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Article

A Dynamic GIS as an Efficient Tool for Integrated Coastal Zone Management

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Abstract: This contribution addresses both the role of geographical information in participatory research of coastal zones, and its potential to bridge the gap between research and coastal zone management. Over a one year period, heterogeneous data (spatial, temporal, qualitative and quantitative) were obtained which included the process of interviews, storing in a spatio-temporal database. The GIS (Geographic Information System) produced temporal snapshots of daily human activity patterns allowing it to map, identify and quantify potential space-time conflicts between activities. It was furthermore used to facilitate the exchange of ideas and knowledge at various levels: by mapping, simulation, GIS analysis and data collection. Results indicated that both captured data and the participatory workshop added real value to management and therefore it was deemed well managed by stakeholders. To incorporate a dynamic GIS would enhance pro-active integrated management by opening the path for better discussions whilst permitting management simulated scenarios.

Keywords: GIS; Integrated Coastal Zone Management (ICZM); supervised maritime activities; management scenarios; participatory workshop; spatio-temporal database

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1. Introduction

Many diverse activities exist along coastal seas [1] playing an essential role in human society [2]. Yet, they quite often result in conflicting interactions [3] and therefore present an ongoing challenge for both society and research [4,5]. Pittman *et al.* [6] identified priority needs to describe spatio-temporal distribution of activities and to better examine existing or potential conflicts. Integration of temporal components, within a multi-activities context, consists of macro- and meso-scales (world to regional) to better assess intensity indexes for each activity [7–10]. Furthermore, spatial researches of social dimensions on coastal/marine environments have progressed significantly [11]. Yet studies considering small spatial scales relevant to local marine planning, by example conducted by Le Tixerant *et al.* [12] in Iroise Sea (France) or by Longdill *et al.* [13] in the Bay of Plenty (New Zealand), still remain scarce. The identification of various potential interactions was distinguished by superimposing the activity zones [14–16]. Spatial intersections were subsequently related to different variables (*i.e.*, the cumulative number of activities, the presence/absence and degree of potential conflicts; and the density of activity per unit of surface area). However, the temporal dynamics were not considered in these approaches.

Opdam [17] and others argue that communication between science and society constitutes a relevant tool to optimize any planning and management. Thus, any incentives to enhance discussions and understanding of various opinions made by stakeholders (decision-makers, experts, general public, involved in local planning) should be promoted. Therefore, spatial planning paves the way for such an approach. It would incorporate a collaborative process whereby allowing multiple stakeholders to actively brainstorm various strategies within a given area. This process has existed for many decades although this is moderately due to the advancements of information technology, such as the GIS and GIS-based tools that illustrate different scenarios [14]. Previous studies have demonstrated the value of GIS in the participatory process of integrated land-use planning, by measures of supporting local and expert spatial knowledge [18–20]. In fact, several involved the combined processes of virtual scenario simulations, particularly in coastal areas [21,22]. However, these studies relied strongly on geographic information technology to optimize management strategies and public participation in integrated management stakes [23–25]. Yet, few studies have explored the evaluation of interactive spatial support tools [20,26]. Hence, this contribution aims to: (i) provide a GIS-based method to better understand the spatio-temporal distribution of supervised maritime activities; (ii) identify potential conflicts between these activities; (iii) develop an approach to share data, information and knowledge among stakeholders; and (iv) test the contribution of this approach for better exchanges between stakeholders toward collective actions and scenarios.

2. Study Area

The Bay of Brest, located on the most western tip of Brittany (France) (Figure 1), is a maritime basin of 180 km^2 and of 8 m depth. Three types of maritime activities exist within this area: commercial fishing, maritime transportation and nautical activities (windsurfing, sailing, kayaking, rowing, and scuba-diving) (Table 1). Like many coastal zones around the world, the Bay of Brest faces potential conflicts among the increasing number of sea space users. All activities must comply with the

ever growing regulations and coastal policies (Natura 2000 and ICZM). Natura 2000 is a European network of natural protected areas established under the 1992 Habitats Directive. For each Natura 2000 area, a management plan must be established after a consultation procedure with stakeholders. France is one of the European countries that conducts the decentralized and contractual approach for all activities in Natura 2000 areas [27,28]. In 2012, two Natura 2000 sites were designed in the Bay of Brest, under the responsibility of the Armorique Natural Park. The Bay of Brest is also concerned with Integrated Coastal Zone Management (ICZM) policy, issued by the European Commission. ICZM requires its state members to establish management strategies by which maritime spatial planning (Maritime policy or "Blue book") would be encouraged to reduce conflict and promote cooperation among activities. In this particular study, the participatory process was conducted by a local agency (Pays de Brest).

Figure 1. Study site.

