Mapping ecosystem services provided by wetlands at multiple spatiotemporal scales: A case study in Quebec, Canada

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Highlights

- Wetland ecosystem services (ES) are degrading all over the world
- Spatially explicit quantification of ES remains under-explored
- We provide a systematic and reproducible approach to map wetland ES
- The spatiotemporal analysis of wetland ES can be used to guide conservation priorities

Abstract

Wetlands are affected by climate and anthropogenic changes, which influence the ecosystem services (ES) they provide. This study presents a spatially explicit quantification of wetland ESs. The study site is the Yamaska river watershed located in Quebec, Canada. The proposed approach includes four main steps: (1) statistical selection of function indicators (FI) to build a composite ecosystem service indicator (ESI); (2) temporal land use mapping for past (1984), recent (2011) and future scenarios (2050); (3) mapping and quantification of FIs and ESIs at all temporal and spatial scales; and (4) synthesis of multispatial and multitemporal information using a diagram representation.

Results present the spatiotemporal evolution of the maintaining habitat ES provided by wetlands in the studied watershed. The historical characterization shows a general degradation of this service on the entire territory for the last 30 years. Multi-scale analyses can target priority sectors in which this service has deteriorated or is lacking. Future scenarios show the urgency to act in order to preserve currently intact areas because even the optimistic scenario indicates that the studied ES would not return to its 1984 state. Finally, the synthesis analysis provides a decision support tool adapted to territory managers. Thus, this study shows that the proposed multi-scale method is reproducible, robust and that it provides simple procedures to assess ES over time and space.

Keywords: Wetland, Ecosystem service, Function indicator, Temporal scale, Spatial scale, Sensitivity analysis

Abbreviations

ESI: Ecosystem service indicator(s)

FI: Function indicator(s)
ES: Ecosystem service(s)
SW: Sub-watershed(s)
MW: Micro-matershed(s)
SLL: St. Lawrence Lowlands
SA: Sensitivity analysis
SD: Sustainable development

1. Introduction

All terrestrial and aquatic ecosystems provide ecosystem services (ES) that benefit society (Mitsch and Gosselink, 2000), such as maintaining habitats for species (Czúcz *et al*., 2018; FAO, 2018). Despite the difficulty of objectively assessing and locating the ecosystem elements that produce these ES, it is essential to develop tools to quantify them (De Groot *et al*., 2010; Kelly *et al*., 2011; Bagstad *et al*., 2013). These tools will help better identify which services are present and plan land development accordingly based on the identified characteristics. Urbanization, agricultural expansion, and forest harvesting, combined with the lack of knowledge about ESs often lead to the loss or reduction of natural environments (Mitsch *et al*., 2000). The degradation of these environments therefore affects the ecological functions they provide, mainly resulting in the destruction of habitats and a reduction of biodiversity (Wang *et al*., 2008). Considering the conservation or restoration of ecosystems in land management is therefore an important solution to ensure that they continue providing essential ESs (Millennium Ecosystem Assessment, 2005; Haines-Young *et al*., 2006).

Wetlands are transitional areas between terrestrial and aquatic environments. The water table is below, above or equal to the land surface, long enough to have aquatic processes, semi-aquatic vegetation, and biological activity adapted to the wet environment. The fauna and flora are adapted to these permanently or temporarily flooded environments (NWWG, 1997; Brinson and Malvárez, 2002; Wang *et al.* 2008). The global wetland area is estimated at 570 million hectares, which represents 6% of the land surface (Ramsar, 2011). As a result, they provide important ESs, despite being among the most neglected ecosystems by human activities (Nielsen *et al*., 2012).

ESs provided by wetlands are beneficial to all human and animal communities. These communities are dependent on several services that can be grouped into three categories: regulating and supporting services, provisioning services, and cultural services (Kremen, 2005; Dodds *et al*., 2008; Niemelä *et al*., 2008). There are many ESs comprised in these categories, including maintaining habitats, gas regulation, disturbance regulation, water supply, soil erosion control, recreational activities, nutrient cycling, etc. (Dodds *et al*., 2008; Wang *et al*., 2008). Wetlands are considered to be unique habitats because they support an important food chain and are known to be biodiversity hotspots (Wang *et al*., 2008). Wetlands are also known as the “kidneys” of the Earth for their ability to accumulate water and sequester pollutants and other elements (Wang *et al*., 2008), which are several important ecological functions. While ESs provided by wetlands strictly refer to the benefits they provide to society, ecological functions relate only to processes and interactions between wetland features and structures (Turner *et al*., 2000; De Groot *et al*., 2010; Ramsar, 2011). Ecological functions therefore represent the ability of ecosystem processes and components to provide ESs and should be considered first when assessing the status and effectiveness of wetlands (De Groot *et al*., 2007).

The analysis of wetland ESs is usually done considering their dynamic role in watersheds, but this requires the use of adapted spatial units since natural and human stresses occur at different spatial and temporal scales. Nonetheless, despite the growing recognition for conservation, the loss of wetlands is accentuated by human activity (Turner *et al*., 2000; Ramsar, 2011). More than half of the existing wetlands were lost during the 20th century in regions experiencing strong anthropic pressures. The main causes are population growth, economic development and more directly, infrastructure development, land conversion, water use and over-exploitation of resources (Millennium Ecosystem Assessment, 2005).

Several actions are possible to counter the harmful effects caused by the loss of wetlands. It is essential to first assess the level of disturbance and the degree of destruction of the wetlands to draw a realistic portrait of the situation. Secondly, it is important to quantify wetland ESs to concentrate the interventions in areas where their numbers have been significantly reduced. However, the development of a decision-support and spatial-support system for land use planning related to the evaluation of landscape functions is not frequent (Meyer and Grabaum, 2008). Yet, land use strategies based on short- and long-term needs increase the resilience of territorial management (Foley *et al.*, 2005) when the three components of sustainable development (SD) are taken into account: ecological, socio-cultural, and economic (Moctezuma-Malagón *et al.*, 2008; Turner *et al.*, 2000). Moreover, de Groot *et al.* (2010) state that only a multi-scale approach can adequately model ESs. The multi-temporal aspect also needs to be considered to help decision-making (Rebelo, 2009). Despite their importance, spatiotemporal ES analysis tools are not available due to their complexity, or the lack of data.

Among the tools developed to assist territorial management related to natural habitats, the one proposed by Wardrop *et al.* (2007) is particularly interesting since it addresses several ESs. However, it does not use a spatial approach in its evaluation, which represents an important aspect for territorial management (Hanson, 2009). In addition, the functional capacity index used only evaluates ESs based on a few limited aspects, since socio-cultural and economic aspects are not considered. This kind of integrated index can, however, be quantitatively analyzed and presented in a diagram illustrating the state of an ES (Foley *et al.*, 2005). Pinzger *et al.* (2005) are among the first to use this visual representation by integrating metrics into a Kiviat diagram. This kind of radar diagram can show the functional and temporal variations of an entity and facilitates the identification of relationships between critical trends (Théau *et al.*, 2015). It also allows the representation of complex metrics to facilitate interpretation and relationship studies. However, the standardization of values is essential to establish thresholds, facilitate comparisons, and prevent an oversized diagram. The axes are connected to one another to form a polygon whose boundaries can fluctuate. The use of the Kiviat diagram to analyze scenarios can also contain a sustainability limit that delimits a trade-off evaluation space for possible developments in the territory (Paracchini *et al.*, 2011; Théau *et al.*, 2015). The purpose of this representation is to find politically acceptable options for sustainability, that is, to determine the space within where trade-offs between different indicators can be assessed.

