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An indicator system for surface water quality in river basins

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Abstract Public utilities, agricultural and industrial economic sectors, and ecosystems depend on the water supplied by the natural environment. The European Water Framework Directive requirements, water demands and key surface water pollution problems identified in a river basin, lead to the need to develop a surface water quality indicator system. This tool allows the assessment of the pressure-state-impact of human activities on natural waters. This paper presents a methodology used for the development and application of an indicator system in the Portuguese River Ave basin, based on the conceptual Pressure-State-Response model, and on chemical and hydro-morphological water quality parameters. It is shown that the most relevant questions for the implementation of an indicator system for the surface waters of this river basin are: eutrophication, bacterial contamination, presence of organic mater, oxidation state and organic metals coming from industrial wastewater discharges.

Key words Ave River basin; European Water Framework Directive; surface waters; water quality indicators; water resources management

INTRODUCTION

Water resources planning and management have undergone an evolution towards integrated water management, with other natural resources, such as soil and forest. The main objective of water resources planning is that there is enough water available, and that it is of adequate quality so that it can be effectively used.

The European Water Framework Directive (EWFD) establishes a common framework for sustainable and integrated management of natural waters. This implies a tight connection between technical water management bodies and instruments of analysis for decision making (Vieira, 2003). One of the objectives established for 2006 by the EWFD is the intercalibration of reference conditions and quality criteria, simultaneously with the standardization of methods for sampling and analysis. Intercalibration allows the interpretation of the class boundary definitions, showing how slight, moderate, major and severe alterations from reference conditions can be quantified (Nõges, 2003).

The definition of instruments for water resources planning and management is based on an environmental information system, collected by data monitoring, after the analysis by previously established methodologies. Data monitoring programmes need to be implemented in order to allow the correct comprehension of the phenomena related to environmental values, and to establish the criteria for management decision making.

Surface waters in a river basin are usually submitted to pressures and changes, due to human activities. These activities are one of the most important causes of the degradation of water quality, which can become dangerous for public health. At a river basin scale there is a need to establish a methodology for systematic data monitoring for the characterization of surface water quality, and for the correct analysis of collected data, so that the present and expected future pressures may be identified and understood. Assessment of pressure-state-impact interaction can be facilitated using environmental indicator tools.

This paper describes a methodology based on the conceptual model PSR (of the original designation ***P**ressure, **S**tate, **R**esponse*), with the main objective of defining final values for environmental indicators. The proposed methodology will be applied in the River Ave basin, in the northwest of Portugal and focused on the selection of an adequate system of indicators. Due to the lack of information regarding biological elements, the environmental description of this river basin will only be based on two quality elements: chemical and hydro-morphological elements.

The organization of the paper is as follows: a review of environmental indicator systems is made in the next section, then the methodology used to construct a system of indicators is presented. The following section presents the case study and the results obtained. The final section summarizes the main conclusions of this work.

INDICATOR SYSTEMS FOR SURFACE WATER QUALITY

The characterization of environmental status, as well as the effects of pollution in rivers, was initiated at the beginning of the 20th century, with the use of biological indicators (Silva, 2002). But, the methodologies proposed to characterize the quality of superficial waters at a river basin scale remain few and underexplored.

Environmental indicators are a subset of the environmental variables usually observed, normalized or integrated over time and space, and contextualized with reference values and objective values, to be accomplished in a specific moment of time (Silva, 2002). According to OCDE (Organization for Economic Co-operation and Development), an indicator should be characterized by its relevance, consistency and measurability (DROTRH, 2001).

Environmental indicators are one of the available tools for environmental quality evaluation, and should be analysed inside their own context. An indicator may have different meanings under different conditions, so it should be analysed under a specific regional, social or economic context. An adequate choice of the environmental indicator to be used is one of the main procedures of the selection process.

In the European Union, EUROSTAT (Statistical Office of the European Communities) proposed a system of indicators for the characterization of human activities with major negative impact in the environment (Lammers & Gilbert, 1999). Indicators for problematic areas, pollution, climate changes and biodiversity problems have been chosen.