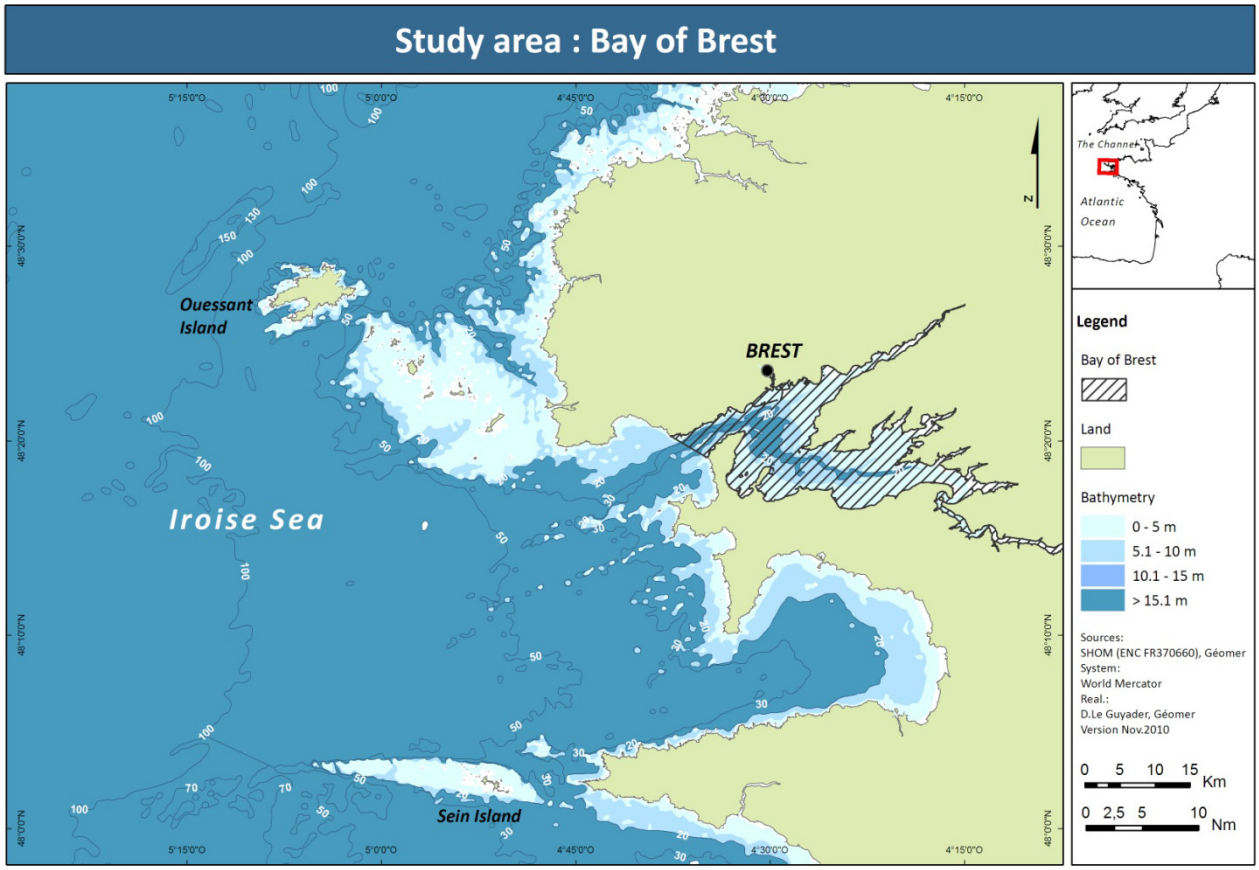


Table 1. Supervised maritime activities in the Bay of Brest.

Activities (Level 1)	Sub-Activities (Level 2)	Number of Sub-Activities (Level 3)
Commercial fishing	Active gears	4 (by example: dragged gears)
	Passive gears	13 (by example: nets gears)
Maritime transportation	Transportation of goods	1
	Transportation of passengers	1
Nautical activities	Supervised nautical activities	6 (by example: Sailing school)
	Water sports events	4 (by example: Windsurfing race)

3. Methods

At various stages throughout the study, a range of geographic information technologies had been used: (i) areas of maritime activities were directly mapped by stakeholders, using a GIS-based interview procedure; (ii) temporal data were linked with area to provide a model of interactions between activities at different dates; (iii) this dynamic GIS was employed to produce a range of maps including spatial or spatio-temporal components on various human activities; (iv) these maps helped facilitate the proposal of spatial simulation based on scenarios. Moreover, the study focused on supervised marine activities organized in a specific manner and for which a representative was identified.

3.1. Data Collection

The marine environment has limited data and is viewed as a common resource [29]. However, this study aimed to identify daily human activity patterns over a one year period. Consequently, heterogeneous data (spatial, temporal, qualitative and quantitative) were obtained and stored in a spatio-temporal database. Furthermore, with the availability of a complete database from the (AIS) Automatic Identification System used by the vessel traffic service, daily precision data could be recorded throughout 2009.

The AIS data were stored in a spatio-temporal database (step 1); daily trajectories of each boat were derived from their position monitored every 10 s (step 2). This study considered shipping lanes as polygons, which encompass a representative number of boat trajectories. The boundaries of these polygons were defined by extracting 90% isopleths (arbitrary threshold) of the Kernel density of trajectories (Kernel type = normal bivariate, scaling factor = 1,000,000; smoothing factor (h) = 100; raster resolution = 40 m) (step 3). Finally, the sum of boats was calculated daily for each shipping lane (step 4) [30]. This data retained daily temporal precision to simplify the description of activities, whilst remaining closed to reality. This, and with the usage of the GIS spatial analysis, permitted the identification, quantification and mapping of daily sea traffic, consisting of maritime transportation for both passengers and goods.

To further describe the supervised activities (Table 1), the study conducted an interview survey using the GIS as a mediation tool to collect spatial data. Thirty one interviews were conducted with the stakeholders, through a framework, which permitted the exchange between researchers and key-informants (Table 2). Semi-structured interviews were used based on the key-informants' opinions, whom were previously identified and presumably holding knowledge about the target population [31,32]. During the face-to-face meeting, each informant could directly draw the spatial activity on a tablet PC using GIS based mapping. Simultaneously, temporal, quantitative and qualitative data were also collected. The origin of the qualitative data came from two methodologies: interviews concerning potential interactions between activities—be it positive, neutral or negative—and a retrospective analysis (regional/local newspapers over a 10 year period). Finally, all data were summarized within a stakeholders-based interaction matrix [33–35].

Furthermore, the temporal data, with daily resolution, could indicate whether or not a given activity was present whereas the quantitative data would specify the number of boats associated with this activity. Both data sets were collected differently: (i) "Real" data were retrieved from the database of

organizations involved in the survey (*i.e.*, maritime transportation—AIS database, sailing nautical activities—nautical center billing database…); (ii) "stakeholder-based" data were obtained from key informants who described their activity patterns (*i.e.*, a typical year with a typical seasonality and/or with typical weeks and days).

Table 2. Semi-structured interviews carried out to collect data per activity type.