Currently, the territorial management of wetlands in inhabited areas is dependent on ESs that are useful to the local population, which often results in economic but not sustainable valuations (Boyer and Polasky, 2004). Therefore, an important challenge for land management operations concerns the identification and sustainable assessment of wetlands and their ESs (Müller and Burkhard, 2012). The objective of this study is to develop a spatial analysis tool to quantify ESs to support decision making regarding the management of wetlands at a watershed scale. The tool aims at being adapted to the practice of the managers of the territory by emphasizing the notion of durability. The specific objectives involve: (1) identifying and designing spatial indicators representative of the functions (FI) of the ESs studied; (2) developing an approach that allows two spatial scales, one for strategic planning and the other for local interventions; (3) mapping past, recent, and future wetland ES states in a complete watershed, and (4) ensuring that the approach is applicable to other watersheds in the same area, as well as to other ESs.

Three ESs were analyzed in this study: maintaining habitats, flood mitigation, and water purification. These three ESs are among the most studied in the literature since they correspond to the dominant ES provided by wetlands (Cedfeldt *et al*., 2000; Mitra *et al*., 2005). They also have relatively simple geospatial features to measure their functional effectiveness. However, for reasons of space constraints in this manuscript, only the maintaining habitat ES is presented. This ES is directly related with wildlife habitat support, which is one of the most fundamental elements in ecology (Brinson, 1993; Wang, 2008).

2. Study area

The St. Lawrence Lowlands (SLL) are mainly composed of sedimentary rocks. It is steep-sided by the southern Laurentians and the Appalachian Mountains, and covers more than 29 000 km^2. The topography is relatively flat, hills are rare, and the climate is moderate and humid, representing the mildest climatic conditions in Quebec, Canada (Li and Ducruc, 1999). The SLL encompasses the vast majority of urban and agricultural areas in the province of Quebec (Jobin *et al*., 2004; Kirby and Beaulieu, 2006). Incidentally, for the last 40 years, watersheds have reportedly lost more than 45% of their wetlands and 65% of the remaining environments have been disturbed by human activities, which profoundly affected the ESs they provide (Joly *et al*., 2008).

The study site is the watershed of the Yamaska River. It is considered as one of the most representative of the SLL. This watershed has a representative and diversified number of wetlands as well as heterogeneity of human and natural pressures (Fournier *et al*., 2013). It covers 4 784 km^2 and 60% of its territory is included in the SLL (Fig. 1). The rest of the watershed's territory is located in the Appalachian Mountains, where the terrain is steeper, which represents an important constraint for agricultural development. Consequently, the majority of the 4% of wetlands included in the watershed is located in this region. Diverse wetlands are present, but swamps dominate in number and area (47% and 40%, respectively). Land use is dominated by two classes: forests (34.6%) and agricultural areas (43.3%). The watershed is drained by three main tributaries: Noire, Yamaska North and Yamaska Southeast rivers, which cross medium-sized towns, including Granby and Saint-Hyacinthe. Anthropic environments (cities, villages, roads) make up 7.3% of the territory (Varin, 2013).

Fig. 1. Study site – Yamaska river watershed.

3. Geospatial data

Table 1 shows the geospatial data used in this study. Multiple sources were used and the minimum map units vary according to each. Different methods were used to produce recent (2011) and historical (1984) data, including the object-oriented approach (Grenier *et al*., 2007; Fournier *et al*., 2013) and photo-interpretation (Kirby and Beaulieu, 2006). These maps were subsequently used to simulate future land use maps (2050), using trends observed between 1984 and 2011.

Table 1. Geospatial data used in this study.

Geospatial data	Year	Mapping technique	Minimum mapping unit (ha)	Data producers
Wetlands	1984	Object-based	1.0	Effigis Geosolutions
	2011	Visual interpretation	0.3	Canards Illimités Canada and MDDELCC*

	2050	Markov chain – IDRISI Taiga	1.0	Université de Sherbrooke
Land use	1984	Object-based	1.0	Université de Sherbrooke
	2011	Object-based	1.0	Université de Sherbrooke
	2050	Markov chain – IDRISI Taiga	1.0	Université de Sherbrooke

* MDDELCC: Provincial Ministry in charge of the environment - *Ministère du Développement Durable, de l'Environnement et de la Lutte contre les Changements Climatiques*.

4. Methods

The ES mapping method is based on the characterization of wetland functions using function indicators (FI) that are spatially defined. The quantification of ESs is therefore performed using weighted and standardized FI summations to provide an ecosystem service indicator (ESI) (Alam *et al*., 2016). Fig. 2 presents the general methodological diagram, which includes the four main steps. The first step is to select the FIs that are parts of the ESI using a statistical analysis. In this study, the maintaining habitat support service was used to illustrate the approach. The second step involves the production of multitemporal land use maps, including 2050 land use scenarios. The third step is the mapping of FIs to calculate the ESI for the targeted wetland ES (*i.e.* maintaining habitat support service) in the selected watershed, at two spatial scales. FI maps were produced for the recent state (2011), the historical state (1984), and for two future scenarios (2050). The final step is a synthesis of the spatial analyses to produce a simplified representation according to functional criteria of sustainability adapted to wetland managers.