Under the EWFD, pilot case studies have been suggested for the construction of water quality indicator systems. In The Netherlands the concept of environmental indicators has been used for long time. The periodic publication of the "Dutch Water Policy Documents", about water quality and planning aspects, intend to define benchmarks and verification criteria about water quality and management. In the UK, methodologies for characterization of the aquatic system were developed. In Scotland, there are procedures already in practice which can be applied to fresh waters. In France, the priority themes for the environmental characterization are associated with public health and environmental balance. In Portugal, for surface fresh waters, a global quality indicator was defined. In Estonia, the main objective of establishing an indicator system for rivers in Lake Peipsi Watershed was pursued (Nõges, 2003), including the river itself, and 32 potential biological indicators were evaluated, resulting in the reference values for a set of 20 biological indicators. In Portugal, Mano & Santana (1990) presented an index system for the evaluation of superficial water quality. Their work resulted in a methodology for the characterization of the inner superficial waters quality (rivers and lakes), used for the development of River Basin Plans, where the water quality parameters are aggregated according to the expected water use, resulting in indexes that allow the definition of the quality class of a specific body of water. Water quality assessment using indicators and indices in transboundary rivers is reported by Silva *et al*. (1994). The use of biological criteria for water quality assessment can be found in Graça & Coimbra (1998), Ferreira (1994a,b), Ferreira *et al*. (1996) and Fontoura & Moura (1994) (in Silva, 2002).

EWFD quality elements for rivers

The EWFD has added new elements for normative definitions of ecological status classifications: high, good or moderate status, based on the quality elements defined in Table 1. The ecological status is classified into five levels, which are qualitatively defined by the changes caused by human activities in quality elements. It should be pointed out that the quantification of this correspondence must be made, so that this law can be effectively applied. So, there is the need for the assessment of reference conditions and the quantification of the five quality classifications. There is also the need for intercalibration of these reference conditions and quality classification when comparing different member states, their climate and ecological conditions.

Table 1 Quality elements for the classification of ecological status of surface waters in rivers (EWFD, 2000).

Biological elements	Hydromorphological elements supporting the biological elements	Chemical and physico-chemical elements supporting the biological elements
Aquatic flora (composition and abundance); Benthic invertebrate fauna (composition and abundance); Fish fauna (composition, abundance and age).	Hydrological regime (quantity and dynamics of water flow; connection to groundwater bodies); River continuity; Morphological conditions (river depth and width variation; structure and substrate of the river bed; structure of the riparian zone).	General (Thermal conditions; Oxygenation conditions; Salinity; Acidification status; Nutrient conditions); Specific pollutants (Pollution by all priority substances identified as being discharged into the body of water; Pollution by other substances identified as being discharged in significant quantities into the body of water).

Criteria for the selection of an environmental indicator

The choice of an indicator should result from the application of the following criteria (adapted from Silva (2002) and Nõges (2003)):

– the indicator must be quantitative, widely and cost-effectively measured in different measuring programmes;
– the indicator must be of easy construction, based on data accessed in reliable conditions;
– the indicator must be officially accepted as a good indicator of water quality, and requires valid water quality standards;
– the indicator must characterize the main water protection problems, being sensitive to management actions, so that its values may reflect the political and management measures undertaken;
– the indicator must describe the health and functioning of the ecosystem, as well as types of pollution in the country, being sensitive to the pressures due to use, and sensitive to spatial and temporal variability;
– the indicator should be able to give information about the evolution of trends, either past or future;
– standard methods for analytical measurements must be available (ensures reliability and comparability of data);
– precision and accuracy of analysis must be maintainable to ensure validity of results.

Conceptual model PSR

There are several conceptual models for indicator systems for environmental quality analysis (Silva, 2002). The most widely accepted framework for environmental indicators is based on the PSR model (Nõges, 2002), adopted by OCDE and EUROSTAT for the characterization of environmental status (Silva, 2002).

The conceptual PSR model seeks to develop indicators which highlight the causal links between human activities, subsequent changes in the state of the environment arising from these pressures, and the responses of society to these changes (Lammers & Gilbert, 1999). This model is elaborated after the definition of three broad types of indicators of: pressure, state and responses (DROTRH, 2001), which should reflect the relationship between environmental effects, their causes and the measures taken (Nõges, 2002). The pressure indicators aim to describe pressures from human activities exerted in the environment. The state indicators are designed to describe the actual condition as the environment changes over time. The response indicators show the extent to which society is responding to environmental change and its concerns (Lammers & Gilbert, 1999). The indicators that are chosen reflect the relationship between environmental effects, and/or their causes and measurements taken (Nõges, 2003).

