

In that sense, we would like to address the following questions about the current WFD:

- Are the current WFD goals strict enough to reach the correct quality status of all the EU member states water bodies?
- Which improvements should be applied in the 3rd 6-year cycle of the RBMP after more than 20 years since its stipulation?
- How the WFD could be adapted to a continuous environmental Global Change?

Currently, there are new and improved restoration measures for the advancement of the monitoring strategies which lead to an improvement of the quality of the freshwater ecosystems, but some of these measures to be implemented to decrease the anthropogenic impact on the ecological status have been proven to be ineffective (Voulvoulis, et al., 2019). To design suitable and efficient strategies to recover the fluvial ecosystems, it is necessary to include, in the management plans, the effects of human pressure on the assessment of the ecological status of rivers. Human pressures are important drivers which alter the functionality and connectivity of the freshwater ecosystems (see Introduction and Research Chapter 2). However, demonstrating the cause-effect link between human pressure and ecological status is challenging. Even though there is a growing number of publications that focus on the variety of stressors and pressures that may perturb river ecosystems (Nõges, et al., 2016), the inclusion of human pressure as a driver in management plans is not widespread.

In this sense, this research aims to amplify the knowledge about the river basin by building new water quality indicators under a new approach including, among others, Global Change effects. In particular, the procedures described below have been applied to two Mediterranean river basins such as Besòs and Tordera (NE Spain). As Global Change driver for this new approach, we have considered Land Use change, a factor that has a strong affectation on fluvial ecosystems. Once the evolution of the ecological quality status of the water bodies that make up the Besòs and Tordera river basins has been evaluated, (Research Chapter 1) and the LULC analysis and to unveil the influence having these changes on water bodies (Research Chapter 2), the proposed modelling to build the new water quality indicators could be carried out. For that purpose, it was considered to include climatic variables (annual precipitation and temperatures), topographic variables (maximum slope and average height) and variables related to anthropogenic pressures (morphological alterations and point sources of pollution).

In that sense, the main objective of this Chapter is to devise and implement new water quality indicators to assess the Global Change effects in water bodies. To that aim, we have used 26 and 13 water bodies in the Besòs and Tordera river basins, respectively, which are the units used by the Catalan Water Agency (ACA in its Catalan acronym) to assess the ecological status and to accomplish the WFD. Moreover, we have considered two different spatial scales: a 100 metres buffer and the return periods in 100 years. The return periods or recurrence interval is an average time between events, in this specific case floods. It is a statistical method based on historical data over a period of time.

2. Methods

2.1. Data compilation/availability

2.1.1. Water quality data compilation

The water quality data used in this chapter has already been described in Research Chapter 1. For the present study, we considered several indicators: two biological (IBMWP and IPS), one hydromorphological (QBR) and five physicochemical (Ammonia (NH_4^+), Conductivity (EC), Phosphates (PO_4^-), Nitrates (NO_2^-) and Nitrites (NO_3^-).

2.1.2. Stressor variables

All the variables used in our analysis are listed in Table 20, including LULC categories in surface (%), the water availability index (WAI), the maximum slope, the mean altitude, the morphological alteration and the punctual pollution sources. All these drivers could influence the quality status of the fluvial systems and adding them to this analysis makes the result of this research more relevant.

Each stressor is analysed by each water body.

Table 20. Stressor group and its variables which are included in the modelling.
▽

Variables modelled	
Stressor group	**Stressor variable**
Land Use and Land Cover	Forested area (%)
	Grassland and Shrubs (%)
	Forested bare soil (%)
	Urban area (%)
	Crops (%)
	Continental water (%)
Climatic variables (Water Availability Index	Annual mean temperatures (°C)
	Annual mean Precipitations (mm)
Topographical variables	Maximum slope (%)
	Mean altitude (m)
Social indicators	Morphological alteration
	Punctual pollution sources

LULC data

The LULC change analysis performed is the same methodology applied in Research Chapter 2. All the detailed methodology is explained there.

Climatic variables

Climatic information was obtained from the Digital Climatic Atlas of the Iberian Peninsula (Ninyerola, et al.,2005) and the Servei Meteorològic de Catalunya. These sources provided collections of digital maps with annual and monthly information for cumulative rainfall and mean temperatures of the Iberian Peninsula and Catalonia, respectively.

For each studied period (1997, 2000, 2009 and 2016), the information for each water body of Besòs and Tordera river basin is extracted through the digitalization using QGIS software. For modelling, we considered the use of the Water Availability Index (Vayreda, et al., 2011) which is an interrelation between precipitation and potential evapotranspiration. In this case the annual WAI can be obtained at monthly level as:

$$WAI= ((P-PET)/PET)*100$$

where P is rainfall (mm/month) and PET is potential evapotranspiration (in mm/month) following Hargreaves and Samani (1982). The annual mean WAI is obtained as the 12-month average.

Topographical variables

The topographical conditions of the water bodies could be another factor which influence the freshwater quality and its ecosystem. For that reason, the maximum slope and mean altitude are considered for each water body and for each studied period using the Profile Tool plug-in of the QGIS software.

Pressure indicators

ACA, the regional public body that is responsible of guaranteeing the accomplishment of the WFD goals, publishes the IMPRESS document every six years. This document integrates the characterization and the definition of the water bodies and addresses the risk of not accomplishing the good quality status goal specified in articles 5, 6 and 7 of the WFD. In our case, we are interested the IMPRESS documents corresponding to years 2005 and 2013, before the RBMP revision (ACA, 2005 and 2013).

The data referring to pressure indicators available in IMPRESS publications that have been considered for this research have been divides into two categories: a) morphological, including dams and channel digging; and b) punctual pollution sources, which include urban, industrial and non-treated discharges. Each indicator ranges from 0 to 3 depending on its impact on the water body, where 0 means no impact and 3 high impact.

2.2. Statistical analysis: Modelling water quality indicators

First, the modelling procedure focused on water quality indicators considering the explanatory variables mentioned above. A linear model was performed to find the relation of each water quality indicator with all the variables. In order to remove collinearity, we calculated variation inflation factors (VIF) for all predictors and sequentially removed those with highest VIF until all VIF<10. In those calculations we used the "vif" function of the "vif" R package (Dongyu et al., 2011). Afterwards we apply the function "predict" to the results of the linear model. The result shows the quantitative value of the indicator considering the influence of the variables.

2.3. Statistical analysis: water quality assessment

A Principal Component Analysis (PCA) was carried out to transform the large set of variables, in that case the water quality indicators, into a smaller one that contains most of the information in the dataset. For this case, we analysed the interrelation between the water quality indicators.

3. Results

3.1. The predictable values of the water quality indicators

In both study cases, the statistical analysis performed proved that exist some differences in the qualitative values of the water quality indicators selected. Generally, as it is seen in Figure 18 and considering the biological and hydromporhological indicators, there is an increase of the number water bodies with incorrect qualitative values (Moderate, Poor or Bad) after modelling in 100 meters buffer and return period in 100 years. On the other hand, the trend in the physicochemical quality indicators is different in N-compounds (NH_4^+, NO_3^- and NO_2^-) (Figure 19 and Supplementary material 7, page 165) where there is an increase of water bodies with correct quality status (High and Good). Moreover, conductivity (EC) and phosphates (PO_4^-) have similar ecological quality status values before and after modelling.

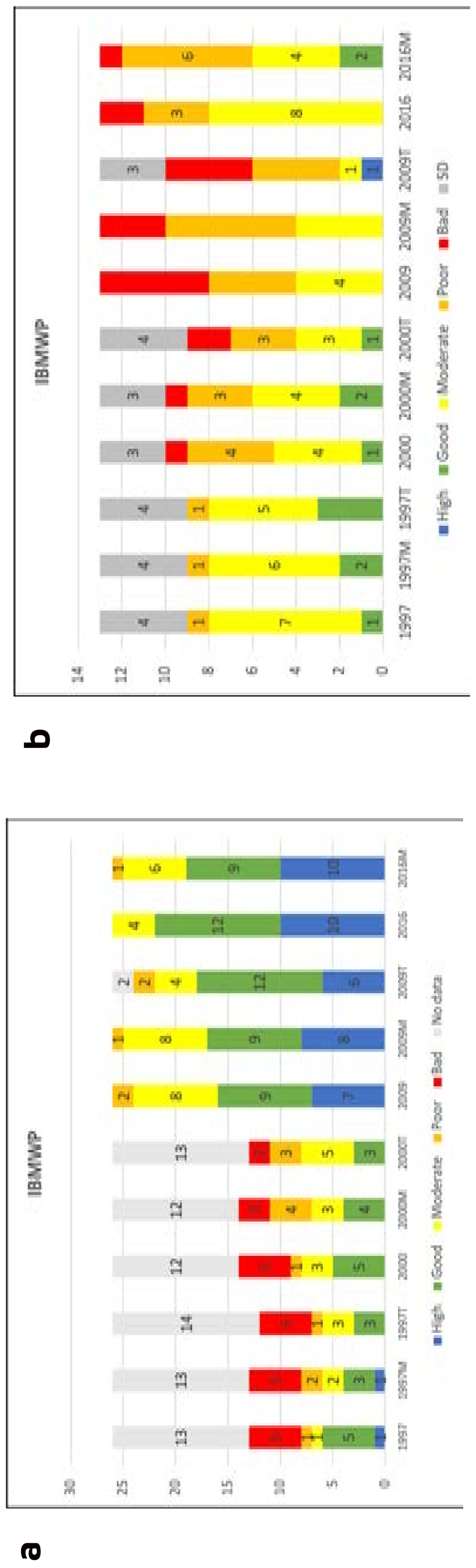


Figure 18. The predictable values of IBMWP index in 1997, 2000, 2009 and 2016 in a) Besòs and b)Tordera river basin and considering the two spatial scales: 100 meters buffer "M" and return periods in 100 years "T".

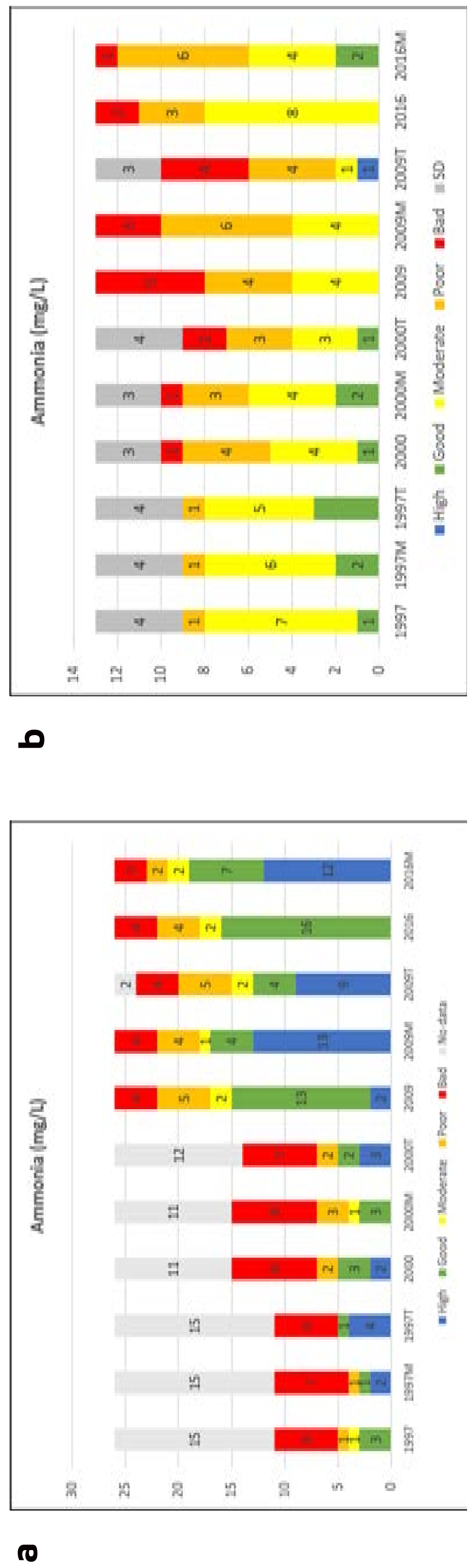


Figure 19. The predictable values of IBMWP index in 1997, 2000, 2009 and 2016 in a) Besòs and b)Tordera river basin and considering the two spatial scales: 100 meters buffer "M" and return periods in 100 years "T".

3.2. PCA analysis: Biological and physicochemical indicators

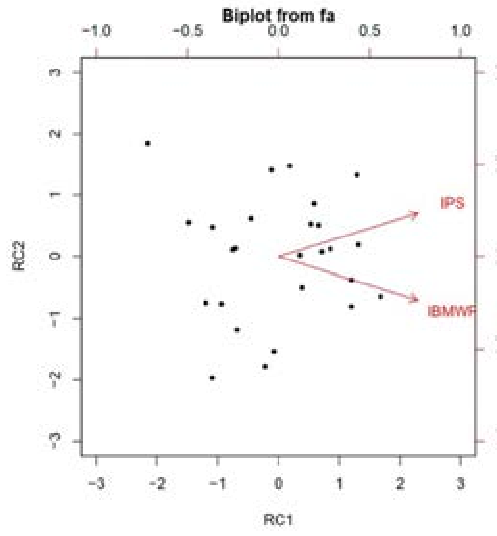
To understand the results of each principal components, it is necessary to examine the magnitude and direction of the coefficients for each water quality indicator. The absolute value of coefficients shows the importance of the corresponding variable. In both cases, the biological indicators in Besòs and Tordera river basins have identical or similar magnitudes and directors (Figure 20, 21, 22 and 23).

On the other hand, the physicochemical are more variable but can be interpretated as one single indicator as it is seen in Figure 20, 21, 22 and 23.

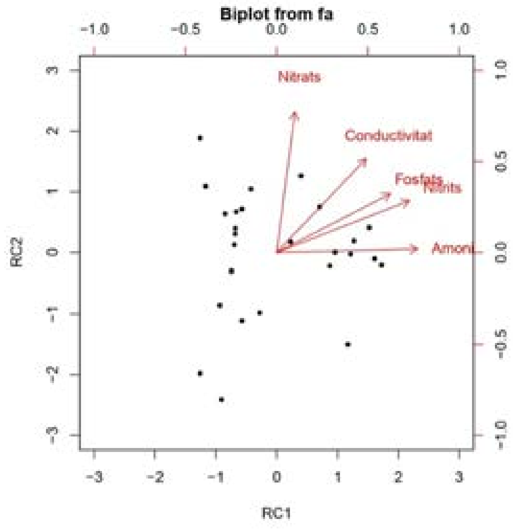
Afterwards, two indicators will be created taking the coefficients resulted of the PCA analysis: biological (IBWMP and IPS) and physicochemical indicators (NH_4^+, Conductivity, NO_2^-, NO_3^-, PO_4^-) for Besòs and Tordera river basins in 2009 and 2016.

The result is considered from a qualitative scale so taking the qualitative intervals stablished in ACA. The indicator value is the sum of the multiplication of each water body by its PCA coefficient (the value of this PCA coefficients is found in Figure 20, 21, 22 and 23).

In the specific case of the biological indicators, could be cases that the qualitative values significantly differ. If these cases are found, we suggest analysing separately when there are more than two qualitative values of difference between two indicators and to find out the possible factors which both indicators diverge.

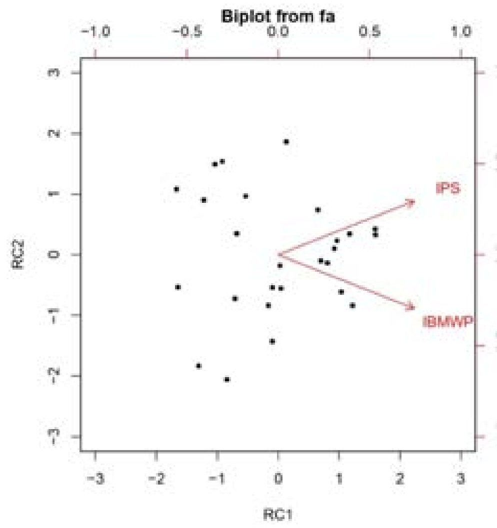


Variable	RC1	RC2
IBMWP	0.96	-0.29
IPS	0.96	0.29
Variance explained	0.915	0.085

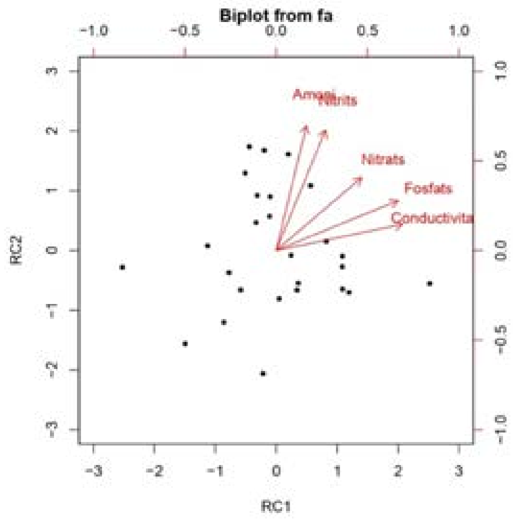


Variable	RC1	RC2
Conductivity	0.66	0.33
Nitrates	0.65	0.82
Ammonia	0.037	0.23
Nitrites	0.12	-0.26
Phosphates	0.81	0.77
Variance explained	0.306	0.297

△
Figure 20. Results the PCA analysis of Besòs in 2009.

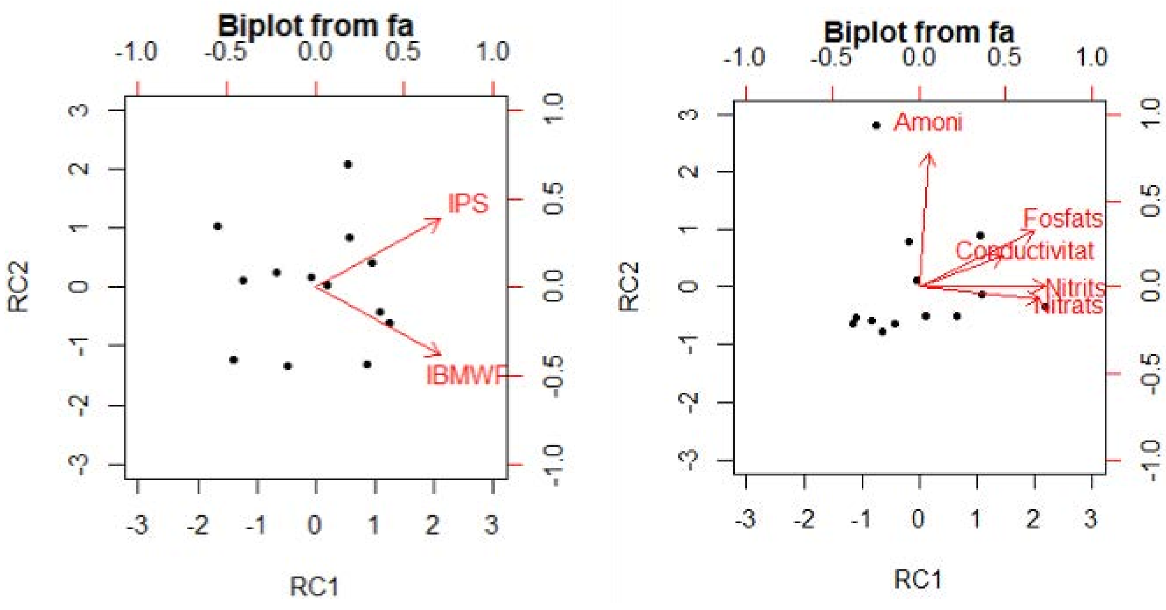


Variable	RC1	RC2
IBMWP	0.93	-0.37
IPS	0.93	0.37
Variance explained	0.864	0.136



Variable	RC1	RC2
Conductivity	0.61	0.28
Nitrates	0.13	0.82
Ammonia	0.97	0.21
Nitrites	0.91	-0.25
Phosphates	0.78	0.78
Variance explained	0.437	0.300

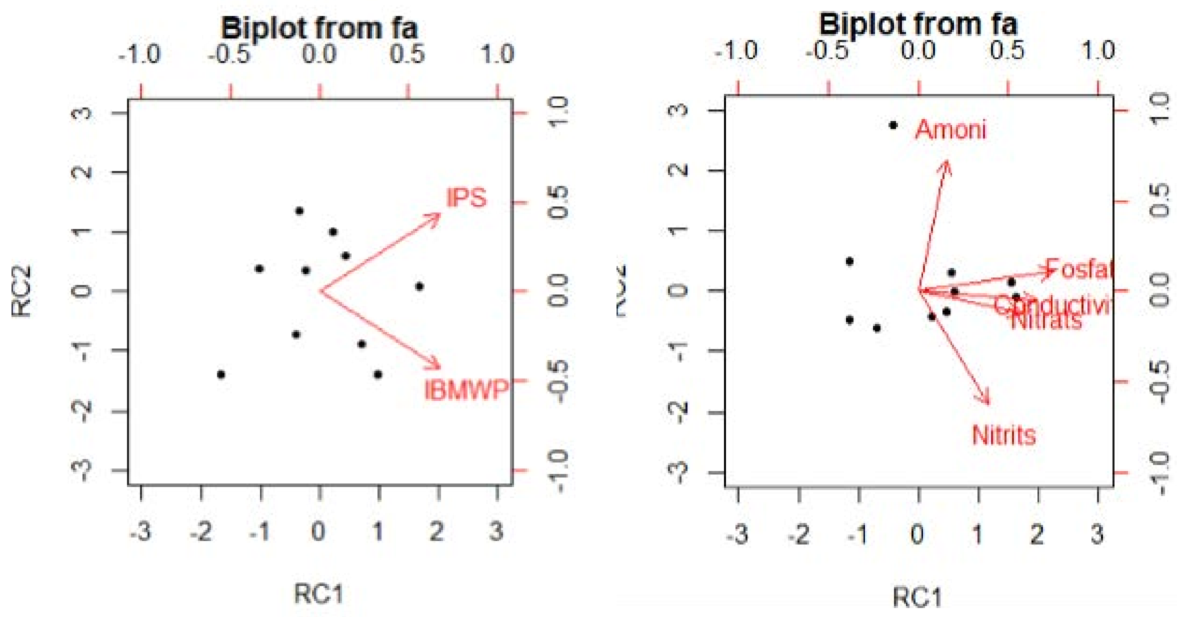
△
Figure 21. Results the PCA analysis of Besòs in 2016.



Variable	RC1	RC2
IBMWP	0.85	-0.53
IPS	0.85	0.53
Variance explained	0.72	0.280

Variable	RC1	RC2
Conductivity	0.39	0.82
Nitrates	0.84	0.07
Ammonia	0.63	-0.02
Nitrites	0.24	0.90
Phosphates	0.96	0.05
Variance explained	0.449	0.299

△
Figure 22. Results the PCA analysis of Tordera in 2009.



Variable	RC1	RC2
IBMWP	0.84	-0.54
IPS	0.84	0.54
Variance explained	0.708	0.292

Variable	RC1	RC2
Conductivity	0.66	0.33
Nitrates	0.65	0.82
Ammonia	0.037	0.23
Nitrites	0.12	-0.26
Phosphates	0.81	0.77
Variance explained	0.306	0.297

△
Figure 23. Results the PCA analysis of Tordera in 2016.

4. Discussion

4.1. Modelling results

The results of the statistical models showed how the biological (IBMWP, IPS and QBR) and physicochemical (NH_4^+, EC, NO_3^-, NO_2^- and PO_4^-) indicators interact with the different explanatory variables within the context of Global Change. Our analysis was performed at two different spatial scales: a 100 meters buffer from the main fluvial axis of each water body and considering the return periods in 100 years. Some studies, as explained above, consider wider influence buffer areas such as 300 or 500 meters, and even up to 1 kilometer (Ullah, et al., 2018; Valerio, et al., 2021). In that case, it is considered the most accurate and influenced buffer area for pointing out the main drivers which can modify the ecological quality status of the fluvial systems studies. However, the proposed tool should consider, in future studies, wider buffer areas in order to extract more detailed information of the different water bodies. In addition, the incorporation of the return periods was added for the last flooding episodes suffered in these areas during January 2020 (ACA, 2020). As it is mentioned in many Climate Change reports such as MedECC, this flooding episodes could be more recurrent in the upcoming years so the tool must take account of those scenarios as well.

Moreover, the application of PCAs to incorporate and merge the different water quality indicators shows that they should not form one single group. On the contrary, they should probably be divided into separate biological and physicochemical indicators. In all these cases, the biological indicators are well correlated having similar or identical coefficients, but this is not the case for the physicochemical indicators, which show differences. For that reason, in some cases it is difficult to express a definitive result for the biological indicators and must be analyzed separately. In that sense, it is stablished to perform this analysis when there are two qualitative categories between IBMWP and IPS.

4.2. How these indicators could be added to reach the Water Framework Directive goals?

In 2000, Catalonia started to set up strategies and create public institutions bodies to be able to reach the goals established in the WFD. Nowadays and more than twenty years after the implementation of the Catalan Water Agency (ACA), the fluvial systems are currently the most threatened natural habitats and the ones that have suffered the biggest biodiversity decrease in the last eighteen years (Brotons, et al., 2020). How was this state reached considering a consolidated legislative tool and a public administration? Which tools are needed to reach this goal?

It is assumed that the WFD implies the implementation of monitoring programs that allow us to identify the ecological status of the fluvial systems, but the river basin vision must be wider in order to really understand which factors modify the ecosystems. First, as it was mentioned above, the WFD should consider the Global Change and their drivers. Fluvial systems are dynamic ecosystems influenced by the tipology of land uses, which change regularly. The model proposed in the present study allows us to acquire this wider river basin vision, to discover how the biological and physicochemical quality status of the water bodies are shaped by Global Change factors and to detect the areas where to focus the efforts to implement management and restoration plans.

Moreover, the last and the upcoming RBMP proposed by ACA considered the public participation as an important characteristic to be included. The indicators implemented in this study do not consider the public perceptions, but Chapter 3 in this thesis demonstrates how this factor could be incorporated. A multi-criteria method should be applied to weight the public perceptions categories such that they can be added to the statistical method as an explanatory variable (Raaijmakers, et al., 2008).

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4. Discussion

4.1. Main findings

In Research Chapter 1, I analysed the evolution of the ecological quality status of both study areas considering IBMWP and IPS as biological indicators and QBR as hydromorphological indicator. The results of the ANCOVA model performed reveal that there is a positive trend (Figure 4 and 5), as indicated by the temporal dynamics of the IBMWP, IPS and QBR indices, in the evolution of the ecological quality status of Besòs and Tordera river basins from 1997 to 2017. The ability to perform a rigorous statistical analysis with those data sets is an illustrative example of how relevant trends can be found.

However, not all river sections in Tordera river basin show these general trends. For example, the middle course of Tordera showed a decrease of IPS and QBR values mainly provoked by the habitat alteration of this section by industrial, infrastructures and urbanization.

Nevertheless, this study reinforces that the implementation of environmental laws is one of the main factors that led to this general improvement of the quality status. This is more relevant considering that the study areas are under a Mediterranean climate conditions (which means annual flow variabilities) and that these rivers are not regulated in their main courses (their flows depend directly on the meteorology and the use of the resources: water abstractions and Wastewater Treatment Plants (WWTPs) effluents).

In that sense, Global Change plays a relevant role on the alteration of the river dynamics and on freshwater biodiversity in Mediterranean river basins. The Living Planet Index (LPI), which evaluates the world's biological diversity status, showed a decline of the 83% of the freshwater biodiversity from 1970 to 2014. Consequently, there is an urgent need to promote strict environmental laws in order to revert the current situation.

Moreover, the implementation of the Catalan Treatment Plan during the 90s in Catalonia was essential to improve the ecological quality status in Besòs and Tordera river basins. Most of the annual river water volume that flows within these areas, especially in Besòs river basin, comes from the WWTP effluents, so these cases are entirely dependent on WWTPs. The additional circumstance of a reduced dilution capacity in these Mediterranean fluvial systems makes urgent the need to implement minimum ecological flows to reduce the risk of transforming rivers, from permanent to temporal.

This assessment also reinforces the impact of the Water Framework Directive (WFD). This European Directive imposes for each river basin a River Basin Management Plan (RBMP) to acquire a good ecological status of all European water bodies. In that sense, the WFD also promotes the implementation of long-term monitoring programs. These programs are key factors to understand the evolution of the fluvial systems and their quality status.

In Research Chapter 2, I assess the effects of two of the main anthropogenic drivers which alter the ecological quality status of the fluvial systems. This research is timely and relevant, and it is a significant addition to the still scarce, although growing, body of literature on the impact of WWTPs and LULC on ecological quality status of fluvial systems.

Ammonia and chlorines with high concentrations could provoke alteration on the ecological quality status. I have implemented non-linear regression models in this Chapter with the aim of assessing the influence of the WWTPs on the biological quality status of the Besòs river basin. For that purpose, I first analysed the evolution of NH_4^+ and Conductivity from 1997 to 2017 to calculate the elimination of N-compounds and chlorines concentrations. Then I evaluated the model to find the trend between IBMWP index and NH_4^+ and Conductivity concentrations. I have shown that the improvement of the treatment systems of the WWTPs leads to a decrease in the concentrations of the parameters studied. In addition, I have also shown that there is a negative correlation between IBMWP and WWTP discharges. To sum up, this Chapter illustrates the importance of investing in N and P compounds elimination treatment processes for all the WWTPs. In that sense, I have demonstrated that the WWTPs without N-compound elimination treatment system discharge higher concentrations of ammonia than others. This may turn out to be one of the main factors that worsen the general quality status of the river basins.

In this Chapter I performed a generalized non-linear model (GLM) for acquiring an estimation in future projections of the WWTPs discharges of ammonia and chlorines to know when these parameters would be in a correct water quality status considering the IBMWP. In both cases, the results indicated that quality levels were worse than the values established in the WFD. In that sense, I showed that there is still a need for promoting and applying new investments in treatment systems to reach acceptable levels in water quality of the WWTPs effluents.