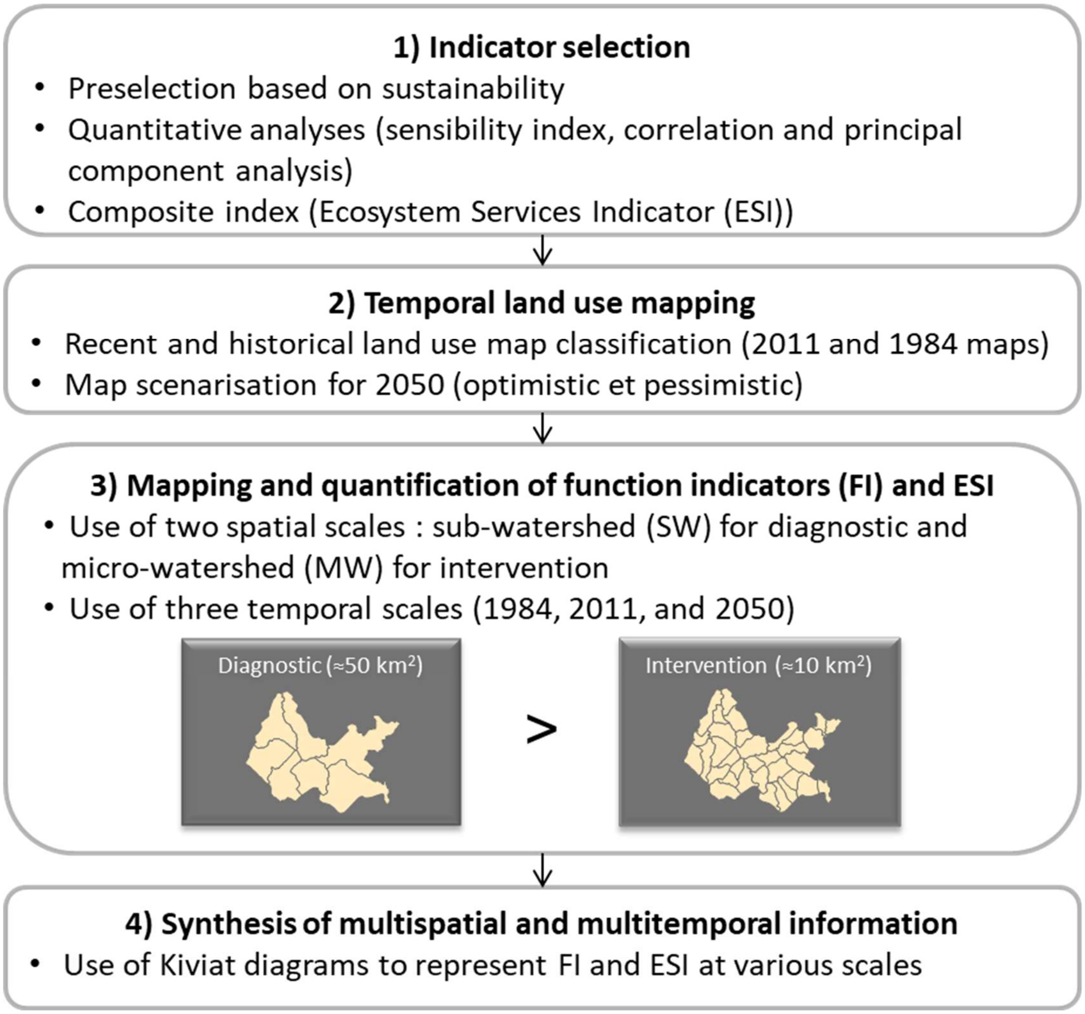


Fig. 2. General methodology of the proposed approach.

4.1. Selection of function indicators for ecosystem service evaluation

FIs were selected to represent the three components of sustainable development: the ecological, socio-cultural and economic components to spatially measure the effectiveness of the maintaining habitat support service. The selection of FIs was performed in two steps. First, a preselection of FIs was done by listing potential candidates based on a literature review. The preselected FIs must symbolize the union of important functions that apply to the ES (Floridi *et al*., 2011). Several criteria were then applied to refine this preselection. Selection criteria include, but are not limited to: (1) applicability to the SLL, (2) degree of support by the literature, (3) spatial representativeness, (4) measurability using GIS with available data, (5) low variability of the response, (6) integrated for the targeted ES, and (7) mutually exclusive between FIs (Cedfeldt *et al*., 2000; Dale and Beyeler, 2001; Feld *et al*., 2009).

Secondly, a sensitivity analysis (SA) was performed on the list to test the representability of FIs. This SA aimed to establish the sensitivity of the ESI to the choice of FIs (Booysen, 2002). In addition to assessing the stability and robustness of the selected FI, the SA also determines the extent to which their number can be reduced to eliminate redundancy (Field, 2000). The SA was therefore divided into three steps: (1) the application of a sensitivity index to FI metrics, (2) the analysis of FIs and ESI correlations (Kolmogorov-Smirnov test) in order to eliminate intercorrelated FIs, and (3) the principal component analysis of FIs to keep the ones that represent the most variance. The sensitivity index was calculated with the equation found in Duchemin and Lachance (2002) for the purpose of keeping the most sensitive metric (highest value) of each FI:

$$\text{Sensitivity index} = (ESImax\text{-}ESImin)/ESImean * (FImax\text{-}FImin)/FImean \quad (1)$$

where *ESImax*, *ESImin* and *ESImean* are the maximum, minimum and mean value of ESI and *FImax*, *FImin* and *FImean* are maximum, minimum and mean value of FIs. The three steps of this SA allowed to make a final and reduced selection of FIs that will lead to an effective quantification of the selected ESs (*i.e.* maintaining habitat support service). The targeted number of FIs was between 4 and 8, covering the three aspects of SD (*i.e.* ecological, socio-cultural, and economic) independently. The ESI was calculated with an average of all selected FI. In this study, an equal weight was attributed to each FI because they are mutually exclusive, regardless of which SD aspect they represent. In addition, FIs were designed to provide normalized values between -1 and 1, which ensures that ESI values are also standardized between -1 and 1, following the approach developed by Greene *et al*. (2010).

4.2. Producing land use scenarios for temporal monitoring

The production of land use change scenarios is a tool of choice in many environmental monitoring studies. It is useful to test hypotheses on demographic developments, spatial policies and location preferences (Quétier *et al*., 2009; Rebelo *et al*., 2009). Using the 2011 and 1984 land use maps as inputs, cartographic simulations were completed for 2050. Two scenarios were generated using the Markov chain and cellular automata to generalize the temporal trends observed. This was done using IDRISI Taiga software to simulate land use (Clark Labs, 2015). These two scenarios were designed as follows: 1) a pessimistic scenario where human development is dominant and where the degradation of wetlands between 1984 and 2011 is increased (decrease of about half of the area of wetlands), and 2) an optimistic scenario with wetland conservation and restoration (15% increase in wetland area).

4.3. Function indicator quantification and mapping

FI mapping was performed to establish the spatial distribution of their values over the study area, at two spatial levels. The sub-watershed (SW) scale used a relatively coarse spatial unit (average area of 50 km^2), which leads to a diagnostic of the study site that is adapted to territory management. The micro-watershed (MW) scale used a fine scale spatial unit (average area of 10 km^2) adapted to field interventions. These two spatial units representing relatively homogeneous hydrological units were generated by adapting a hydrological analysis using the PHYSITEL model (Varin, 2013; Fossey *et al*., 2015).

Each FI map presents the spatial distribution of the indicator at the SW or MW scales. The transition from the finer scale (MW) to the coarser scale (SW) provides a generalization of the information. A simple semiology was chosen to represent FI values. Spatial units whose state is associated to critical values are represented in red, whereas values representing healthy states are represented in a green scale. Five classes (quantiles) were defined using an equal interval method based on the year 2011 for the reference thresholds. As values were normalized for all SW and MW, a critical SW could not appear as such at the MW level. For example, one or several MW can provide better ESs than other MW included in the same SW. The interpretation of these results is therefore relative to the scale. This two-scale mapping was produced for each FI as well as for the ESI representing the overall maintaining habitat support service, for each time period.

4.4. Synthesis of spatial analysis information

The spatial indicators (FIs and ESI) were mapped for 1984, 2011 and for the two 2050 scenarios. It was therefore possible to analyze the study area over a 66-year period, and to detect spatial variations of FIs and ESIs, as well as the possible influence of anthropogenic activities. This exercise collects observations on the maintaining habitat support service and analyses its evolution over time to establish whether there is improvement, stability or deterioration of the state of wetlands in the watershed.

The analysis of maps produced at these different spatial and temporal scales was performed to target problematic areas by comparing ESIs. Areas that were in a critical condition in 2011, which require human intervention, have been selected to study the evolution of their ES condition. In this paper, a detailed analysis was carried out on a representative case of temporal changes. The representation of the results in maps facilitates the interpretation, but their visualization on a Kiviat diagram, where each axis corresponds to an FI (Théau *et al*., 2015), is essential to confront the state of the wetlands with respect to different periods (Foley *et al*., 2005). A shape index of the polygonal area illustrated by the diagram provides information on the resilience of the ES in relation to the equivalent extent of its FIs (Varin *et al*., 2013). Such a representation made it possible to concretely illustrate how this information can be used to assist territory managers by integrating a quantification of the natural state of the ecosystems (Greene *et al*., 2010).