The DPSIR model (***d****riving forces,* ***p****ressure,* ***s****tate,* ***i****mpact,* ***r****esponse*) can be considered as a more sophisticated version of the PSR model (Nõges, 2002). This is a model of integrated environmental evaluation that accounts for the fields of human activity responsible for generating pressures i.e. ***d****riving forces*, and considers elements of the impact on the environment, that call for answers materialized in different sectors (macro-economical and political actions). These models search for the interactions between the environment and social-economical development, and are very useful in structuring the gathering of information. The state of the environment cannot be understood unless the pressures that it is submitted to are understood (Silva, 2002).

METHODOLOGY

The construction of an indicator system and its application to a river basin requires the development of an adequate methodology to characterize its surface waters (Silva, 2002), which consists of the following procedures:

Identification of the items to be considered The relevant items are related to the physical characterization of the case study, and their main uses (current and planned), such as point and non-point pollution. The data available in the environmental monitoring of water quality, hydrometric and meteorological stations should be taken into account.

Conceptual model to be adopted The methodology developed in this work is based on the conceptual model PSR.

Selection of the parameters to be observed For each item considered at the first step, the next step consists of selecting the parameters associated with pressure, with state, and with response indicators.

Definition of the descriptive references and the determinants The descriptive reference values are the natural characteristics of surface waters, i.e. water with high quality, which expresses background values of river water not directly influenced by human activity. These values are transformed into indicators, when they are significant and enable the system to be judged.

Definition of the reference conditions and objective values The reference values for different parameters are obtained in different ways, depending on the availability of data. Data collected in environmental monitoring or from specific studies have been used among others (Nõges, 2003). The objective values are usually in between the observed values and the reference values.

Characterization of the case study The environmental description of the River Ave basin will be based on two quality elements: chemical and hydro-morphological elements, due to the lack of information regarding biological elements. These elements will provide the significant values, according to those proposed in the EWFD.

Dimension removal and normalization of the significant values determined on the previous step This step consists of the dimension removal and normalization of the significant values, applying algebraic and graphical operators. After this, it is possible to establish the concordance with the desired environmental quality (Silva, 2002).

Definition of the class boundaries based on the selected indicators. Applicability to case study According to the EWFD, the class boundaries in quality

Table 2 General definition of ecological status for rivers (adapted from EWFD, 2000).

Ecological status	Level	Human activity effects	General definition
High status	I	Minimal	There are no, or only very minor, anthropogenic alterations to the values of the physico-chemical and hydromorphological quality elements for the surface water body type from those normally associated with that type under undisturbed conditions. The values of the biological quality elements for the surface water body reflect those normally associated with that type under undisturbed conditions, and show no, or only very minor, evidence of distortion.
Good status	II	Light	The values of the biological quality elements for the surface water body type show low levels of distortion resulting from human activity, but deviate only slightly from those normally associated with the surface water body type under undisturbed conditions.
Moderate status	III	Strong	The values of the biological quality elements for the surface water body type deviate moderately from those normally associated with the surface water body type under undisturbed conditions. The values show moderate signs of distortion resulting from human activity and are significantly more disturbed than under conditions of good status.
Poor status	IV	Severe	Major alterations to the values of the biological quality elements for the surface water body type and in which the relevant biological communities deviate substantially from those normally associated with the surface water body type under undisturbed conditions.
Bad status	V	Very severe	Severe alterations to the values of the biological quality elements for the surface water body type and in which large portions of the relevant biological communities normally associated with the surface water body type under undisturbed conditions are absent.

classification are set using five ecological quality ratios (ERQ), i.e. a numeric index showing the degree of deviation of any studied parameter from the initial reference value (Nõges, 2003). The extent of deviation is usually classified on a 5-level scale. These class boundaries are related in Table 2, which provides a general definition of ecological quality.

Usually, the class boundaries are defined by the indicator that reveals the "worst" environmental situation.

CASE STUDY—THE RIVER AVE BASIN

Characterization

The River Ave basin is located in the northwest of Portugal (Fig. 1) and has an area of about 458 km^2, 247 km^2 belonging to the River Este basin and 340 km^2 belonging to the River Vizela basin, the two most important tributaries in this river basin.