Activity Type	Interviews (n)	Mapping Interviews (n)
Maritime transportation	4	3
Commercial fishing	7	6
Nautical activities	22	19
Total	***31***	***28***

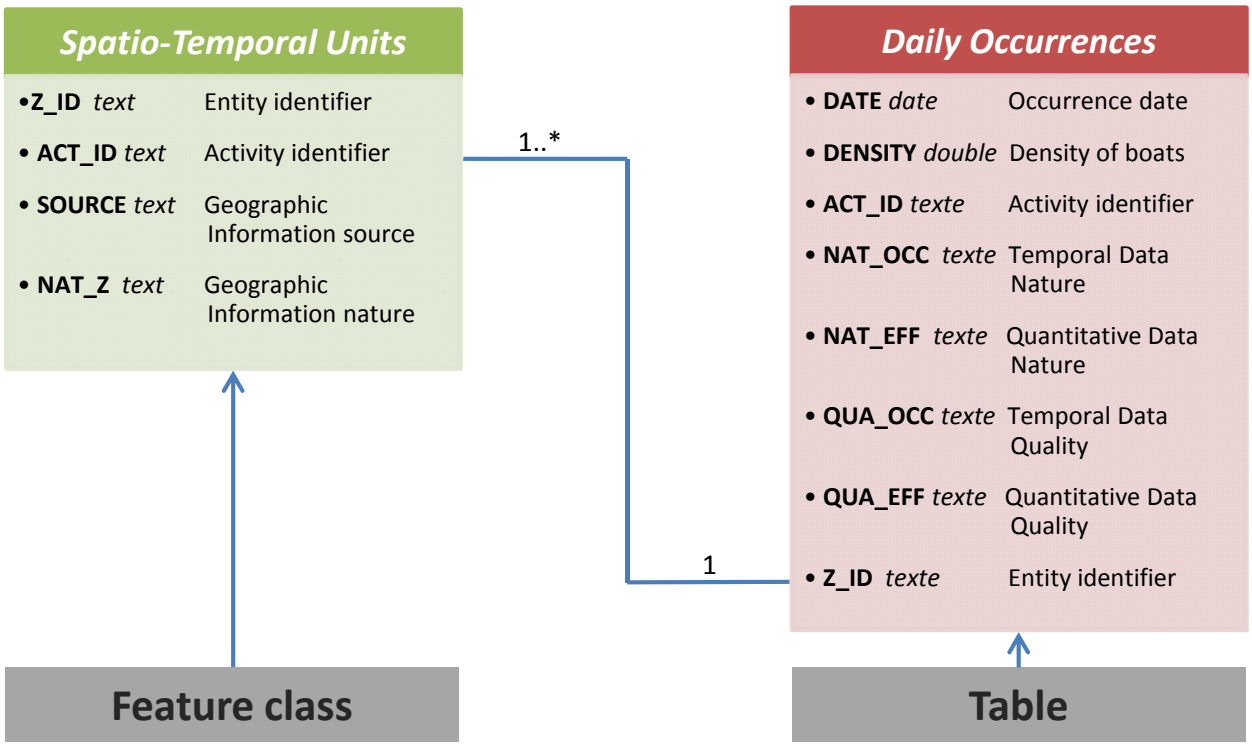
3.2. Spatio-Temporal Database (STDB)

The spatio-temporal unit (STU) is an elementary unit associated with a thematic attribute and is consistent with both temporal and quantitative data (*i.e.*, maritime transportation for each shipping lane would correspond to a STU). Therefore, these heterogeneous data were specifically structured and classified into a spatio-temporal database (STDB) [36] (Figure 2) to obtain a spatio-temporal perspective. All spatial data containing the STUs were stored in a shapefile. Each STU contains attributes of geographic information, relative to its nature and source, along with the activity and geometry identifiers. Meaning, the daily occurrences of activities associated to quantitative data (*i.e.*, the date, boat density, data quality, and identifiers) were stored in a table. Five quality classes have been defined, from "very weak" (stakeholders based data indicating archetypal activity patterns of a typical seasonality) to "very good" (AIS data or nautical center billing databases). To use the STDB would require the application of spatio-temporal queries to associate with various geo-processing tools. Therefore, to have these tasks automated, two tools were developed by ModelBuilder in ArcGIS to (i) identify and map the daily location of activities over a one year period; (ii) calculate and map the boat density distribution (per polygon).

3.3. Spatio-Temporal Conflict Analysis

The study objectives were to identify, quantify, and qualify (through time and space) the potential negative interactions among maritime activities. The hypothesis stated that spatio-temporal interactions could be approached by computing spatio-temporal intersections; and in 2009, such intersections were calculated at daily resolution. A specific tool had been developed using an algorithm that calculated the spatial intersections between STUs. Each entity of the resulting file contained information regarding the subject of concerned activities: date, number of spatio-temporal intersections, and the sum of boat density. Since the activities within spatio-temporal intersections indicated no systematic conflict, a weighting was applied to correspond with the key informants-based interaction matrix. The index value was binary: 0 = no interaction or 1 = potential negative interaction. Ultimately, to ensure the analysis of the spatio-temporal intersections, the study performed a spatial aggregation on a uniform hexagonal lattice and an identification of spatial outliers by using the Local Index of Spatial Autocorrelation (LISA) [37].

Figure 2. Spatio-temporal database (STDB).



3.4. Supporting Discussion and Building Collective Scenarios Phase

The participatory workshop consisted of representatives from local commercial fisheries and five local agencies interested in coastal management; including several whom represented the Natura 2000 and ICZM. The session structure appointed an observer and moderator whom managed and recorded the reactions and discussions of all participants. A questionnaire previously prepared by researchers addressed the relevance for different types of data and information on a three-main step ICZM process: diagnosis, planning, concertation. All participants were briefed of the objectives concerning the questionnaire survey procedure. The captured data included the perceptions of methodology, the dynamic GIS and its possible relevance to initiate simulations for the Bay of Brest. Questionnaire example: "*Is a matrix a relevant representation for diagnosis, planning, concertation*?" Furthermore, the three steps of the workshop were also questioned in terms of participant interest, *i.e.*, feedback regarding research work, collective scenarios, and evaluation.