5. Results and their interpretation

5.1 Selection of function indicators for ecosystem service evaluation

The literature review permitted a first selection of six potential FIs, which were processed with the SA. This first selection includes four ecological FIs and two sociocultural FIs (Table 2). FI1 is a measure of the wetland connectivity inside a spatial unit (SW or MW). The closer wetlands are to each other, the higher is the indicator's value (McHatti*e et al*., 2004). FI2 evaluates the fragmentation of habitats by analyzing the shape of each wetland. A filiform wetland is more sensitive to an edge effect than a compact wetland (McHatti*e et al*., 2004). FI3 measures the hydrological connectivity. The closer the wetland is to a water body, the more it can be a habitat for fauna (Cedfeldt *et al*., 2000). FI4 reflects the anthropogenic pressure on the wetland. The higher the urban density within a 500 m buffer zone, the lower is the FI value (Nielsen *et al*., 2012). FI5 analyzes wetland diversity types inside a wetland complex (group of wetlands at a distance of 30 m or less (Kirby and Beaulieu, 2006). The more complex the diversity, the greater the social benefit. FI6 gives a high aesthetic value if the wetlands have a high forest density around their edges (Dramstad *et al*., 2006). Finally, an economic FI (FIe) was independently added to this selection because a statistical method, such as the cost-benefit analysis, needs to be used to assign an economic value to this ES (Brinson, 1993; Mitsch and Gosselink, 2000). This FI was elaborated in a related study and also integrates a spatial approach (He *et al*., 2015). The FIe represents the economic equivalent in stock for wetlands within each spatial unit (SW and MW).

Table 2. Spatial indicator preselection for the characterization of maintaining wetland habitats support function (indicators in bold were selected for the analysis).

Function Indicator's code	Indicator	Indicator's description	Source	Sustainability aspect
FI1	**Wetland connectivity**	When two wetlands are separated by less than 100 m, the free movement of species is facilitated, thus they should contain more species than isolated habitats. Closely located habitats ensure fauna exchanges. Moreover, if wetlands are at a distance inferior to 30 m, they form a wetland complex.	McHattie *et al.*, 2004; Kindlmann and Burel, 2008; Uuema *et al.*, 2009	Ecological
FI2	Habitat fragmentation	A more compact wetland is less affected by edge effects (less fragmentation). The Miller roundness index is used to characterize circular habitats, which are known to minimize contact between the protected inner habitat and the adjacent environment, while long and narrow habitats have proportionally more edge effects.	Environmental Law Institute, 2003; McHattie *et al.*, 2004	Ecological
FI3	Water connectivity degree	A wetland provides a greater diversity of fish and invertebrates if it is connected to the hydrological network. Aquatic diversity is superior in third order Strahler streams and higher.	Adamus *et al.*, 1991; Cedfeldt *et al.*, 2000	Ecological
FI4	**Anthropogenic barrier**	The density of anthropogenic structures inside a buffer zone of 500 m around the wetlands. Wetlands in watersheds dominated by impervious surfaces are less effective.	Adamus *et al.*, 1991; Nielsen *et al.*, 2012	Ecological
FI5	**Natural heterogeneity**	The Shannon diversity index helps determine the degree of diversity of wetland complexes, which are socially attractive.	Dramstad *et al.*, 2006	Sociocultural
FI6	Natural aesthetics	The density of natural environments (wetlands and forest) within a radius of 1 km around the wetlands brings an important social dimension. Around the habitats, a vegetation strip of 300 m is preferred.	Environmental Law Institute, 2003; Hoeltje and Cole, 2009	Sociocultural

After this first selection, the sensitivity index was used to choose between several metrics measuring these FIs. Metrics with the highest significant weight were chosen (Table 3), except for FI6. In this case, the metric sensitivity index didn't show any significant differences. Thus, the most used metric in the literature was adopted (FI6_1) (Weller *et al.*, 2007). The second step, the correlation analysis, demonstrated that the majority of the FIs were not intercorrelated, which demonstrates a successful preselection. Some exceptions were found, such as FI3, which was correlated with all other FIs (except FI2). Both sociocultural FIs, FI5 and FI6, were also intercorrelated. These results indicate that FI3 has a smaller influence and that a choice between FI5 and FI6 must be made. The third step, the principal component analysis, locates the weight and power of the six FIs in four quadrants generated from the first two components which represent almost 80% of the total variance (Fig. 3). Only FI4 is alone in the first quadrant, indicating its independence with all the other FIs. Several FIs are present in the second quadrant, but FI1 has the longest vector, which indicates that it bears most of the variance found in its quadrant. The third quadrant is composed of two FIs, but the longest vector is FI5. Therefore, three FIs were selected following this third step: FI1, FI4 and FI5. The ESI was then recalculated using these three FIs and compared with the original ESI calculated with the six FIs. These two ESIs show a correlation of 0.94, indicating that this reduced selection captures most of the information contained in the whole preselection of FIs. Moreover, these three FIs show the highest correlation when testing all other possible combinations. The FIe was finally added to this set to complete the sustainability aspects.

Table 3. Sensitivity index for the spatial metrics of each indicator (only spatial metrics in bold were selected).

Indicators	**Spatial metrics**		**Sensitivity index**
(FI1) Wetland connectivity	**(FI1_1)**	**Parcel proximity**	0.99
(FI2) Habitat fragmentation	**(FI2_1)**	**Miller's circularity adjusted with a wetland size factor**	2.08
	(FI2_2)	Shape index (FRAGSTATS)	1.87
	(FI2_3)	Miller's circularity adjusted with a wetland complex size factor	0.45
(FI3) Water connectivity degree	**(FI3_1)**	**Proximity to a hydrological network without Strahler order's factor**	1.79
	(FI3_2)	Proximity of a hydrological network with Strahler order's factor including intermittent streams	1.00
	(FI3_3)	Proximity of a hydrological network with Strahler order's factor excluding intermittent streams	0.88
	(FI3_4)	Proximity of a hydrological network without bog wetland type	0.88
(FI4) Anthropogenic barrier	**(FI4_1)**	**Anthropogenic density with a 500 m buffer**	2.26
	(FI4_2)	Anthropogenic density with a 30 m buffer	1.69
(FI5) Natural heterogeneity	**(FI5_1)**	**Shannon's diversity index**	2.57

(FI6) Natural aesthetics	**(FI6_1)**	**Forest density with a 1000 m buffer**	2.63
	(FI6_2)	Forest density with a 500 m buffer	2.71
	(FI6_3)	Forest density with a 300 m buffer	2.80

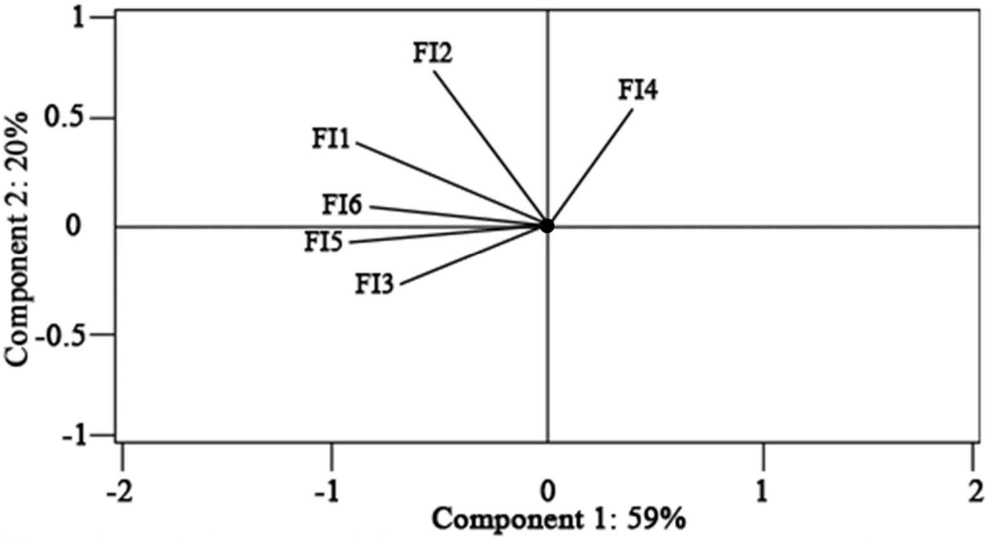


Fig. 3. Principal component analysis of function indicators (FI).