On the other hand, a Land Use and Land Cover (LULC) analysis was performed to assess landscape dynamics in these basins from 1997 to 2017. Although most pronounced changes in LUCL in the study area occurred during the second half of the twentieth century, the selected period offers relevant changes.

In the Besòs river basin the 46.48% of the surface is classified as forested area and the 23.12% as urban area whilst Tordera river basin has the 71.96% of its surface classified as forested area and 8.81% as urban area in 2009. From that point, the Besòs river basin presents a higher heterogeneity: headwaters are large forested areas, whereas middle and lower courses display the effects of a considerable anthropogenic pressure, a fact that is partly due to, and exacerbated by, the presence of the Barcelona Metropolitan Area within basin' limits.

However, it is also proved that both areas followed the same trend from 1997 to 2017. There is a remarkable decrease of crops and forested areas and an increase of grassland and shrubs and urban areas. These results also illustrate the noticeable sociodemographic differences between both cases, where more than 2 million people live within the Besòs basin, of which about 30% correspond to the population of Barcelona city, whereas the Tordera basins encloses around 500,000 inhabitants. In addition, the Besòs river basin is far more industrialized than the Tordera river basin, especially in middle and lower courses.

Moreover, I analysed the impact of LULC on the ecological quality status. The study focused on 100-metre buffers, which were considered to be most relevant. The results of the statistical analysis showed that, in general, forested areas have a positive influence on the ecological quality indicators whereas, on the other hand, urban areas interact negatively with the indicators studied. There is a direct link between forested areas and the QBR index such as the continuity of the habitat and the better quality and structure of the cover which in turn imply less alteration of the fluvial system dynamics. From that point, it also influences biological indices such as the IBMWP and IPS for the nutrients supplies and the reduction of the levels of anoxia. On the other way, the prevalence and the increase of the urban areas suppose the occupation of the fluvial channel and its alteration. This reduces the quality and structure of the riparian covers, which has a measurable impact on the biological indices.

Most of the RBMPs contemplate the participation of the public into the decision-making processes. But in terms of a social approach, the knowledge about the interaction between public perception and ecological quality status is still scarce. In Research Chapter 3, this interaction is analysed and used to carry out a methodological framework which will allow the use of these perceptions for the assessment of the fluvial systems from a social point of view.

Firstly, a frequency analysis was implemented between the number of perceptions and the biological quality status of the Caldes sub-basin to uncover correlations. Generally, river headwaters, characterised by larger forested areas and sparser human population, are less considered for the society than downstream waters. This is probably so because most of the population, who lives predominantly in the middle and lowest sections of the river, is unfamiliar with, and oblivious to, areas upstream. This fact is confirmed by the results of our analysis, namely that citizen science experiences linked to ecological quality status could affect the changes in their perceptions. At the same time, we have also shown the importance that society gives to the well-being and socio-cultural aspects of a river.

In Research Chapter 4, I build a new approach to assess the quality status of Mediterranean fluvial systems. First, one needs to know the ecological quality status of the area from the assessment of the evolution of the ecological quality status (Research Chapter 1). To that purpose I considered the quality indicators stablished in the WFD: biological indicators (IBMWP and IPS index), hydromorphological (QBR) and physicochemical (NH_4^+, EC, NO_2^-, NO_3^- and PO_4^-). Moreover, it is essential to have the longest temporal data series available to reflect the most accurate evolution of a river basin. Second, LUCC has been considered as the main driver due to its strong influence on fluvial ecosystems (Research Chapter 2). Moreover, and to amplify the interdisciplinarity of this new approach, I also considered climatic (Water Availability Index (WAI)), topographical (mean slope and altitude) and anthropogenic pressures variables (morphological alterations and punctual pollution sources).

The assessment was performed in two different spatial scales: a 100-meters buffer and the return periods in 100 years for each water body. As explained in Research Chapter 2, a 100-meters buffer is the most important area to understand the dynamics of the ecological quality status of the fluvial systems. The return periods were added to the flooding episodes suffered in these areas during January 2020, which can often be due to climate change effects.

After that, a linear regression model was implemented to find how the explanatory variables modify the ecological quality status. Previously, collinearity effects between relevant environmental drivers were filtered out. This analysis shows how these drivers altered the quality value of each water quality indicator and proposes a more holistic vision of a river basin and proved that the interaction with these drivers altered the quality status of fluvial systems. In that sense, the biological (IBMWP and IPS) and hydromorphological indicators (QBR) show an increase in the number of water bodies with low quality values (Moderate, Poor and Bad) in both spatial scales. On the other hand, there is an increase of number of water bodies with favourable quality status (High and Good) considering the N-Compounds quality indicators (NH_4^+, NO_3^- and NO_2^-).

From that point, the results of the model showed that there are differences between biological and physicochemical indicators that can be evaluated separately. For that purpose, a Principal Component Analysis (PCA) was implemented to examine the magnitude and direction of the coefficients for each water quality indicator. The results confirm that the biological and physicochemical indicators have similar magnitudes.

The sum between the results of the model and the PCA coefficients led to implement two new indicators: biological (grouping the IBMWP and IPS datasets) and physicochemical (assembling the NH_4^+, Conductivity, NO_2^-, NO_3^-, PO_4^- datasets) for Besòs and Tordera river basins in 2009 and 2016.

4.2. How could this research be applied to future management plans?

Overall, this thesis proposes three different research frameworks which can be integrated into a single tool to assess the quality status of Mediterranean fluvial systems from a Global Change perspective. Firstly, I explained how the ecological quality status improved during the last 20 years in these specific cases. However, the analysis also highlighted the fragility of the Mediterranean systems and its dependence on the WWTP, which was also demonstrated in Research Chapter 2. In that sense, that assessment is an innovative tool to explore the interaction between the ecological quality status and the discharges from WWTP.

In Research Chapter 2, I also implemented two statistical models to determine the importance of LULC categories for water quality indicators in Mediterranean river basin. There is plenty of literature that describes these interactions but, on the other hand, there is a lack of methodological proposals that can be applied to determine and measure them. Both models could be used as a tool to detect the main problematic sources that can then be included in the RBMP.

Another relevant factor studied was the public perceptions as it is seen in Research Chapter 3. There, I demonstrated the interaction between perceptions and ecological quality status, as shown in previous works. However, there are very few methodological frameworks that consider public perceptions as an additional explanatory variable for the assessment of fluvial systems as implemented in this research. The test and the application of this methodological framework will serve to consider the public perceptions as another explanatory variable to include in the new fluvial systems quality status assessment.

The former two frameworks were combined into a statistical model to acquire an interdisciplinary and integrative tool that allows having a broader vision of a river basin and from the current Global Change perspective. Moreover, this thesis emphasizes the need of implementing long-term monitoring programs, so the compilation of the information provided by these programs were a key point. The implementation of this tool could allow to detect weaknesses and strengths in the water bodies that compose a river basin. These integrative results could become a key relevant aspect for future RBMP.

4.3. Future research

Study setting

The results of this thesis are limited to two Mediterranean river basins: Besòs and Tordera river basins. The results found provided useful information under a Global Change scenario in a Mediterranean context, but the tool is potentially profitable for other river basins with different hydromorphological scales and socioeconomic characteristics. Therefore, these findings need to be replicated in other study cases.

Study design

The model performed was used considering two spatial scales: 100 meters and return periods in 100 years buffers. As it is mentioned in the discussion of Research Chapter 4, the 100 meters-buffers are useful scales to detect alterations to the fluvial systems, but other spatial scales such as 300m, 500m and/or 1km buffers will provided other perspective to be analysed.

Furthermore, a future study could explore the importance of the heterogeneity of the land covers such as forested and urban areas. Not all the forested areas present the same structure, density and composition, so this heterogeneity must be extrapolated in the following LULC analysis for extracting more accurate results. This is also applied to the heterogeneity of the urban areas for presenting disperse or compact urban settlements. The design here proposed considered more generic land covers.

Moreover, this new approach enables us to uncover the weaknesses and strengths of each water body, but the next steps will allow to analyse further those changes and to decide which measures are most appropriated.

Water availability

As it is mentioned in Introduction and Research Chapter 1, the flow level of Besòs and Tordera river basins are subjected to two crucial factors: 1) the climatic variability of the Mediterranean climate which is emphasized due to Climate Change and 2) the water availability.

In this thesis, climatic conditions are analysed and added to the tool, but flow levels of both study cases have not been considered. We need to consider the hydrological regime of these cases since a high percentage of water comes from WWTPs discharges. This feature is a relevant aspect to consider in future research for deeply analysing the Global Change effects.

Forest and water management challenges

Historically in seasonal dry Mediterranean regions, forest ecosystems are well adapted to water stress, but extended and frequent droughts could provoke a decrease on the forest productivity and its water availability. One of the strategies to mitigate these effects is based on forest surface reduction to increase the flow of the fluvial systems and forest productivity as well. However, this research shows that the areas with higher percentage of forests are associated with higher water quality. This is yet another relevant aspect of water management that should be included in any discussion about the trade-offs between ecological services in the Mediterranean river basins.

Public perceptions

In Research Chapter 3, a methodological framework is proposed to find relations between public perceptions and ecological quality status. This new framework must be tested and applied to different time and spatial scales for corroborating its functionality. Afterwards, this will allow us to add public perceptions as another driver to the tool and to enhance the public perceptions and to be added into the decision-making processes such as the RBMP.

Assessment of the potential bioindicator role of species linked to Mediterranean fluvial Systems

Historically, the presence and absence of different animal species or taxa (birds, fish, amphibians, reptiles, crabs and aquatic mammals) has been considered a valid indicator of the state of quality and alteration of river systems. Nevertheless, there is a lack of literature evaluating the bioindicator degree and potential of these species to show this quality or disturbance of fluvial ecosystems.

Future research will aim at: i) evaluating the bioindicator degree and potential of different species and ii) standardizing quality and alteration indicators of each research area to evaluate the quality status of Mediterranean fluvial systems.

For that purpose, a process of expert's consultancies will be performed to identify the bioindicator degree of the species or taxa. Finally, through an outranking multicriteria methodology (yet to be determined), bioindicator potential will be evaluated and weighted. As a result, a quality and alteration indicator of the ecological status will be obtained, such as those established in the WFD.

5. Conclusions

There is a general improvement on the ecological quality status in both study areas but in the middle and lower courses of Tordera river basin, the IPS and the QBR indices experimented a decrease trend. In general terms, there is a period of time in these areas when the size of the population increased for tourism, specially in the lower course and the mouth of the basin where some camping areas are stablished, so the anthropogenic impact is higher. In addition, these results reinforce the implementation of strict environmental laws such as the WFD and the need of long-term monitoring programs to know the status of our fluvial systems.

After analysing the impact of the WWTP and the LULC in the ecological quality status, it is proved the relevant role that the treatment systems play on Mediterranean river basin where the amount of water that flows in these fluvial systems are strictly linked to the WWTPs discharges. Moreover, this research also confirms the need to invest in N and P compounds elimination treatment processes for the impact of these physicochemical parameters have in the rivers. The future projections performed proved that even the general improvement there is a still need to reach the correct quality status.

The importance of the LULC categories on the ecological quality status of Mediterranean river basin is analyzed. Firstly, it is proved that the LULC changes is one of the main Global Change factors which can alter the ecological quality status. Secondly, it is seen that the forested areas are the most relevant LULC category on the biological indicators (IBMWP and IPS) and it is intensified through the studied period. The physicochemical indicators are more reliable but also proves the interaction with urban and forested areas in a positive and negative trend, respectively.

To develop a methodological approach for valorizing the public perception of water bodies could be a valuable tool in assessing and managing from an ecological vision. One thing is certain from all the information reviewed: the perception of the public in valorizing their local landscape is indispensable as we face a period of increasing climate changes. The holistic union of top down and bottom-up information must be achieved in order to appropriately manage natural resources. Furthermore, in order to achieve this and thus empower the public to have a clear concept of ecological quality status, environmental educational programs are necessary. It is logical that the public would consider riparian landscapes within the tangible parameters of water colour, smell and vegetation. However, in order to democratize natural resource management beyond specialists and empower communities to engage with local landscape, it is vital to give them the tools to comprehensively understand their natural landscapes through implementing environmental education.

From all, building a new tool for assessing the Global Change effects of Mediterranean river basins allows to acquire a broader vision. The results of this thesis proved that considering the selected drivers the ecological quality status of the different water bodies could be different in a positive and/or a negative sense. This research could become as a key tool for the future RBMP which allows to find out the areas where to focus the efforts to implement management and restoration plans.

Supplementary materials

Supplementary Material 1

Statistical analysis of water quality status indices

We will first check the temporal trends in the three selected water quality status indices (IBMWP, QBR and IPS) across the Besòs river course i.e. highwaters, middle and low) between 1997 and 2017. Due to the construction and set up of the waste-water treatment (WTP) plants described in the text, those indices were expected to steadily improve from their low (i.e. poor) initial values at all locations.

The temporal behavior of each index separately will be modelled by assuming a linear trend, where time (in years) will be the continuous covariate. It is not known a priori whether the data sets fulfill the main assumptions of a regression analysis, i.e. whether there is a) homogeneity of the slopes (i.e. the slopes of the trends are different for different river courses), b) normality of the residuals (i.e. the residuals of the fits follow a Gaussian distribution), c) homogeneity of the variances of the residuals (i.e. variances of residuals are not different between levels of factor), and d) homocedasticity of the residuals (i.e. variance does not vary with expected value).

Homogeneity of the slopes

```
a <- read_excel("..\\Analysis IBMWP and river
course\\BD_Indicadors_Besos.xlsx") a$Course <-
factor(a$Course,levels=c("Headwaters","Middle","Lower"),ordered=F) dat <-
data.frame(Year=c(rep(a$Year,3)),Course=rep(a$Course,3),
                          Y=c(a$IBMWP,a$QBR,a$IPS),Index=c(rep("IBMWP",length(a$IBM
                          WP)),

                                                          rep("QBR",length(a$QBR)),

                                                          rep("IPS",length(a$IPS))))

indices <- c("IBMWP","QBR","IPS")
for (i in indices) print(kable_styling(kbl(as.matrix(summary(
  lm(Y~Year*Course,data=dat[dat$Index==i,]))$coefficients),
  caption=paste("Homogeneity-of-slope test for ",i,"
  index",sep=""),digits=4,
  booktabs=T,linesep=""),latex_options="hold_position"))
```

Firstly, we will test a) by checking if there is an interaction between river course and time.

Table SM1: Homogeneity-of-slope test for IBMWP index.

▽

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-7275.0048	1408.8723	-5.1637	0.0000
Year	3.6866	0.7019	5.2524	0.0000
CourseMiddle	-349.2832	2006.5637	-0.1741	0.8625
CourseLower	1079.5525	2096.4140	0.5150	0.6087
Year:CourseMiddle	0.1484	0.9997	0.1484	0.8826
Year:CourseLower	-0.5802	1.0447	-0.5554	0.5809

Table SM2: Homogeneity-of-slope test for QBR index.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-2049.7384	768.9677	-2.6656	0.0104
Year	1.0576	0.3833	2.7593	0.0082
CourseMiddle	425.6907	1104.0225	0.3856	0.7015
CourseLower	1167.5022	1142.2617	1.0221	0.3119
Year:CourseMiddle	-0.2337	0.5504	-0.4247	0.6729
Year:CourseLower	-0.6118	0.5695	-1.0743	0.2880

Table SM3: Homogeneity-of-slope test for IPS index.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-533.0883	382.5402	-1.3935	0.1804
Year	0.2713	0.1901	1.4270	0.1707
CourseMiddle	78.6163	540.9935	0.1453	0.8861
CourseLower	-156.4033	601.9424	-0.2598	0.7979
Year:CourseMiddle	-0.0399	0.2688	-0.1485	0.8836
Year:CourseLower	0.0749	0.2991	0.2505	0.8050

For each index, factor "Course" does not significantly interact with the "Year" variable at p=0.05 level (see Tables SM2, SM3 and SM4 below). That is, slopes do not depend on whether they refer to high, middle or lower river course. This supports assumption a) and allows us to write our model simply as:

$$Y = a + b \times Year + Course \quad (1)$$

for each index. That is, we fit the data as follows:

```
r <- lapply(setNames(indices,indices),function(i)
lm(Y~Year+Course,data=dat,subset=Index==i))
```

Normality of the residuals

Next, we will check whether a Gaussian distribution is a satisfactory distributional model for the residuals of the fit. To that aim we apply the Shapiro-Wilk test to the corresponding residuals.

Table SM4: Shapiro-Wilk test of normality of residuals

```
re <- sapply(indices,function(i) residuals(r[[i]]))
kable_styling(kbl(as.matrix(sapply(indices,
                    function(i)
                    unlist(shapiro.test(re[[i]])[1:2]))), caption="Shapiro-
                    Wilk test of normality of residuals",digits=4,
                    booktabs=T),latex_options="hold_position")
```


Table SM4: Shapiro-Wilk test of normality of residuals.

	IBMWP	QBR	IPS
statistic.W	0.9779	0.9653	0.9888
p.value	0.3447	0.1188	0.9927

Therefore, we cannot reject the null hypothesis of the Shapiro-Wilk test that the residuals for each index have not been drawn from a Gaussian distribution, thus supporting assumption b).

Homogeneity of variances of residuals.

We will now verify assumption c) that variances of residuals are not different between the high, middle and lower river courses, for every index. To that aim we will apply the Brown-Forsythe test as implemented in the "car" package.

Table SM5: Brown-Forsythe test for homogeneity of variances.

	IBMWP	QBR	IPS
statistic	5e-32	5.7e-31	3e-31
p.value	1e+00	1.0e+00	1e+00

The Brown-Forsythe test statistic is always < 10-30 and shows not significant (p-value~1) for all indices, which confirms assumption c).

Homocedasticity of residuals

Finally, we will check assumption d) of homocedasticity by applying the Breusch-Pagan test from the "olsrr" package.

```
bp <- sapply(indices,function(i) unlist(ols_test_breusch_pagan(r[[i]])[c(1,2)]))
rownames(bp) <- c("statistic","p.value")

kable_styling(kbl(bp,caption="Breusch-Pagan test per
                 index",digits=4,booktabs=T),
                 latex_options="hold_position")
```

Table SM6: Breusch-Pagan test per index.

	IBMWP	QBR	IPS
statistic	1.1684	0.2142	0.0000
p.value	0.2797	0.6435	0.9967

The Breusch-Pagan test for the three indices fails to reject the null hypothesis that we can assume homocedas- ticity of the residuals, hence supporting the hypothesis that data Post-hoc tests for differences between river courses

```
for    (i in indices) {

  plot(ggplot(dat[dat$Index==i,],aes(Year,Y,colour=Course),na.r
    m=TRUE)  +
    scale_colour_manual(values=c("red","blue","green")) +
    geom_point(aes(shape=Course),size=3,na.rm=TRUE)  +
    ylim(0,max(dat$Y))  +
    labs(x="Year",y=i,caption=paste("Figure",which(indices==i)))
    +
    geom_smooth(method=lm,formula=y~x,aes(fill=Course),alph


    theme(axis.text=element_text(size=15),axis.title=element_
          text(size=16),
          plot.caption=element_text(size=16),legend.text=el
          ement_text(size=13),
          legend.title=element_text(size=13)))

  su <- summary(r[[i]])

  pval <-
  pf(su$fstatistic[1],su$fstatistic[2],su$fstatistic[3],lower.tail=
  FALSE)pval  <-  ifelse(round(pval,)==0,"<1e-4",round(pval,4))
  print(kable_styling(footnote(kbl(su$coefficients,digits=4,

                  caption=paste("Summary of regression  results for
                  ",i,sep=""),booktabs=T), general=c(paste("R2/R2-
                  adj.=",round(su$r.squared,4),"/",
                                  round(su$adj.r.squared,4),sep=""),
                            paste("F-statistic/p-
                                  value=",round(su$fstatistic[1],4),"/",
                                  pval,sep="")),
                  general_title=""),latex_options="hold_position"))

res <- lapply(indices,function(i)
  data.frame(x=re[[i]],y=dat$Course[dat$Index==i &
  !is.na(dat$Y)]))

names(res) <- indices

lv  <-  sapply(indices,function(i)
unlist(bf.test(x~y,data=res[[i]],verbose=F)[c(1,3)]))
kable_styling(kbl(lv,caption="Brown-Forsythe test for homogeneity of
variances",

                     digits=32,booktabs=T),latex_options="hold_position")
```

To check whether there are differences between river courses, controlling for the covariate "Year", we will apply the Tukey HSD test. Save for the middle-headwaters difference for the IPS, all differences are shown to be statistically significant at p-value< 0.01.

```
for (i in indices) print(kable_styling(kbl(suppressWarnings(
  TukeyHSD(aov(Y~Year+Course,data=dat,subset=Index==i),
  "Course")$`Course`), caption=paste("Post-hoc  Tukey
  HSD  tests  for  ",i,sep=""),digits=4,booktabs=T),
  latex_options="hold_position"))
```


Supplementary Material 2

Wastewater Treatment Plans of the Besòs river basin

Table SM7. WWTP in the Besòs river basin: * Selected WWTP for the analysis in the research. + 1: Physicochemical, 2: Biological, 2a: Biological with N elimination, 2b: Biological with P elimination and 2c: Biological with N and P elimination. Source: Own elaboration through the data provided by Consorci Besòs Tordera (CBT).

▽

Id	Location	River	Treatment system	Volume of wastewater (m^3/day)	Connected PE (h-e)
1	Besòs	Besòs	2	525,000	2,843,750
2	Montcada	Ripoll	2c	72,600	423,500
*3	La Llagosta	Besòs	2c	43,000	358,333
*4	Montornès del Vallès	Congost	2c	40,000	300,000
5	Sabadell	Ripoll	2c	35,000	296,333
6	Sabadell	Ripoll	2c	30,000	200,000
*7	Granollers	Congost	2c	30,000	121,500
*8	Castellar del Vallès	Ripoll	2c	8,000	76,667
*9	La Roca del Vallès	Mogent	2c	11,700	48,000
10	Centelles	Congost	2c	5,333	35,553
*11	Caldes de Montbui	Caldes	2c	6,000	30,000
*12	La Garriga	Congost	2c	7,000	29,166
*13	Sta Eulàlia de Ronçana	Tenes	2c	5,050	25,250
*14	Vilanova del Vallès	Mogent	2c	5,000	25,000
15	St Antoni de Vilamajor	Mogent	2b	3,300	18,425
*16	Sant Quirze de Safaja	Tenes	2c	2,600	13,650
*17	Cànoves i Samalús	Mogent	2c	2,500	12,500
18	Sant Feliu de Codines	1995	2c	2,900	12,083
19	Matadepera	Ripoll	2	1,500	8,125
*20	Aiguafreda	Congost	2a	1,150	5,942
*21	Bigues i Riells	Tenes	1	920	4,600
22	Sant Llorenç de Savall	Ripoll	2	900	3,000
23	Can Canyameres	Caldes	2	152	800
24	Muntanyà	Congost	2c	6,000	583
25	Font Espardanyera	Ripoll	2	100	500
26	Corró d'amunt	Congost	2	50	300

Supplementary Material 3

Recategorization of the Land Use and Land Cover categories

Table SM8. Recategorization of the LCMC legend for the versions 1997 and 2000.

▽

Recategorization of the LCMC		
Id	Location	River
b	Bosc	Forestal arbrat
cg	Granges	Conreus
ch	Altres conreus herbacis	Conreus
ci	Hivernacles	Conreus
cl	Fruiters no cítrics	Conreus
cv	Vinyers	Conreus
da	Abocadors	Sòl nu urbà
dm	Zones d'extracció minera	Sòl nu urbà
eb	Conreus abandonats - boscos	Conreus
em	Conreus abandonats - matollars	Conreus
ep	Conreus abandonats	Conreus
f	Fruiters	Conreus
gl	Vegetació d'aiguamolls litorals	Aigües continentals
gm	Vegetació d'aiguamolls continentals	
h	Horts	Conreus
ib	Zones cremades	Sòl nu urbà
ka	Autopistes i autovies	Sòl nu urbà
kc	Carreteres	Sòl nu urbà
kg	Zones verdes viàries	Sòl nu urbà
kp	Zones portuàries	Sòl nu urbà
kt	Vies de ferrocarril	Sòl nu urbà
kv	Aeroports	Sòl nu urbà
l	Platges	Aigües continentals
na	Sòls nus urbans no edificats	Sòl nu urbà
nc	Conreus en transformació	Conreus
nl	Lleres naturals	Aigües continentals
nn	Sòl erosionat per agent natural	Sòl nu forestal
o	Oliverars	Conreus
p	Prats	Forestal no arbrat
r	Roquissars	Sòl nu forestal
sc	Càmpings	Sòl nu urbà
sg	Camps de golf	Sòl nu urbà
ss	Zones d'esport	Sòl nu urbà
t	Tarteres	Sòl nu forestall
uc	Artificial compost	Sòl nu urbà
ui	Industrial	Sòl nu urbà
ul	Urbà mixt	Sòl nu urbà
um	Cementiris	Sòl nu urbà
uv	Parcs urbans	Sòl nu urbà
v	Vinyes	Conreus
wb	Basses agrícoles	Aigües continentals
wc	Llacs i llacunes continentals	Aigües continentals
we	Embassaments	Aigües continentals
wl	Llacunes litorals	Aigües continentals
wp	Preses	Sòl nu urbà
wr	Rius	Aigües continentals
wu	Basses urbanes	Aigües continentals

Table SM9. Recategorization of the LCMC legend for the version 2009 and 2016.

▽

Recategorization of the LCMC		
Level 5	Cover	River
baa20	Avetosa (>= 20%cc)	Forestal arbrat
barb20	Arboçar (>= 20%cc)	Forestal arbrat
bca20	Avellanosa (>= 20%cc)	Forestal arbrat
bcad20	Altres caducifolis (>= 20%cc)	Forestal arbrat
bcad5	Altres caducifolis (5- 20%cc)	Forestal arbrat
bcadp	Plantacions d'altres caducifolis	Forestal arbrat
bcon20	Altres coníferes (>=20%cc)	Forestal arbrat
bcs20	Castanyeda (>=20%cc)	Forestal arbrat
bcs5	Castanyeda (5-20%cc)	Forestal arbrat
bcsp	Plantacions de castanyer	Forestal arbrat
bfe20	Freixeneda (>=20%cc)	Forestal arbrat
bfs20	Fageda (>=20%cc)	Forestal arbrat
bfs5	Fageda (5-20%cc)	Forestal arbrat
bph20	Pineda de pi blanc (>= 20%cc)	Forestal arbrat
bph5	Pineda de pi blanc (5- 20%cc)	Forestal arbrat
bphf	Franja de protecció de pi blanc	Forestal arbrat
bphp	Plantacions de pi blanc	Forestal arbrat
bphr	Regeneració de pi blanc	Forestal arbrat
bpm20	Pineda de pi pinastre (>=20% cc)	Forestal arbrat
bpm5	Pineda de pi pinastre (5-20% cc)	Forestal arbrat
bpmf	Franja de protecció de pinastre	Forestal arbrat
bpmp	Plantacions de pinastre	Forestal arbrat
bpmr	Regeneració de pinastre	Forestal arbrat
bpp20	Pineda de pi pinyer (>= 20%cc)	Forestal arbrat
bpp5	Pineda de pi pinyer (5- 20%cc)	Forestal arbrat
bppf	Franja de protecció de pi pinyer	Forestal arbrat
bppp	Plantacions de pi pinyer	Forestal arbrat
bps20	Pineda de pi roig	Forestal arbrat
bpsp	Plantacions de pi roig	Forestal arbrat
bqc20	Roureda de roure africà (>=20% cc)	Forestal arbrat

bqc5	Roureda de roure africà (5-20% cc)	Forestal arbrat
bqf20	Roureda de roure de fulla menuda (>=20% cc)	Forestal arbrat
bqh20	Roureda de roure martinenc (>= 20%cc)	Forestal arbrat
bqh5	Roureda de roure martinenc (5-20%cc)	Forestal arbrat
bqhf	Franja de protecció de roure martinenc	Forestal arbrat
bqhr	Regeneració de roure martinenc	Forestal arbrat
bqi20	Alzinar (>= 20%cc)	Forestal arbrat
bqi5	Alzinar (5-20%cc)	Forestal arbrat
bqif	Franja de protecció d'alzina	Forestal arbrat
bqir	Regeneració d'alzina	Forestal arbrat
bqp20	Roureda de roure de fulla gran (>= 20%cc)	Forestal arbrat
bqp5	Roureda de roure de fulla gran (5-20%cc)	Forestal arbrat
bqr20	Roureda de roure pènol (>= 20%cc)	Forestal arbrat
bqr5	Roureda de roure pènol (5-20%cc)	Forestal arbrat
bqs20	Sureda (>= 20%cc)	Forestal arbrat
bqs5	Sureda (5-20%cc)	Forestal arbrat
bqsf	Franja de protecció d'alzina surera	Forestal arbrat
bribc20	Boscos caducifolis de ribera amb una cobertura (>= 20%cc)	Forestal arbrat
bribc5	Boscos caducifolis de ribera amb una cobertura (5-20%cc)	Sòl nu urbà
canya	Canyars	Forestal no arbrat
cd	Prats de dall	Forestal no arbrat
ch	Altres conreus herbacis	Conreus
chb	Altres conreus herbacis en bancals	Conreus
chbr	Altres conreus herbacis en bancals en regadiu	Conreus
chr	Altres conreus herbacis en regadiu	Conreus
ci	Hivernacles	Conreus
cii	Conreus d'horta sota plàstic	Conreus
cl	Fruiters no cítrics	Conreus
clb	Fruiters no cítrics en bancals	Conreus
clbr	Fruiters no cítrics en bancals en regadiu	Conreus
clr	Fruiters no cítrics en regadiu	Conreus
co	Oliverars	Conreus
cor	Oliverars en regadiu	Conreus
cv	Vinyes	Conreus
da	Abocadors	Sòl nu urbà
dip	Altres construccions	Sòl nu urbà
eia	Edificis aïllats	Sòl nu urbà
eb	Conreus abandonats - boscos	Conreus
ehp	Altres conreus herbacis abandonats - prats en zones agrícoles	Conreus
ehpr	Altres conreus herbacis abandonats regadiu no regat - prats en zones	Conreus
elp	Fruiters no cítrics abandonats- prats en zones agrícoles	Conreus
elpr	Fruiters no cítrics abandonats regadiu no regat - prats en zones	Conreus
em	Conreus abandonats - matollars	Conreus
eme	Edificis entre mitgeres	Sòl nu urbà
epf	Conreus abandonats - prats en zones forestals	Conreus
evp	Vinyes abandonades - prats en zones agrícoles	Conreus

gm	Vegetació d'aiguamolls continentals	Aigües continentals
had	Habitatges unifamiliars adossats	Sòl nu urbà
hua	Habitatges unifamiliars aïllats	Sòl nu urbà
l	Platges	Aigües continentals
m	Matollars	Forestal no arbrat
mel	Matollars en línies elèctriques	Forestal no arbrat
mf	Matollars en tallafocs	Forestal no arbrat
mfp	Franja de protecció de matollars	Forestal no arbrat
mr	Matollars de formacions de ribera	Forestal no arbrat
mt	Matollars procedents de tallades arreu	Forestal no arbrat
na	Sòls nus urbans no edificats	Sòl nu urbà
nac	Zones urbanes en construcció	Sòl nu urbà
nau	Naus	Sòl nu urbà
nc	Conreus en transformació	Conreus
nl	Lleres naturals	Aigües continentals
nn	Sòl erosionat per agent natural	Sòl nu forestal
nna	Sòl nu per acció antrópica	Sòl nu urbà
nnael	Sòl nu en línies elèctriques	Sòl nu urbà
nnt	Sòl nu en tallafocs	Sòl nu forestal
p	Prats i herbassars	Forestal no arbrat
pam	Prats i herbassars d'alta muntanya	Forestal no arbrat
pcon	Plantacions de coníferes no autòctones	Forestal arbrat
pel	Prats i herbassars en línies elèctriques	Forestal no arbrat
peu	Plantacions d'eucaliptus	Forestal arbrat
pfp	Franja de protecció de prats i herbassars	Forestal no arbrat
pk	Zones d'aparcament	Sòl nu urbà
pkc	Grans vials	Sòl nu urbà
pkv	Àrees de vianants sense vegetació	Sòl nu urbà
ppl	Plantacions de plàtans	Forestal arbrat
ppo	Plantacions de pollancres	Forestal arbrat
pt	Prats i herbassars procedents de tallades arreu	Forestal no arbrat
r	Roquissars	Sòl nu forestal
ra	Rompudes agrícoles	Conreus
t	Tarteres	Sòl nu forestal
tgv	Moviments de terres	Sòl nu urbà
viva	Vivers agrícoles	Conreus
vivef	Vivers forestalls	Conreus
wb	Basses agrícoles	Aigües continentals
wc	Llacs i llacunes continentals	Aigües continentals
we	Embassaments	Aigües continentals
wr	Rius	Aigües continentals
wu	Basses urbanes	Aigües continentals
zu	Zones verdes artificials urbanes	Sòl nu urbà
zua	Arbrat urbà	Sòl nu urbà
wu	Basses urbanes	Aigües continentals
zu	Zones verdes artificials urbanes	Sòl nu urbà
zua	Arbrat urbà	Sòl nu urbà