4. Results

4.1. Data Collection

Spatio-temporal analysis of the AIS database mapped seven shipping lanes in total, for maritime transportation in 2009. The display capacity for the multi-scale dynamic GIS permitted this study to create geographic data layers on the foundation of scales used by stakeholders, whilst mapping their activity zones. Among the 28 mapping interviews conducted (Table 2) for spatial data, 26 key informants successfully controlled the GIS software to map their activity zones. A total of 123 entities corresponding to the location of activities were recorded. All activities were described without

considering tidal and meteorological conditions. The zones described by key informants were mapped for validation and completed in the geographic database. During the interviews, temporal data concerning the period of activities and quantitative data (number of boats) were also recorded. These heterogeneous data allowed for the mapping of all activity zones, as well as creating calendars of activities associated with quantitative data for 29 activities (Figures 3 and 4).

Figure 3. An example of an activity map.

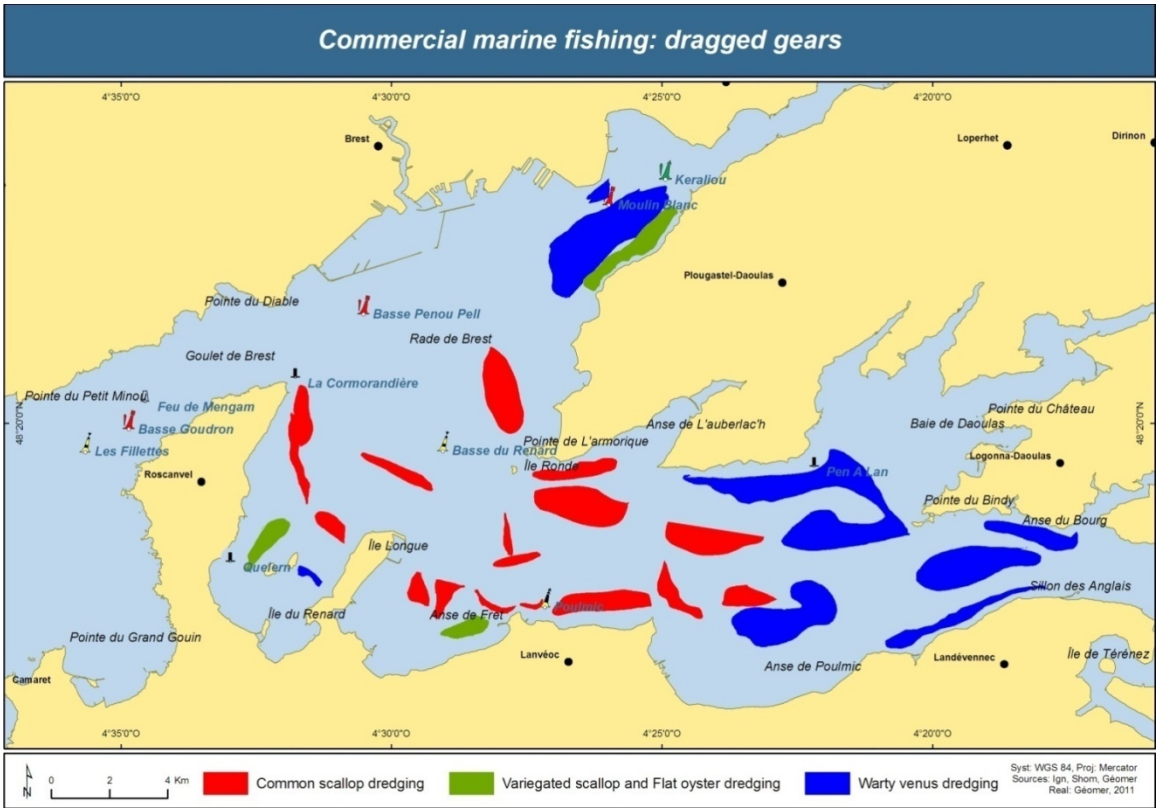
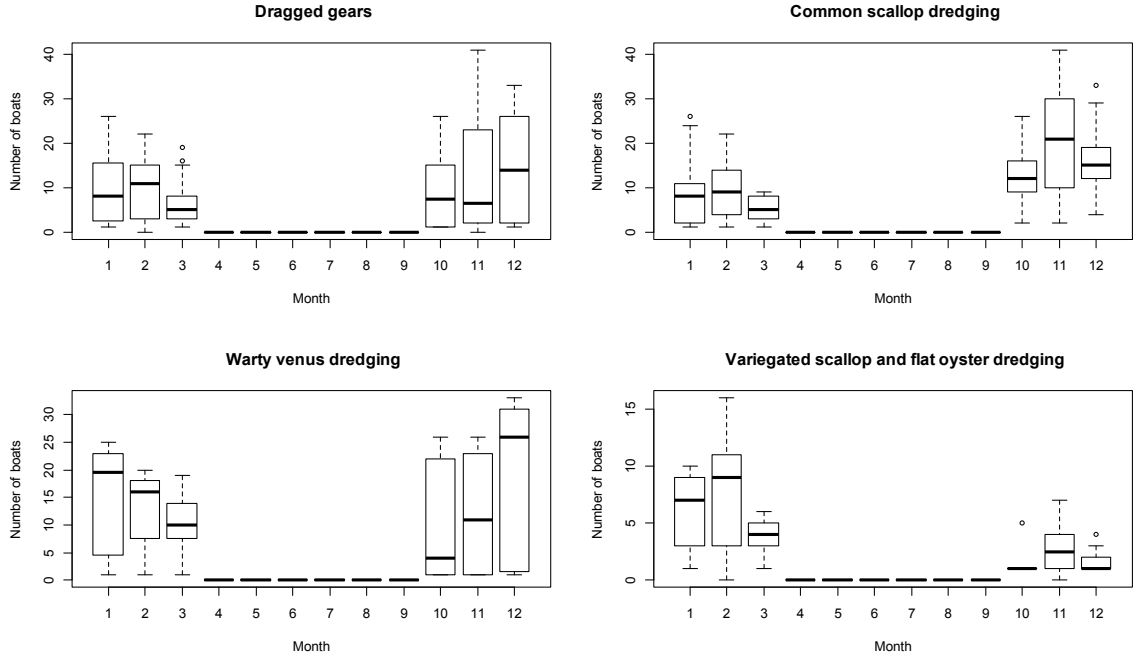


Figure 4. An example of an activity calendar (data aggregated per month).