5.2. Production of land use scenarios for temporal monitoring

The overall land use changes over time, which can modulate the state of an ES. This is what the 2050 mapping simulations and the use of the 1984 and 2011 data allowed to analyze (Table 4). The studied watershed underwent a reduction in its agricultural cover from 1984 to 2050, while urban development and forest increased. Historically, almost 5% of the territory was composed of wetlands and that number decreased to 4.4% in 2011. The pessimistic scenario of 2050 exaggerated this trend with a loss of 1.1% of wetlands (2.3% remaining), mostly to the benefit of agriculture and urban development. For the optimistic scenario of 2050, an increase of wetlands was simulated to reach 5.1%. The optimistic scenario simulation led to smaller agricultural, urban, and forest areas than the pessimistic scenario because these areas were rather used for the restoration of wetlands. Finally, the optimistic scenario is composed of more natural environments than in 2011, which means that it contains more forests and wetlands.

Table 4. Land use temporal changes in the Yamaska river watershed.

Classes (%)	**1984**	**2011**	**2050 (pessimistic scenario)**	**2050 (optimistic scenario)**
Agriculture	56.3	42.5	31.1	29.3
Anthropogenic	4.0	7.1	10.6	10.4
Forest	30.4	35.3	43.9	43.7
Wetland	4.9	4.4	2.3	5.1
Other	56.3	42.5	31.1	29.3

5.3. Function indicator quantification and mapping

FI mapping was first applied at the SW scale for 2011. Fig. 4 presents the results of the ESI and the four FIs: ecological FI1 and FI4, which respectively represent the connectivity between wetlands and anthropic barriers, the sociocultural FI5, which evaluates the diversity of the wetland complex, and the FIe, which measures the economic value of the ES. Results show variable spatial patterns for FIs and ESIs. Typical examples are presented below. ESI results show that the most problematic areas are located in the central western part of the watershed. Areas in this part of the territory are mainly SW with no or very few wetlands. This pattern is also present in FI1, FI5 and FIe maps. The northern part of the watershed is characterized by relatively low ESI values. This tendency is caused by very low values observed for FI1, FI5 and FIe, whereas FI4 show high values. These patterns can be explained by the presence of wetlands that are not connected to one another, and whose diversity is limited. In contrast, the high values of FI4 reflect a low level of urban development. FI4 exhibits a highly contrasted distribution over the territory, where critical areas form scattered clusters corresponding to the main cities of the watershed. It is interesting to see that in these areas, mainly in the central southern part of the watershed, wetlands are possibly located in urban environments. However, they show a high diversity and, to a lesser extent, remain connected inside complexes, which is reflected by the higher values of indicators FI1 and FI5. An overview of the ESI shows that it represents a synthesis of its four FIs. Indeed, although the central west area remains critical, the north and the south were modulated by FI4 by averaging the values of the other FIs. These results also illustrate the equivalent influence of each FI on the ESI given that they have the same weight in the equation.

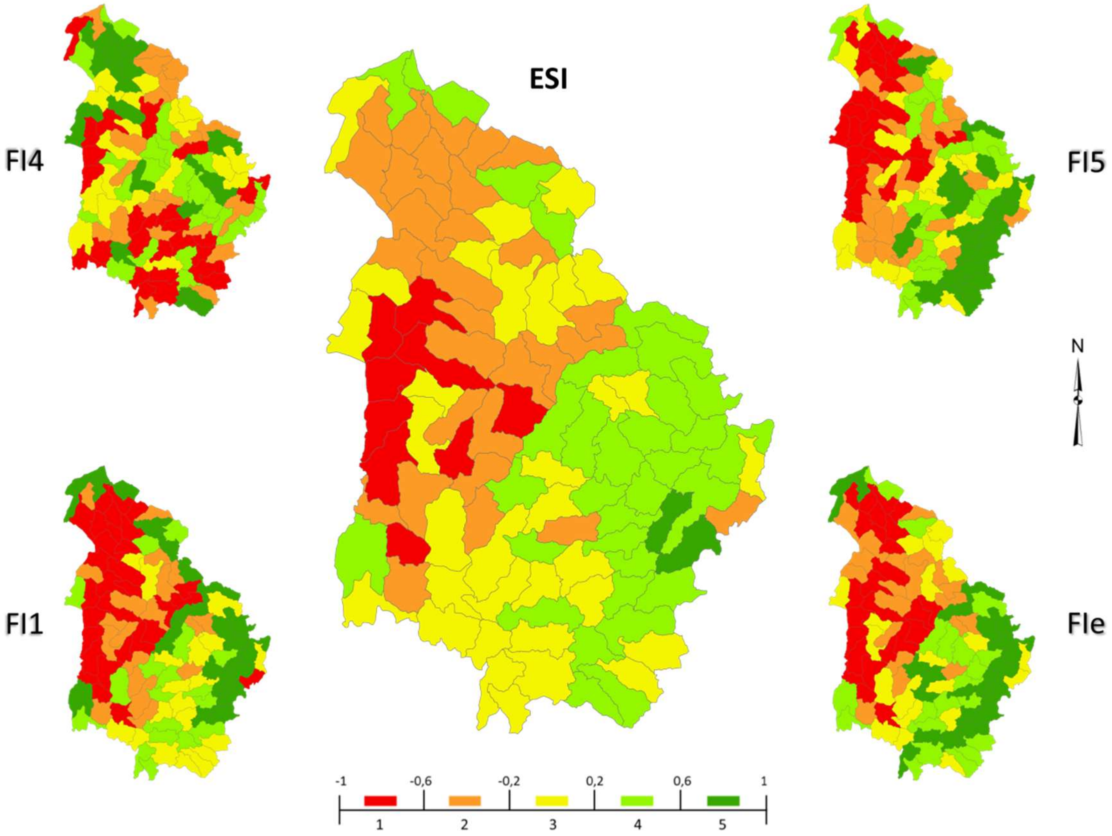


Fig. 4. Indicator maps for the maintaining habitat support service in 2011, at the sub-watershed scale (diagnostic) (FI1: wetland connectivity, FI4: anthropogenic barrier, FI5: natural heterogeneity, FIe: economic indicator and ESI: ecosystem service indicator).

Fig. 4 presented the ESIs and FIs at the SW scale, allowing a global diagnostic of the territory. When applied at a finer scale (Fig. 5), these values are subdivided over the territory, which offers the possibility of better targeting potential interventions to restore or conserve wetlands. This smaller spatial unit (MW) makes it possible to detail the trends observed at the SW scale. Below are presented typical situations. For example, it can be observed that the SWs that are in bad condition are generally composed of MWs in very bad condition. In that situation, both scales generally indicate the same conclusion, *i*.e. a high intervention priority. However, in some cases, it can be observed that a SW in bad condition can be composed of MWs presenting various conditions going from bad to good. A better understanding of these particular cases can be achieved by examining each FI at both scales. This MW scale thus makes it possible to identify intervention areas to prioritize for ecological function restorations in order to concentrate resources.