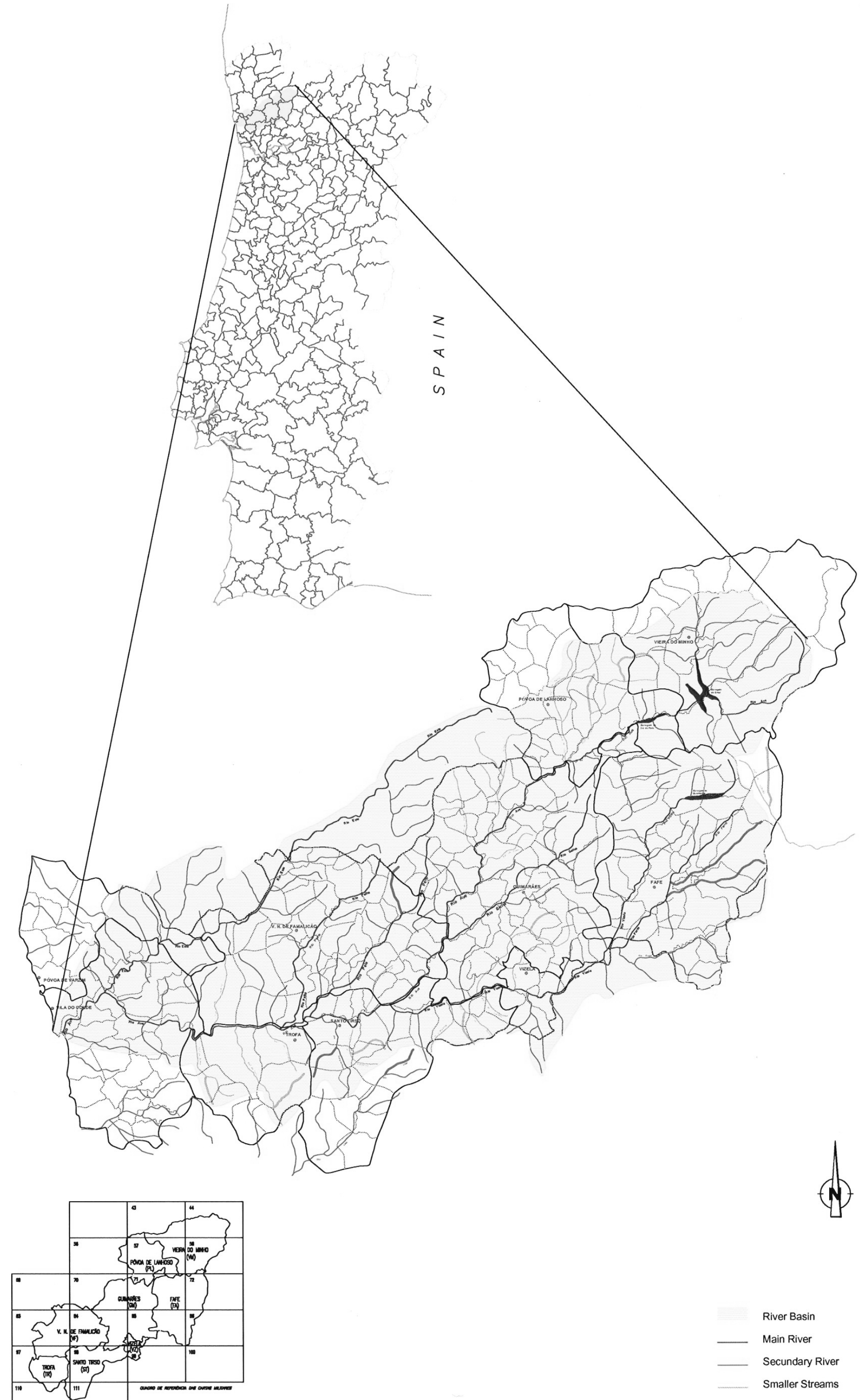

Fig. 1 River Ave Basin.

For the past 30 years, the River Ave main watercourse has been subjected to multiple discharge of wastewater, without previous treatment, due to strong industrial textile activity. This situation caused the deterioration of the water quality, resulting in water that is not only inappropriate for several uses, such as water supply for domestic and industrial use, recreation uses, fishery and irrigation, but that is also dangerous to public health.

