Perceptual modelling of environmental Indicators to assess land uses impacts on water quality

Nathalie Lalande, Flavie Cernesson, Marie-George Tournoud

Perceptual Modelling Of Environmental Indicators To Assess Land Uses Impacts On Water Quality

Nathalie Lalande[1], **Flavie Cernesson**[2], **Marie-George Tournoud**[3]
[1]*IRSTEA/Cemagref, UMR TETIS, F-34093 Montpellier, France*
[2]*AgroParisTech, UMR TETIS, F-34093 Montpellier, France*
[3]*Univ. Montpellier 2, UMR 5569 HydroSciences, F-34095 Montpellier, France*
[1]*nathalie.lalande@teledetection*

Abstract: The stream functioning is closely influenced by land uses, along the stream itself and throughout the catchment. Land uses can be seen as both the expression of the natural environment and the result of increasing human activities. Land uses generate various (in kind and intensity) pressures (positive or negative) that alter river water quality at different scales of time and space. The objective of this research is to conceptualize and quantify the interactions between river water quality and land use through spatial modelling. Our methodology is based on (i) the design of a system of indicators using the DPSIR framework and (ii) the development of the relevant environmental indicators able to characterize the spatio-temporal evolution of water quality, land uses and their interactions. The methodology is applied on the Saône River (France). Water quality status is characterized by a bioindicator based on invertebrate population. Pressures indicators were identified during a literature review, and built according to the nature of the land use, their distance to rivers and their location in the watershed. The construction of indicators was limited by the representativeness and homogeneity of data gathered from national databases. These data were supplemented by the results of a very high spatial resolution land use mapping work and a spatio-temporal change detection analysis.

Keywords*:* Environmental indicators; DPSIR; Land use; Water Quality; Saône catchment; Spatial scale.

1 INTRODUCTION

Interactions between land uses and water quality are difficult to assess because of the huge number and the complexity of the processes that are involved. We define water quality by its ecological state, and this led us to work on bioindicators and more specifically on invertebrate populations. The importance of the landscape and vegetation of the valley on its river was highlighted since 1975 by Hynes [Allan 2004] and through the river continuum concept proposed by Vannote et al. [1980]. Ward [in Johnson and Host 2010] defines four dimensions to describe interactions between surrounding environment and rivers: (1) longitudinal connection, (2) lateral connection, (3) vertical exchange between the channel and ground water, and (4) temporal dynamics. This conceptual approach strongly links upland and aquatic ecosystems, leading to a unique spatially hierarchical system. The recent review made by Johnson and Host [2010] shows the historical evolution and the growing importance of studies linking land use indicators to water quality. The available literature discusses local versus upstream catchment land uses impacts on water quality and identifies three scales to study them: (1) the micro-scale which concerns land uses in the proximity of the water quality station, and a few meters away upstream; (2) the meso-scale which corresponds to land uses on the banks on the upstream river segment of the water quality station and (3) the macro-scale that includes land uses of the upstream catchment. Some authors favour micro-scale and meso-scales that directly influence the local aquatic habitats characteristics [Lammert and Allan 1999]. The meso-scale land uses influence the diversity and the abundance of the local habitats, and more generally geomorphological processes. Other authors favour the macro-scale at which the main environmental pressures (climate, geology and land cover…) are exerted on the river network. The environmental context influences the main river characteristics such as water temperature, flow regime [Johnson et al. 2001, Allan and Johnson 1997, Allan et al. 1997, Roth et al. 1996]. However, the nature and the intensity of the relationships between land use and ecological responses are difficult to establish because of the high variety of land uses, but also because of the dynamics of changes (climate, hydrological regime, land uses) and their consequences that may take decades to stabilize. In the end, management actions could as well enhance or modulate the effect of land uses on water quality [Strayer et al. 2003]. The complexity of this issue is reinforced by numerous stakeholders involved in water management who have specific but different needs, objectives and scales of action.