Supplementary Material 4

The statistical analysis of the assessment of the effects of the WWTP on the ecological quality status

Temporal evolution of NH_4^+ and Conductivity
NH_4^+ vs. time

We first read the dataset, which includes temporal NH_4^+ concentration and Conductivity data, and select the former.

```
a <- data.frame(read_excel("G:/TD_Toni/PUBLICACIONS/Paper EDARS
Besos/Model_EDAR's.xlsx"))
x <- NULL
y <- NULL
for (i in 2:ncol(a)) if (length(grep("NH4",colnames(a)[i]))==1)
{
  x <- c(x,a[!is.na(a[,i]),1])
  y <- c(y,a[!is.na(a[,i]),i])
}
```

A plot of mean anual [NH_4^+] vs. time (Figure 4) shows a trend towards lower values at recent years, i.e. after WWT plants were installed. There are also some outlier data points higher than NH_4^+=25 and larger than Year=2006 that do not follow that trend.

```
ggplot(data.frame(x=x,y=y),aes(x,y),na.rm=TRUE) +
  geom_point(size=3,na.rm=TRUE,colour="black") +
  labs(x="Year",y="[NH4+] (mg/l)",caption="Figure 4") +
  theme(axis.text=element_text(size=15),axis.title=element_text(
size=16),
        plot.caption=element_text(size=16))
```

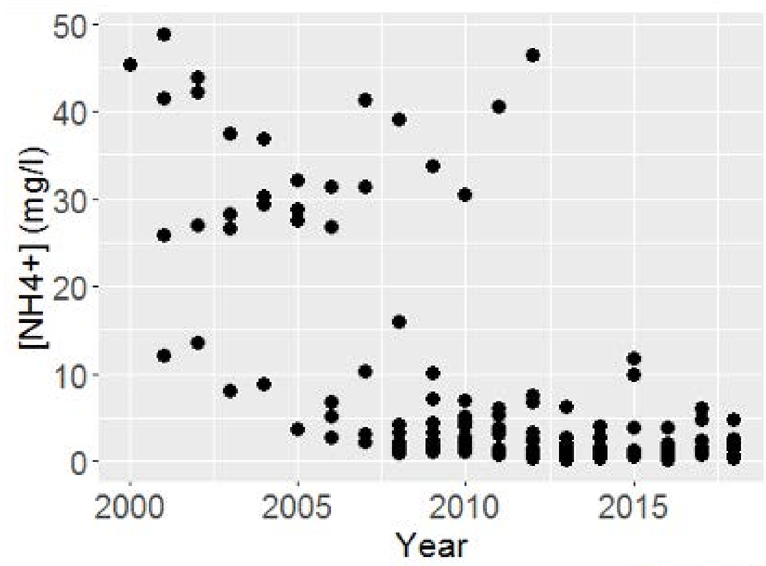



Figure 4

Once we filter out those points where NH_4^+>25 and Year>2006, we notice (not shown) that the variance of NH_4^+ (*Var* NH_4^+ hereafter) apparently increases with its expected value (μNH_4^+ hereafter). That suggests the presence of heteroscedasticity (i.e. data variance varies with expected value), hindering the application of standard linear regression techniques. Thus, we set up a simple procedure to find out which power function of μNH_4^+ would best explain the relationship between μNH_4^+ and *Var* NH_4^+. Thus, *Var* NH_4^+ is regressed against increasing powers of μNH_4^+ and their corresponding AIC values are compared.

```
outlier <- x>2006 & y>25
x <- x[!outlier]
y <- y[!outlier]
mean.y <- sapply(min(x):max(x),function(i) mean(y[x==i]))
var.y <- sapply(min(x):max(x),function(i) var(y[x==i]))
tabl <- data.frame(Model=c("Null","$\\mu$","$\\mu^2$","$\\mu^3$"
,"$\\mu^4$"),
                   AIC=c(AIC(lm(var.y~1)),
                         sapply(1:4,function(i) AIC(lm(var.y~-1+
I(mean.y^i))))))
kable(tabl,caption="AIC values for different power functions of
the mean",digits=4)
```

Table SM10. AIC values for different power functions of the mean.

▽

Model	AIC
Null	216.1419
µ	172.3329
µ^2	183.0212
µ^3	191.2311
µ^4	196.4398

The results of this analysis indicates that it is reasonable to assume a relationship *Var* $NH_4^+\mu$, leading us to choose a quasi-likelihood approach (Wedderburn 1974). Next, an inspection of Figure 2 above suggests that the NH_4^+ concentration data be fitted with the following function:

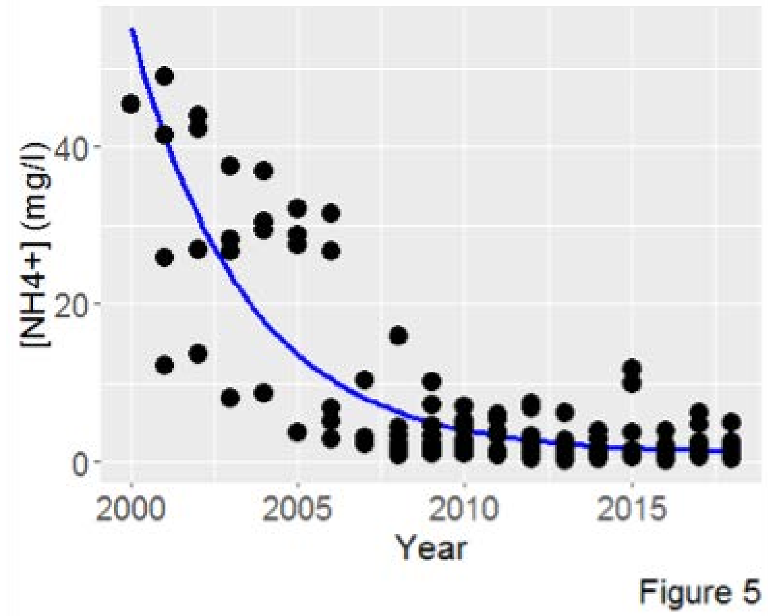
(Equation 2)

$$Y = a + b \times e^{-c \times Y}$$

where Y stands for either NH_4^+ , Y indicates time (in years), and a, b and c are the parameters to be calculated. Equation 2 allows for the visible drop in NH_4^+ as time increases. It also accounts for a basal value, i.e. a minimum value (represented by parameter a) that Y would eventually reach at $T \to \infty$. The evident nonlinearity of Equation 2 in the parameters a,b,c has led us to apply the function "gnm" from the "gnm" R package (Turner and Firth 2007).

```
xx <- x-2000
z <- coef(lm(log(y)~xx))  # First educated guess.
z <- coef(gnm(y~1+Mult(1,Inv(Exp(x))),verbose=F,start=c(0,exp(z[
1]),-z[2])))
r.gnm <- gnm(y~1+Mult(1,Inv(Exp(xx))),start=z,
             family=quasi(link="identity",variance="mu"),verbose
=F)
x.new <- data.frame(xx=seq(2000,2018,length=100)-2000)
ggplot(data.frame(x,y),aes(x,y),na.rm=TRUE) +

  labs(x="Year",y="[NH4+] (mg/l)",caption="Figure 5") +
  theme(axis.text=element_text(size=15),axis.title=element_text(
size=16),
        legend.text.align=0,legend.text=element_text(size=14),
        plot.caption=element_text(size=16)) +
  geom_line(data=data.frame(x=x.new$xx+2000,
                            y=predict(r.gnm,newdata=x.new)),colo
r="blue",size=1.2) +
  geom_point(size = 4,na.rm=TRUE,colour="black")
```


```
s <- summary(r.gnm)$coefficients
rownames(s) <- c("a","b","c")
kable(s,caption="Regression coefficients for the non-linear gamm
a regression",digits=4)
```

Table SM11. Regression coefficients for the non-linear gamma regression.

▽

	Estimate	Std. Error	t value	Pr(>|t|)
a	1.1309	0.5012	2.2563	0.0256
b	53.9569	6.4957	8.3065	0.0000
c	0.2924	0.0332	8.8007	0.0000

Conductivity vs. time

Next, we select the Conductivity data.

```
x <- NULL
y <- NULL
columnlabs <- colnames(a)
for (i in 2:ncol(a)) if (length(grep("Conductivitat",columnlabs[
i]))==1) {
  x <- c(x,a[!is.na(a[,i]),1])
  y <- c(y,a[!is.na(a[,i]),i])
}
```

Similar to the NH_4^+ data, a plot of Conductivity vs. time (Figure 6) shows a trend towards lower values at recent years. Likewise, there are some outlier points higher than Conductivity=3000 and larger than Year=2007 that depart from that trend.

```
ggplot(data.frame(x=x,y=y),aes(x,y),na.rm=TRUE) +
  geom_point(size=3,na.rm=TRUE,colour="black") +
  labs(x="Year",y="Conductivity (卯桔S/cm)",caption="Figure 6")
+
  theme(axis.text=element_text(size=15),axis.title=element_text(
size=16),
        plot.caption=element_text(size=16))
```

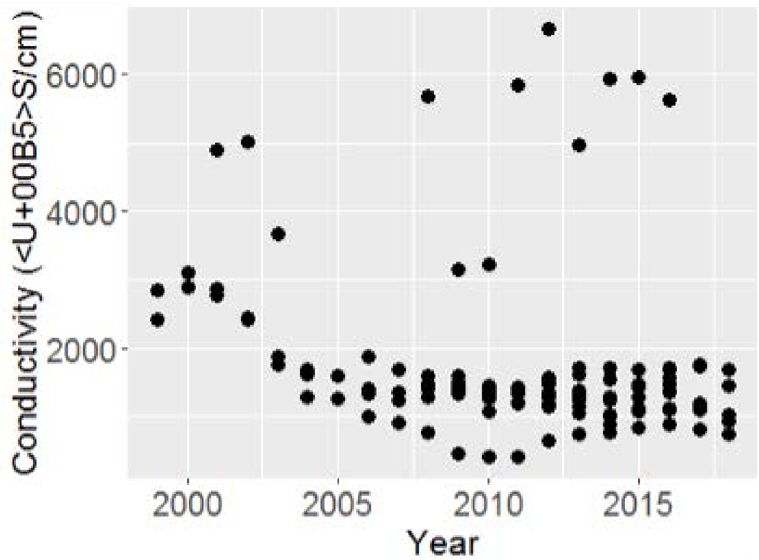


Figure 6

Unlike the NH_4^+ data, however, due to the difficulty of defining a consistent variance-mean function that may account for the observed relationship we have simply fitted the dataset by non-linear least-squares with Eq. 2 as our model. Although the final fit seems very reasonable (see Figure 7), we must keep in mind that the standard error of the regression coefficients may be biased due to the presence of unaccounted heteroscedasticity, though the coefficients themselves are unbiased. Therefore, care must be exerted when interpreting the statistical significance of those coefficients.


```
outlier <- x>2007 & y>3000
x <- x[!outlier]
y <- y[!outlier]
r.nls <- nls(y~a+b*exp(-c*(x-2000)),start=list(a=1000,b=1400,c=.
2))
ggplot(data.frame(x=x,y=y),aes(x,y),na.rm=TRUE) +
  geom_point(size=3,na.rm=TRUE,colour="black") +
  labs(x="Year",y="Conductivity (µS/cm)",caption="Figure 7") +
  theme(axis.text=element_text(size=15),axis.title=element_text(
size=16),
        plot.caption=element_text(size=16)) +
  geom_line(data=data.frame(x=seq(1999,2018,by=.1),
                            y=predict(r.nls,newdata=data.frame(x
=seq(1999,2018,by=.1)))),
            size=1.2,color='blue') + ylim(0,max(y)+200)

kable(summary(r.nls)$coefficients,
      caption="Regression coefficients for the Conductivity vs.
Year model",digits=4)
```

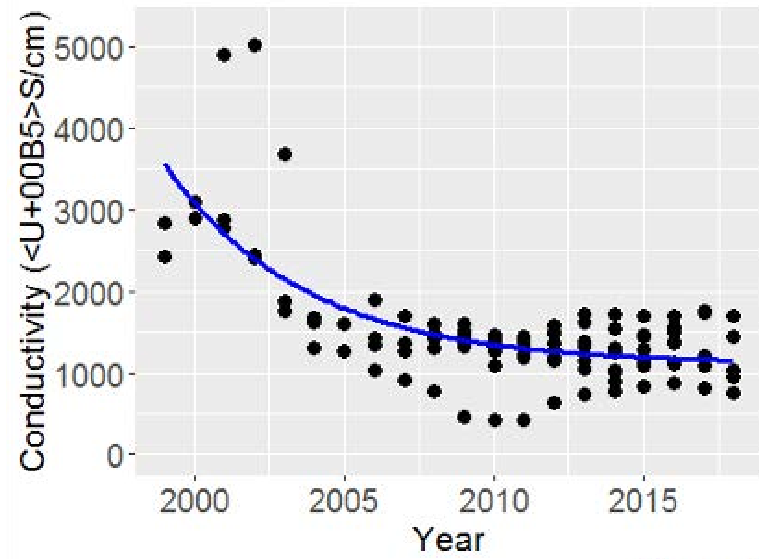


Figure 7

Table SM12. Regression coefficients for the Conductivity vs. Year model.

▽

	Estimate	Std. Error	t value	Pr(>|t|)
a	1110.0283	107.9791	10.2800	0
b	1977.9528	187.0510	10.5744	0
c	0.2139	0.0462	4.6264	0

Dependence of IBMWP on NH_4^+ and Conductivity

The final stage in the analysis of our WTP data consists of understanding the dependence of the IBMWP index on NH_4^+ and Conductivity.

Correlation between NH_4^+ and Conductivity

Before setting up any model to account for the aforementioned dependence we must figure out whether that dependence can be studied separately (i.e. two separate regressions IBMWP~NH_4^+ and IBMWP~Conductivity) or not. To that aim we can plot NH_4^+ vs. Conductivity and carry out a test for association between both variables with the Pearson correlation coefficient. Although the test shows a statistical significance very close to 0.05, the low Pearson correlation (≈0.18) and the relatively unclear relationship shown in Figure 8 have prompted us to treat the dependence of IBMWP on NH_4^+ and Conductivity separately.

```
NH4.stations <- c("NH4_Caldes","NH4_Castellar", "NH4_Congost", "
NH4_Canoves",
                  "NH4_SantQuirzeS","NH4_Bigues","NH4_LaRoca", "
NH4_LaGarriga",
                  "NH4_Granollers","NH4_LaLlagosta", "NH4_Vilano
va")
Con.stations <- c("Conductivitat_Caldes","Conductivitat_Castella
r",
                  "Conductivitat_Congost","Conductivitat_Canoves
",
                  "Conductivitat_SantQuirzeS","Conductivitat_Big
ues",
                  "Conductivitat_LaRoca","Conductivitat_LaGarrig
a",
                  "Conductivitat_Granollers","Conductivitat_LaLl
agosta",
                  "Conductivitat_Vilanova")
x <- NULL
y <- NULL
for (i in 1:length(NH4.stations)) {
  j <- match(NH4.stations[i],colnames(a))
  k <- match(Con.stations[i],colnames(a))
  if (!is.na(j) & !is.na(k)) {
    x <- c(x,a[,j])
    y <- c(y,a[,k])
  }
}
ggplot(data.frame(x=x,y=y),aes(x,y),na.rm=TRUE) +
  geom_point(size=3,na.rm=TRUE,colour="black") +
  labs(x="NH4+",y="Conductivity",caption="Figure 8") +
  geom_smooth(method="lm",alpha=0.1,na.rm=TRUE) +
  theme(axis.text=element_text(size=15),axis.title=element_text(
size=16),
        plot.caption=element_text(size=16))
kable(t(unlist(cor.test(x,y,method="pearson")[c(4,1,2,3)])),
      caption="Pearson correlation test between NH4+ and Conduct
ivity")
```

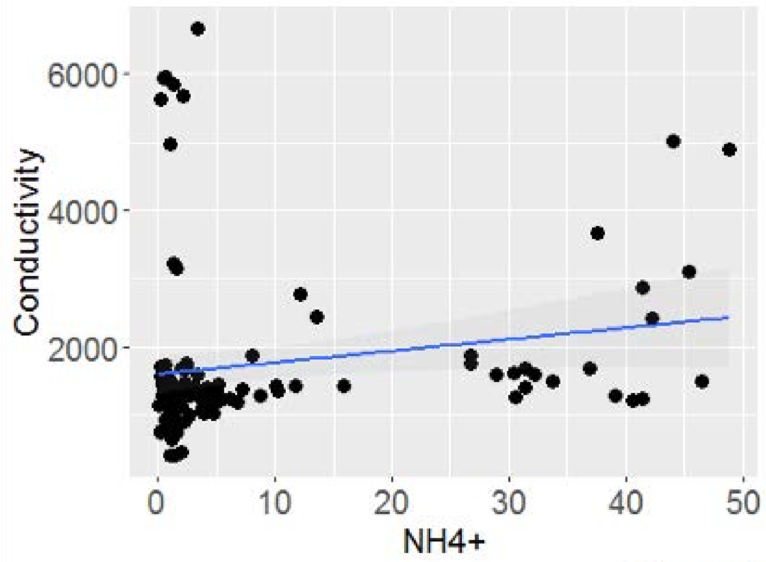



Figure 8

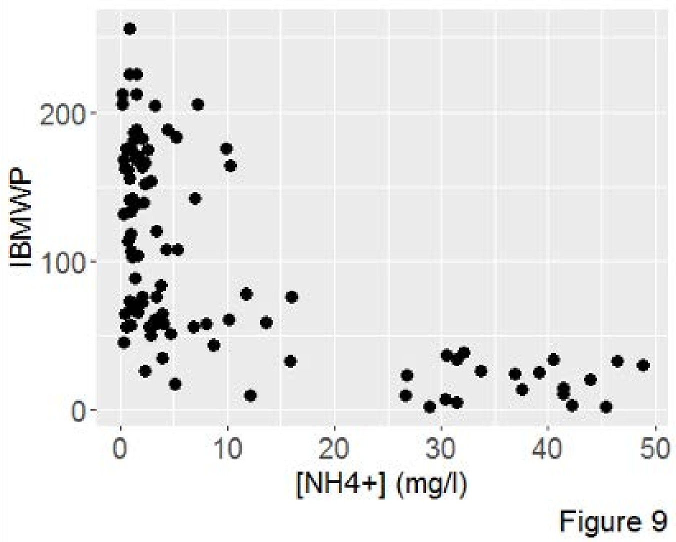
Table SM13. Pearson correlation test between NH4+ and Conductivity.

estimate.cor	statistic.t	parameter.df	p.value
0.1824688	1.955254	111	0.0530669

IBMWP as a function of NH_4^+

When the NH_4^+ vs. IBMWP data are plotted (Figure 9), a dependence between expected value μ_{IBMWP} and variance Var_{IBMWP} seems conspicuous. That is, points with lower IBMWP value show less dispersion than points with higher IBMWP values. We therefore assume that IBMWP variance is proportional to a power of IBMWP mean.

```
IBM.stations <- c("IBMWP_Caldes","IBMWP_Castellar", "IBMWP_Congo
st", "IBMWP_Canoves",
                  "IBMWP_SantQuirzeS","IBMWP_Bigues","IBMWP_LaRo
ca", "IBMWP_LaGarriga",
                  "IBMWP_Granollers","IBMWP_LaLlagosta", "IBMWP_
Vilanova")
x <- NULL
y <- NULL
for (i in 1:length(NH4.stations)) {
  j <- match(NH4.stations[i],colnames(a))
  k <- match(IBM.stations[i],colnames(a))
  if (!is.na(j)) {
    x <- c(x,a[,j])
    y <- c(y,a[,k])
  }
}
j <- is.na(x) | is.na(y)
x <- x[!j]
y <- y[!j]
ggplot(data.frame(x=x,y=y),aes(x,y),na.rm=TRUE) +
  geom_point(size = 3,na.rm=TRUE,colour="black") +
  labs(x = "[NH4+] (mg/l)", y = "IBMWP",caption="Figure 9") +
  theme(axis.text=element_text(size=15),axis.title=element_text(
size=16),
        plot.caption=element_text(size=16))
```



To decide upon the best model to describe the observed relationship between Var_{IBMWP} and $v\mu_{IBMWP}$ we have taken the same approach as in Table 10.

```
xi <- seq(min(x),max(x),length=10)
mean.y <- sapply(2:length(xi),function(i) mean(y[x>=xi[i-1] & x<
xi[i]]))
var.y <- sapply(2:length(xi),function(i) sd(y[x>=xi[i-1] & x<xi[
i]])^2)
tabl <- data.frame(Model=c("Null","$\\mu$","$\\mu^2$","$\\mu^3$"
,"$\\mu^4$"),
                   AIC=c(AIC(lm(var.y~1)),
                         sapply(1:4,function(i) AIC(lm(var.y~-1+
I(mean.y^i))))))
kable(tabl,caption="AIC values for different power functions of
the mean",digits=4)
```

Table SM14. AIC values for different power functions of the mean.

▽

Model	AIC
Null	144.2623
μ	126.8495
μ^2	124.1605
μ^3	128.5074
μ^4	131.2149

The smallest AIC coefficient is found for Var_{IBMWP} μ^2_{IBMWP}, which is equivalent to assuming a constant coefficient of variation. Therefore, we will fit the data with the non-linear model in Equation 3 and with a gamma distributional model. In this case, a model with a basal constant (i.e. the value of IBMWP for $NH_4^+ \rightarrow \infty$) would not be realistic.

(Equation 3)

$$Y= b\ x\ e^{-c\ x\ Y}$$

```
z <- coef(lm(log(y)~x))  # Some guesses.
z <- coef(gnm(y~-1+Mult(1,Inv(Exp(x))),verbose=F,start=c(exp(z[1
]),-z[2])))
r.gnm <- gnm(y~-1+Mult(1,Inv(Exp(x))),start=z,family=Gamma("iden
tity"),verbose=F)
ggplot(data.frame(x=x,y=y),aes(x,y),na.rm=TRUE) +
  geom_point(size = 3,na.rm=TRUE,colour="black") +
  labs(x="[NH4+] (mg/l)",y="IBMWP",caption="Figure 10") +
  theme(axis.text=element_text(size=15),axis.title=element_text(
size=16),
        plot.caption=element_text(size=16)) +
  geom_line(data=data.frame(x=seq(min(x),max(x),by=1),
                            y=predict(r.gnm,newdata=data.frame(x
=seq(min(x),max(x),by=1)))),
            size=1.2,color='blue') + ylim(0,max(y))
```

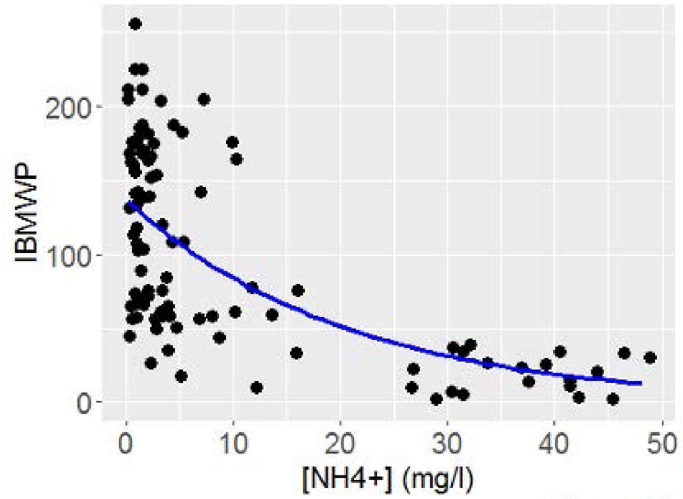


Figure 10

```
su <- summary(r.gnm)$coefficients
rownames(su) <- c("b","c")
kable(su,caption="Regression coefficients for the IBMWP vs. NH$_
4^+$ model",digits=4)
```

Table SM15. Regression coefficients for the IBMWP vs. NH_4^+ model.
▽

	Estimate	Std. Error	t value	Pr(>|t|)
b	137.2653	9.0642	15.1437	0
c	0.0493	0.0038	12.9154	0

IBMWP as a function of Conductivity

Similar to the NH_4^+ vs. IBMWP analysis, in this case a dependence between expected value μ_{IBMWP} and variance Var_{IBMWP} is also apparent (Figure 11). Therefore, we will assume again that IBMWP variance is proportional to a power of IBMWP mean.

```
x <- NULL
y <- NULL
for (i in 1:length(Con.stations)) {
  j <- match(Con.stations[i],colnames(a))
  k <- match(IBM.stations[i],colnames(a))
  if (!is.na(j)) {
    x <- c(x,a[,j])
    y <- c(y,a[,k])
  }
}
j <- is.na(x) | is.na(y)
x <- x[!j]
y <- y[!j]
ggplot(data.frame(x=x,y=y),aes(x,y),na.rm=TRUE) +
  geom_point(size = 3,na.rm=TRUE,colour="black") +
  labs(x="Conductivity",y="IBMWP",caption="Figure 11") +
  theme(axis.text=element_text(size=15),axis.title=element_text(
size=16),
        plot.caption=element_text(size=16))
```

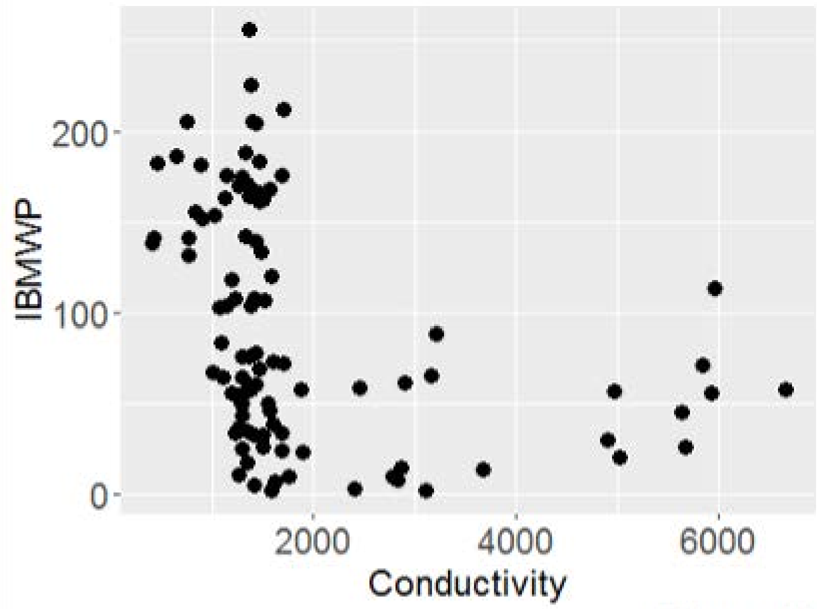


Figure 11

The best model to describe the observed relationship between Var_{IBMWP} and μ_{IBMWP} is found likewise.

```
xi <- seq(min(x),max(x),length=10)
mean.y <- sapply(2:length(xi),function(i) mean(y[x>=xi[i-1] & x<
xi[i]]))
var.y <- sapply(2:length(xi),function(i) sd(y[x>=xi[i-1] & x<xi[
i]])^2)
tabl <- data.frame(Model=c("Null","$\\mu$","$\\mu^2$","$\\mu^3$"
,"$\\mu^4$"),
                   AIC=c(AIC(lm(var.y~1)),
                         sapply(1:4,function(i) AIC(lm(var.y~-1+
I(mean.y^i))))))
kable(tabl,caption="AIC values for different power functions of
the mean",digits=4)
```

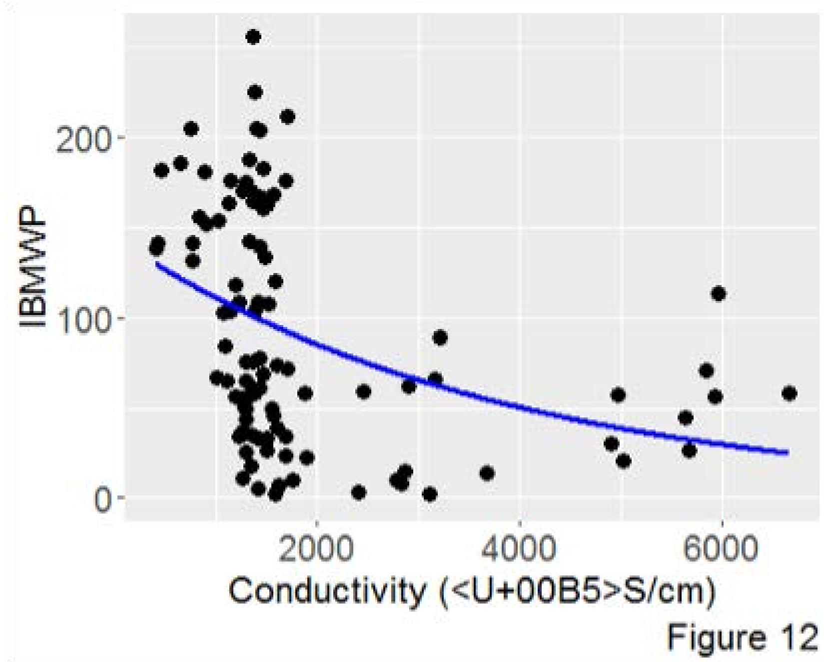
Table SM16. AIC values for different power functions of the mean.