4.2. Maritime Activities in a Spatio-Temporal Perspective

The STDB contains 149 STUs which associate to 9346 of daily occurrences describing 29 activities. Potential boat density associated with each occurrence was calculated along with estimation for daily quality indexes, density and quality data of each occurrence. These respectively relied on the quality of daily comparative percentage for each occurrence and density. For instance, if more than 50% of occurrences belong to the quality class "very weak" for any given day, then daily quality index of occurrences would be considered "very weak" for that particular day. The quality of indexes ranged from "good" to "very good" for 84% of the days in terms of occurrences, and 90% of the days for boat density. Thus, using the STDB within the study's GIS provided temporal snapshots over 2009 and a daily time step actually associated with the data related quality indexes. The successive use of snapshots permitted this study to construct an explicit spatial representation of supervised maritime activities in the Bay of Brest (Figure 5A). Additionally, this enabled us to produce original information, much like the spatial distribution of the cumulative sum of daily boat density for several or singular activities (Figure 5B).

4.3. Spatio-Temporal Conflicts between Activities

For 2009, spatio-temporal intersections between activities (n = 820,861) were calculated at a daily time step (Figure 6). Intersections between potential conflicting activities represented a sum of 20% for spatio-temporal intersections. Spatio-temporal intersections (i) between transportation of passengers and nautical activities amounted to 87% of negative spatio-temporal intersections; (ii) 8% between passive gears and transportation of passengers; (iii) 3% between transportation of goods and nautical activities; (iv) 2% between supervised nautical activities and water sports events. The analysis of the temporal evolution for spatio-temporal intersections enabled the study to identify the presence of monthly/seasonal variations and extreme values in 2009 by considering activities of totality or pairs. For example, the annual extreme value for the daily sum of spatio-temporal intersections between passenger transportation and supervised nautical sports had been reached by 20 June. The spatial analysis of the spatio-temporal intersections led to the mapping of significant clusters for high and low values ($p < 0.01$) by considering any given day or whole year period.

To better identify potential conflicts between maritime activities, further analysis had been conducted to balance the information of spatial approach, against the spatio-temporal approach. Consequently, the significant LISA clusters [37] of low (LL) and high (HH) values for area spatial intersections were compared with those identified in the spatio-temporal intersections. This indicated that 70% of significant clusters failed to correspond with those identified by a single spatial analysis. These results therefore indicated that integration of spatio-temporal dynamics for the identification of potential conflicts between maritime activities provides a significant difference in pattern when compared to a single spatial consideration (Figure 7).

Figure 5. Activity zones for supervised maritime activities in the Bay of Brest (**A**) and boats density (**B**), by example on Monday, 26 October 2009.