A systemic approach such as the DPSIR (Driving force– Pressure–State–Impact–Response) framework promoted by the European Environment Agency allows to describe and to show this complexity for environmental policies implementation [Benini, 2010]. It is an indicator-based approach that divides a given environmental issue in five compartments. When applied to the specific issue of human impacts on river water quality, the five compartments can be described as follows: *Driving forces* represent human activities and the natural environment that can influence river quality or functioning. *Pressures* generated by driving forces can vary in kind and intensity: physical pressure (sediment and particulate input to the river, or increase in runoff water flow) or chemical pressure (exported by agricultural land uses, transport infrastructures, artificial areas). *State* of the environment is influenced by pressures, like increased concentrations of nitrates, phosphorus compounds, and suspended matter that modify water quality and local habitats, resulting in degraded fauna or flora [Allan and Johnson 1997, Allan 2004, Gergel et al. 2002, Little et al. 2003, Roth et al. 1996, Wasson et al. 2005, Zhang et al. 2010]. *Impacts* are the effects that the changes have on human society and on the environment. *Responses* are the reactions of the society and stakeholders to face the impacts, such as environmental policies or restoration actions.

The aim of our paper is to present a methodology to assess influences of land uses on river ecological quality, taking in account the complexity of the involved processes. We first describe the adaptation of the DPSIR framework to our objectives. Subsequently, we discuss spatio-temporal issues. Finally, we present an application on the Saône Catchment (France).

2 METHOD

2.1 DPSIR Adaptation

The DPSIR framework is adapted to the issue of land uses impact on river water quality and depends on the data available. It is not easy to assess driving forces because available data are not exhaustive and homogeneous enough. We chose land uses data, studied on different scales. These data are homogeneous, spatially defined and quite easily available. To capture the best reflection of the diversity of pressures, we have to build a specific hierarchical nomenclature.

Pressures are only estimated through land use indicators and are not quantified by tools such as biophysical models or flux quantification methods. We consider that these indicators characterised by land use classes and geometric characteristics represent a “pollution package” that can be positive or negative for the river system. The indicators were selected after a literature review. Indicators built at

global to meso scales express diffuse pressures whereas indicators built at meso to micro scales indicators represent localised pressures.
The ecological state was estimated with the IBGN, the French benthic macro-invertebrates bio-indicator [AFNOR T90-350]. It is based on the abundance and the selective sensitivity of river benthic invertebrates to stresses (flow, substrate, dissolved substances, temperature, light, pH, turbidity ...). The IBGN index is mainly used to follow an organic pollution, but it could also indicate the presence of chemical or toxic substances, or a local habitat deterioration [Wasson et al. 2006]. Using a bio-indicator rather than a physico-chemical parameter allows assessing a wider range of pressures.
The impact is only analyzed through the environmental aspect, by calculating the EQR IBGN, the IBGN standardized index by comparison with a reference situation.
We retain three main spatial challenges for documenting the responses: (i) identify stake areas: natural areas of high ecological interest (as wetlands) and high pressure areas (as borrow pits); (ii) make an inventory of the in-bed and bank restoration actions that have already been done and assess their effectiveness according to the methodology proposed by Palmer et al [2005]; (iii) study the potential for restoration in the riparian area.
The global scheme of the DPSIR adaptation is presented in **Figure 1**.