▽

Model	AIC
Null	124.7115
μ	123.7695
μ^2	127.3699
μ^3	129.0755
μ^4	129.8422

The smallest AIC coefficient is found for Var_{IBMWP} μ_{IBMWP}. This means that a Gamma distributional model may not be appropriate for the dataset. Therefore, we have turned again to quasi-likelihood models with the help of the “gnm” R package and the use of Equation 3.

```
z <- coef(lm(log(y)~x))  # Some guesses.
z <- coef(gnm(y~-1+Mult(1,Inv(Exp(x))),verbose=F,start=c(exp(z[1
]),-z[2])))
r.gnm <- gnm(y~-1+Mult(1,Inv(Exp(x))),start=z,
             family=quasi(link="identity",variance="mu"),verbose
=F)
ggplot(data.frame(x=x,y=y),aes(x,y),na.rm=TRUE) +
  geom_point(size = 3,na.rm=TRUE,colour="black") +
  labs(x="Conductivity (丣特S/cm)",y="IBMWP",caption="Figure 12"
) +
  theme(axis.text=element_text(size=15),axis.title=element_text(
size=16),
        plot.caption=element_text(size=16)) +
  geom_line(data=data.frame(x=seq(min(x),max(x),by=1),
                            y=predict(r.gnm,newdata=data.frame(x
=seq(min(x),max(x),by=1)))),
            size=1.2,color='blue') + ylim(0,max(y))
```


```
su <- summary(r.gnm)$coefficients
rownames(su) <- c("b","c")
kable(su,caption="Regression coefficients for the IBMWP vs. Cond
uctivity model",digits=4)
```

Table SM17. Regression coefficients for the IBMWP vs. Conductivity model.

▽

	Std.			
	Estimate	Std. Error	t value	Pr(>|t|)
b	144.1966	18.6196	7.7443	0e+00
c	0.0003	0.0001	3.6538	4e-04

Supplementary Material 5

Articles from the thematic literature review

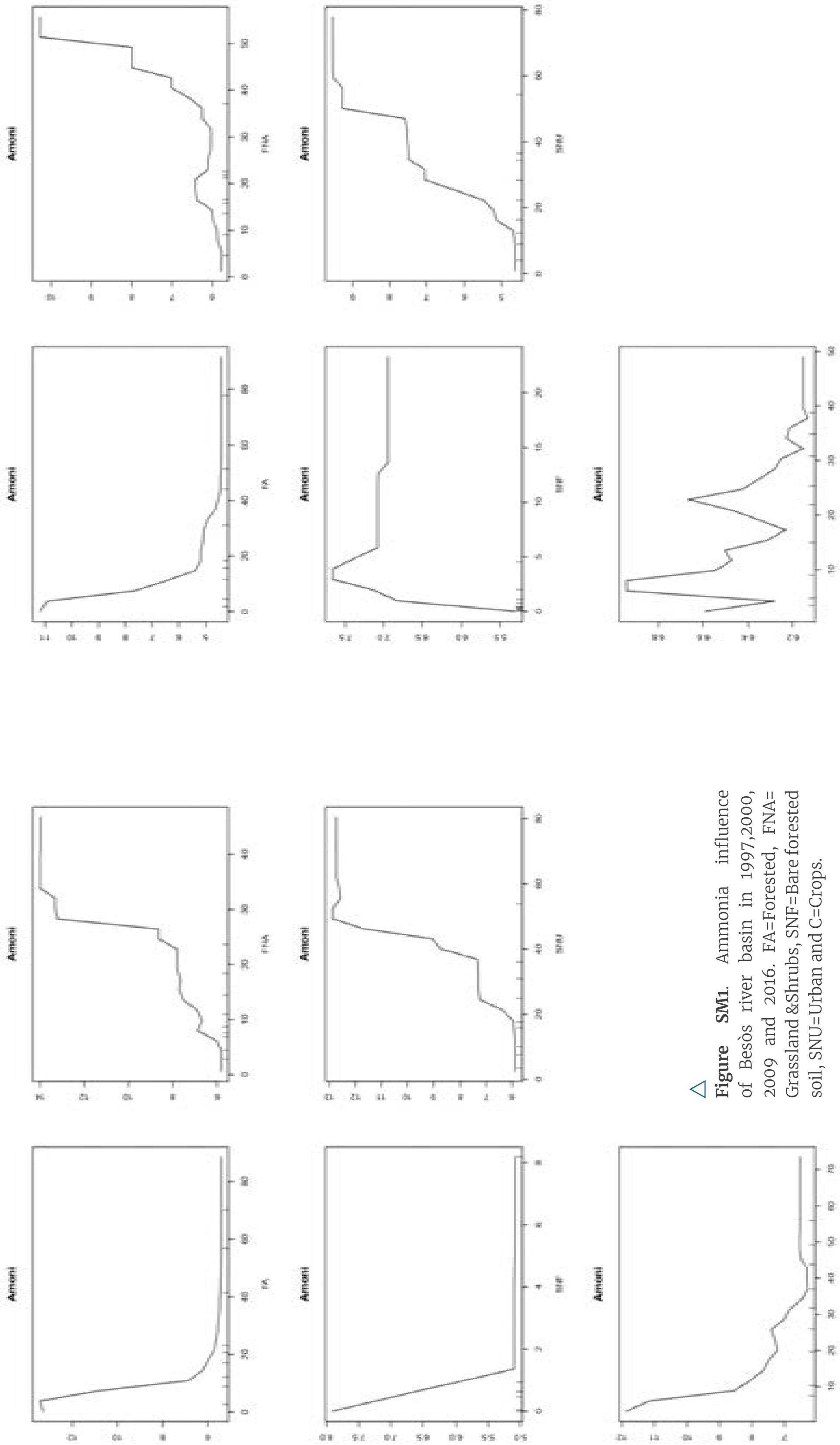
Table SM18. Reviewed articles trough the thematic literature review. Source: Own elaboration through the data obtained from the Web of Science (WOS).

▽

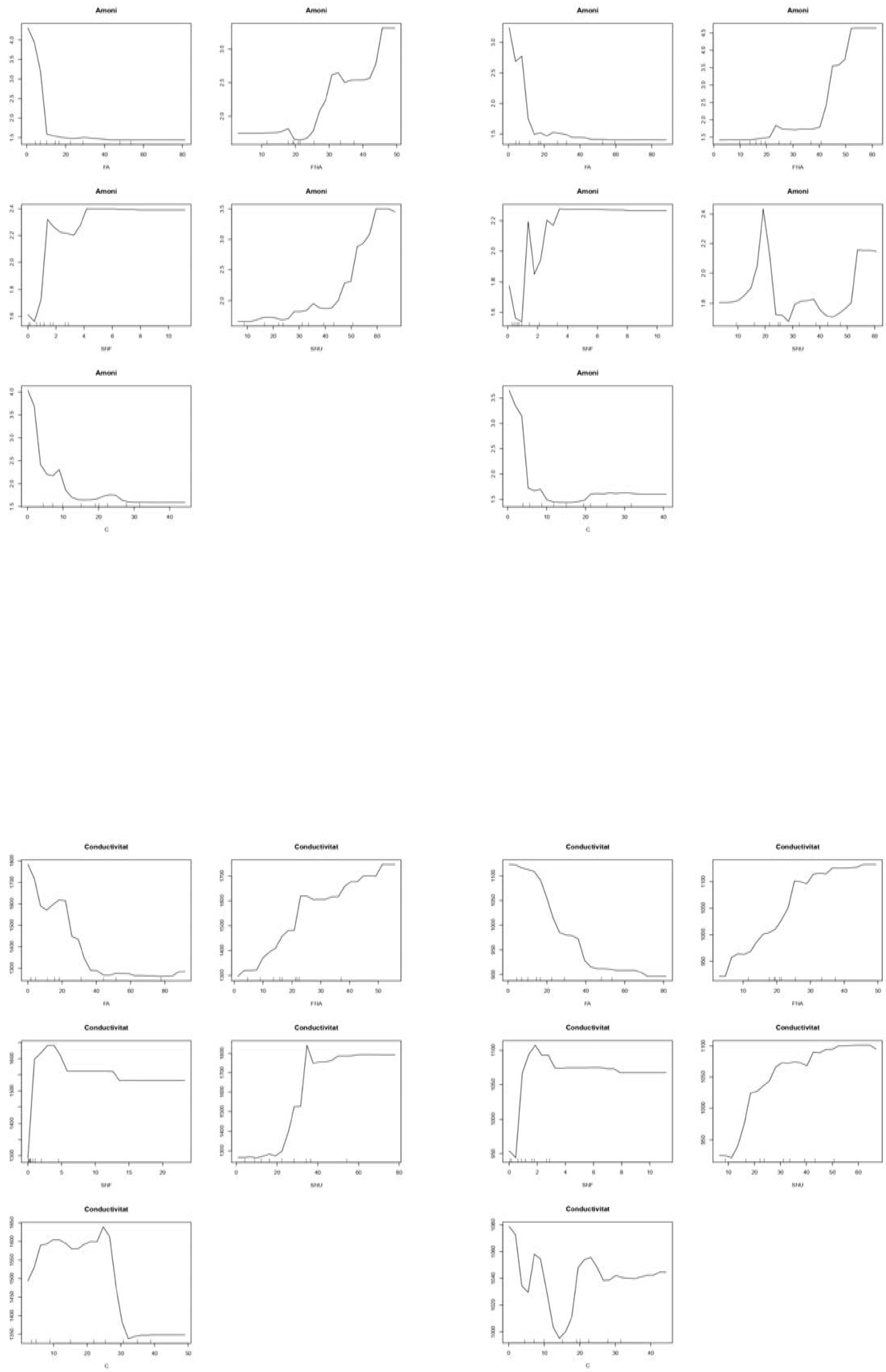
Article no.	Authors (year) and location	Aims
1	Ortiz, Martí and Puig (2005). Catalonia (Spain)	To assess the effects of the point source on the structure and functional organization of the benthic macroinvertebrate community
2	Ortiz and Puig (2007). Catalonia (Spain)	To assess the effects of the point source on the structure and functional organization of the benthic macroinvertebrate community
3	Kroll, Navarro-Llácer, Cano and Heras (2009). Castilla-La Mancha (Spain)	To determine the influence of land use on the quality of the fluvial ecosystems within Castilla-La Mancha, Spain
4	Pinto, Varandas, Coimbra, Carrola and Fontaínhas-Fernandes (2010). Portugal	To evaluate the effect of the wastewater treatment plant (WWTP) in Febros River water quality and ecosystem health through gudgeon (Gobio gobio) and mullet (Mugilcephalus) liver histopathology (biomarker) and some macroinvertebrate community indexes and metrics (bioindicator)
5	Ladrera and Prat (2013). La Rioja (Spain)	To find out the macroinvertebrate community and biotic indices provoked by anthropogenic activities derived
6	Halabruka, Lawrence, Bischel, Hsiao, Plumlee, Resh and Luthy (2013) California (USA)	To assess the economic and ecological merits of a recycled water project that opted for an inland release of tertiary-treated recycled water in a small stream and wetland compared to an ocean outfall discharge
7	Arnon, Avni and Gafny (2015). Israel	To evaluate how the improvement in the treated wastewater quality from the secondary to the tertiary level influenced N uptake, P uptake, and macroinvertebrate assemblage
8	Colin, Maceda-Veiga, Flor-Arnau, Mora, Fortuño, Vieira, Prat, Cambra and de Sostoa (2016). Catalonia (Spain)	To evaluate the ecological impact of textile industry waste in a Mediterranean river using diversity measures and scores of 10 bioindicators based on diatoms, macrophytes, macroinvertebrates and fish
9	Ruhí, Acuña, Barceló, Huerta, Mor, Rodríguez-Mozaz and Sabater (2016). Catalonia (Spain)	To study the entrance of emerging pollutants and their flow through riverine food webs in an effluent- influenced river through the analysis of the composition and concentrations of a broad spectrum of PhACs (25 compounds) and EDCs (12 compounds) in water, biofilm, and three aquatic macroinvertebrate taxa with different trophic positions and feeding strategies
10	Sànchez-Morales, Sabater and Muñoz (2018). Catalonia (Spain)	To determine how hyporheic habitat are affected by wastewater discharges

Supplementary Material 6

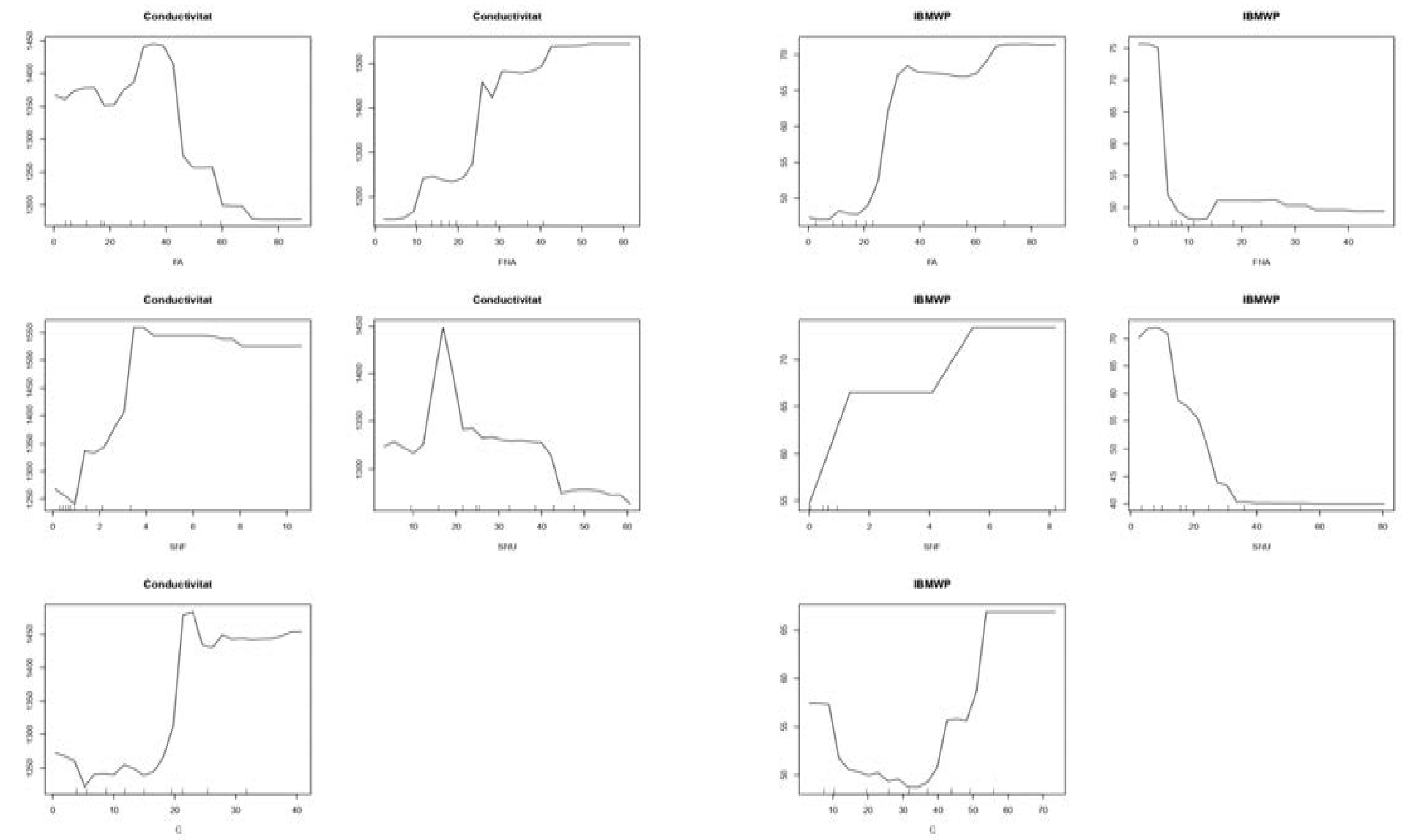
The LULC importance on the water quality indicators



◁ **Figure SM1**. Ammonia influence of Besòs river basin in 1997,2000, 2009 and 2016. FA=Forested, FNA= Grassland &Shrubs, SNF=Bare forested soil, SNU=Urban and C=Crops.



△
Figure SM2. Ammonia influence of Besòs river basin in 1997,2000, 2009 and 2016. FA=Forested, FNA= Grassland &Shrubs, SNF=Bare forested soil, SNU=Urban and C=Crops.



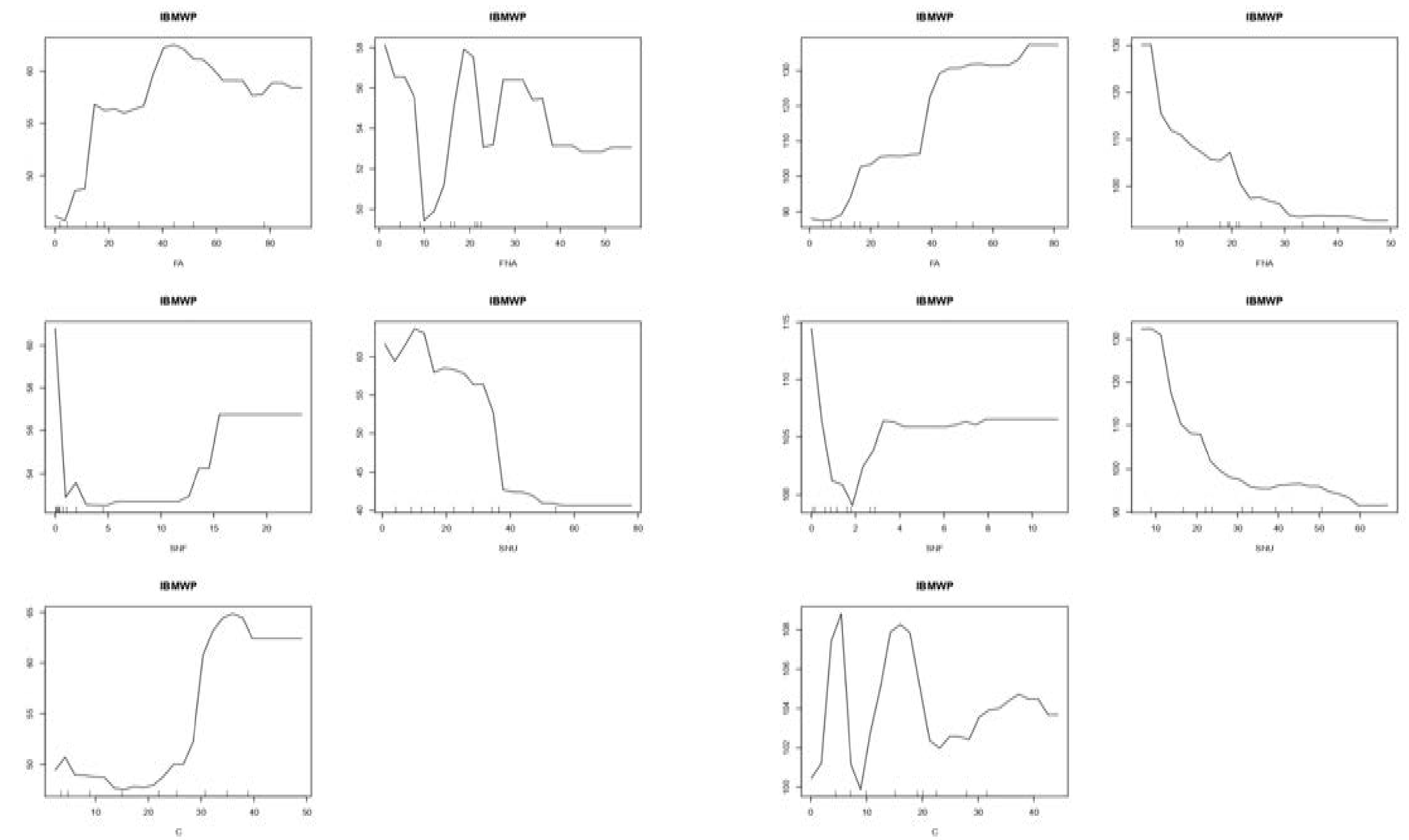


Figure SM3. Ammonia influence of Besòs river basin in 1997,2000, 2009 and 2016. FA=Forested, FNA= Grassland &Shrubs, SNF=Bare forested soil, SNU=Urban and C=Crops.

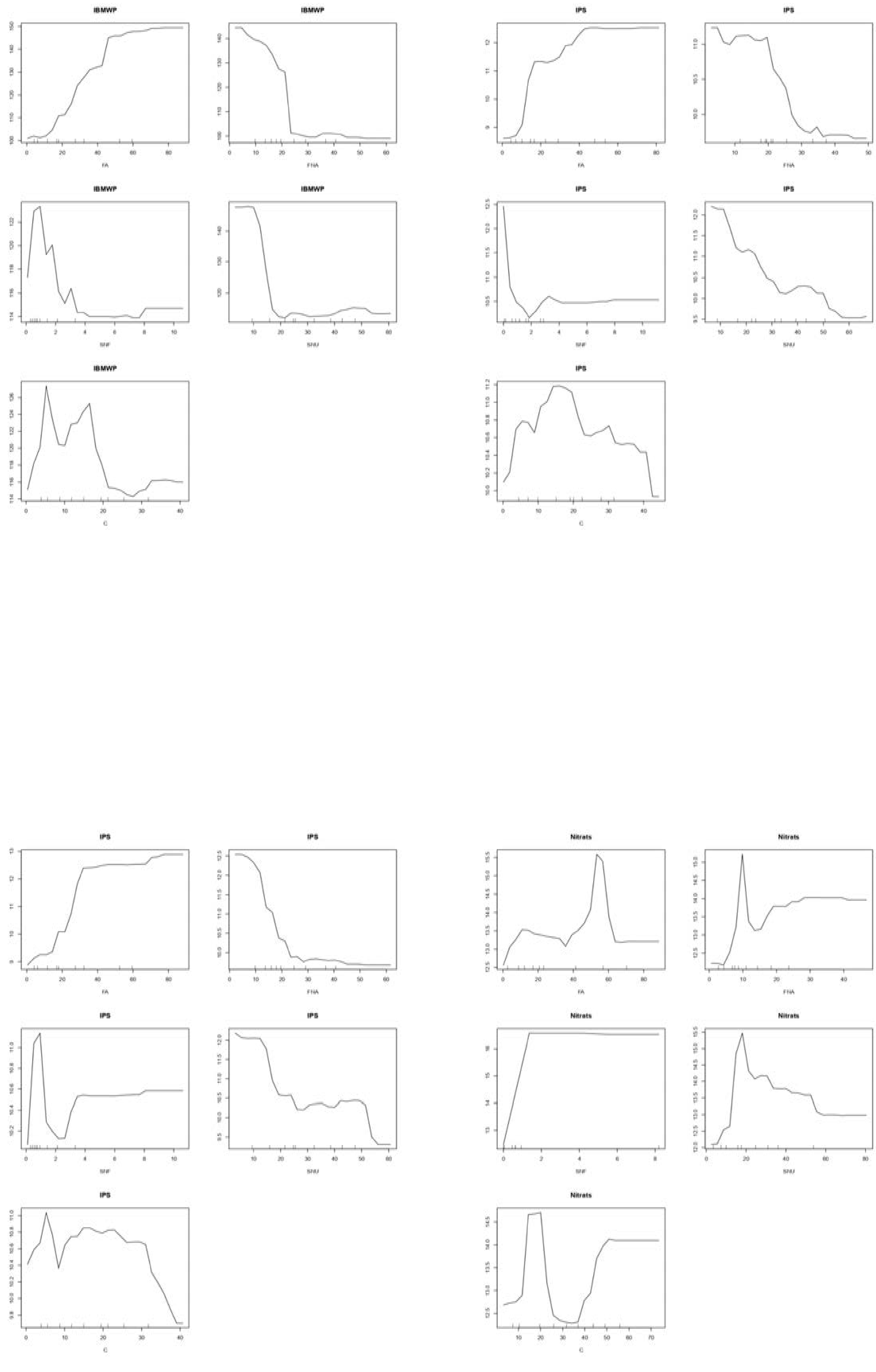


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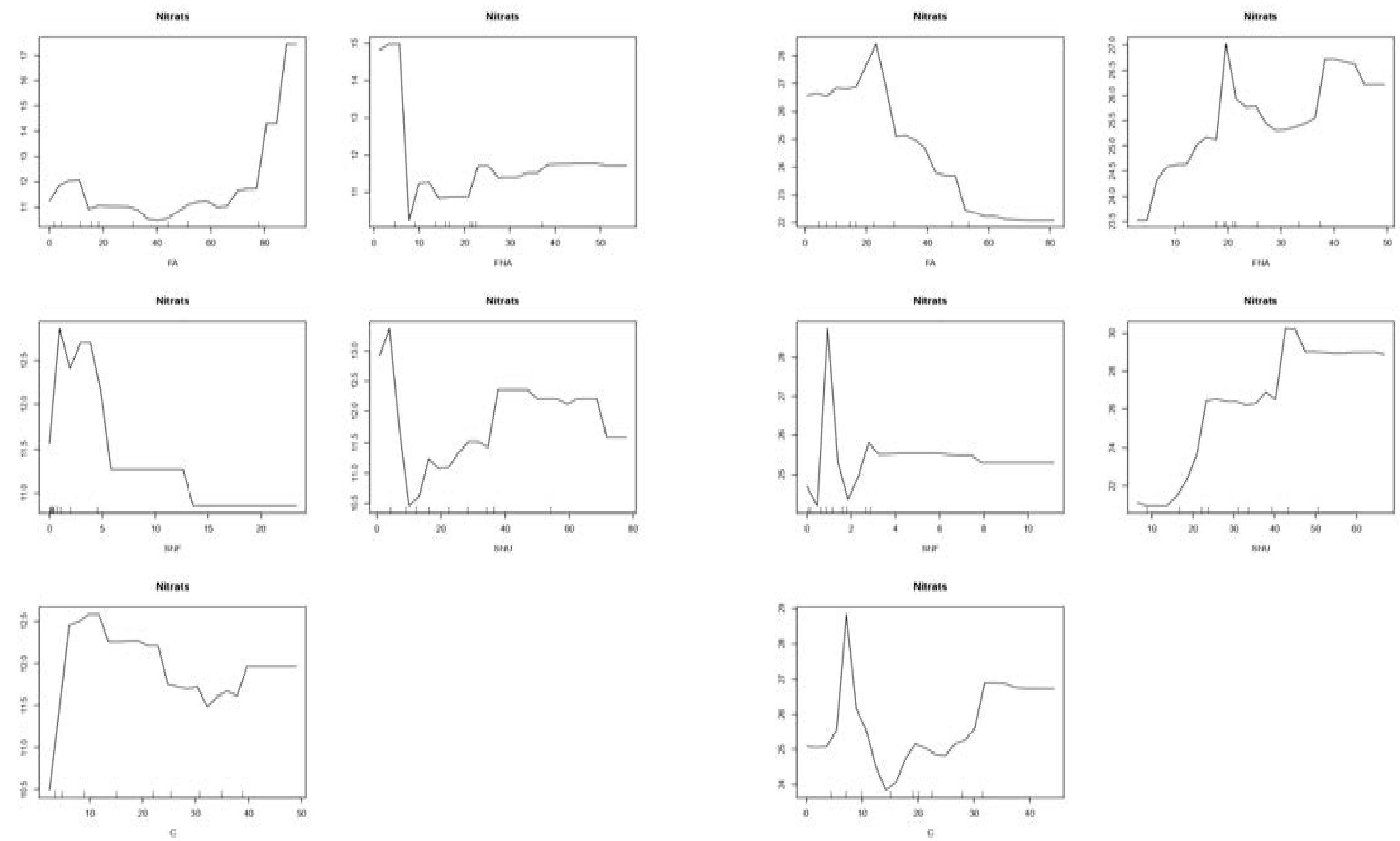
Figure SM4. Ammonia influence of Besòs river basin in 1997,2000, 2009 and 2016. FA=Forested, FNA= Grassland &Shrubs, SNF=Bare forested soil, SNU=Urban and C=Crops.