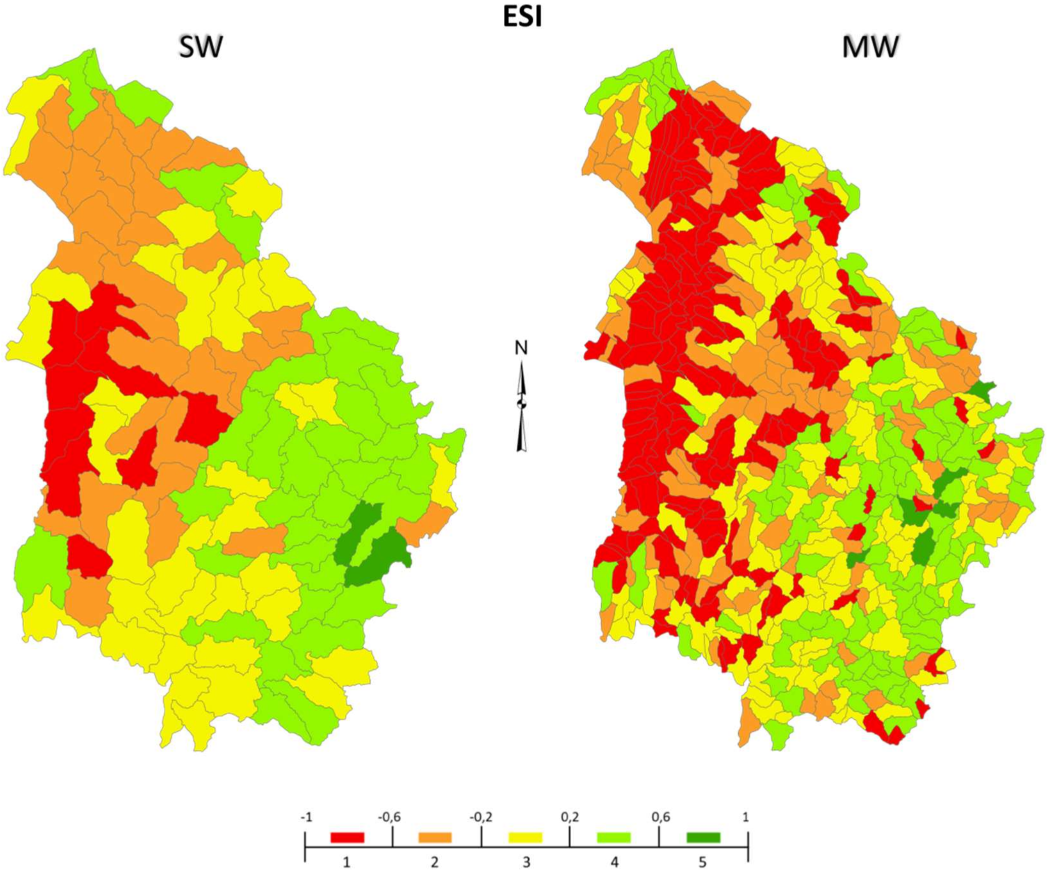


Fig. 5. Maps of the ecosystem service indicators (ESI) for the maintaining habitat support service at two spatial scales (sub-watershed (SW) and micro-watershed (MW)) in 2011.

The multitemporal approach made it possible to monitor the state of the selected ES over time (Fig. 6). In general, we can see that there are more critical areas in 2011 when compared to the historical situation (1984), which indicates a degradation of the ES provided, specifically in the central western part of the territory. In fact, this area contains an increasing number of SWs without wetlands. On the opposite, it can be observed that certain SWs improved their situation during this period, such as those located in the eastern part of the territory. This situation can be explained by an increased diversity of wetlands caused by their fragmentation over time. In our ESI, the loss of wetlands was then compensated by an increased diversity, which is considered an important factor for maintaining habitat support. For the pessimistic scenario, we can see that many SWs are degraded when compared to 2011, while only a few of them are improved. More particularly, an important degradation of wetlands is predicted in the central western part of the territory. This area corresponds to the downstream of the watershed, where increased anthropogenic activities are expected in the future. Conversely, the optimistic scenario shows an overall improvement as it reflects the restoration and the creation of new wetlands on the territory. Overall, this is visible with the distribution of greener SW, although the difference is not as marked as the opposite (pessimistic) scenario. This difference between the two scenarios is due to the fact that the pessimistic or optimistic scenarios both include territorial development (*e.g.* increase of the urban territory), which affects the FI, even in an optimistic scenario. However, habitat degradation is slowed down with an optimistic scenario. These results also indicate that even if important restoration efforts are carried out until 2050 (*i.e.* optimistic scenario with a higher area covered by wetlands compared to 1984), the situation would not return to that of 1984. This illustrates the importance of conservation by opposition to restoration when we compare the cost and benefits of each regarding the preservation of ES.

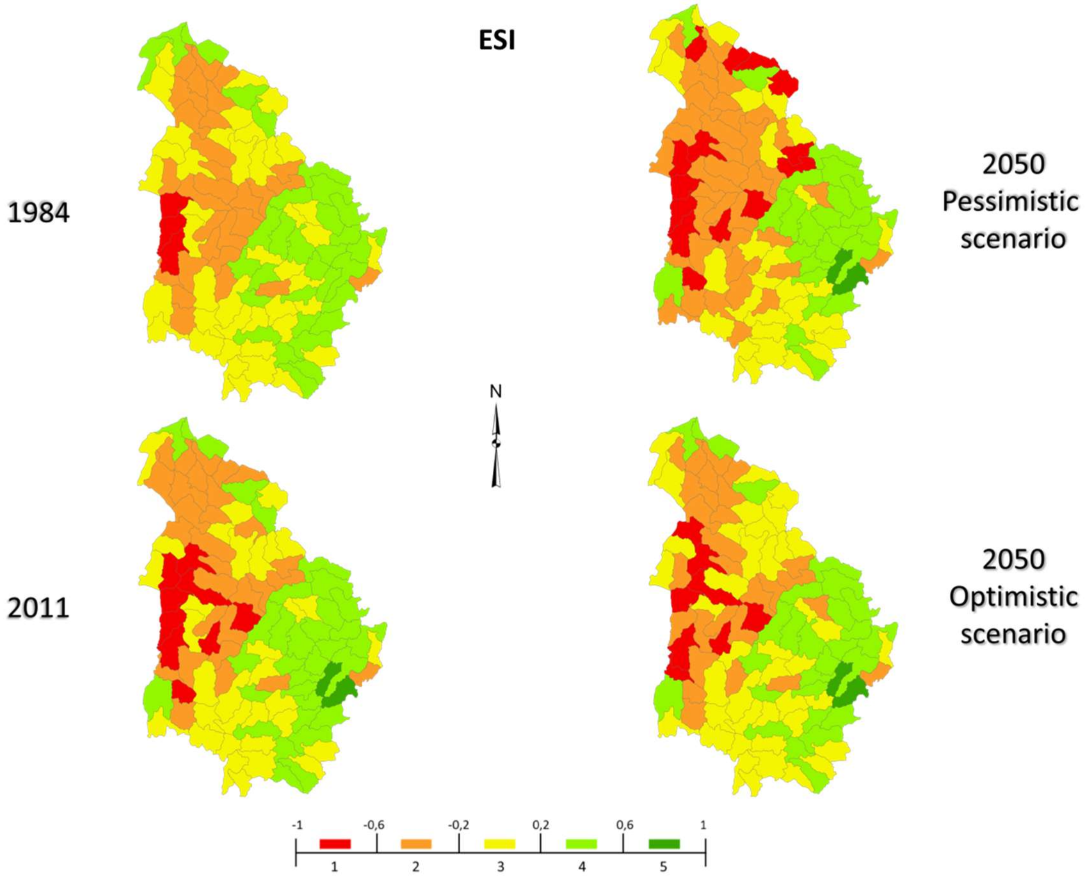
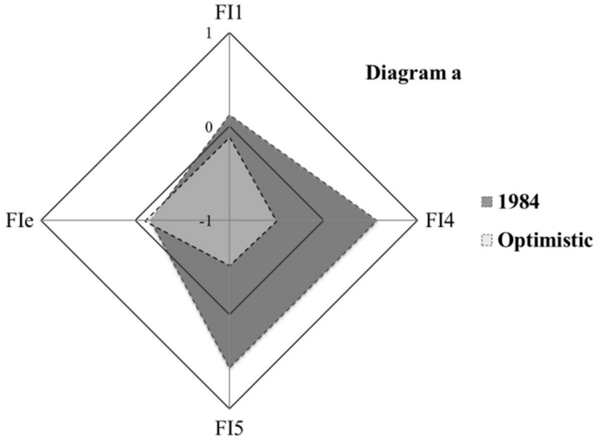