Due to these extreme pollution problems the Integrated Management Commission of the River Ave basin was created in 1985, with the purpose of studying, planning and executing the necessary measures for the correct management of water resources in the river basin. As a result, a system involving municipals, economic agents and the state itself (SIDVA—Sistema Integrado de Despoluição do Vale do Ave) was created, with the purpose of rehabilitating this river basin, since 1997. The SIDVA infrastructures were planned and developed on a river basin scale, with an integrated and mutual solution of collecting and treatment of wastewater, composed of three main collecting systems and three wastewater treatment plants located on the most polluted area of the basin.

The main surface water quality problems are: organic pollution, turbidity and colour problems, due to domestic and industrial discharges in receiving water with inadequate insufficient treatment; eutrophication; pollution caused by harmful substances—specific pollutants, heavy metals, natural organic matter and organic metals emissions.

Available data

For this work data were collected from environmental monitoring (water quality and quantity), i.e. data collected from 24 water quality stations, eight automatic hydrometric stations and 20 meteorological stations. Until January 2005, data series were available in only nine of these 24 stations, classified in Table 3. The remaining 15 stations are very recent, and data is not yet available.

According to the National Surface Water Quality Network, reference stations intend to evaluate the natural characteristics and collect previous information about anthropogenic influence; and fishing waters stations intend to evaluate the aptitude of a water course for aquatic life. The stations that intend to quantify the human pressures on water course, are catchment stations, with the goal of classifying the quality of water sources for water supply; and impact stations, which are located in areas with strong anthropogenic influence and in classified sensitive areas. Finally, the flux stations intend to evaluate the special evolution of water quality of a water course.

Table 3 Characterization of Water Quality Stations located on River Ave basin, in December 2004.

Code	Watercourse	Station name	Goal	Type
AV1	Ave	Cabeceira do Ave	Reference, fishing waters	Conventional
AV2	Pequeno	Foz do Pequeno	Fishing waters	Conventional
B5	Vizela	Golães	Catchment	Conventional
B6	Vizela	Vizela (Santo Adrião)	Catchment, fishing waters	Automatic + *On-line* + Conventional
B8	Ave	Taipas	Catchment, fishing waters	Conventional
B15	Ferro	Ferro	Catchment, fishing waters	Conventional
G3	Ave	Riba d'Ave	Impact	Conventional
G4	Ave	Santo Tirso	Impact	Conventional
F1	Ave	Ponte da Trofa	Impact, Flux	Conventional

Items to be considered

The identification of the items to be considered obeys a number of criteria, related to legal obligation and its relation with ecological status, aquatic life and public health. This selection is also related to the main existing pollution problems. The list of relevant items was completed for this case study, resulting in Table 4. The selection of the items takes the existence, or not, of data into consideration, so that the default of data limits the possibility of the implementation of a system indicator.

To fulfil the objectives proposed, i.e. implementation of an indicator system of surface water quality of the River Ave basin, long-term hydrological, physical and hydrochemical data were collected. The database contains data on flow rates, precipitation, behind others, and on about 47 chemical parameters for this river basin since 1996.

Table 4 Relevant Items and selection criteria.

Item	Criteria Legislation	Relevance Ecological	Public healthy	Available data	Final result
Eutrophication	+ (d), (f), (g)	+	–	+	+
Contamination by bacteria	+ (b), (a), (f), (g)	–	+	+	+
Oxidation state	+ (f), (g)	+	–	+	+
Emissions of organic matter	+ (f), (g)	+	–	+	+
Heavy metals and organic metals emissions	+ (c), (a), (f), (g)	+	+	+	+
Aesthetic quality (colour)	+ (f), (g)	+	–	– /+	–
Habitats integrity	+ (e), (g)	+	–	–	–
Hydrological regime	(g)	+	–	+	+
Morphological conditions	(g)	+	–	+	+

(a) Directive 75/440/EEC (EU Quality of Surface Water used for Drinking Water Directive); (b) Directive 76/160/EEC (EU Bathing Waters Directive); Directive 76/464/CEE (EU Discharges of Toxic Substances), plus sub-directives; (c) Directive 91/271/CEE (EU Urban Wastewater Treatment Directive) and Decreto-Lei 152/97, 15 September (Portuguese Law); (d) Directive 92/43/CEE (EU Conservation of Natural Habitats and of Wild Fauna and Flora Directive); (e) Decreto-Lei 236/98, 1st August (Portuguese Law); (f) Directive 2000/60/CEE, 23 October (EU Water Framework Directive).