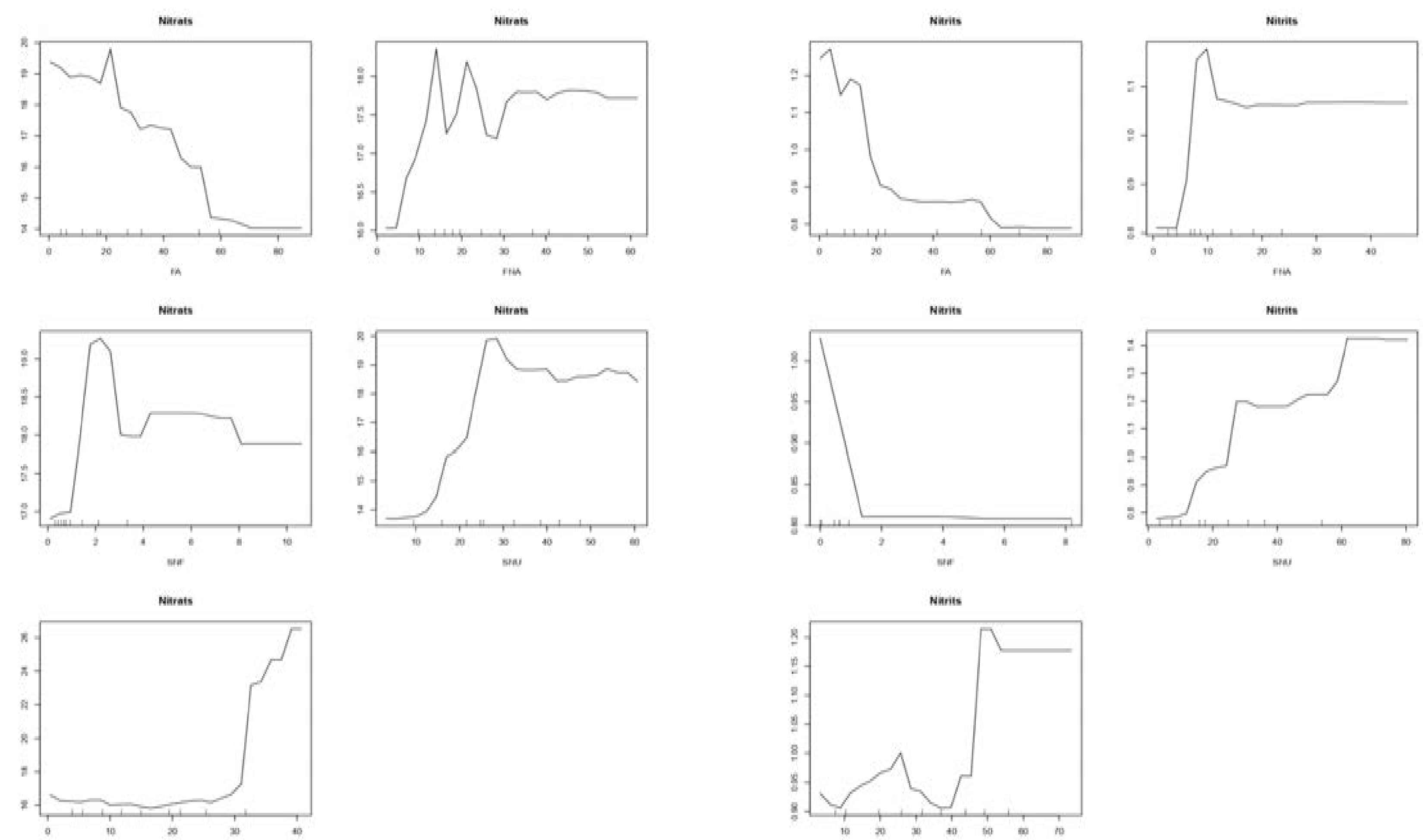
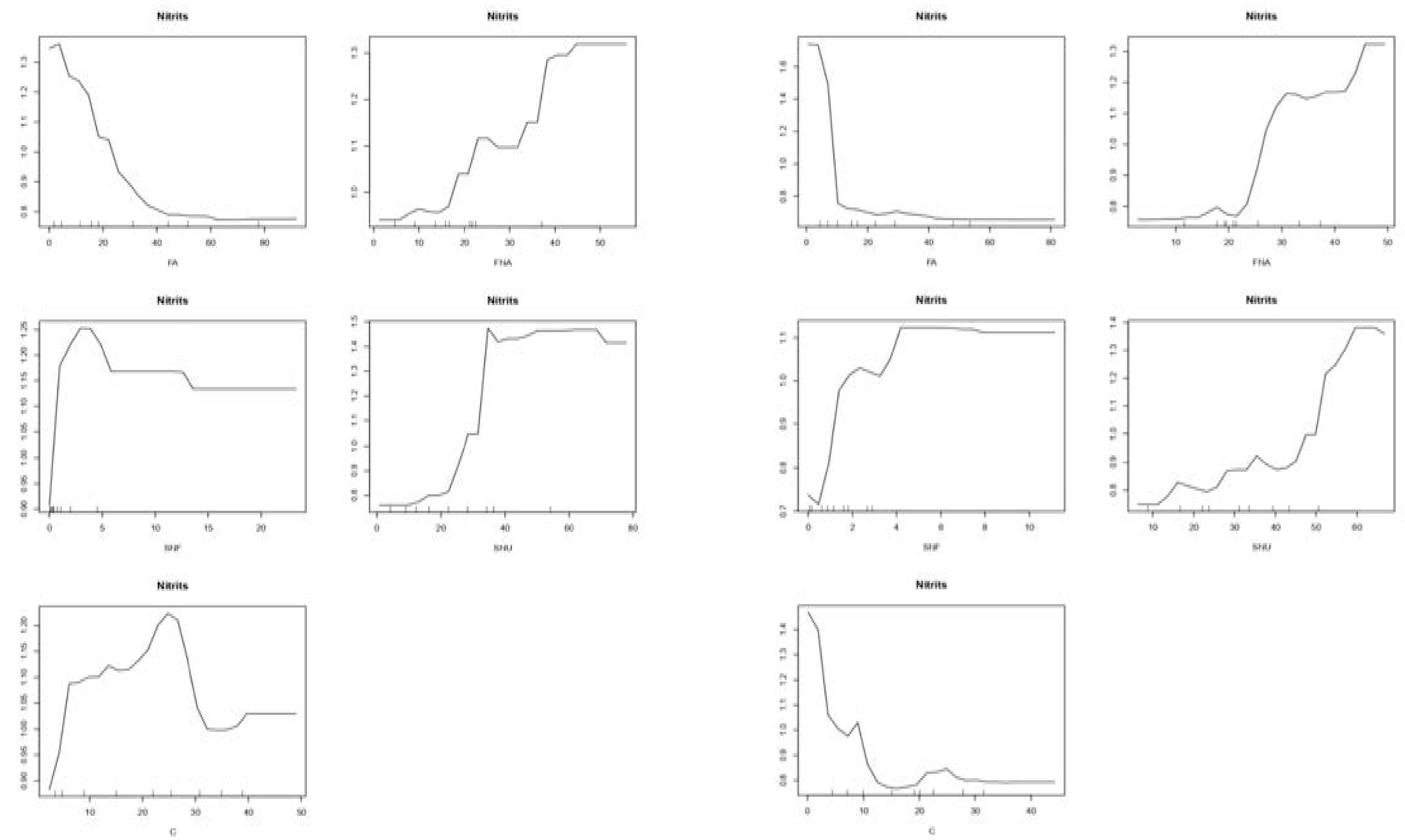


Figure SM5. Ammonia influence of Besòs river basin in 1997,2000, 2009 and 2016. FA=Forested, FNA= Grassland &Shrubs, SNF=Bare forested soil, SNU=Urban and C=Crops.



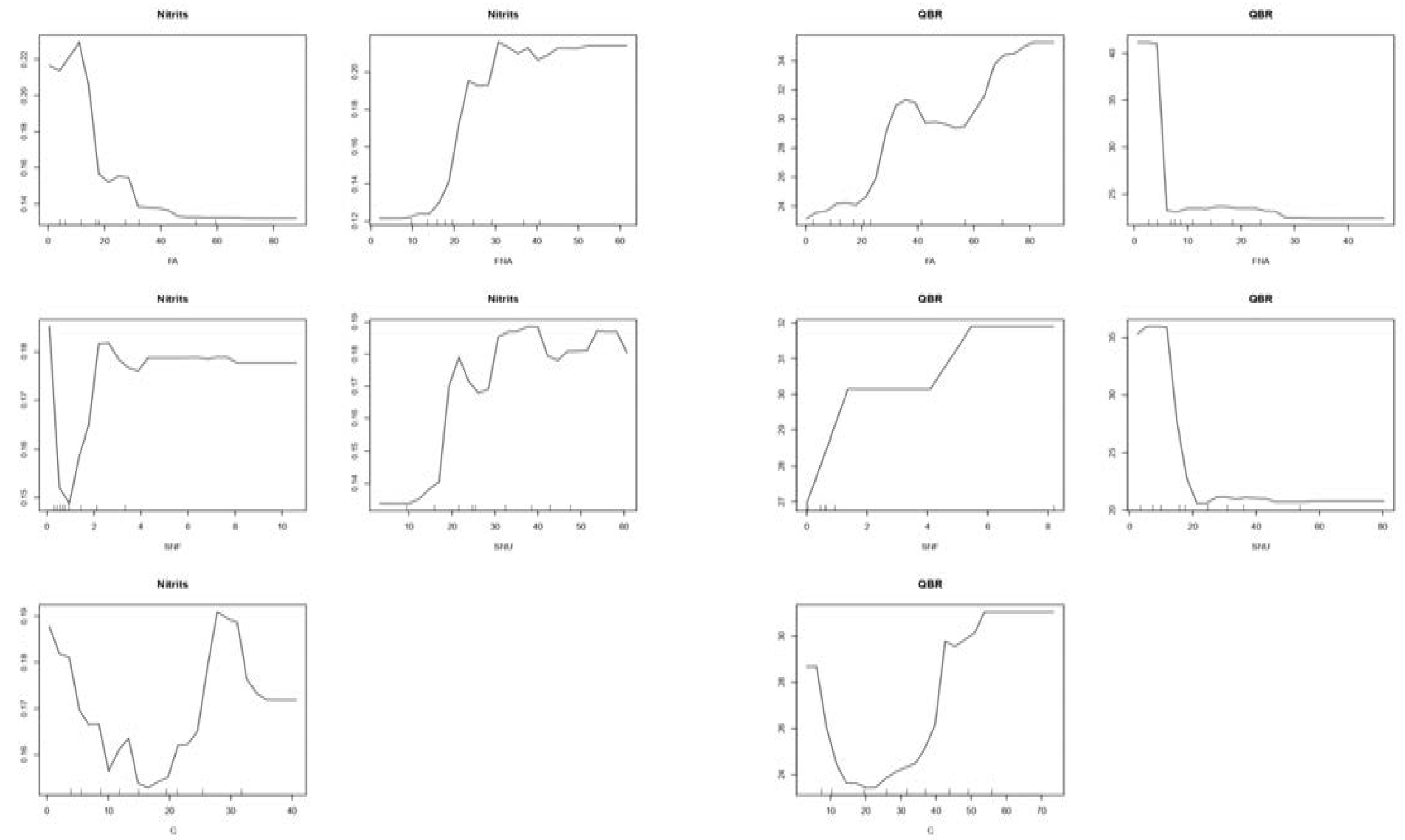


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Figure SM6. Ammonia influence of Besòs river basin in 1997,2000, 2009 and 2016. FA=Forested, FNA= Grassland &Shrubs, SNF=Bare forested soil, SNU=Urban and C=Crops.

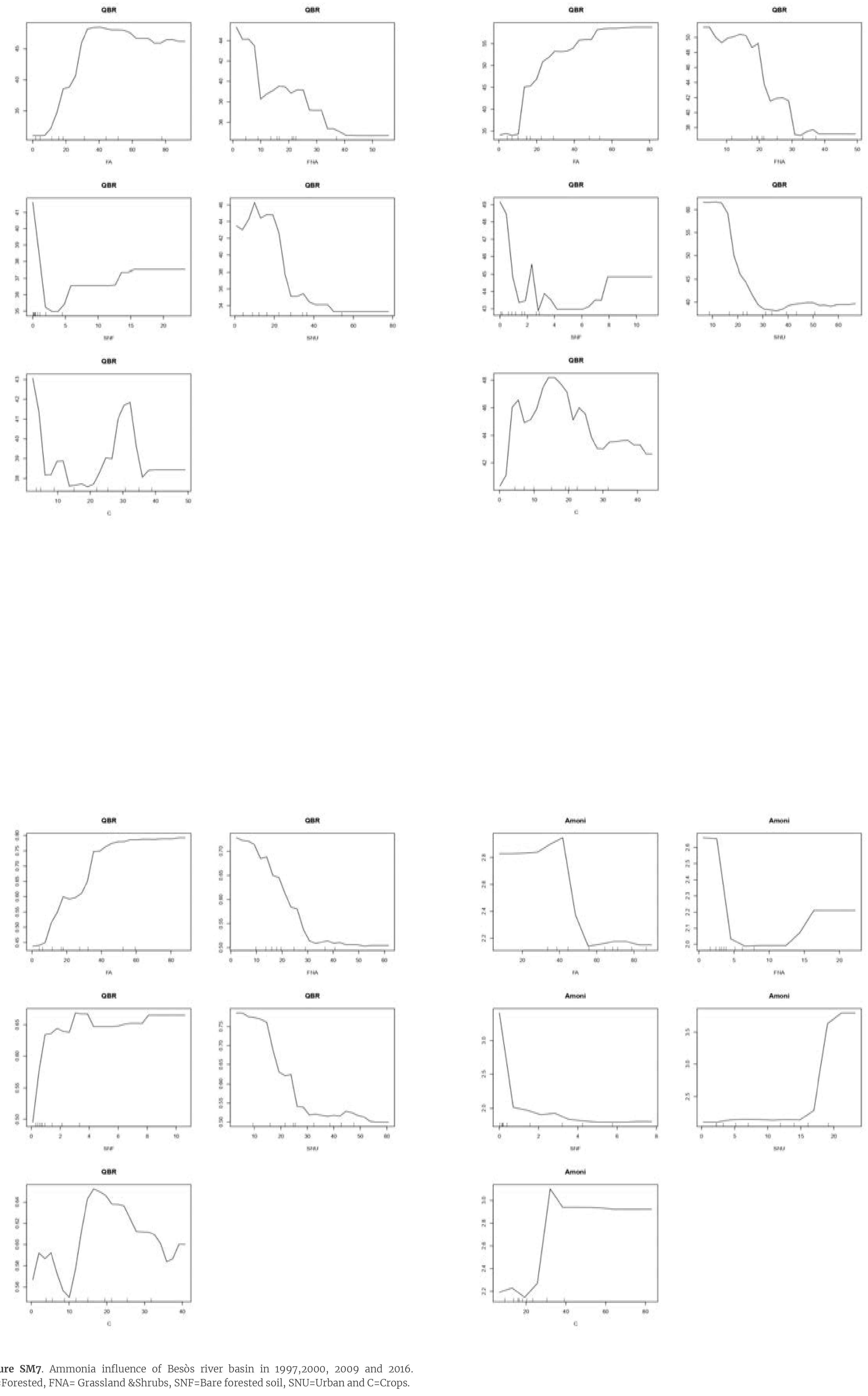

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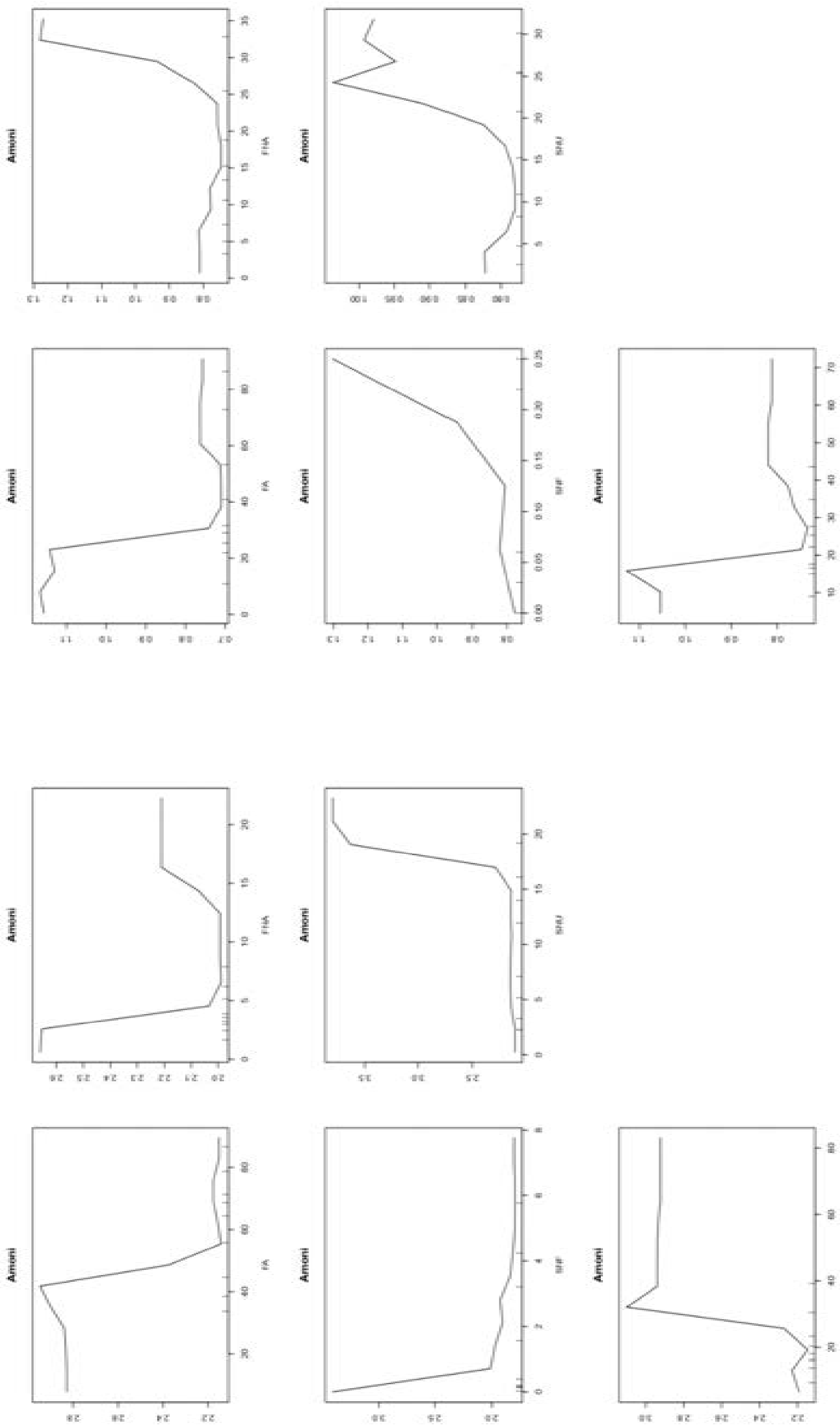
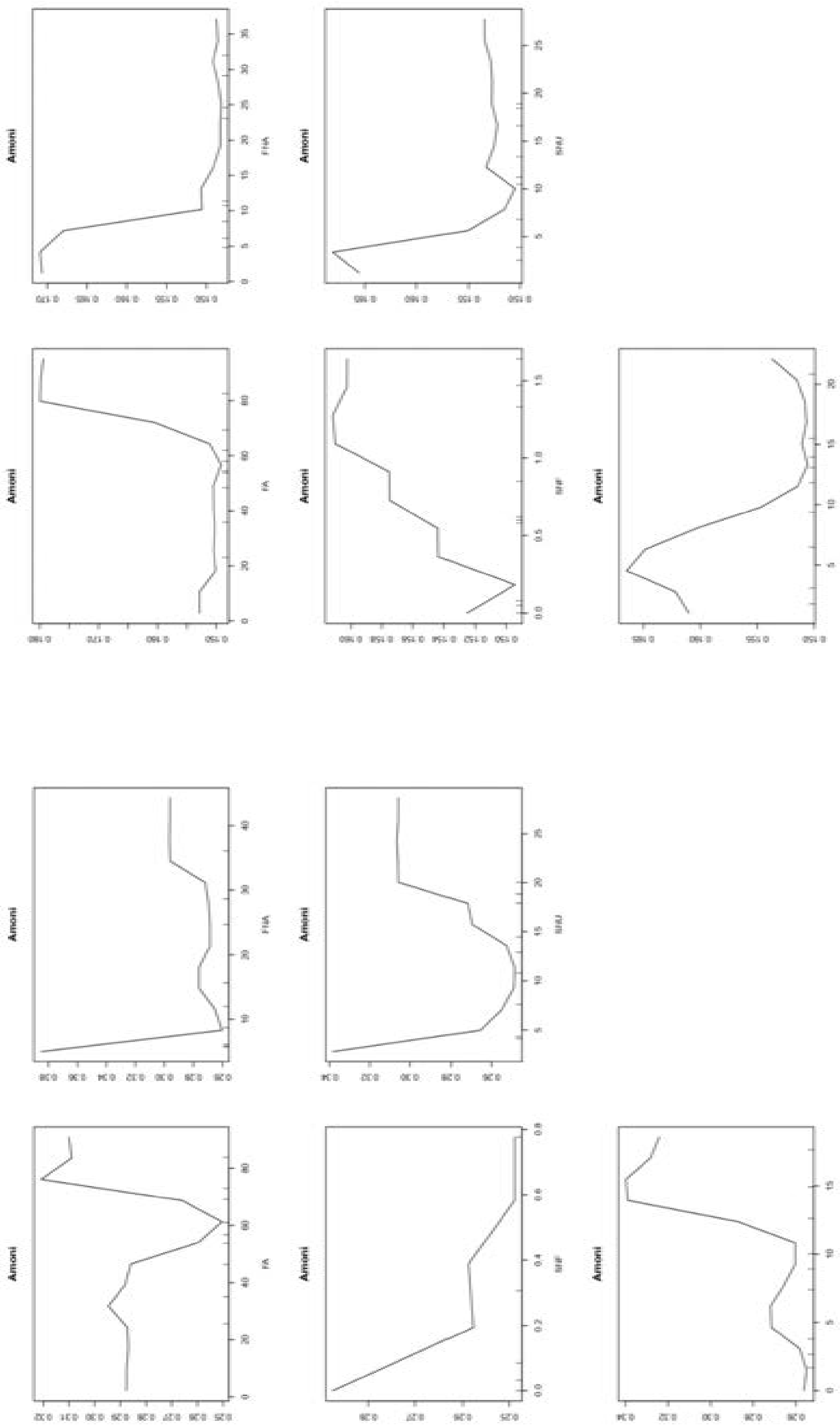
Figure SM7. Ammonia influence of Besòs river basin in 1997,2000, 2009 and 2016. FA=Forested, FNA= Grassland &Shrubs, SNF=Bare forested soil, SNU=Urban and C=Crops.





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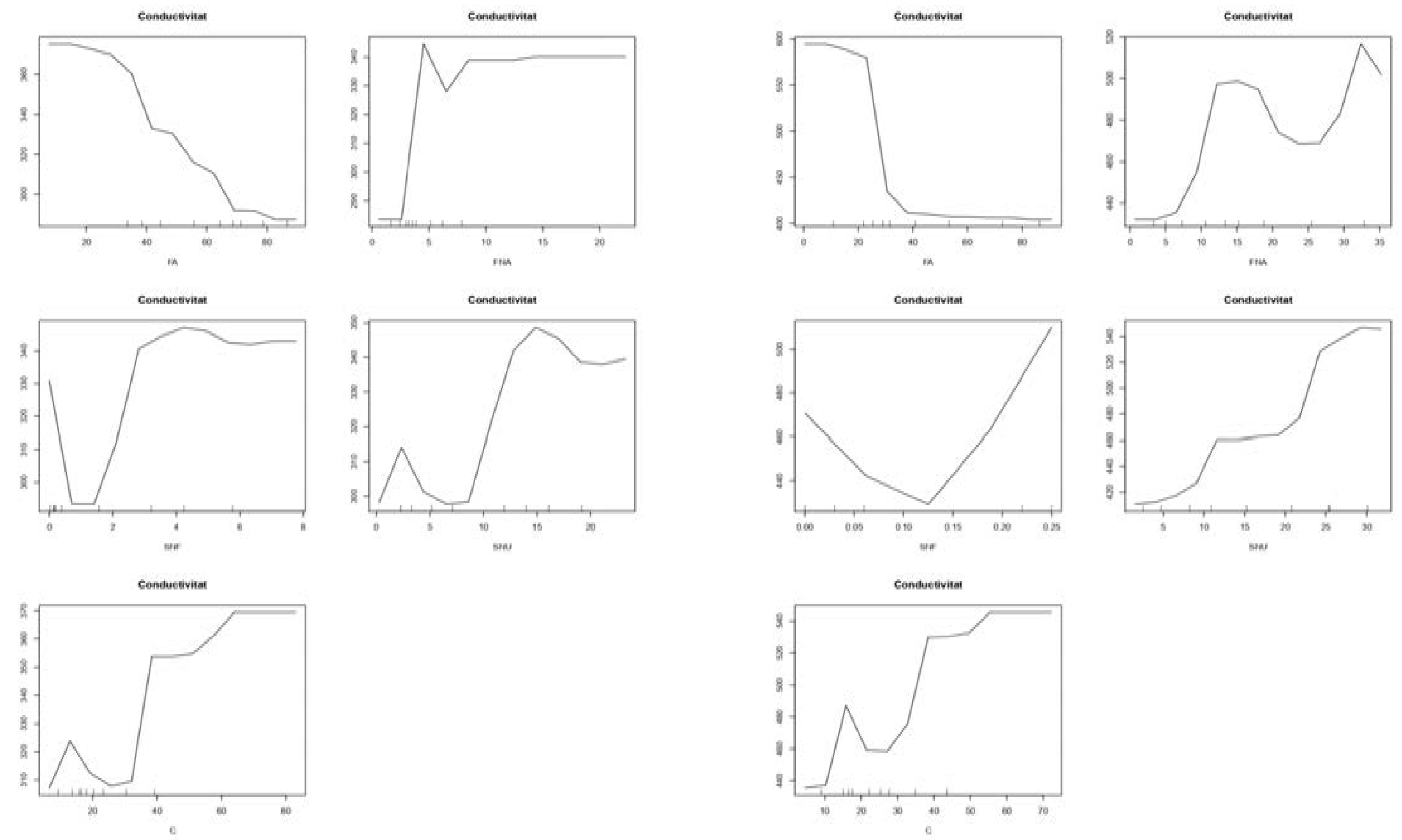


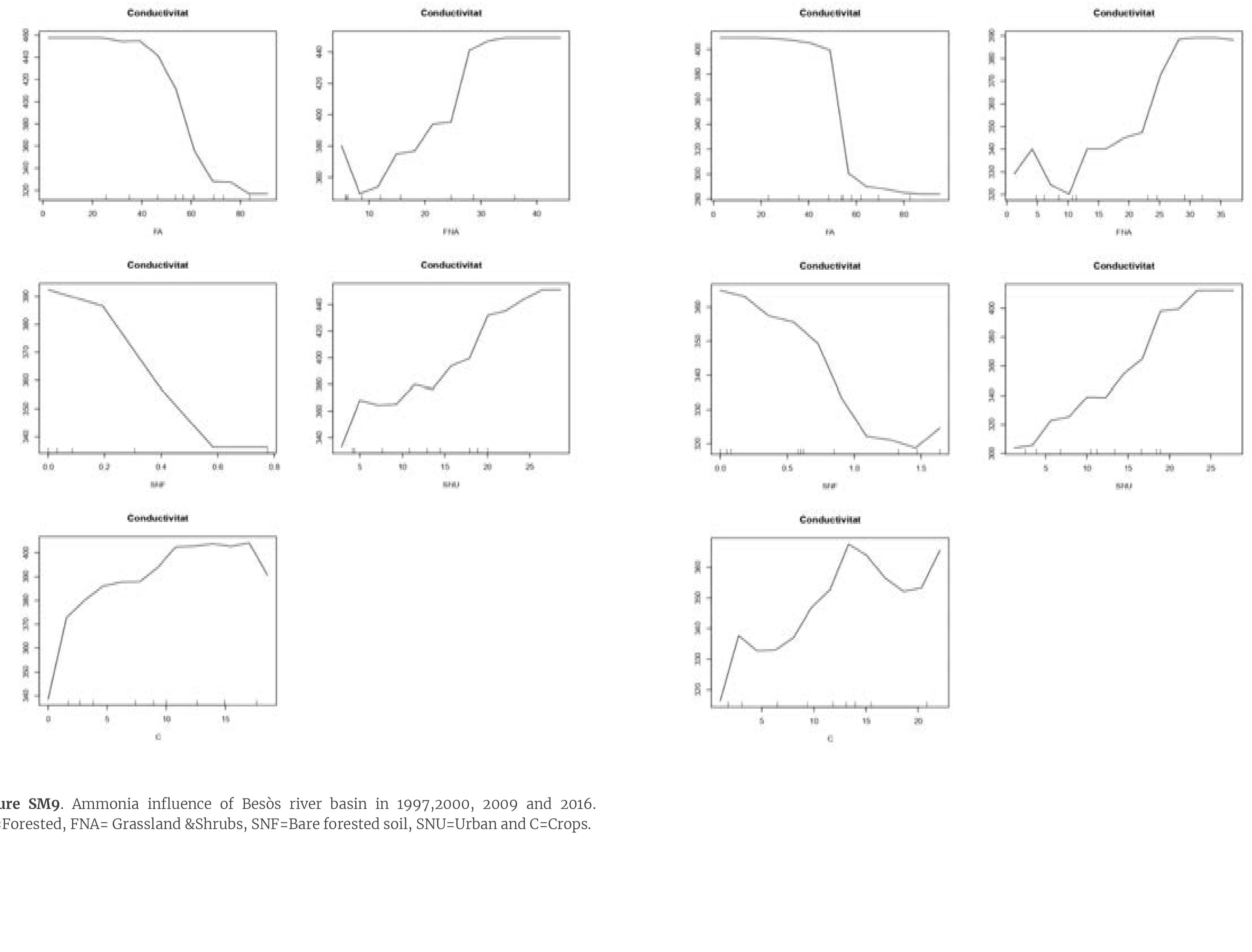


Figure SM9. Ammonia influence of Besòs river basin in 1997,2000, 2009 and 2016. FA=Forested, FNA= Grassland &Shrubs, SNF=Bare forested soil, SNU=Urban and C=Crops.