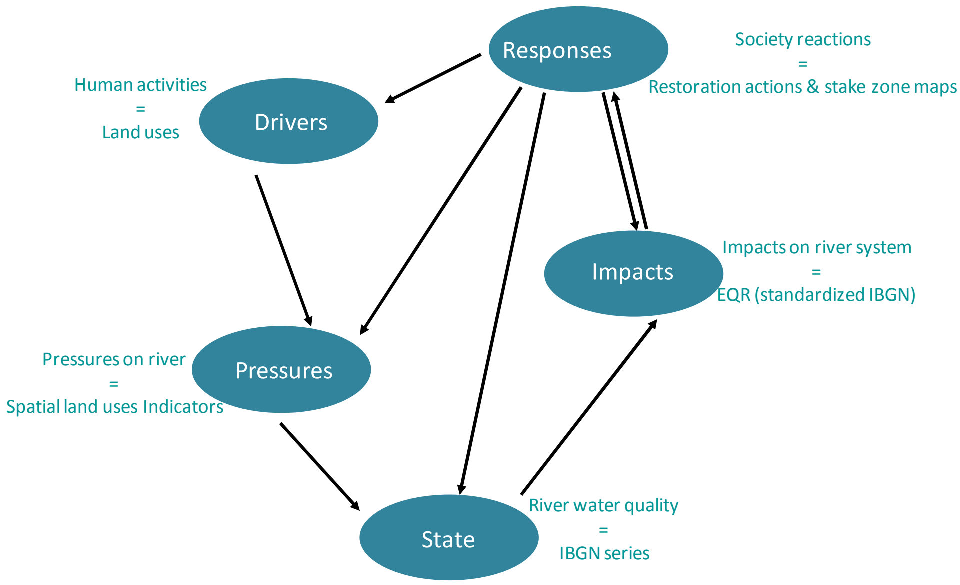


Figure 1: The adapted DPSIR framework

2.2 The scale issue: which site coverage for river corridors?

Firstly, the global scale represents the whole area of the upstream catchment. To define the micro scale and the meso-scale is more difficult. How wide the riparian zone must be in order to take into account all the processes involved between the river and its background, has not found a clear answer in the scientific community, as the processes involved vary depending on catchment conditions (soil type, vegetation, land use, rainfall…). We retain a downstream distance of 500m which includes IBGN stations area that typically stretch over 100m. The available literature indicates different upstream lengths (longitudinal dimension): from 30m to 2000m [Allan 2004, Allan and Johnson 1997, Roth et al. 1996, Sponseller et al. 2001, Wang et al. 2001] that need to be tested. For the lateral

Table 1: Links between the river Strahler order and the width of the river corridors

Strahler order	Buffer width (m)
1, 2, 3	400
4, 5	800
6	1200
7	2400

dimension, recommendations range between 10 to 250m [Johnson and Host 2010]. In France, Souchon et al. [2000] demonstrated the link between the Strahler order and the width of river corridors as shown in **Table 1**. However, these rules are too restrictive, especially for sloped catchments and large rivers where the buffer is included in the flood plain. Finally, the riparian area width combines buffers of **Table 1** and the flood plain.

2.3 The temporal issue: how to detect changes?

Time analysis is an integral part of the study of interactions between land and river water quality. For Driving forces and Pressures, land use changes can be assessed by comparing maps at different dates. However, few homogeneous multi-date land use data are available. The only available database is the Corine Land Cover (CLC) [EEC 1993] that allows change analyses in 1990, 2000, 2006. We study land use changes between 2000 and 2006 as these periods are compatible with land use processes and water quality data. We analyse the evolution of driving forces and pressures changes at three spatial scales: the entire catchment, the riparian corridor network and the proximity of water quality stations (through the study of land use changes within a circle of radius 300m and 500m).
Identifying temporal changes other than “natural variations” in the State compartment is not an easy task as IBGN time series are often very short and irregularly sampled. Many factors can influence invertebrate populations, such as life cycle stage and the hydrologic regime. More other, sampling and bio-identification depend on operator skills. Usual mathematical tools were not found applicable. So we built a two-step methodology for detecting trends in the IBGN series based on the combination of three statistical tests (linear regression, Mann Kendall and Spearman rho tests) that are well adapted to the study of incomplete small-size datasets and plot analysis. There is no time analysis for the Impact indicator because results would be the same as State. Responses change is, as for driving forces, done by a multi-date map analysis. However, this task is still complicated because very few spatial data are available on restoration actions or on stake areas. After the temporal analyses, it was possible to create synthetic indicators that were used further in the model DPSIR.

3 CASE STUDY

The Saône catchment has an area of 30000km² and a 9000km river network. The Saône draws its source from the acid Vosges Mountains then flows over marls, silt substrates then calcareous plateaus to reach the Rhône river at Lyon [Godreau et al. 1999]. The climate is semi-continental; mean annual rainfall is 860mm (Météo-France, 1983–94) [Grevilliot et al. 1998]. With a population of 2.6 million people, the basin is relatively sparsely urbanized and industrial centres are located near major population centres. Livestock dominates the upper basin, while in the left bank and the lower valley we mostly find grain farming and market gardening. The right bank is characterized by wine production. According to CLC2006, the basin has 33% of grasslands, 30% of crops, 30% of forests and less than 5% of artificial area. The basin governance is very active with over 80% of the total surface subject to a water management plan.