According to the criteria showed in Table 4 and available data, the most relevant questions to the case study, are: eutrophication, the contamination by bacteria, the presence of organic mater, the oxidation state and heavy and organic metals emissions.

After identifying the items to consider, and bearing in mind the Conceptual *PSR Model*, it is possible to build Table 5, where the selected variables and associated indicators (pressure, state and response) are shown.

Table 5 Variables and indicators proposed.

Thematic	Pressure	Indicator definition	State	Response
Eutrophication and trophic level	Total nutrient: Total Nitrogen (N) Total Phosphorus (P)	Load of nitrogen (N) and phosphorus (P) from land sources (domestic and industrial sources)	Dissolved Oxygen (mg O_2 L^{-1}) Nitrate Nitrite Nitrogen Phosphate Chlorophyll *a* Pigments	Increase the rate of wastewater treatment; Provide an increase of the relation Water collected / water treated; Raise connected industries with the total pollution content of treated wastewater; Provide good practices on the application of pesticides and fertilizers in agriculture.
Contamination by bacteria	Total and faecal coliform bacteria Faecal *Streptococcus* Bacteria	Quality requirements for drinking water due to legal obligation and public health protection	Total coliform bacteria Faecal coliform bacteria *Salmonella* Faecal *Streptococcus* bacteria	Increase the rate of wastewater treatment; Increase the efficiency of treatment.
Oxygen balance	Biochemical Oxygen Demand (BOD)	Over-saturation and oxygen deficit may significantly influence ecosystem. Biochemical oxygen demand measures of discharged wastewater	BOD Dissolved Oxygen (% Sat) Dissolved Oxygen (mg O_2 L^{-1})	Increase the rate of wastewater treatment; Increase the efficiency of treatment.
Heavy metals and organic metals emissions	Heavy metals concentration organic metals concentration	The total discharge to aquatic ecosystems of heavy metals (*e.g.* lead, chromium, copper, mercury, cadmium, zinc, arsenic) from all sources (industrial, agricultural, domestic).	Pb Cr Hg Cd Zn As	Raise connected industries with the total pollution content of treated wastewater; Adopt “clean technologies” on industrial processes
Organic Matter	Biochemical Oxygen Demand (BOD) Chemical Oxygen Demand (CQO)	Quantity of organic material discharged due to human activities (domestic, industrial and agricultural).	Oxidable Organic Matter	Increase the rate of wastewater treatment; Increase the efficiency of treatment.
Aesthetic quality (colour)	Colour	Colour Presence	Colour Presence (not visible on 1:20 dilution)	Raise connected industries with the total pollution content of treated wastewater; Adopt “clean technologies” on industrial processes
Hydrological regime	---	Hydrodynamics	Minimal runoff: flow, natural flow and modified flow	---
Morphological conditions	---	Hydrodynamics	river depth and width variation Structure and substrate of the river bed; structure of the riparian zone	---

CONCLUSIONS

The construction of an indicator system and its application to a river basin requires the development of an adequate methodology to characterize its surface waters, which consists of a number of procedures, namely: the identification of the items to be considered related to physical characterization, and their main uses and problems, specifically, source/point and non-point pollution; the adoption of the *PSR* conceptual model; the selection of appropriate parameters, and subsequently the definition of the adequate values that enable the comparability with the databases available—the reference values and objective values (the environmental objectives)—and finally the definition of the quality class boundaries.

The River Ave basin was chosen as a case study due to the pollution problems that have been affecting it for the past four decades. To fulfil the proposed objectives, long-term hydrological, physical and hydro-chemical data were collected. The database contains data on flow rates, precipitation, among other variables, and on about 47 chemical parameters collected since 1996.

Related to the parameters selection, the most relevant questions to be considered in the case study are: eutrophication (total nitrogen and phosphorus indicates the eutrophication and trophic level of waters); the contamination by bacteria (as an indicator of faecal pollution and also organic pollution, the concentration of coliform and faecal bacteria and *Salmonella* were the chosen parameters); the presence of organic mater (showed by the content of dissolved oxygen, chemical and biochemical oxygen demand); the oxidation state, heavy and organic metals emission and aesthetic quality (indicated by colour presence).

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