Fig. 6. Maps of the ecosystem service indicators (ESI) for the maintaining habitat support service at the sub-watershed scale (diagnostic) for different periods and scenarios.

5.4. Synthesis of spatial analysis information

All spatial analyses produced in this study can be synthesized to provide critical information when targeting priority areas. Multi-scale and multitemporal approaches can be structured using Kiviat diagram representation. This simplified representation aims to support decision-making regarding the restoration and conservation of wetlands in the territory. Taking the example of a MW, Fig. 7 presents comparisons between 1984 and the 2050 optimistic scenario (Fig. 7a), and between 2011 and the 2050 pessimistic scenario (Fig. 7b). The areas covered by these FIs show shape indexes of 0.23, 0.44, 0.24 and 0.13 for 2011, 1984, 2050 optimistic scenario and 2050 pessimistic scenario, respectively. The higher the index, the more compact the area, which means that FIs have equivalent values. This indicates a balanced and sustainable distribution for the selected ES. Fig. 7a) represents two very different situations, where the majority of FIs were higher in 1984 compared to the 2050 optimistic scenario. The economic FI, on the other hand, remained stable. This shows that in wetland restoration, it is difficult to return to the original state. For example, between the two periods, there was a loss of wetland diversity and an increase in anthropogenic barriers. This tool helps guide decision makers toward the restoration of some types of wetlands and better protect the wetlands near urban areas in this particular case. Fig. 7b) shows two similar situations, where the FIs remain relatively stable between 2011 and the 2050 pessimistic scenario, except for a degradation of FI5, and FI1 to a lesser extent. In this example, wetland degradation has caused a decrease in wetland diversity in the complexes. The management team for this territory should thus focus on the conservation of diversified wetland complexes or on the restoration of diversified wetlands in existing complexes.



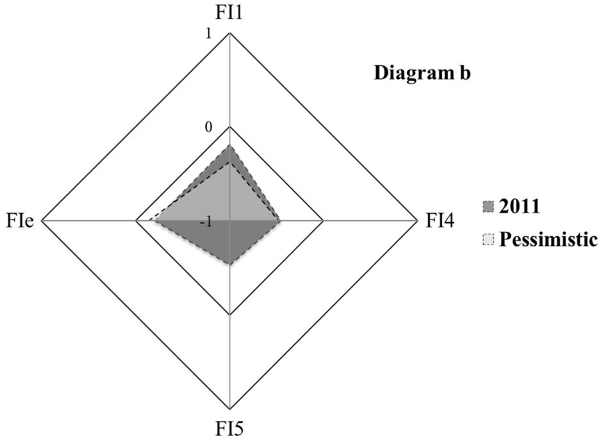


Fig. 7. State of the maintaining habitat support service represented by a Kiviat diagram. State comparison between 1984 and optimistic scenario 2050 (a), and 2011 and pessimistic scenario 2050 (b) for a selected sub-watershed unit (FI1: wetland connectivity, FI4: anthropogenic barrier, FI5: natural heterogeneity, FIe: economic indicator).

6. Discussion

This study proposes an approach to map the ESs provided by wetlands, aiming for a watershed-level diagnostic. This new approach can also guide potential initiatives for land conservation and restoration. Our approach differs from existing studies on five main aspects: (1) ES mapping procedures, (2) the presence of a multi-scale diagnostic, (3) various temporal assessments, (4) a visual representation of ES according to SD, and (5) the ability to generalize and transfer the approach.

Spatially explicit quantification of wetland ESs is still a methodological challenge and remains insufficiently explored, even if this information is relevant to most stakeholders and decision-makers (Bennett *et al*., 2015; Lavorel *et al*., 2017). Only a few studies link wetland functional traits with their spatial domain (Wolff *et al*., 2015). The method we proposed provides information on such links, by using wetland spatial metrics describing the maintaining habitat support service on a landscape perspective. Our method also includes evaluation techniques for a rigorous and objective quantification of ecological functions that are both easy to apply and reproducible. An exhaustive list of FI spatial metrics, available in raster or vector format, is first identified through a literature review and expert assessment. Then a selection of the most relevant FI spatial metrics is based on a SA which greatly reduces the number of metrics, keeping only those that are mutually exclusive and the one having the greatest magnitude. Such procedures take advantage of all available data, while providing the ability to map wetland ES over large areas.

The interaction between ESs at different scales is also a relevant element for decision-makers and stakeholders, but is once again insufficiently discussed in the literature (Martínez-Harms and Balvanera, 2012; Geijzendorffer and Roche, 2014; Bennett *et al*., 2015; Maes *et al*., 2016). The ES of wetlands are strongly associated to their hydrological unit. We proposed two spatial units based on sub-watershed boundaries that were in turn based on criteria related to landscape management. The proposed spatial units were the following: the first one averaging 10 km^2 (MW), adapted to landscape management, and the second one averaging 50 km^2 (SW) for general watershed diagnostics. Defining relevant reporting spatial units enhances the importance of the spatial scale in relation to either managing or reporting, two components that need to be integrated. As an example, it is possible that the same ES is procured in different ways according to the selected spatial unit (Mitsch, 2000; Hanson, 2012). Our results display such a scale effect. As some areas appear in ES deficit at the SW level, it becomes clearer what MW may be the source of this situation when mapping at the MW level. To a certain point, an SW may appear to have an average ES level, but after looking at the MW level, we notice that it actually contains extreme values that average themselves. In such a situation, a coarse level map may mask a critical situation found at a finer lever. This scaling hierarchy allows to target specific areas at the finer scale for which landscape management decision are critical. It also facilitates prioritizing efforts where it is required. Conversely, coarse scale maps are useful to extract a general snapshot of the situation of a large watershed. Defining the relevant reporting spatial units is yet an important aspect to explore from project to project in accordance with constraints like landscape management objectives, biophysical configuration and existing datasets.