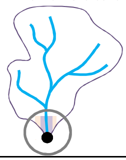
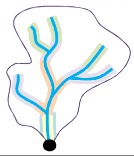
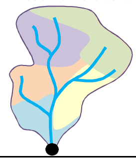
4 RESULTS

4.1 Driving forces and pressures

Driving forces information was provided by land use maps with resolutions that match the required scales. The CLC2006 database was used for the macro scale. For micro-scale and meso-scale, a high resolution map was built in river corridors

following the methodology developed by Tormos et al. [2012]. It is a multisource mapping procedure combining satellites and aerial images with several national spatial thematic data. From these land use maps, spatial indicators were built to summarise the pressures from land uses.
Natural land uses have numerous influences at micro-scale and meso-scale [Naiman et al. 1993, Roth et al. 1996]. They increase the channel stability, play a filter role for sediment and nutrients, influence water light and temperature, or provide terrestrial and stream habitats [Barling and Moore 1994, Maridet 1995, Roth et al. 1996]. At the catchment scale, forest area can play the role of biodiversity tank, providing food, clear water and a good range of aquatic habitats. Agricultural land uses lead to sedimentation, and nutrient and contaminant increase. These inputs increase turbidity, alter substrate suitability and disrupts primary production and food quality [Allan 2004]. Presence of strips of natural vegetation with grass and riparian trees can drastically reduce runoff inputs up to 70% for sediments and 95% for nutriments [Barling and Moore 1994, Vought et al. 1994]. Numerous studies illustrate alterations in river systems and communities caused by agricultural land use in catchments [Roth et al. 1996]. Urban land use and associated areas (industrial zones, quarries, roads...) are characterized by impermeability. They lead to decreased infiltration in the catchment and increased surface runoff, loading nutrients, metals, pesticides, and other contaminants to rivers. These increases alter the hydrology and geomorphology of rivers [Maridet 1995, Paul and Meyer 2001]. Although the relative overall urban surface area is not very large, its ecological footprint is considerable and urbanization ranks second as the major cause of stream impairment [Paul and Meyer 2001]. Pressures consider artificial land uses (impermeable area) as a whole rather than differentiate between artificial land uses. However, roads are still being separated. The indicators, extracted from the literature, are detailed in **Table 2**.

Table 2: Pressures indicators per land use and scale.

Land use type	Micro-scale 	Meso-scale 	Macro-scale 
Natural land uses (forest & grassland)	10m - 30m 50m	10m - 30m Maximum width	Yes
Agricultural land uses (crop & farming)	Contact (5m) 100m – 150m	200m Maximum width	Yes
Artificial land uses (impervious & transport areas)	Contact (5m) 100m – 300m	200m Maximum width	Yes

4.2 State and impacts

This study is based on the IBGN, its measurements consist in a series of invertebrates sampling, counting and identification. The protocol leads to an index which is an integer value between 0 and 20 [Archaimbault et al. 2010]. The values gathered by the Rhone, Mediterranean sea and Corsica water agency collected on the Saône catchment from 1988 to 2010. From 812 exiting stations, only 71 stations series have at least 10 observed IBGN values with a maximum of 26 observations. The study is limited to these 71 stations.

4.3 Temporal evolution

The time analysis shows that almost two thirds of the series are stationary series and one third has a significant trend. All the stations with a significant trend have a positive increase of IBGN, except one. Spatial results of IBGN time analysis are presented in **Figure 2** Stationary series were mainly observed on stations on the Saône and the Doubs rivers, the two main rivers. Non stationary series were found at stations situated at the head of sub-watersheds. Only one station was left unclassified.