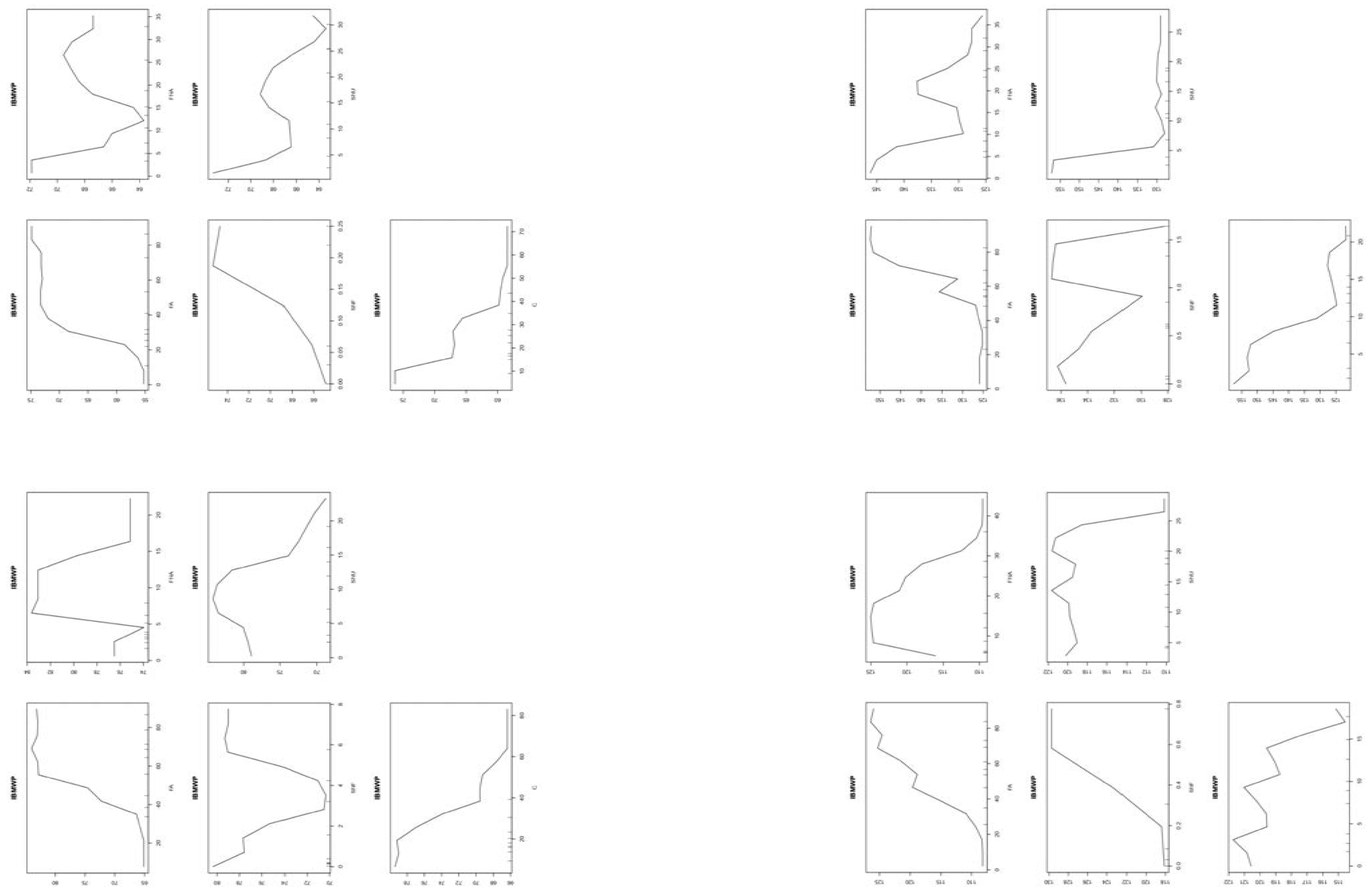
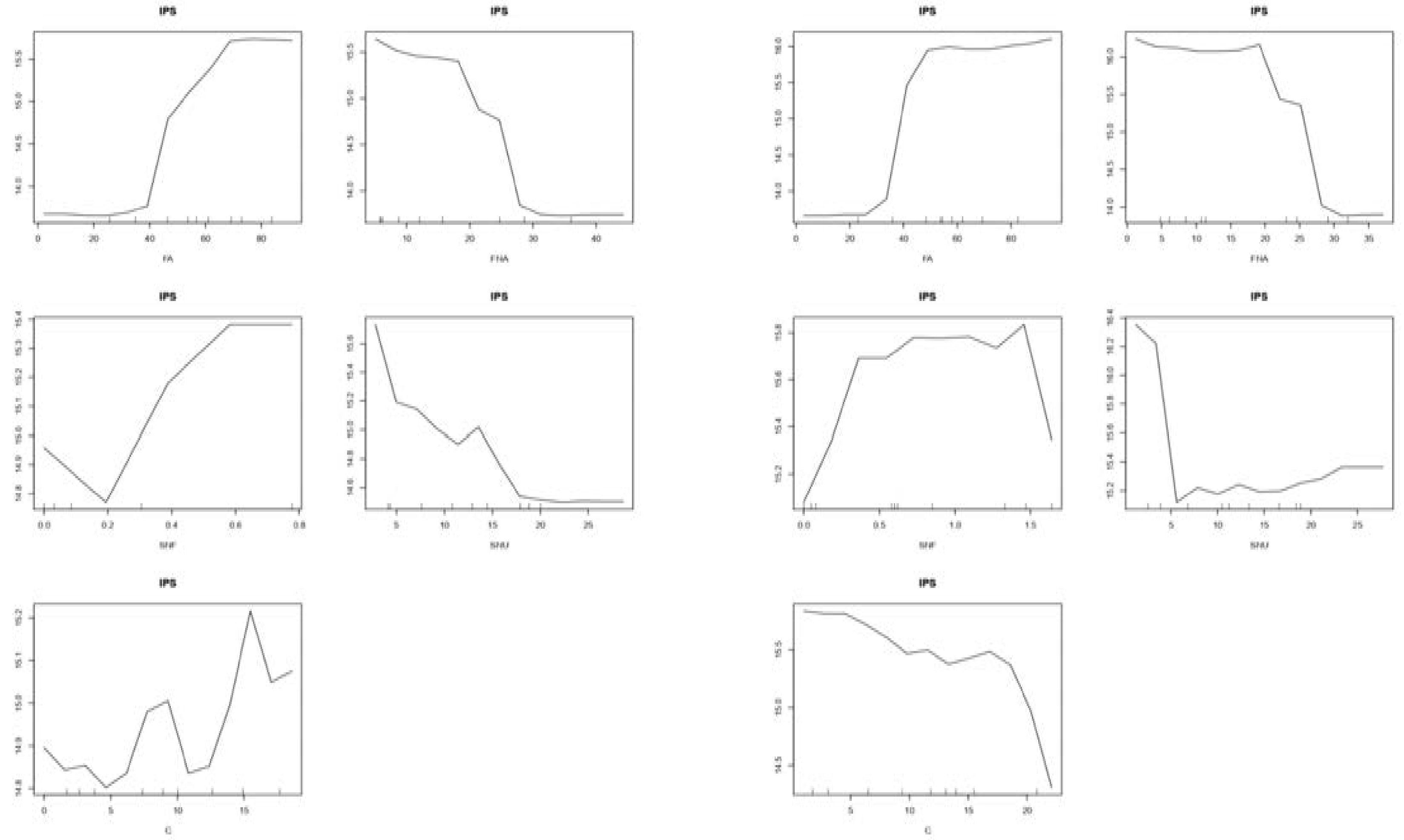


Figure SM10. Ammonia influence of Besòs river basin in 1997,2000, 2009 and 2016. FA=Forested, FNA= Grassland &Shrubs, SNF=Bare forested soil, SNU=Urban and C=Crops.



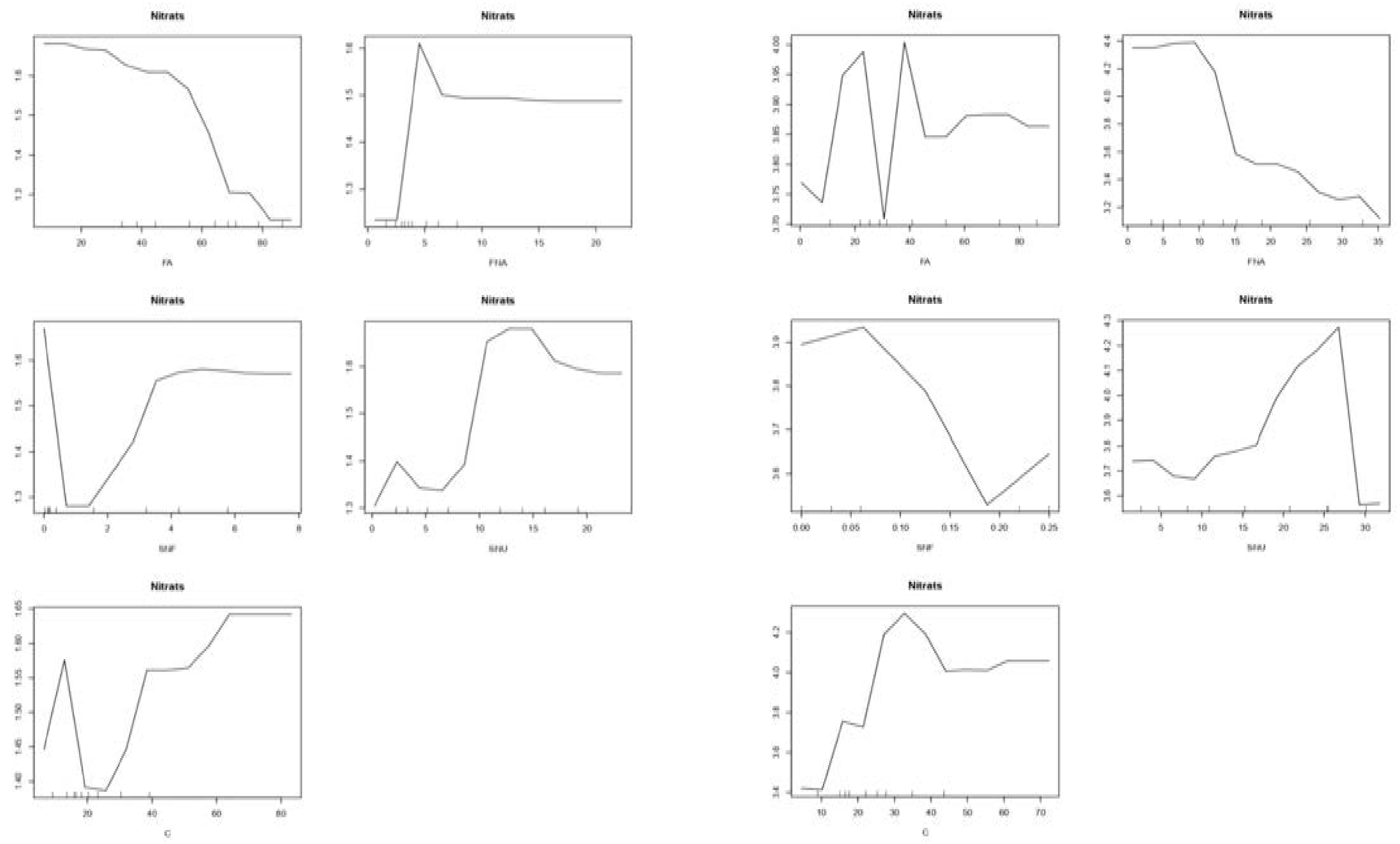
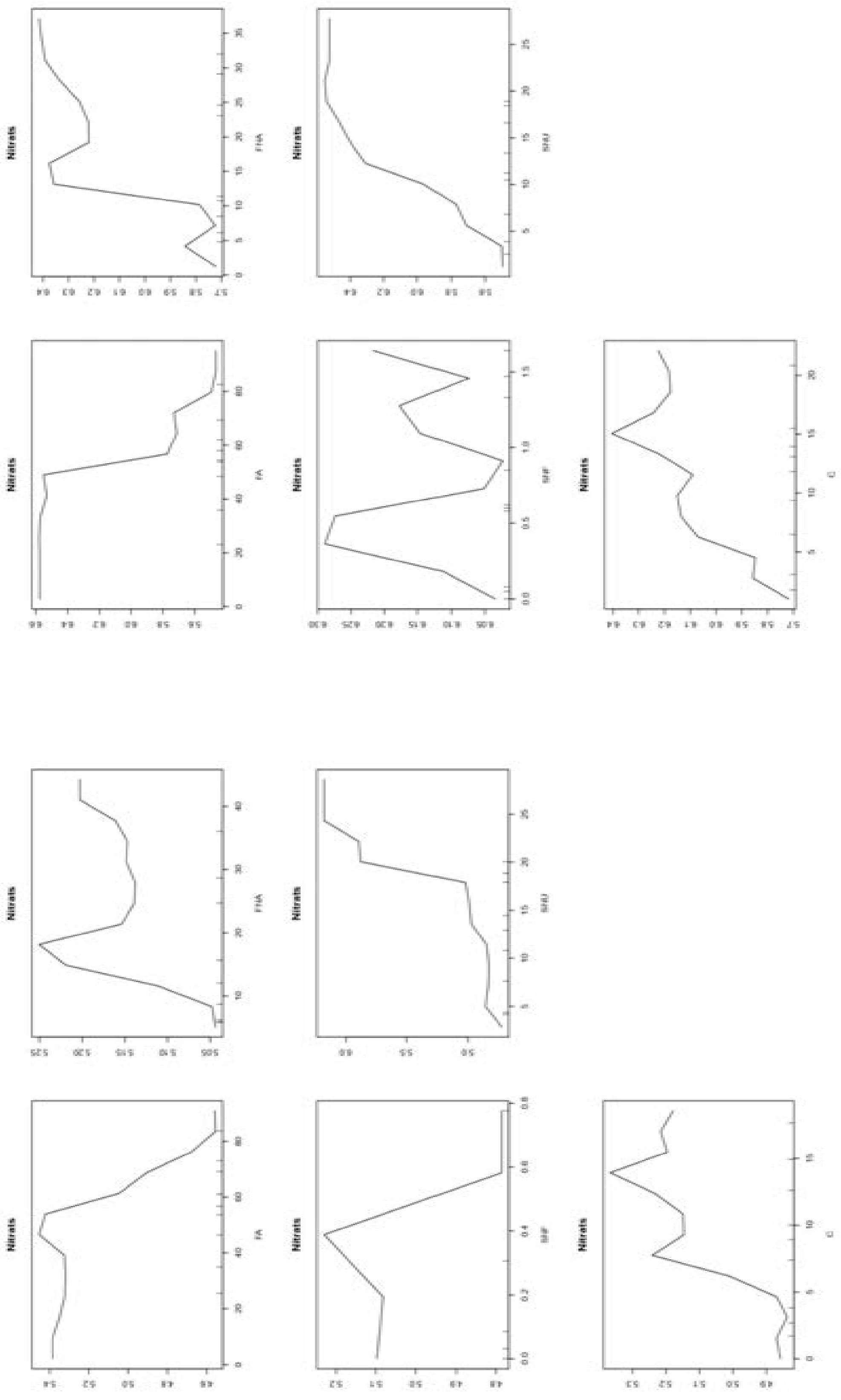


Figure SM11. Ammonia influence of Besòs river basin in 1997,2000, 2009 and 2016. FA=Forested, FNA= Grassland &Shrubs, SNF=Bare forested soil, SNU=Urban and C=Crops.



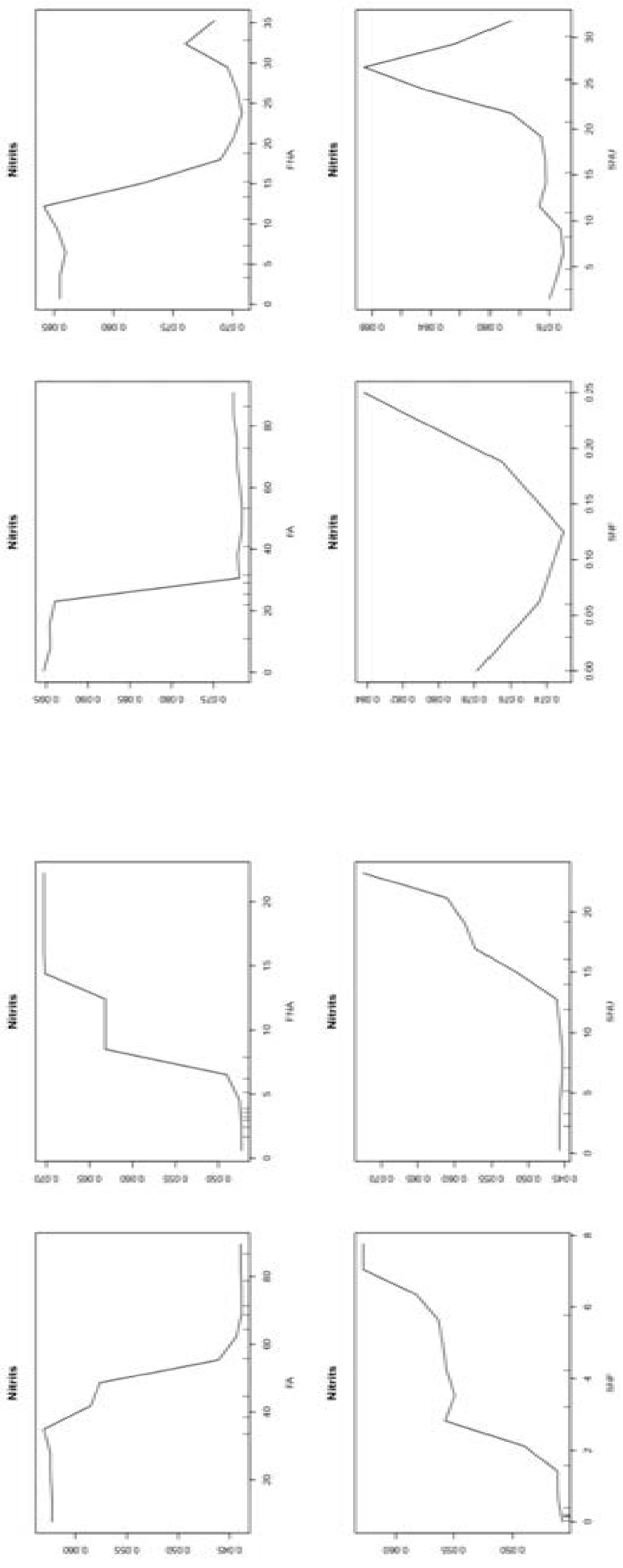
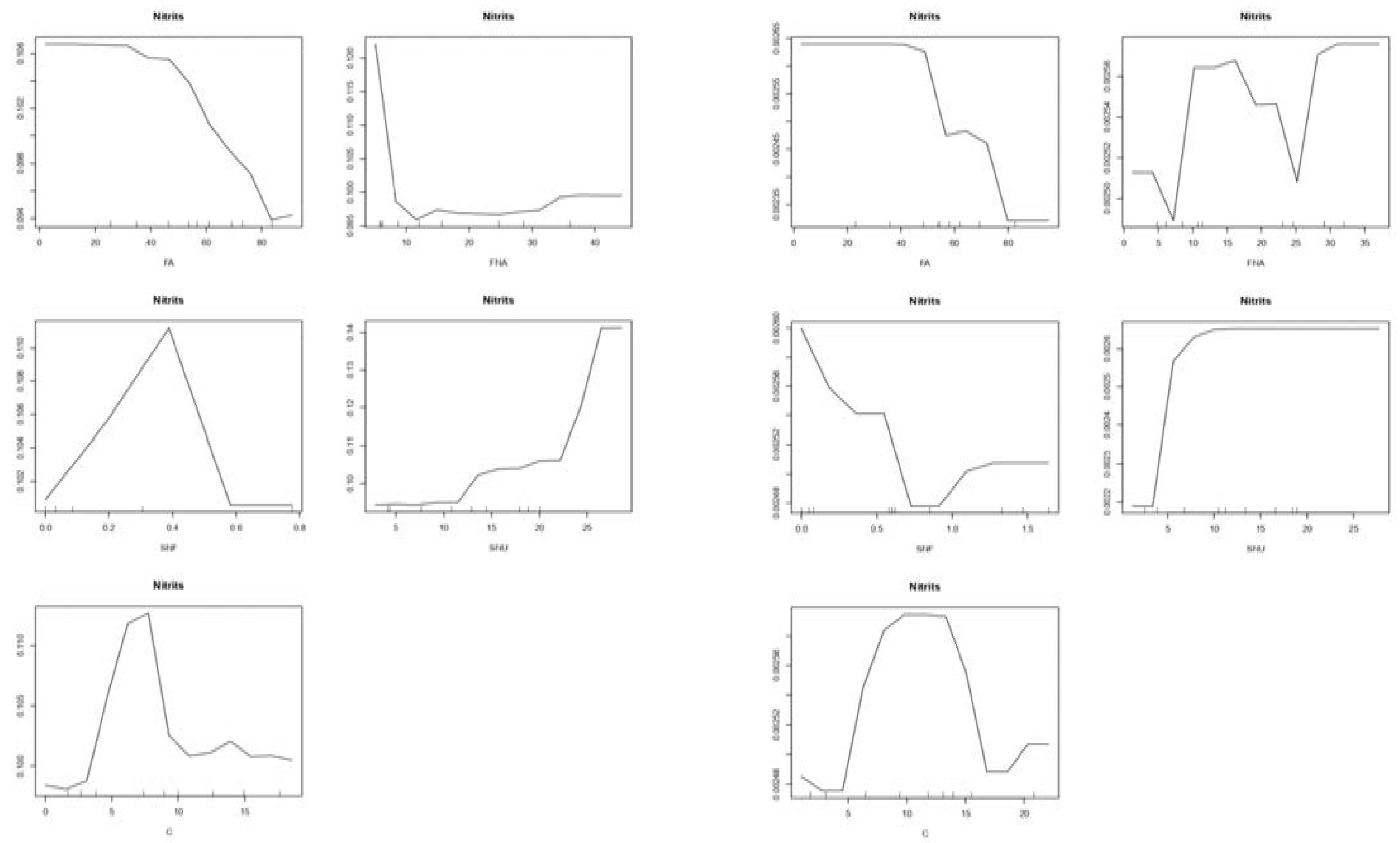


Figure SM12. Ammonia influence of Besòs river basin in 1997,2000, 2009 and 2016. FA=Forested, FNA= Grassland &Shrubs, SNF=Bare forested soil, SNU=Urban and C=Crops.



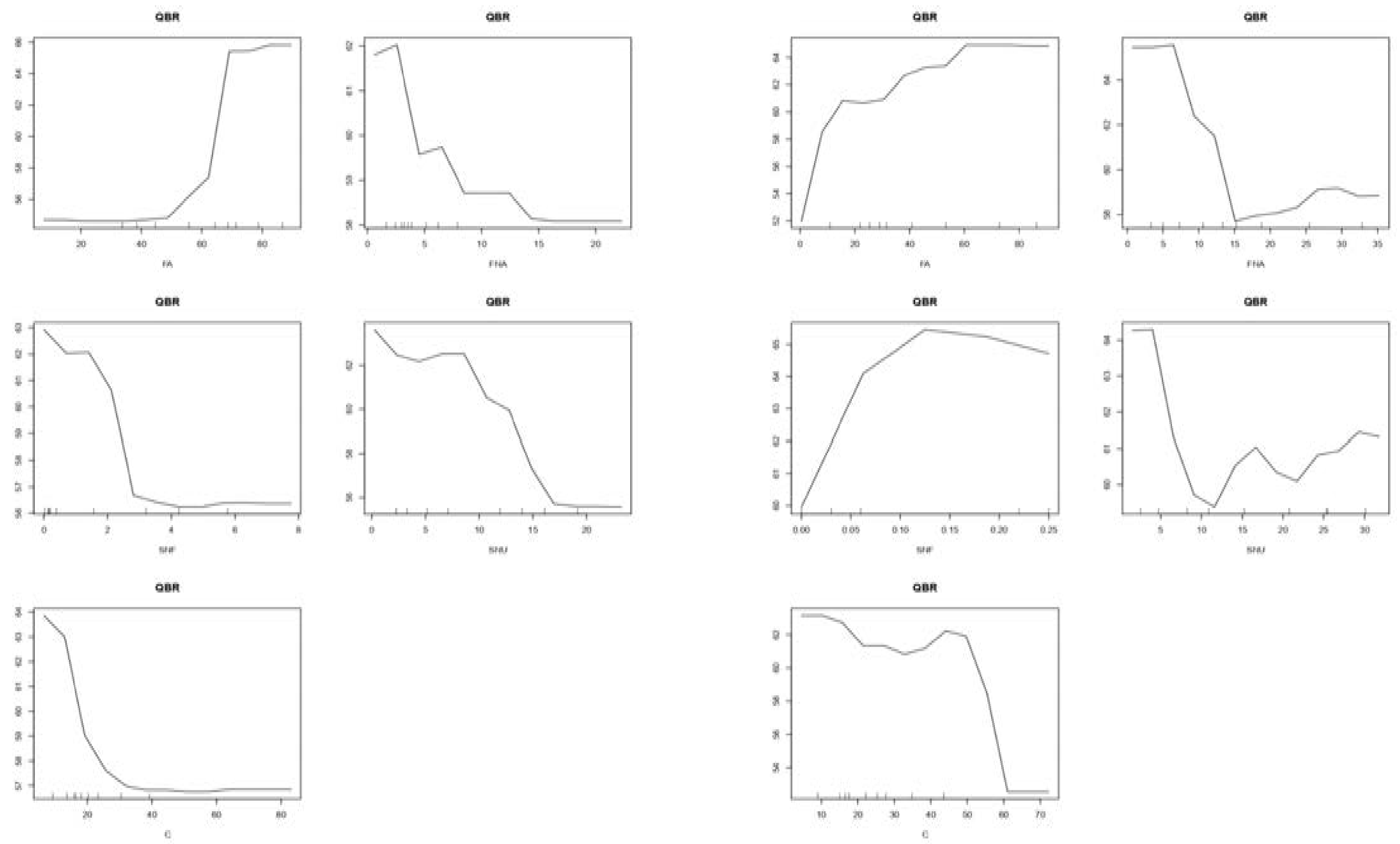


Figure SM13. Ammonia influence of Besòs river basin in 1997,2000, 2009 and 2016. FA=Forested, FNA= Grassland &Shrubs, SNF=Bare forested soil, SNU=Urban and C=Crops.