Temporal assessment is a major contribution of this study but it is lacking in other similar studies. Moreover, neither historical nor predictive assessments are generally present (Kremen, 2005; Bennett *et al*., 2015; Wolff *et al*., 2015). However, this aspect is essential to better understand the drivers that influence ESs, their response delay, and the interactions between these ESs (Lautenbach *et al*., 2011; Wolff *et al*., 2015). This study presented an assessment of one ES over a historical period of 27 years (1984 to 2011) and a predictive period of 39 years (2011 to 2050) using two wetland conservation scenarios. This procedure is directly linked to the changes in land use. In general, results show that there are more critical areas in 2011 compared to the historical situation in 1984, due to habitat degradation. This is probably related to the significant loss of wetlands in the territory between these two periods. For the pessimistic scenario, it can be discerned, compared to 2011, that many SWs are degrading, but in some cases, they can even improve. Several explanations can be derived from this latter phenomenon. For example, a few big fragmented wetlands can create several wetlands, potentially benefiting FI1 and FI5, by forming new complexes. The optimistic scenario of 2050 shows that a few SWs may be in a worse condition than in 2011. In fact, the expansion or agglomeration of many wetlands may have the effect of reducing the complex's diversity by mitigating connectivity. This shows the importance of the choice of FIs and how complex interpretation can become.

The temporal assessment can also support which decision to take concerning land use change. For example, a critical MW could be explained by two alternatives. First, this MW could either have no wetland at all for a long time or have a reduced wetland area over time. Secondly, wetlands could be functionally ineffective for this ES. In the case where the ES would have degraded between 1984 and 2011, this state could be further amplified for a pessimistic scenario, but it is also possible for the ES to return to its original state (1984) by making restoration actions. If the ES is degrading even in an optimistic scenario, maybe the restoration of a few wetlands is not enough in a region where an ecological threshold has been reached. This aspect is part of the proposed tool to support informed decision-making and guide land use.

The choice of FIs representing all fields of SD is an innovative element of this study, which increases the social acceptability of the decisions. ESs, in some ways, are tied to human needs, but their characteristics and value vary from the stakeholder's perception (Van Hecken and

Bastiaensen, 2010; Barnaud and Antona, 2014; Bennett *et al*., 2015). The value attributed to an ES has multiple dimensions, but the ones that are usually put forward are the ecological, socio-cultural and economic values (Wang *et al*., 2008; Greene *et al*., 2010). These three fields were represented by the selected FIs and were integrated into a single multidimensional ESI. The values of this composite indicator were then plotted on a Kiviat diagram as a way to synthesize ES values according to different scenarios which in turn ease interpretation for decision-makers. This simplifies and complements the interpretation of the detailed analysis of maps with the spatial units (Théau *et al*., 2015). The Kiviat diagram is a convenient way to illustrate the relationship between different ESIs in an area for a multi-temporal plan.

The method is intended to be systematic, reproducible and applicable to other ESs and watersheds. The work described in this article is only a subset of a larger study where our method has been applied on two other ESs (flood regulation and sediment retention) using new series of FIs and applied to another watershed of the SLL (Bécancour River watershed) (Fournier *et al.*, 2013). The transferability of the approach was confirmed by the complete exercise, demonstrating the contrast between multiple ESs at the same time. However, the study of ES interactions at different scales and temporal periods is not yet fully demonstrated (Bennett *et al*., 2015; Xin *et al*., 2018). More research is needed to better understand and characterize spatial synergies and trade-offs between ESs to manage the territory in a sustainable way (Egoh *et al*., 2011; Baral *et al*., 2014). We developed a flexible tool allowing to map multiple ESs, to address multi-temporal changes, and to illustrate the resulting data with a Kiviat diagram. This method is thus suitable to study the relationships between ESs in greater depth.

Although the approach we proposed is flexible and adapted to complex ecological systems, we identified three main limitations. The first limitation was the importance of using consistent data to allow method reproducibility. This limitation was also pointed out by Müller and Burkhard (2012). Indeed, FIs are very sensitive to the data used, as they measure wetlands or their immediate environment. For example, the minimum wetland mapping unit was different for our input map used between 2011 (0.3 ha) and 1984 (1 ha). Therefore, some small wetlands could have been omitted in 1984. To limit the impact of this difference, all wetlands of 2011 that were non-existent in 1984 (except those that were artificially created) were added in the 1984 layer. The working premise being that an existing wetland in 2011 must have existed 27 years earlier.

The second limitation concerns the socio-economical FI. Our research was based on the selection of diverse FIs following the three aspects of SD (ecological/sociocultural/economical). Those FIs were selected from the literature, but the number of FIs found was uneven between the 3 types. In fact, there was fewer FIs of the sociocultural and economical type in comparison to those from the ecological type. Moreover, socio-cultural FIs are usually picked from a social interpretation of ecological processes (Haines-Young *et al*., 2006). More precisely, the sociocultural FIs we chose (*i.e.* Natural heterogeneity and Natural aesthetics) were convenient structural metrics but more relevant metrics could be inferring the socio-cultural function. Despite the fact that these indicators are hard to formalize, it is still an important aspect of SD to characterize (Alessa *et al*., 2008). For our economic indicator, we used the benefit-transfer method to assess a value from a meta-analysis (He *et al*., 2015). This involved several uncertainties for the monetary evaluation of wetland ESs since the assigned values were inferred from data collected in other countries, at different spatial scales and from studies with various objectives. Instead, the use of primary data should be prioritized for economic indicators of natural environments (Cimon-Morin *et al*., 2013). This is a complex subject to address with many potential perspectives because appropriate valuation approaches should differ for each ES. One of them would involve the cost of replacement for maintaining ecosystem (Farber *et al*., 2002; United Nations *et al*., 2014). Overall, is it important that the selected FIs make sense for the decision-makers because adoption of the mapping framework depends on their perception. It is therefore critical that the approach allows to assign certain weights to specific FIs, and also add the necessary FIs to represent the three spheres of SD.

The third limitation of the proposed approach concerns the fact that all wetlands were consolidated into one class. We have decided to regroup them for simplicity, but it is clear that not all wetlands are similar. Our land cover maps identified seven wetland classes (*i.e.* fen, bog, forested peatland, marsh, wet meadow, swamp and shallow water). Each wetland class has functions of different nature and amplitude. For example, marshes have a much better water retention ability for flow control than bogs (Price *et al*., 2005; Smith *et al*., 2008). Although this simplification brings greater ease of application, it would be interesting to measure its effect compared to a modulated approach considering the wetland class.

7. Conclusions

This study proposes an approach to map and quantify ESs by using a statistical selection of FIs representative of ecological, socio-cultural and economical aspects at watershed scales. Two spatial scales were used and four periods (1984, 2011 and two scenarios in 2050). Based on this spatiotemporal analysis, changes at the level of the ESI represent a valuable tool to analyze the evolution of the territory, and to guide management and conservation actions. The development of a graphical tool to synthesize complex information is adapted to guide decision makers in various organizations. This tool can support territory managers in their planning process, which often involves compromises between conservation and development. The study focuses on the characterization of the maintaining habitat ES provided by wetlands in a targeted watershed. As the approach is systematic, it can be replicated for other ESs in different territories. For example, it could also be applied to other areas such as forest and aquatic environments. The approach could also be improved by adjusting the weight of FIs to local needs, and by adapting FIs for each wetland class.

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