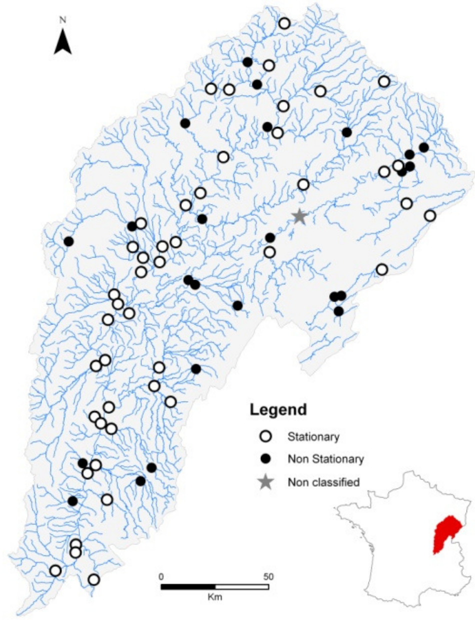


Figure 2: Results of IBGN time analysis

Driving forces time analyses show that land use changes appear on less than 0.6% of the whole catchment and on all river corridors. At the station scale, results on land use changes are very heterogeneous. On the 71 series studied, respectively 69 and 62 stations do not have land use changes within their 300m and 500m buffers. On the 9 stations left, 7 have an expected evolution, such as regeneration becoming forest, mature forest being harvested and building site becoming urban or industrial areas. Two stations show a land use change that can highly increase the human print on river. For the first station, grassland becomes a borrow pit. For the second one, agricultural lands become industrial areas.

4.4 Responses

The study of the Responses compartment is ongoing. Until now we have only focused on the identification of stake areas on the Ognon basin, a sub-catchment of our study area. Ognon basin has an area of 2300km² (almost 7% of the Saône catchment) with a river network of 1050km. Its land use composition is similar to that of the Saône, with more forest (45%) and less grassland (15%). This work requires a close cooperation with the local managers of the Ognon Basin. We define positive stake areas as areas with the presence of specific natural areas with a high ecological interest such as wetlands and ZNIEFF (Natural Zones of Animal and Plant Ecological Interest) nature reserves. Similarly, we define negative stake areas as areas where we find borrow pits in the low water channel and in the floodplain. The distribution of these two kinds of stake areas is illustrated in the **Figure 3**. Areas in green represent natural areas with positive stakes, wetlands are in blue, while areas in red represent negative stakes.

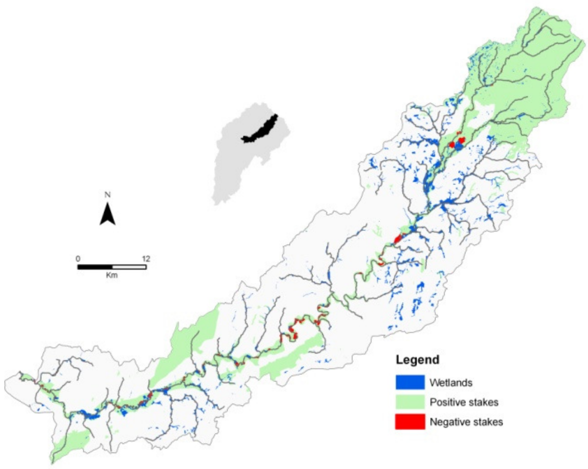


Figure 3: Stakes areas on the Ognon catchment

5 DISCUSSION AND CONCLUSION

The DPSIR framework from the European Environmental Agency clearly helped us to take into account the complexity of the environmental issues of human impacts on river water quality which involved numerous scales, processes and actors. However this conceptual background was not always easy to materialize. We chose to represent Driving forces by land use description and Pressures by spatial land use indicators. Although the available literature promotes the use of land use data to assess pressures on river, land use management can strongly modify the nature and the intensity of pressures. This is particularly true for agricultural land use pressures that are highly modulated by the diversity of the crops and cultural practices. According to our DPSIR adaptation, the Impact compartment corresponds to environmental impacts without taking into account management, social and economic impacts. Similarly, the Responses compartment is limited to the analysis of restoration actions. Despite this restriction, the Responses compartment difficulties are being met in its implementation.

The results presented for temporal analyses are not complete; especially because land use dynamics was based on only two dates and was carried out without high resolution data for meso- and local-scales.

For further work we will try to link land use indicators with water quality indicators through a spatial model. Before modeling we will have to build landscape indicators that take into account landscape complexity and will complete the Driving force pressures on rivers assessment. We will have to face several issues that have not been explored yet and that need further investigations to support our modeling work. Firstly, the temporal windows are not the same for the Pressures and States compartments. Then, we have to take into account the upstream/downstream dependencies of the indicators. Finally, we also have to analyse and discuss the representativeness of our input data. At present, the States indicators are based on only 71 stations. It could be interesting to develop a method for using the water quality information of the 741 stations left out because of their poor IBGN temporal sampling. These stations could help to strongly improve our spatial sampling.

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