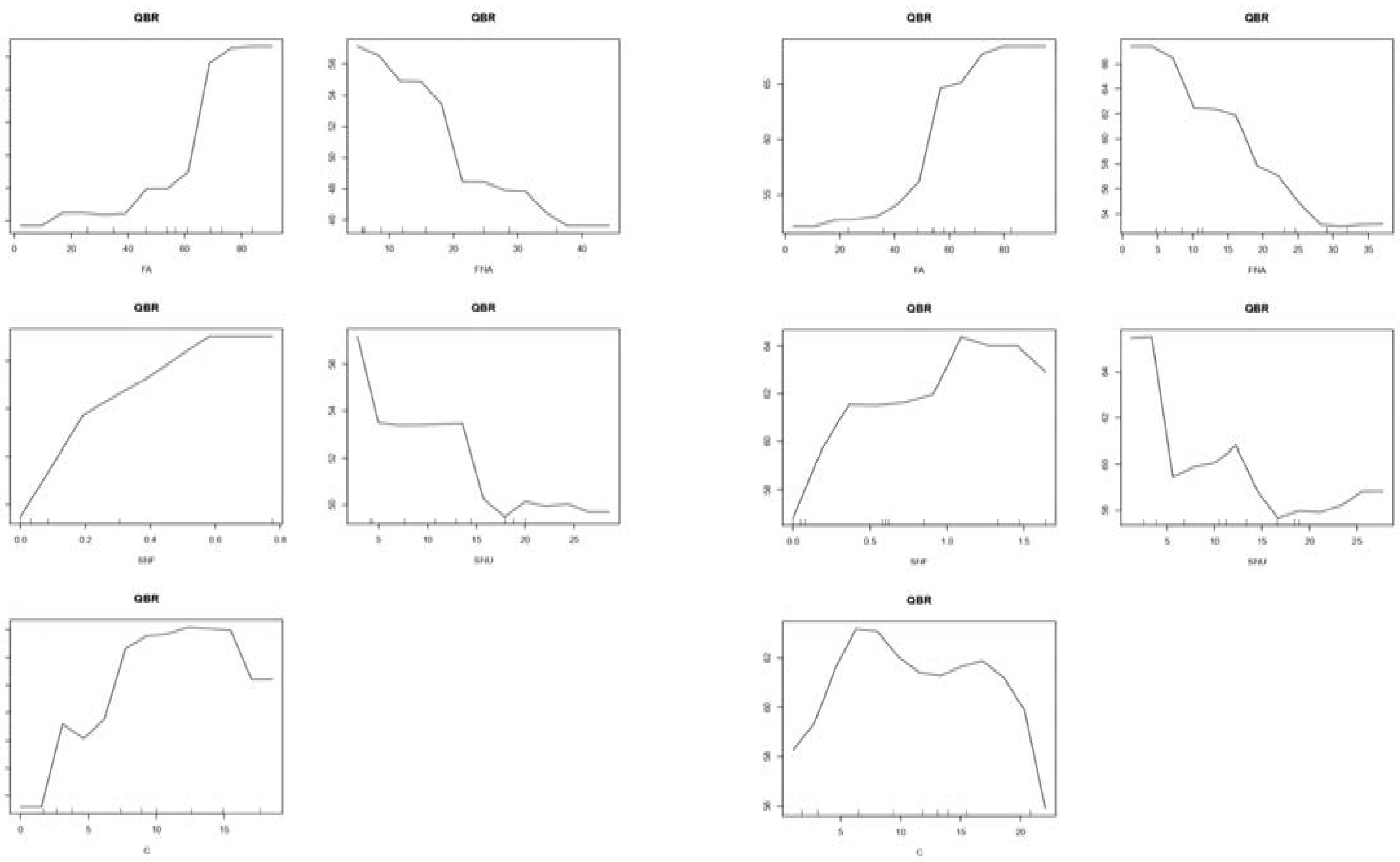
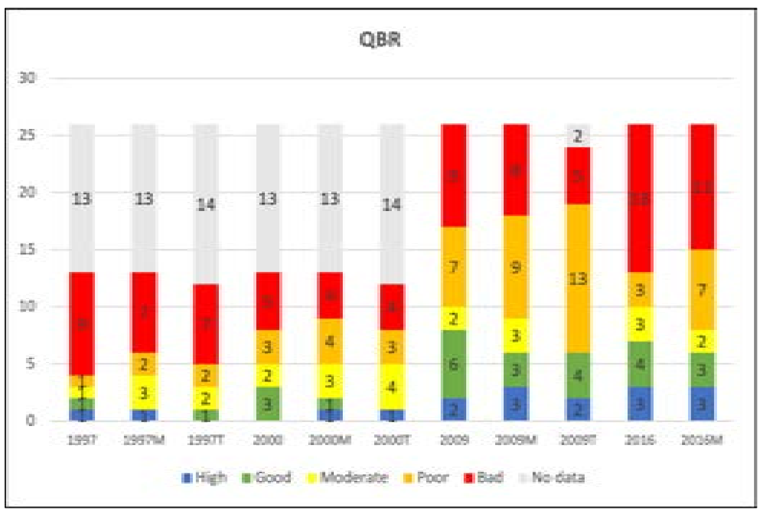
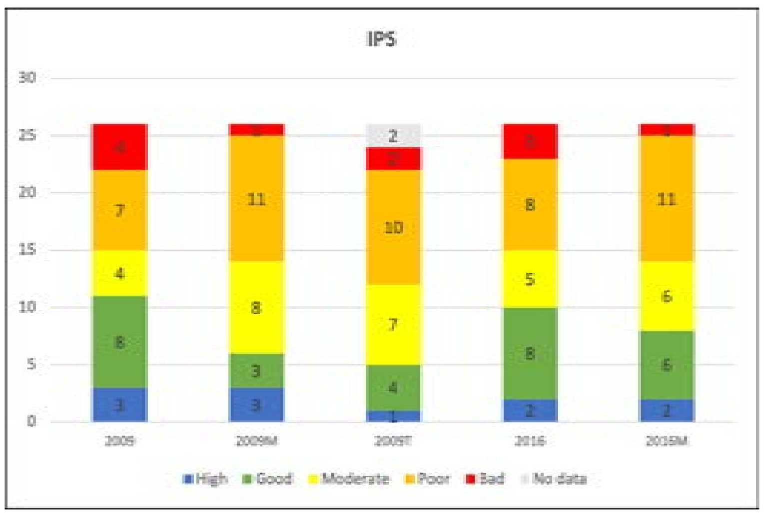


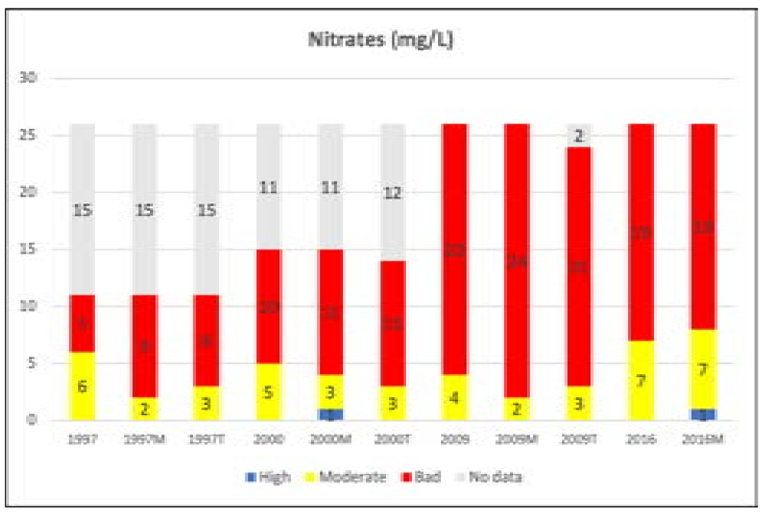
Figure SM14. Ammonia influence of Besòs river basin in 1997,2000, 2009 and 2016. FA=Forested, FNA= Grassland &Shrubs, SNF=Bare forested soil, SNU=Urban and C=Crops.

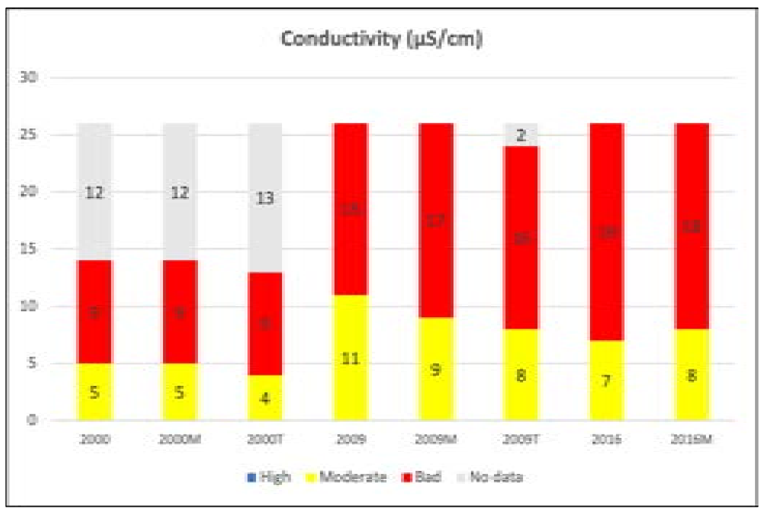
Supplementary Material 7

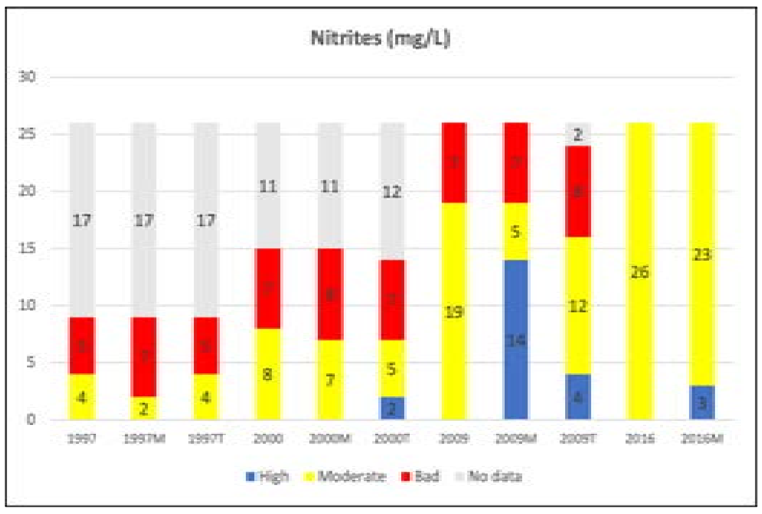
Results of the new fluvial system assessment on the water bodies











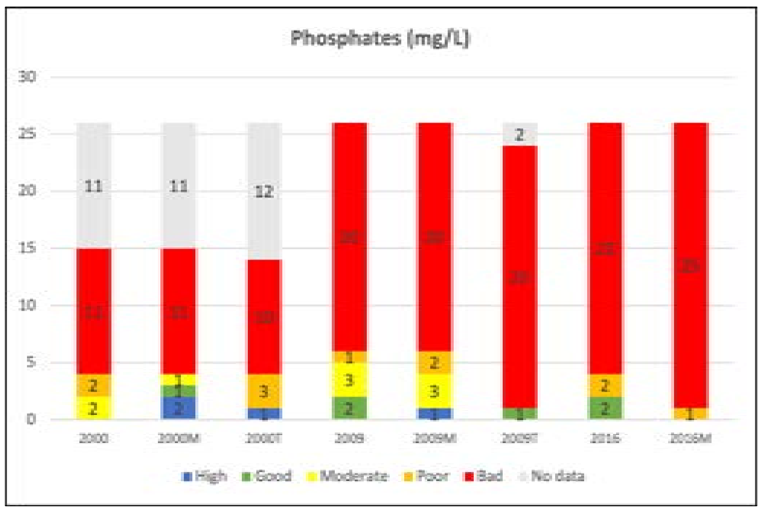


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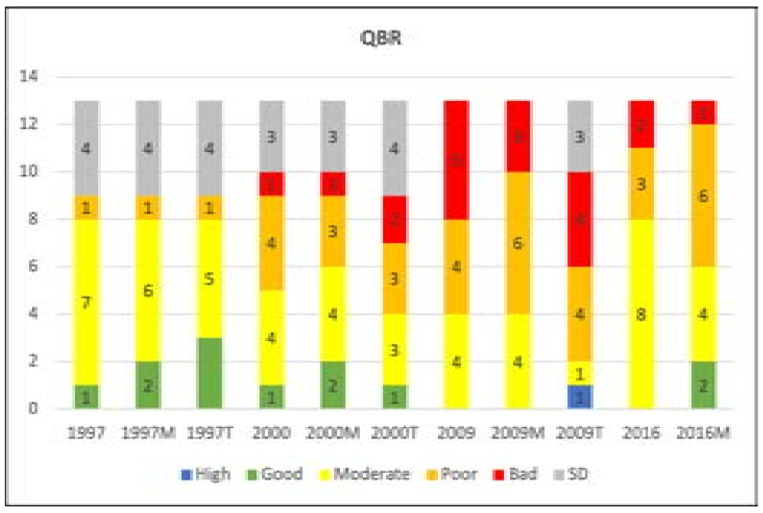
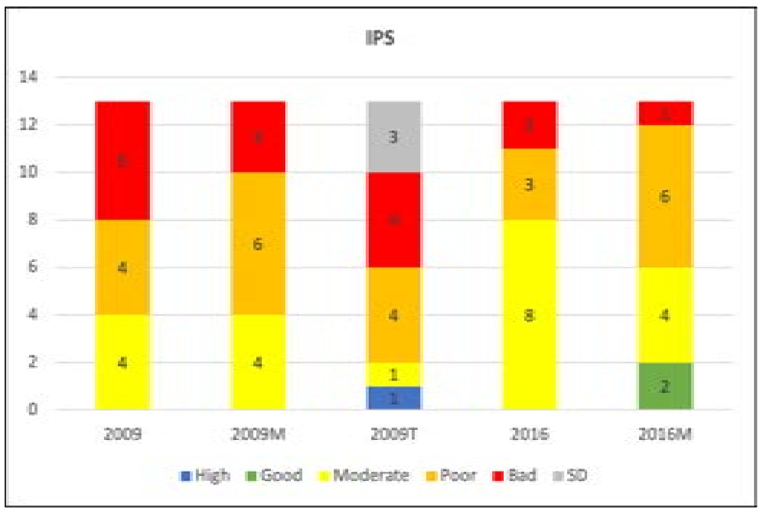
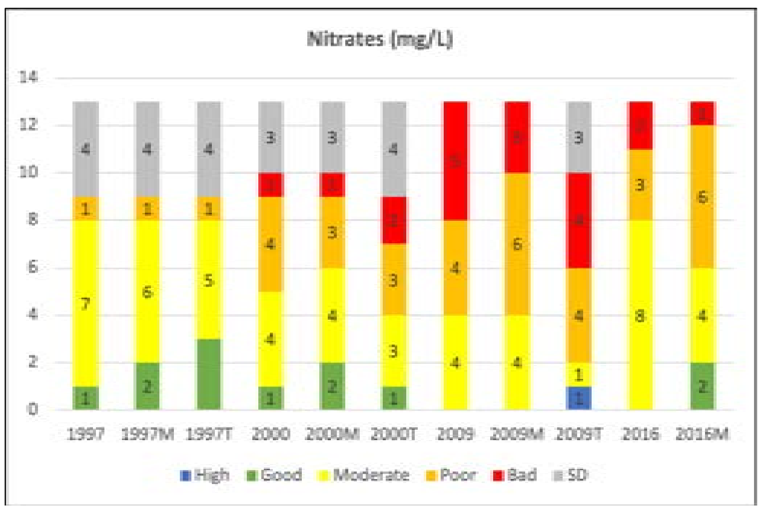
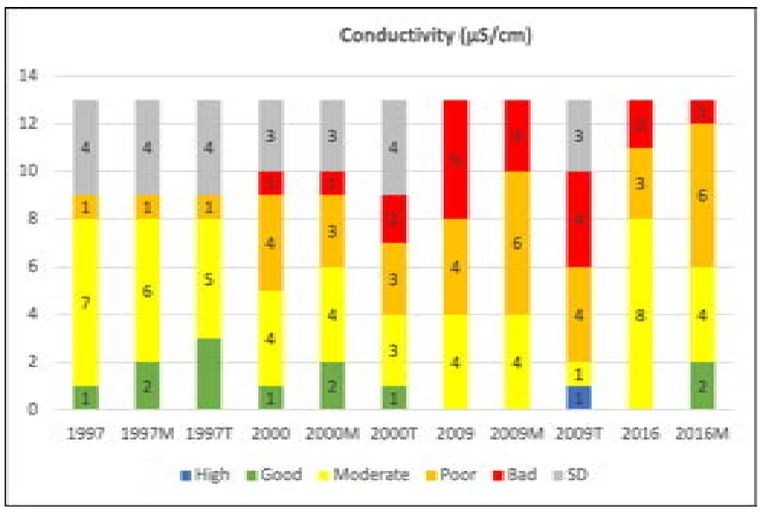
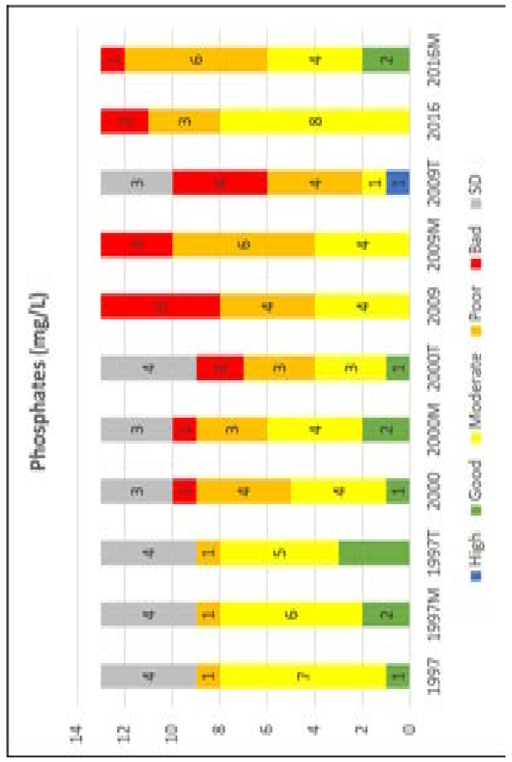
Figure SM15. The predictable values for each water quality indicator in 1997, 2000, 2009 and 2016 in Besòs river basin and considering the two spatial scales: 100 meters buffer "M" and return periods in 100 years "T".











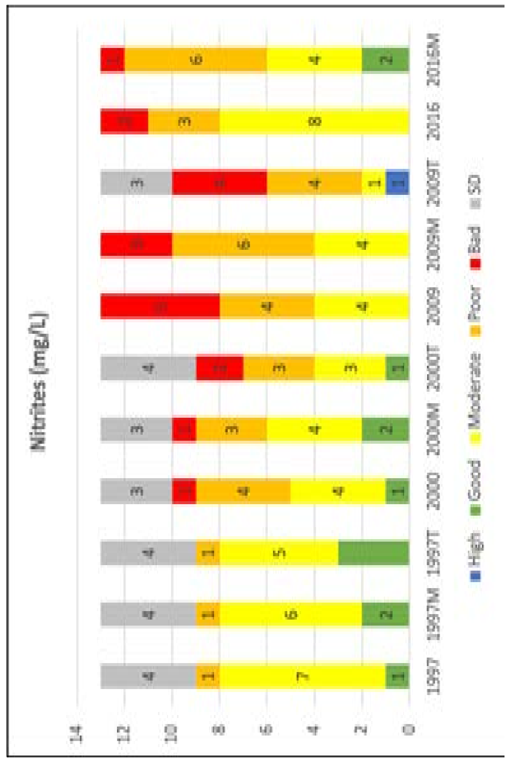


Figure SM16. The predictable values for each water quality indicator in 1997, 2000, 2009 and 2016 in Tordera river basin and considering the two spatial scales: 100 meters buffer "M" and return periods in 100 years "T".

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ORIGINAL ARTICLE

Assessing the Effects of Wastewater Treatment Plant Effluents on the Ecological Quality Status in a Mediterranean River Basin

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Abstract Many Mediterranean rivers are characterized by an inter-annual climatic variability, additionally intensified by climate change. Moreover, these rivers have limited extensions and a reduced dilution capacity which make them vulnerable to human pressures, especially to water pollution. During the 1970s, the Besòs river basin had historically suffered the continuous discharge of untreated residual water, leading to be considered as the most polluted river in Europe. During the 1990s and 2000s, environmental laws such as the Catalan Treatment Plan and the Water Framework Directive (2000/60/EC) were implemented to resolve the problem. Consequently, the number of wastewater treatment plants (WWTPs) and long-term monitoring programs to assess the ecological status increased in the territory. In order to evaluate these changes, this study assesses the biological quality status (IBMWP, QBR and IPS) in the Besòs river water at three spatial scales (headwater, middle and lower sections). Our results clearly show that water quality across the basin has been improved. This improvement has become more significant after the implementation of new treatment systems. The trends in ammonia concentrations (NH_4^+, in mg/L) and conductivity (EC, in µS/cm) discharged from 13 selected WWTPs during the period 2000–2018 displays a clear decreasing tendency. Finally, we have applied a thorough statistical analysis to the IBMWP dataset to demonstrate the positive influence of the treatment systems on the ecological quality status across the river basin. We conclude that the implementation and enforcement of environmental laws are valid and effective tools to improve water quality in Mediterranean rivers.

Highlights

- Wastewater treatment plant upgrading has positive effects on biological quality status.
- High NH_4^+ and conductivity levels provoke alterations on biological quality status.
- Correct quality status (IBMWP) is reached when $NH_4^+ < 1$ mg/L and EC is within 500–2000 µS/cm.

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Keywords Ecological quality status · Long-term monitoring program · Mediterranean river basins · Wastewater treatment plants · Besòs River basin

1 Introduction

1.1 The Mediterranean Hydric Systems in a Climate Change Scenario

The Mediterranean basin is characterized by a strong inter-annual climatic variability, with a dry period in summer and driving rains in spring and autumn (Cudennec et al. 2007; Bonada and Resh 2013). Moreover, due to climate change, the average annual temperatures on these areas are now approximately 1.5 °C higher than the pre-industrial period (1880-1899) and may be warmer in 2040 by 2.2 °C (Mediterranean Experts on Climate and environmental Change (MedECC Network) 2019). In addition, some climate models point to reduced rainfalls in coming decades (Saadi et al. 2015). In the specific case of Catalonia (North-East Spain), climatic models also indicate an upward temperature trend during the coming decades. From the period 1971-2000 to 2031-2050, models indicate that the annual average temperature in Catalonia will increase by 1.4 °C. Although there is a higher uncertainty about precipitations, projections also show an annual rainfall decrease of 7% (Consell Assessor per al Desenvolupament Sostenible et al. 2017).

The Mediterranean region, due to an intense human activity derived mainly from a high population density, has suffered pronounced negative pressures and impacts on its environment (Blondel et al. 2010). Due to a fast industrialization process during the 1960s and 1970s, profound economic changes taking place in that region led to a process of land abandonment in rural areas, especially in headwaters (Otero et al. 2011; Sànchez-Mateo and Boada 2011; Voza et al. 2015). This process, coupled with the reduced dilution capacity of Mediterranean rivers (Benejam et al. 2010; Navarro-Ortega et al. 2014), has affected freshwater quality and quantity as a consequence (Vega et al. 1998; Hermoso and Clavero 2011). Freshwater resources in the Mediterranean basin, considering a 2 °C warming, will decrease by 2% to 15%, being the largest freshwater decrease in the world (Gudmundsson and Seneviratne 2016).

1.2 The Importance of Wastewater Treatment Plants (WWTPs): The Case of Catalonia (NE, Spain)

Wastewater, including domestic, industrial and storm water, must receive an adequate treatment before being discharged into the fluvial systems in order to reduce the fluvial ecosystem impact. During the 1970s, most of the cities in Catalonia did not have any urban wastewater treatment system. In addition, the increase of the industrial settlements in the territory with uncontrolled discharges provoked significant pollution episodes in most of the rivers in the territory. In this context, in 1995 the Catalan government approved the Catalan Treatment Plan (Generalitat de Catalunya 1995) to accomplish the Council Directive 91/371 (European Commission 1991) with the main purpose of reducing and eliminating the present pollutants in Catalan fluvial systems.

Later, in 2000, the European Commission and Parliament approved the Water Framework Directive (WFD, 2000/60/EC) (European Commission 2000). The WFD defines a normative tool where all the member states of the European Union must specify their own public management plans to improve the water quality status of European rivers. In Catalonia, the

Catalan Water Agency (ACA in its Catalan acronym) is the public administration responsible for the transposition and implementation of the WFD. Finally, in 2019, twenty-four years after the Treatment Plan of Catalonia was approved, water treatment systems in Catalonia experimented a considerable change, both in the WWTP number and in treatment processes. At present, 514 WWTPs are installed in the Catalan region to treat the wastewater generated by the population, including economic and industrial activities, which produce similar discharges with respect to the urban water in terms of quantity. As a consequence, the water discharges of approximately 97% of the population are currently processed by a nearby water treatment plant (Agència Catalana de l'Aigua (ACA) 2017).

1.3 The Relevance of Long-Term Monitoring for Freshwater Quality Assessment in Mediterranean River Basins

The quality of surface waters, considering biological and physicochemical parameters within a global change context, depends on the interaction of natural and anthropogenic factors (James and Marcus 2006). This is considered as one of the major problems facing the world (European Environment Agency (EEA) 2008; United Nations. Water for Life Decade 2014). In the European context, the WFD was established in 2000 to promote monitoring programs to assess the ecological status of the European rivers. Its main goal was to achieve a good water quality status and to prevent pollution of fluvial resources. The enforcement of the WFD and similar international environmental laws led to national and/or regional administrations investing in efficient wastewater management technologies and implementing a set of new environmental laws. The imposition of sanctions has also limited pollution discharges to fluvial systems, although the situation is still far from ideal and further enforcement of environmental laws is required (Faure 1995; Gherardi et al. 2009).

Direct assessment of water quality in rivers and other sources can be carried out by monitoring their chemical (e.g., pH, presence of heavy metals, organic compounds or pesticides), physical (e.g., turbidity) and microbiological (e.g., presence of harmful bacteria) status. Indirect assessment, on the other hand, can be done by evaluating its biological quality, which is reflected by the presence or absence of different groups of organisms that act as proxies for water quality (Poff et al. 1997). It is relevant to highlight the importance of both strategies in long-term monitoring programs, which are valid and complementary in the ecological assessment. These programs provide robust and long time-series data about the ecological status of the freshwater ecosystems, which becomes more relevant under a climate change context (Angeler et al. 2014). In that sense, we argue that these monitoring strategies should be included in all governmental agendas and management plans, with the aim of improving the quality of freshwater ecosystems. Different examples of procedures for the prevention, control and treatment of water pollution to guarantee the good ecological quality status of fluvial systems can be found in previous studies (see e.g., Ene et al. 2010; Gatica et al. 2012; Griffiths et al. 2017; Su et al. 2017).

1.4 The Influence of WWTPs on Fluvial System Quality: The Case of Besòs River Basin

The Besòs river basin (North-East Iberian Peninsula; Figure 1) is a paradigmatic case study. During the 1960s and 1970s, the Besòs basin suffered from great water demand in order to meet the needs of an increasing population of the Barcelona metropolitan region, which brought about a rise in anthropogenic activities such as intensive farming and livestock production, industrial development and tourism. During this period, the Besòs river basin suffered the continuous discharge of untreated residual water of industrial, domestic and farming origin, being ultimately considered as the most polluted in Europe (Gordi 2005). After WWTPs started to be implemented, in accordance to the WFD, it was essential to promote long-term monitoring programs for assessing and measuring the ecological status of the Besòs fluvial system.

The main objective of the present study is the assessment of the effects of the WWTPs on the ecological quality status of the fluvial system of the Besòs river basin from 2000 to 2018. Considering the changes of the territory under a socioecological perspective and the policies applied, this research aims to evaluate the interaction between the ammonia concentration

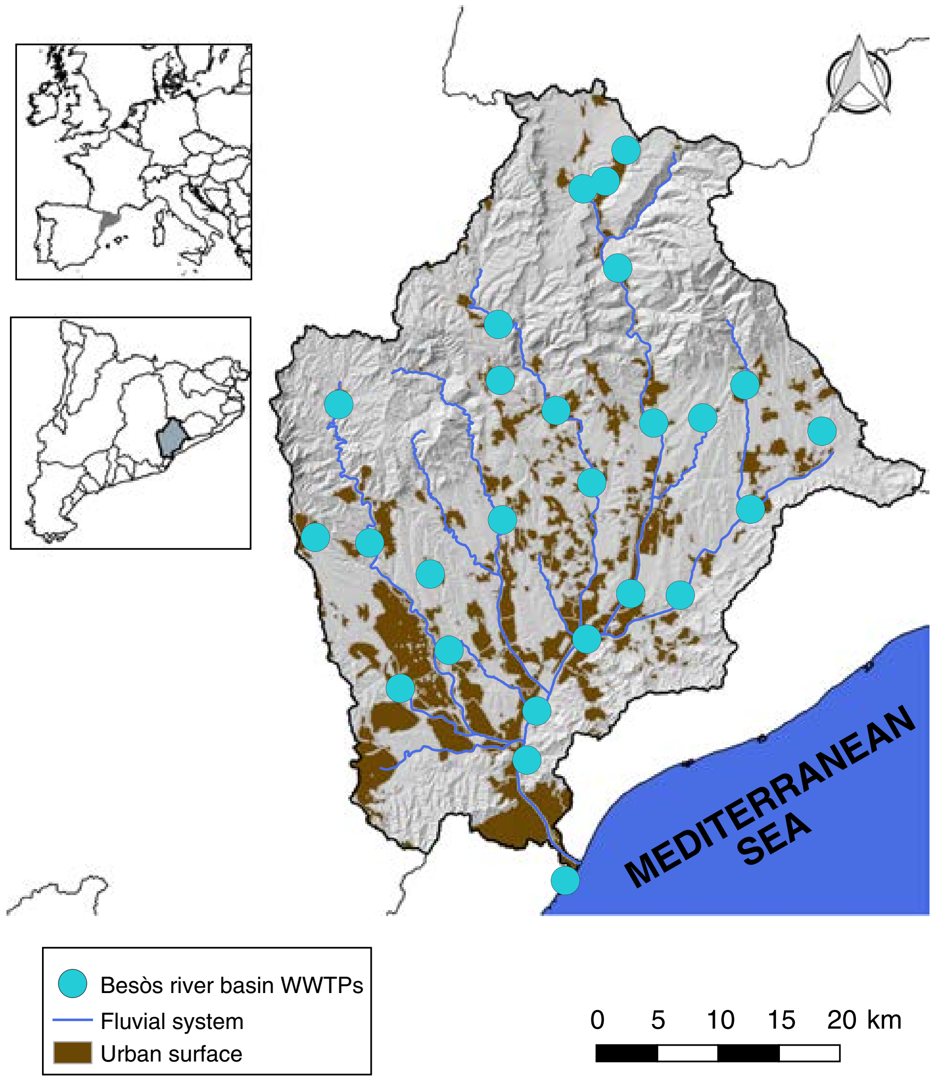

Fig. 1 The Besòs river basin and the location of the 26 WWTPs. See Supplementary Material I for details of the Besòs river basin WWTPs

NH_4^+ (mg/L) and the conductivity (EC) (μS/cm) discharged by 13 selected WWTPs (Supplementary Material I) and the Iberian Biological Monitoring Working Party index (IBMWP) which determines the ecological quality status using families of macroinvertebrates as biological indicators (Alba-Tercedor 2002; Agència Catalana de l'Aigua (ACA) 2006; Munné and Prat 2009). This research proposes a novel method to assess the effects of WWTPs on Mediterranean river systems, considering that most of the studies published so far have not focused on biological quality indicators such as the IBMWP index. Three research questions are aimed to be answered: (1) Has there been any noticeable improvement in the quality of the water from a biological point of view that can be ascribed to WWTPs? (2) How are the temporal evolutions of NH_4^+ (mg/L) and EC (μS/cm) discharges from the selected WWTPs and their future scenarios? and (3) What is the observed relationship between the IBMWP index and NH_4^+ and EC in the Besòs fluvial systems?

2 Materials and Methods

2.1 Description of the Study Area

The Besòs river basin (North-East Iberian Peninsula) has a total drainage surface of 1,038 km^2 and a mean annual flow of 2.9 m^3/s. It includes six main sub-basins with their own characteristics: 1) Mogent, 2) Congost, 3) Tenes, 4) Caldes, and 5) Ripoll, which all drain to 6) Besòs (Table 1). The Besòs river basin, subjected to a Mediterranean climate, is within the province of Barcelona and includes part of its Metropolitan Area (Figure 1).