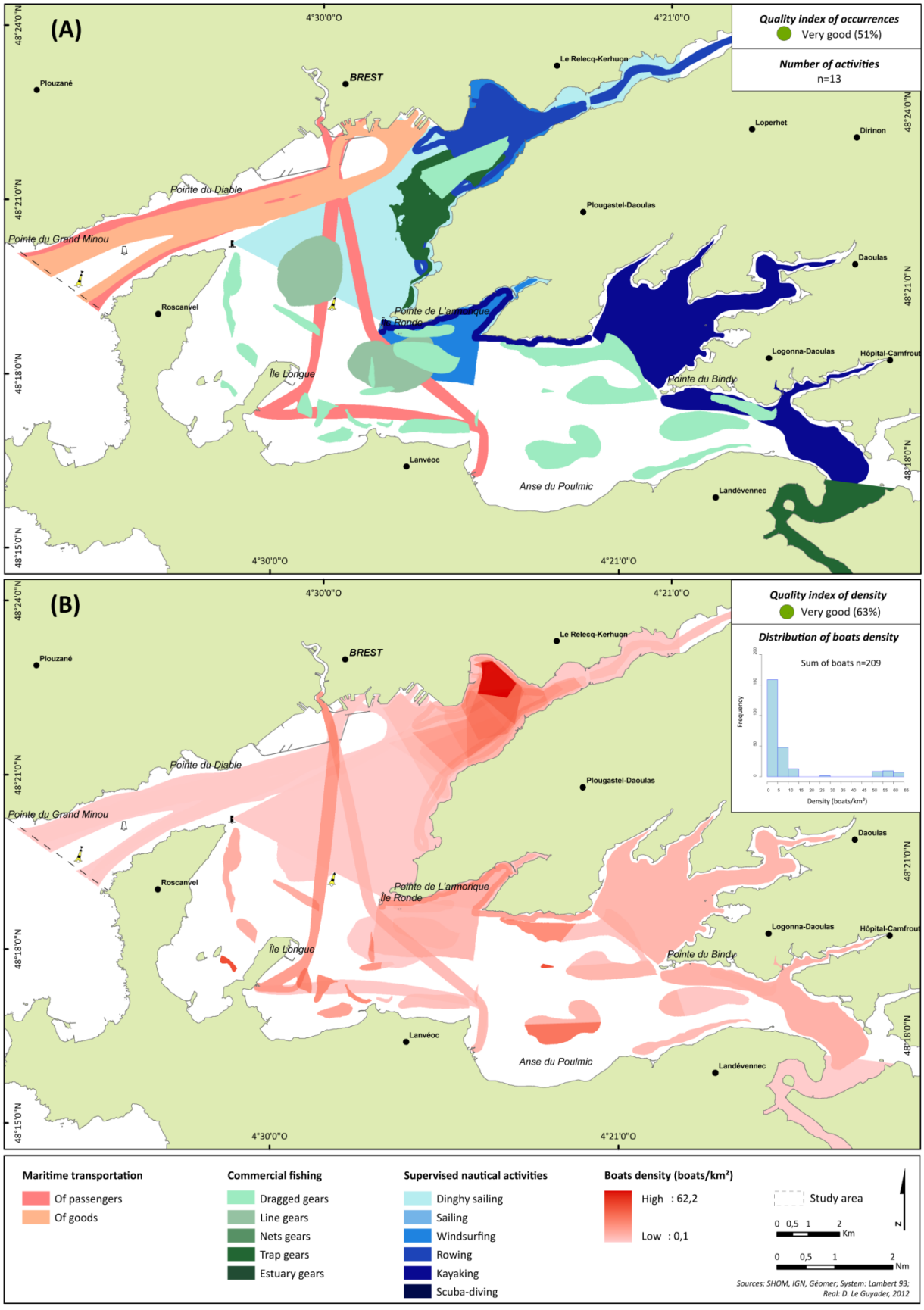
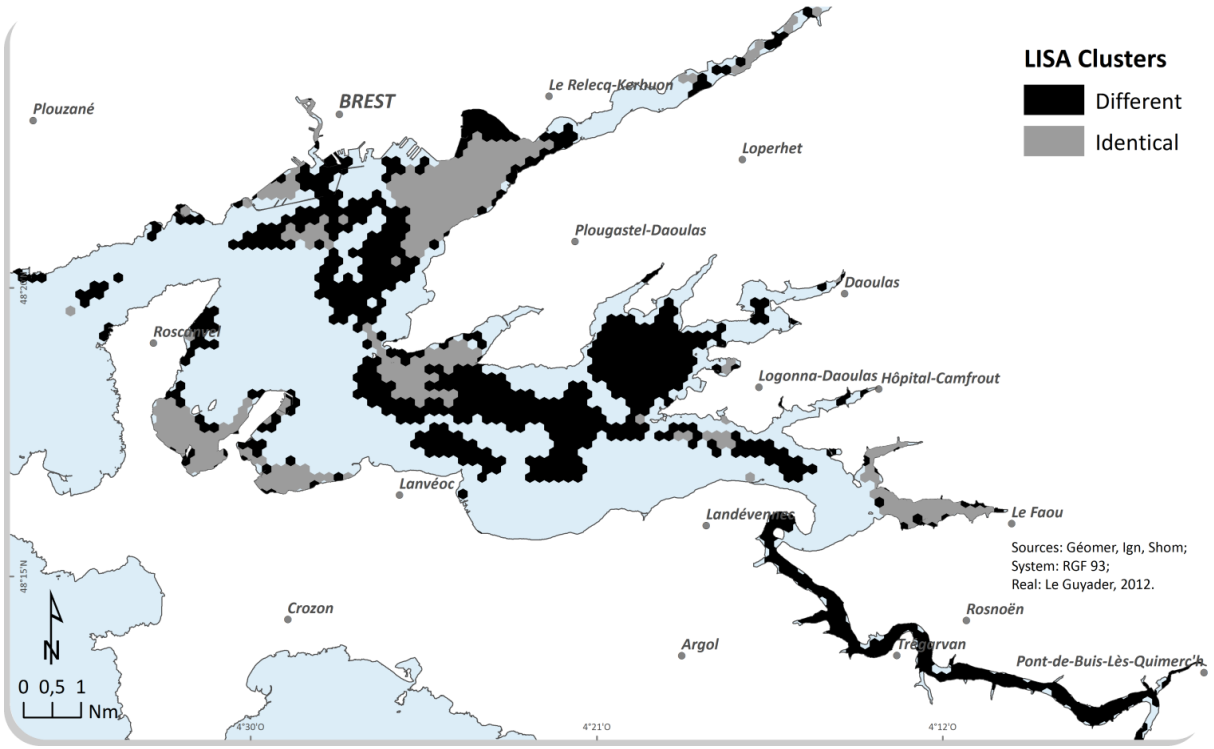


Figure 6. Spatio-temporal intersections among main types of supervised maritime activities (2009, Bay of Brest). Spatial intersections between the activity zones were performed at a daily time step. Negative spatio-temporal intersections are quoted in yellow.

Commercial fishing	Active gears	127					
	Passive gears	0	0				
Maritime transportation	Transportation of goods	0	343	0			
	Transportation of passengers	499	14,242	6833	78,484		
Nautical activities	Supervised nautical activities	2050	52,576	4633	146,508	509,280	
	Water sports events	9	547	161	1385	2950	722
		Active gears	Passive gears	Transportation of goods	Transportation of passengers	Supervised nautical activities	Water sports events
		Commercial fishing		**Maritime transportation**		**Nautical activities**	

Figure 7. Comparison of significant clusters identified by the spatial intersections between activity zones to those identified by the spatio-temporal intersections between activity zones (2009, Bay of Brest).



4.4. Contribution to Knowledge, Discussion and Building of Collective Scenarios

During the participatory workshop, modeling human activities in the Bay of Brest had been discussed among participants. They positively assimilated this dynamic GIS and its high potential in terms of spatial simulations. By example, a local agency representative in charge of ICZM stated:

"*The simulations bring a unique representation of the activities in the Bay of Brest*". Three other participants noticed that "planning" required simulations of the finest time step (half a day) and suggested meteorological and tidal conditions should also be considered.

Subsequently, the participants were asked to collectively suggest an overall scenario possible for implementation. Three individual proposals were presented: (i) what would be the consequences of a new transportation line across the Bay of Brest over current activities? (ii) Regarding different activity calendars, when was the foremost period for extracting the invasive macro-algal seasonal blooms (*Ulva sp*.) near the Brest harbor? (iii) Where should the less stressed areas for any further aquaculture be developed? The dynamic GIS provided answers. For example, concerning the extraction of macro-algal seasonal blooms (*Ulva sp*.) occurring every year near the Brest harbor (Figure 8). Simulation results, mostly concerning nautical activities, indicated potential interactions (88% of the spatio-temporal intersections) and maritime transportation of passengers (12%). Considering the spatio-temporal intersections and boat density, the least stressed periods for extracting the algae extended during 6–18 April, 18–22 May, and 1–19 September.