Headwaters are characterized by the presence of different Natural Protected Areas (NPAs) with high socio-ecological values, e.g., the Montseny Biosphere Reserve. The mid and lower courses of the Besòs rivers have suffered an evident transformation in the last decades provoked by increasing industrial activity and population growth. Regarding the latter, the population within the river basin has increased tenfold during the last 50 years, and it currently amounts to almost 2 million inhabitants (Sànchez-Mateo et al. 2017).

2.2 Wastewater Treatment System in the Besòs River Basin

Before the Treatment Plan of Catalonia was approved in 1995, only two WWTPs were installed in the Besòs river basin: Besòs WWTP, located at the mouth of Besòs river (1 in Fig. 1 and Supplementary Material I), and Bigues i Riells WWTP (16 in Fig. 1 and Supplementary Material I), located in the upper-middle course of the Tenes river. Currently, there are 26 WWTPs distributed across the 6 sub-basins: 4 in Mogent, 7 in Congost, 4 in Tenes, 3 in Caldes, 4 in Ripoll and 4 in Besòs (Fig. 1). Apart from increasing the number of plants, WWTP treatments were also improved to cope with the increase of demographical and industrial activities in the Besòs river basin, especially downstream. At present, the main wastewater treatments carried out in the river basin are physicochemical and biological (Supplementary Material I). In most cases, the biological treatment represents the last treatment stage before the discharge to the fluvial course; but in others, there is an additional stage for nutrient elimination of phosphorus and/or nitrogen compounds, which mainly derive from urban waters. The nutrient elimination treatment is the most efficient, but it is not yet available in all WWTPs that implement a biological treatment.

Table 1 Main characteristics of the six sub-basins of the Besòs river basin

Besòs sub-basins						
River/Stream	Congost	Mogent	Tenes	Caldes	Ripoll	Besòs
Source and municipality (altitude)	Font de Can Regàs – Hostalets (920 m)	Pi Novell – Tagamanent (620 m)	La Collada – Collsuspina (935 m)	Sant Sadurní – Gallifa (951 m)	Sot Galí – Sant Llorenç Savall (640 m)	Congost-Mogent – Montmeló (72 m)
Surface (km^2)	210.04	180.68	154.46	111.57	243.3	138.26
Longitude of the main course (km)	43	31.4	28	22.6	39.2	17.7

The Bigues i Riells WWTP is the unique plant that is still implementing the physicochemical treatment system. The other 25 WWTPs have different biological treatment processes (Supplementary Material I). In addition, six WWTPs do not implement nutrient elimination; two of them include phosphorus elimination; another two incorporate nitrogen elimination and 15 combine nitrogen and phosphorus elimination. This means that 96% of the WWTPs in Besòs river basin are functioning with biological treatment system only, and 71% of these (that is 68.2% of all WWTPs plants) have a nutrient elimination system (Supplementary Material I).

As has been mentioned above, 13 WWTPs were chosen for analysis (Supplementary Material I) because they were the only WWTPs managed by the Consorci Besòs Tordera (CBT) that provided robust and long series data. In addition, these 13-selected WWTPs are representative of the different sub-basins of the study area (data provided by CBT, WWTPs management body).

2.3 Thematic Literature Review

Before setting out to respond to the main research objectives, a search of relevant scholarly literature has been performed through a thematic literature review method (Snyder 2019). This method was selected to discuss about literature based on theorical concepts, in this case, to show the lack of research which assesses the effects of WWTPs relating biological indicators in Mediterranean river basins. All the searches were conducted through the Web of Science (WOS) database considering the keywords “macroinvertebrates”, “IBMWP”, “wastewater treatment”, “WWTP”, “Mediterranean”, “south Europe” and “southern Europe”.

2.4 Water Quality Data Compilation

In 2017, biological (IBMWP index (macroinvertebrates) and IPS index (diatom algae)) and hydromorphological (QBR, riparian forest quality index) quality data of the Besòs river basin from 1997 to 2017 were collected as in Carceller et al. (1999) and Sànchez-Mateo et al. (2017) to analyze the evolution of the ecological quality status. The analysis was performed in 26 study units determined as surface water bodies by ACA, as it is required by the WFD.

To assess the effects of the WWTPs on the water quality status of the Besòs river basin, the interaction between IBMWP index and WWTPs discharges of NH_4^+ (mg/L), and EC (μS/cm) were considered. Generally, the concentration variability of these physicochemical parameters directly affects freshwater biodiversity, especially macroinvertebrates (Monda et al. 1995). They occupy different micro-habitats along the river, in the benthic habitat of freshwater systems, and are considered as the most reliable biological indicators for the ecological water quality assessment (Rosenberg and Resh 1993). Due to their wide range of tolerance to water pollution, the presence or absence of concrete macroinvertebrates at a site can act as a proxy of water quality and so the alteration and pollution stress of a fluvial course which can be provoked by high physicochemical concentration levels such as NH_4^+ and EC (Mayo et al. 2008). The IBMWP index is a sum of the indicator values of the macroinvertebrate taxa sampled in the study site. Each taxon has an indicator value ranging from 1 (the lowest indicator value) to 10 (the highest indicator value) depending on the ecological requirements of all the species of the group. Generally, the IBMWP index can be classified into five categories: High (>120), Good (71–120), Moderate (41–70), Poor (20–40) and Bad (<20) (Alba-Tercedor 2002; Agència Catalana de l’Aigua (ACA) 2006; Munné and Prat 2009).

Diatoms are the most studied microalgae and are often employed as bioindicators for water quality assessment. Due to its tolerance for pollution, they are useful for indicating and monitoring the pressures on the environment caused by eutrophication and by increments in organic matter and salinity. Moreover, diatoms represent 80% of the total number of the fluvial algae species. To assess water quality based on diatom, the Catalan Water Agency (ACA), responsible for the application of WFD in Catalonia, has selected the IPS (Specific Polluosensitivity Index, Cemagref 1982; Descy and Coste 1991) to be the most suitable index.

Riparian habitats and their structure are a key element for the fluvial dynamics (Tabacchi et al. 1998; Ward et al. 1998). They hold a high percentage of the freshwater biodiversity, protect the fluvial channel from the effects of temporary alterations and provide food and shelter for wildlife. There exist a number of methodologies to assess habitat conditions in rivers (Wright et al. 1998; Turak et al. 1999) and to evaluate their health status (Meyer 1997; Boulton 1999), but very few have focused specifically on riparian forests and perennial vegetation. In that sense, the Riparian Forest Quality index (QBR for its original acronym in Catalan) was developed in order to assess the quality of riparian hydromorphological conditions and the degree of alteration of the riparian forests (Munné et al. 1998). The calculation of this index is carried out in the field by using easily identifiable measures in relatively short stretches of river between 100 and 200 m: degree of coverage of the riverbank, structure of the vegetation, quality of the cover and presence or absence of man-made river channel alterations.

2.5 Statistical Analyses

Different statistical analyses were performed using R v. 3.1.2. (R Development Core Team 2014), depending on the question aimed to answer. All the statistical analyses are detailed explained in the Supplementary Material II, and were as follows: (1) to determine whether water quality had improved across the Besòs basin (i.e., headwaters, middle and lower courses), as measured by the IBMWP, QBR and IPS water quality indicators, we applied an ANCOVA model with the "lm" function of the "stats" R package; (2) to model the temporal evolution of NH_4^+ and EC, as well as the relationship between IBMWP and NH_4^+ or EC, we employed linear ("lm" function of the "stats" R package) and non-linear ("nls" function of the "stats" R package) models.

3 Results

3.1 Literature Review of Previous Works

As a preliminary step in our study, we carried out a search of any previous article or report in the scientific literature that dealt with the assessment of the effects of the WWTPs in Mediterranean river basins. Our thematic search turned out 10 research papers (Supplementary Material III) whose study area included at least one Mediterranean river. Namely, 7 articles dealt with WWTPs along rivers in Spain (of which 5 are in Catalonia) and 3 articles dealt with WWTPs along rivers in Portugal, Israel and United States, one per country. In that set of 10 articles, only one paper focused explicitly on the interaction between the IBMWP index and WWTPs physicochemical discharges (Pinto et al. 2010), although these authors used a statistical analysis different from what is performed here. Moreover, the other 9 articles focused only on how the anthropogenic activities (in some cases derived by WWTPs

discharges) altered the macroinvertebrates habitat structure and communities, but without the use of the IBMWP index (Supplementary Material III).

3.2 Water Quality Status in the Besòs River Basin from 1997 to 2017

Figure 2 shows the results of the ordinal regression model that analyze the water quality evolution through three different water quality indices such as IBMWP (macroinvertebrates), IPS (diatoms) and QBR (riparian vegetation) in the Besòs river basin from headwaters to lower courses and over the period 1997–2017. The regression model results indicate a general improvement of the ecological quality status of the three main river courses (headwaters, middle and lower courses) of the Besòs river basin during this period.

The increasing trend shown in the three plots is always statistically significant (significance of slope coefficients $p < 0.05$, see Table SM2, Table SM3 and Table SM4 in Supplementary Material II), demonstrating a general improvement in the water quality of the different river courses and indices. In general, the linear models seem to satisfactorily explain the observed trend, although some wiggling around the model can be seen in some of the datasets. In addition, post-hoc tests (Supplementary Material II) show that there are significant differences

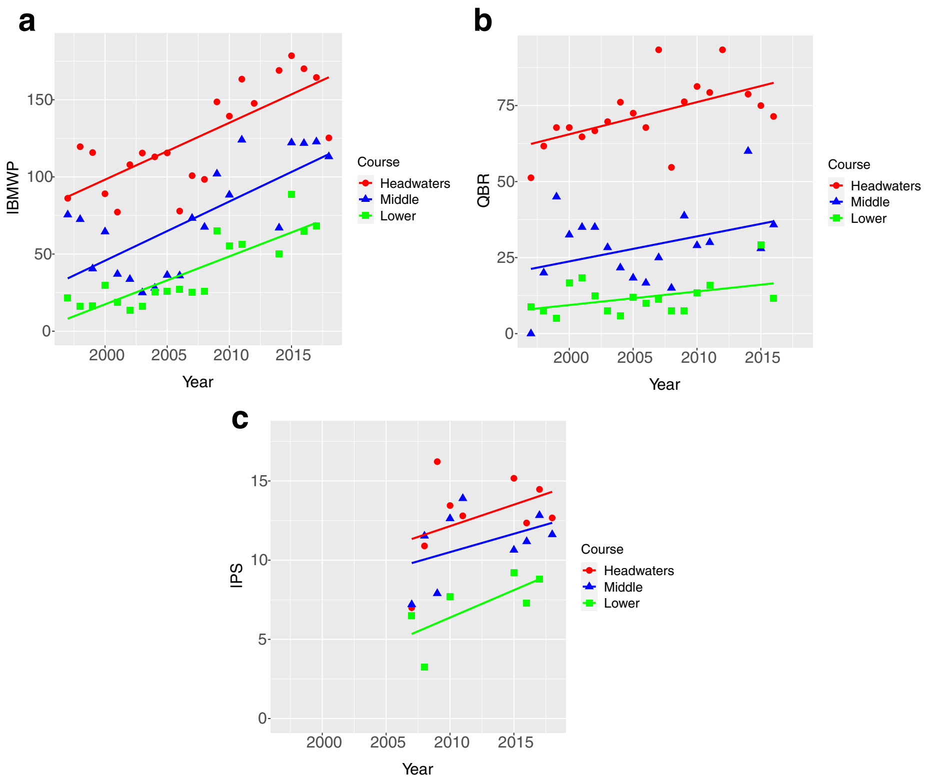

Fig. 2 Results of the ordinal regression (lines) with a cumulative link model and the observations (points) for IBMWP (a), QBR (b) and IPS indices (c), from 1997 to 2017 for the different river courses (Headwater in red; Middle course in blue; and Lower course in green) of the Besòs river basin. See Supplementary Material II for details

between river courses, controlling for the time (in years) covariate, except for the middle-headwater difference in the IPS index.

3.3 Evolution of the WWTPs Discharges (2000–2008) and Future Projections

The NH_4^+ and EC values were obtained from the data available and provided by the CBT for the selected WWTPs (Supplementary Material I) from 2000 to 2018. The NH_4^+ and EC values of discharged effluents have decreased through time, a fact that is mainly explained by the upgrading of the treatment systems from physicochemical to biological with elimination of nutrients (N and P compounds). High N and P concentration levels derived from the WWTPs have significant consequences for the water quality status of the Besòs river basin so they are one of the main factors which alter the fluvial ecosystem and the biodiversity linked to it (Monda et al. 1995).

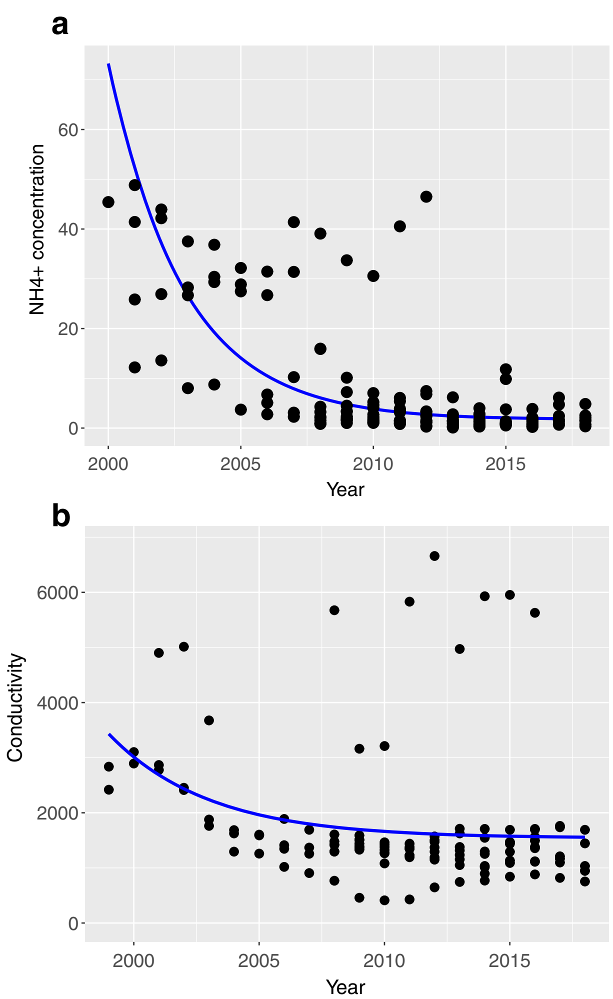

Fig. 3 (a) Evolution of the NH_4^+ (mg/L); and (b) EC (µS/cm) discharged by the 13-selected WWTPs between 1997 to 2018. See Supplementary Material II for details

Table 2 Regression coefficients for the NH_4^+ (mg/L) vs. year model. See Supplementary Material II for details

	Estimate	Std. Error	t value	Pr(>|t|)
a	1.1309	0.5012	2.2563	0.0256
b	53.9569	6.4957	8.3065	2.2×10^{-16}
c	0.2924	0.0332	8.8007	2.2×10^{-16}

Figure 3a shows results for ammonia. From 2000 to 2005, most of the WWTPs discharged high levels of NH_4^+ ranging between 30 mg/L to 48 mg/L, affecting the water quality status of the fluvial systems. During 2005 and 2008, concentrations started to suffer a considerable decrease because of the implementation of the denitrification plants, except for La Llagosta WWTP, which currently does not have a denitrification process and its NH_4^+ discharge is still in the range of the 30 mg/L. In general, in 2018, the concentrations were relatively low, varying between 0.34 mg/L to 2 mg/L. Figure 3b, in turn, shows results for EC values. Like the case for ammonia, the decline in NH_4^+ is also noticeable. From 1999 to 2005, there were high levels of EC, but wastewater treatment made these concentrations decrease from 2005 to 2018 (Fig. 3b). Based on the observed trends, we regressed the NH_4^+ or EC data against time by assuming the following non-linear model (Eq. 1):

$$Y = a + b\,e^{-c\,X} \tag{1}$$

where Y corresponds to the dependent variable (NH_4^+ or EC), X stands for time (in years) and a, b and c are the parameters to be calculated. In Eq. (1) we have included a basal level a that is reached when time tends to infinite, which is apparent in Fig. 3a and b and is statistically significant (Tables 2 and 3). To reduce heteroscedastic effects, we previously log-transformed the dependent variable Y (i.e. NH_4^+ or EC; see details in the Supplementary Material II), such that (Eq. 2):

$$\log Y = \log\left(a + b\,e^{-c\,X}\right) \tag{2}$$

To fit the non-linear model specified by Eq. (2) we employed the "nls" function of the "stats" R package.

Tables 2 and 3 show that NH_4^+ or EC approached minimum basal values of 1.13 mg/L and 1110 µS/cm as time increased.

3.4 Influence between WWTPs Discharges and Biological Water Quality Status (IBMWP)

After inspection of the data, we regressed the IBMWP index against NH_4^+ or EC with a negative exponential model (Eq. 3):

Table 3 Regression coefficients for the EC (µS/cm) vs. year model. See Supplementary Material II for details

	Estimate	Std. Error	t value	Pr(>|t|)
a	1110.0283	107.9791	10.2800	2.2×10^{-16}
b	1977.9528	187.0510	10.5744	2.2×10^{-16}
c	0.2139	0.0462	4.6264	2.2×10^{-16}

$$Y = b\, e^{-c\,X} \quad (3)$$

where Y stands for the IBMWP index and X corresponds to the explanatory variables NH_4^+ or EC. Similar to the analysis above, we previously log-transformed the IBMWP values to avoid heteroscedastic effects, such that (Eq. 4):

$$\log Y = \log b - c\,X \quad (4)$$

In this case, unlike Eq. (1), we did not deem necessary to include a basal value. Notice that the model in Eq.(4) is linear and, therefore, could be calculated with a linear regression algorithm (i.e. function "lm" in the "stats" R package) with parameters. Our results show that there is a significant relationship between the IBMWP index and NH_4^+ (Fig. 4a), as well as between IBMWP and conductivity (Fig. 4b; see also Tables 4 and 5). In general, lower values of NH_4^+ and EC imply higher IBMWP values. In that sense, the model shows that when there are

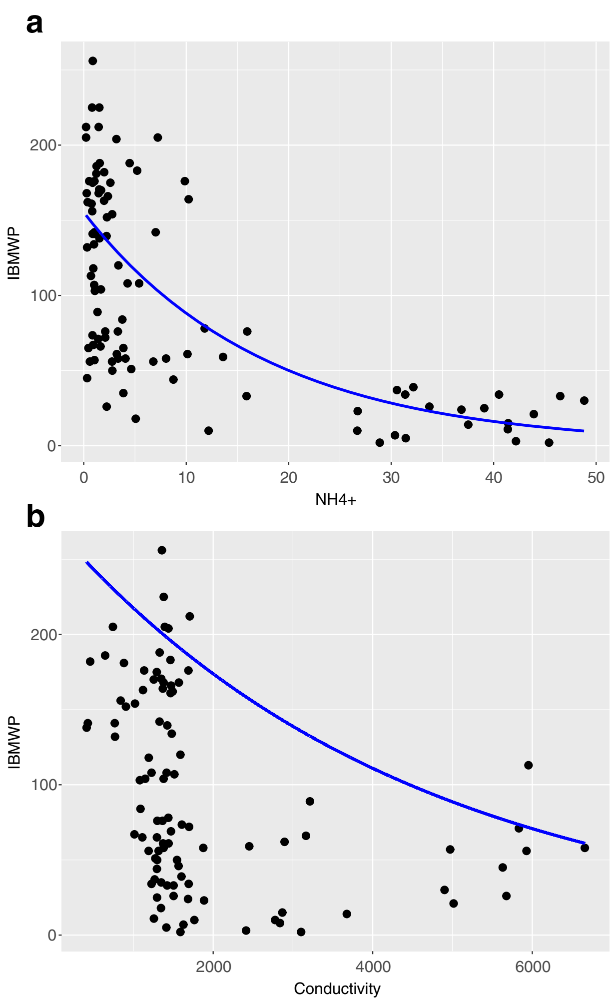

Fig. 4 Results for the regression between the IBMWP index: (a) NH_4^+ (mg/L); and (b) EC (μS/cm) (See Supplementary Material II for details)

Table 4 Regression coefficients for the IBMWP vs. NH_4^+ (mg/L) model. See Supplementary Material II for details

	Estimate	Std. Error	t value	Pr(>|t|)
log*b*	137.2653	9.0642	15.1437	0
c	0.0493	0.0038	12.9154	0

discharges of ammonium concentrations between 0 and 1 mg/L, which correspond to a correct water quality status, the IBMWP values ranges from 100 to 250 showing a correct water quality status (European Commission 2000; Alba-Tercedor 2002. On the other hand, the model also indicates that when the ammonium concentrations increase (a situation which would correspond, in our context, to a lack of water treatment), IBMWP values tend to zero (Fig. 4a). In relation to the interaction between IBMWP index and conductivity, when conductivity is between 500 μS/cm and 2000 μS/cm, the IBMWP index also presents a good water quality status. In addition, when the conductivity increases due to elevated concentrations, the IBMWP index values tend to zero (Fig. 4b).

4 Discussion

The research presented here, focused on a Mediterranean river basin, is timely and relevant, and it is a significant addition to the still scarce, although growing, body of literature on the impact of WWTPs on ecological quality status of fluvial systems. Our study demonstrates the positive influence of the treatment plants on water quality status and it provides a set of predictive models for the Besòs river basin which could be used as a tool in management and policymaking.

Our research results distinctly show that the three main river courses of the Besòs river basin (headwaters, middle and lower course) underwent a considerable water quality improvement from 1997 to 2017 thanks to the operation of a series of water treatment plants. Although index values differ in absolute value, temporal trends in all three quality indices (IBMWP, QBR and IPS) show a similar relative upward trend in time across all river courses (Fig. 2). We conclude that the implementation of environmental laws is likely the main factor that could explain this quality improvement (Faure 1995). It confirms the impact of implementing the WFD in 2000, which promoted monitoring programs to reach a correct quality status in all EU state members.

4.1 The Influence of Climate Change on Mediterranean River Basins

Climate change has direct effects on river dynamics and on freshwater biodiversity. For example, the Living Planet Index (Collen et al. 2009; World Wildlife Fund (WWF) 2018),

Table 5 Regression coefficients for the IBMWP vs. EC (μS/cm) model. See Supplementary Material II for details

	Estimate	Std. Error	t value	Pr(>|t|)
log*b*	144.1966	18.6196	7.7443	0
c	0.0003	0.0001	3.6538	4e-04

which evaluates the state of the world's biological diversity, showed a decline of 83% from 1970 to 2014. Dudgeon et al. (2005) reviewed the main five threats categories for freshwater biodiversity, namely overexploitation, water pollution, flow modification, degradation of habitat and invasion by exotic species. Thirteen years later, Reid et al. (2019) updated that list with twelve new threats on freshwater biodiversity due to global change effects: changing climate, e-commerce and invasions, infectious diseases, harmful algal blooms, expanding hydropower, emerging contaminants, engineered nanomaterials, microplastic pollution, light and noise, freshwater salinization, declining calcium and cumulative stressors. This marked increase in the number of threats to freshwater biodiversity demonstrates the need to promote strict environmental laws to reverse the current situation. The WFD imposes a River Basin Management Plan (RBMP) for each river basin, which, in our case, established specific environmental objectives, such as good ecological status of water bodies for each case study and how to proceed (Nõges et al. 2007). For these reasons and, because of the complexity of the Mediterranean fluvial systems, a multidisciplinary perspective is required for assessing the ecological quality status of these ecosystems. On the other hand, climate change has given rise to a global freshwater biodiversity crisis, which has led to an 83% drop in its availability from 1970 to 2014 (Collen et al. 2009; World Wildlife Fund (WWF) 2018). Therefore, applications of future RBMPs must consider conservation and adaptation programs for the upcoming conditions provoked by global change effects on freshwater ecosystems, such as the emerging threats on freshwater biodiversity described in Reid et al. (2019).

4.2 The Relevance on the Implementation of WWTPs in the Besòs River Basin

Moreover, the installation of the treatment systems plays an important role on the water quality status of the Mediterranean river basins. In the specific case of Catalonia, the implementation of the Catalan Treatment Plan during the 90s led to important investments for building WWTPs in all the territory. Furthermore, the water quantity that flows in the Besòs river basin is mostly dependent to the WWTPs discharges. In fact, 70% of the annual volume that flows in the Besòs rivers comes from WWTP discharges and the other 30% comes from natural sources (Consorci Besòs Tordera 2019). For these reasons, it is urgent that we implement minimum ecological flows to tackle the reduced dilution capacity of Mediterranean freshwater ecosystems, an action that would reduce the risk of transforming from permanent to temporal rivers, thus helping to keep or improve the ecological status of river basins. The annual river flow in some Mediterranean fluvial systems is altered due to human population growth and the pressure on water availability derived (Benejam et al. 2010).

Generally, the discharges derived by industrial and agricultural activities are one of the main pollution sources that alter the ecological quality status of the fluvial systems (Voza et al. 2015). The inappropriate and the excessive use of inorganic and organic fertilizers are considered as one of the main pollution sources. In fact, surface waters and groundwater are the most affected by intensive livestock farming and intensive agriculture. In Catalonia, 64.2% of groundwater, 6.7% of river waters and 2.9% of coastal waters are affected by industrial discharges. Agricultural activities affected 69.8% of groundwater, 57% of river waters, 44.1% of coastal waters, 25% of wetlands and 13.3% of reservoirs (Agència Catalana de l'Aigua (ACA) 2008). For instance, the Besòs river basin receives one of the main industrial pollution discharges of Catalonia reflected by the presence of metals, organic compounds and organochlorides in its fluvial systems (Agència Catalana de l'Aigua (ACA) 2008).

High concentration levels of wastewater contaminants such as ammonia (NH_4^+) and chlorines (EC) have significant consequences on the ecological quality status, which are mostly apparent when a threshold is exceeded (Momba et al. 2006; Osode and Okoh 2009). The statistical analysis conducted in this research highlights the importance of investing in N and P compounds elimination treatment processes for all the WWTPs of the study site. In fact, some of the WWTPs that did not have N-compound elimination treatment system (2 and 2b in Supplementary Material I) discharged high amounts of NH_4^+ to the fluvial system (main outliers of Fig. 5 in Supplementary Material II) which could be the main factor behind the lack of improvement of the general quality status of the river basin (WFD 2000). In that sense, future projections for all the WWTP discharges of ammonia and chlorines considered in this study were performed to show whether these physicochemical parameters would be under a correct water quality status threshold (between 0.1 and 0.4 mg/L for NH_4^+ and < 100 μS/cm of EC; Fortuño et al. 2018). In both cases, the NH_4^+ and EC presented levels (1.13 mg/L and 1110 μS/cm, respectively: Tables 2 and 3) higher than the values of a correct water quality status. Therefore, these future scenarios show that there is still a need for promoting new investments in treatment systems to reach acceptable levels in water quality.

4.3 How this Assessment Could be Profitable for the River Basin Management?

The approach proposed in the present study to studying the impact of WWTPs on water quality could be used as an integrative procedure that could be added as a tool to the 3rd round of the Water Management Plan (WMP) for the 2022–2027, considering the importance of the climate change in Mediterranean river basins. The WMP is a legislative tool for integrating a set of proposals, which is being currently prepared by the Catalan Water Agency (ACA), in accordance with the principles of the WFD. It is aimed at storing and rationalizing the use of water, as well as ensuring the good condition of the aquatic systems. In that sense, to respond to the Directive 91/271/EC for the treatment of urban wastewater, and to achieve the environmental goals of the WFD (2000/60/EC), some investments are done to improve the treatment systems to guarantee a greater environmental and health security.

The results shown in the present study corroborate the positive influence of the WWTPs on the Besòs river basin. Statistically significant positive trends could be seen in the three IBMWP, QBR and IPS indices. As we have mentioned above, the results for the IBMWP index are most relevant from an ecological point of view, because of the data availability and for that index being considered one the most suitable biological indicators for quality status assessment (Alba-Tercedor 2002). Despite this, future assessments could incorporate other biological and hydromorphological quality indicators established in WFD, such as IPS, IBICAT2010 index and QBR index, if the data availability is robust enough and continuous over the studied period, for a better ecological assessment of the river ecosystem (Pinto et al. 2010). In addition, similar statistical techniques could be applied to other Mediterranean fluvial systems. Furthermore, the complexity of the Mediterranean fluvial systems underscores the need for any ecological quality status assessment to be contemplated from a multidisciplinary perspective, including global change, especially climate change, and Land Use and Land Cover (LULC) change. LULC changes are considered as one of the main global change effects (Garg et al. 2019), which may give rise to important alterations on water quality, e.g., benthic macroinvertebrates are sensitive to land use changes and to fluvial habitat alterations, mainly derived by the increase of built-up area (Pinto et al. 2010).

5 Conclusions

This research demonstrates that there was a clear improvement in water quality of the Besòs river basin after new wastewater treatment plants were built and new treatment processes were implemented. These improvements resulted in statistically significant positive temporal trends at the three spatial scales studied (i.e., headwater, middle and lower course). The implementation of environmental laws, such as WFD, demonstrates the relevance of investing in long-term monitoring programs to assess ecological status of different fluvial systems and to detect the main problematic sources. Moreover, future projection of temporal trends in NH_4^+ and electrical conductivity, considering the future Climate Change consequences, underline the need to improve the treatment process even further to reach a satisfactory quality status in all the water bodies of the study area. In that sense, this assessment, considering the availability of long and robust water quality indicator data series, could be applied on other water management plans.

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Authors' Contributions All authors contributed to the study conception and design. The conceptual framework of the paper was performed by Eduard Pla and Sònia Sànchez-Mateo. Material preparation and the data compilation were performed by Antoni Mas-Ponce and the analysis were performed by Roberto Molowny-Horas. The first draft of the manuscript was written by Antoni Mas-Ponce and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability Data available in a public (institutional, general or subject specific) repository that does not issue datasets with DOIs (non-mandated deposition).

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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