To better establish an evaluation utility and significance of scientific products, the questionnaire provided guidance for each main step of the ICZM process (Table 3). Most scientific products were considered 100% useful by the participants at the three steps: (i) matrix and plots (non-spatial data); (ii) cartographic atlas (spatial data); (iii) volunteered geographic information (origin of spatial data); (iv) cumulative boat density, and spatio-temporal intersections between activities (thematic contents of spatial data). All participants considered the workshop efficient for the construction of a collective scenario. Moreover, stakeholder discussions revealed: (i) a better understanding of both time and space on maritime activities (daytime) and the type of interactions occupying the bay; (ii) an appreciation for the workshop organized by researchers to support discussion in a "neutral arena"; (iii) the session structure could positively modify the collective perception of the ICZM stakes.

All participants asked for a second workshop to discuss the results of simulations based on the three scenarios, in addition to one workshop tailored for decision makers involved in ICZM and another tailored for fishers.

5. Discussion and Conclusions

For local marine planning, understanding activity interaction would require prior knowledge of spatial and temporal patterns of activities at a relevant scale. This study provides a methodology based on the collection and integration of data in a spatio-temporal database. The GIS enables us to describe the spatio-temporal distribution of supervised activities on a daily time step within a retrospective model, over a one-year period. To facilitate the detection of potential conflicts among maritime activities, daily spatial intersections were calculated. The analysis of these spatio-temporal intersections allow us to: quantify the occurrences of intersections among activities, to emphasize their temporal

evolution, and detect significant spatial clusters of low/high intersections occurring for both space and time. Whilst considering the time taken and the complexity of the study of dynamic human activity, this approach provides great relevance and information accuracy instead of only considering the spatial component. However, if assuming ambiguity of the potential interacting activities occurring through a spatio-temporal interaction at a daily time step, this method emphasizes the reason and importance of conducting the finer time step and should consider spatial uncertainty in order to achieve the best results for stakeholders.

Figure 8. An example of scenario: removal of macro-algal blooms.

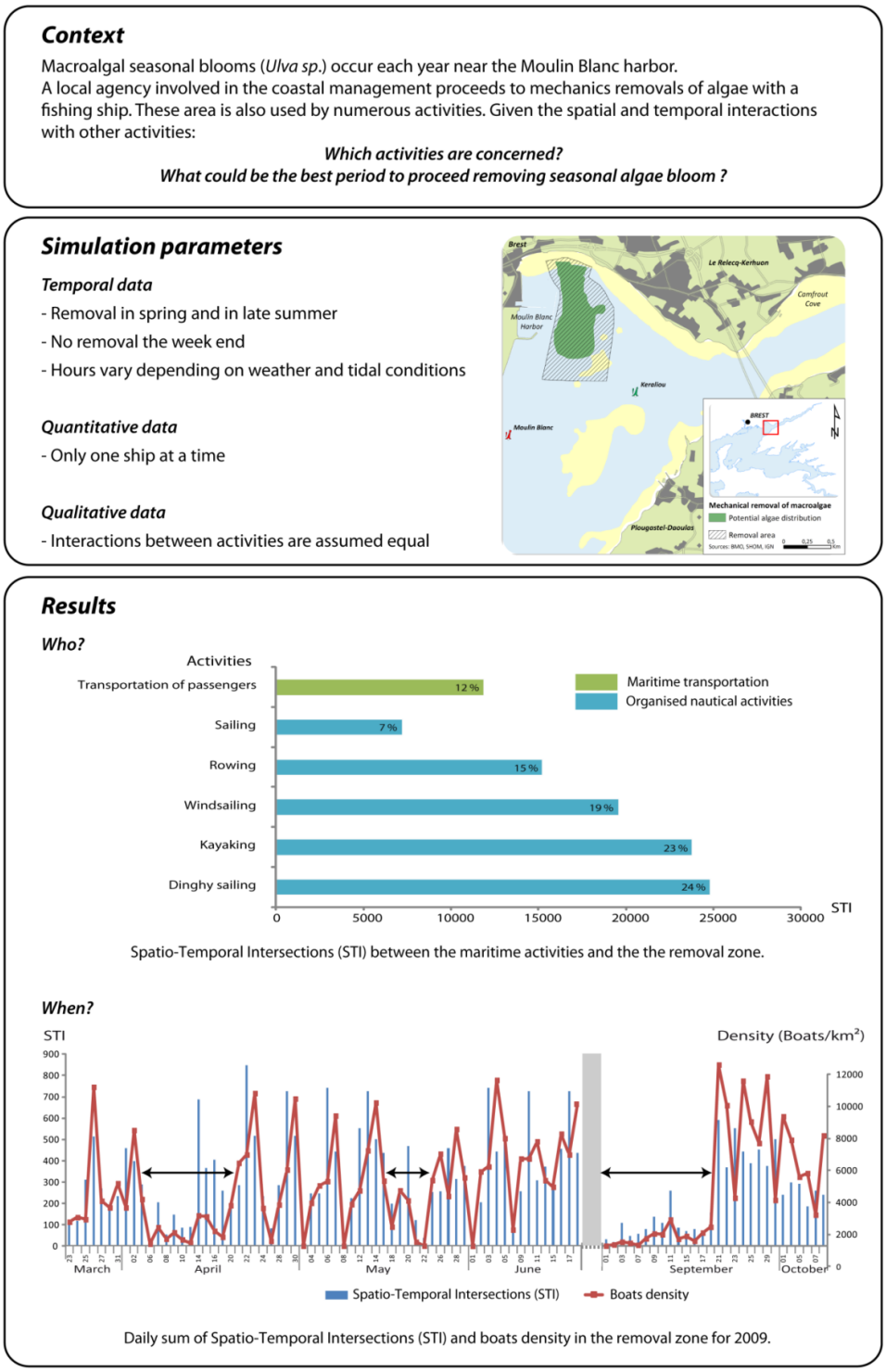


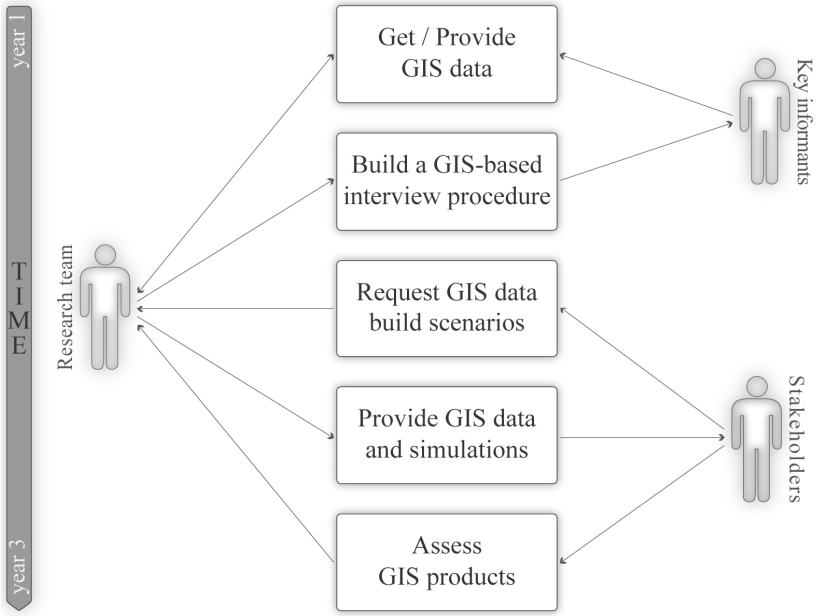
Table 3. Synthesis of stakeholders' responses to the questionnaire.

	Diagnosis	Planning	Concertation
Non-spatial data classified according to the representation type			
Matrix	***	***	***
Network graphs	***	**	***
Plots	***	***	***
Spatial data classified according to the representation type and associated tools			
Cartographic atlas	***	***	***
Geographic Information Base	***	**	**
Temporal Geographic Information Base	***	***	**
GIS geo-processing tools	***	***	*
Spatial data classified according to their origins			
Reference geographic information	***	***	**
Volunteered geographic information	***	***	***
Spatial data classified according to their thematic contents			
Activity zones	***	**	***
Activity calendars	***	**	***
Cumulative boats density (per activity)	***	***	**
Cumulative boats density (for all activities)	***	***	***
Spatio-temporal intersections between activities	***	***	***
Simulations			
Backward simulation	***	**	**
Forward simulation	**	***	***
Workshop sessions			
Feedback on the research work			**
Collective Scenarios construction			***
Stakeholders' evaluation			**
Label	If ≥50% of "useful" answers	If ≥75% of "useful" answers	If =100% of "useful" answers
Code	*	**	***

Within current integrated and participative management approaches of coastal zones, a GIS-based framework would strongly promote the relationship between researchers and stakeholders over a given coastal area via the exchange of data, information and simulation [23,38]. The model developed in this project encompasses a multiple database along with an interactive mapping device that led to feasible spatio-temporal simulations of maritime activities. This demonstration therefore encourages the exchange of knowledge and perception of stakeholders holding various skills and backgrounds (Figure 9). Concerning the relationship between various maritime researchers and space users, this study contributes to the integration of local knowledge with the (ongoing) management process. The integration of knowledge has ignited great interest among stakeholders active in natural area management. Furthermore, the volunteered geographic information described by key informants often constitutes to being the only solution for obtaining data concerned with their activities. Yet, acquiring

public involvement in gathering relevant data is one of the many existing challenges for citizen science [39,40]. Hence, for this study (and with the request from those responsible for Natura 2000 and ICZM processes), to successfully contribute to real management, it has since conveyed all collected GIS data into a Spatial Data Infrastructure managed by the researchers (http://www.indigeo.fr/).

Figure 9. GIS dynamic sharing process.



Spatial dimension introduced by maps as visual artefacts stimulate the exchange between researchers and stakeholders to better address complex issues [20]. Yet, the dynamic component of the GIS appears to be of prime importance. It also yields novel information about spatio-temporal interactions, which allow stakeholders to qualify the activities from the viewpoint of intersection occurrences. The on-going evolution of both activity area and location for low high densities (of possible conflicts) can be emphasized and subsequently discussed. Nevertheless, stakeholders do understand the possibility of using the GIS to test scenarios; yet are reluctant to use it in a public sphere [41]. Furthermore, it is evident that not only does the building of relevant collective scenarios (that really can be included) into a decision making process require further time and meeting sessions, but also the potentially useful and necessary computer scenario based simulations for stakeholders exchange does in fact hold little sufficiency.

The usage of computer models and simulation methods ignites questions concerning the emergence of socio-technical democracy [42] and their instrumentalization in public policy [23,41]. The information and knowledge, along with the complexity and duration of the process, signifies a critical issue [20]. Presently, these tools are restricted to research only. However, this study provides the basis for future development as it clearly demonstrates the successful tool usage of stakeholders, under controlled conditions [14]. The temporal component of information, supplied by this study, verifies its great significance for planning instead of only considering the spatial component. It also demonstrates the necessity to tailor spatial tools for a specific context [26]. Indubitably, both the GIS-based approach and computer simulations do, in fact, promote stakeholder involvement, whilst encouraging the

exchange of knowledge and acceptance of scientific products, under the condition that they are modified to meet their specific needs.

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Author Contributions

Françoise Gourmelon managed the full project. Damien Le Guyader conducted the fieldwork and prepared GIS data analysis. Guy Fontenelle supervised the scenario approach with stakeholders. All three shared the writing of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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