Using fuzzy cognitive maps for predicting river management responses: A case study of the Esla River basin, Spain

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ABSTRACT

The planning and management of river ecosystems affects a variety of social groups (i.e., managers, stakeholders, professionals and users) who have different interests about water uses. To avoid conflicts and reach an environmentally sustainable management, various methods have been devised to enable the participation of these actors. Mathematical modelling of river systems is highly recommended to forecast, but we do not always have enough information to do it. In these cases, the soft and meta-models can be valid alternatives to simulate these complex systems.

The Fuzzy Cognitive Maps (FCMs) are presented as a tool that facilitates the modelling of ecological systems, functions and services. FCM networking concepts are intertwined through causal relationships. The FCM concept spatial arrangement and the use of fuzzy logic facilitate the integration of different expert opinions. In our study, from a panel of seven experts from representatives of different social sectors, an aggregated FCM was obtained. The most central concept in the aggregated map was cross barriers, dams and weirs. Using our FCM expert model, we performed a number of simulations from different possible scenarios, such as the continuous degradation of natural conditions and the improvement of river natural conditions. A regular increment in the natural conditions generates a substantial enhance in variables as natural water flow and sediment transport. Conversely, the increment in human activities as agro-forestry production addresses to a deterioration of river banks among other variables.

In the Esla River, the FCM indicators showed an ecosystem that was greatly influenced by human activity, especially by the presence of barriers, in which the economic variables presented high network influence even though their centrality indices were relatively low. Meanwhile, the essential elements for the proper functioning of this ecosystem, as a natural flow regime, showed very low values that were visibly affected by anthropogenic variables.

FCM methodology enabled us not only to understand the perception of current fluvial ecosystems but also to generate plausible management scenarios based on expert knowledge in this field.

1. Introduction

Mediterranean fluvial ecosystem has always been difficult to manage due to the large number of natural and human factors that affect them. Moreover, the pressure of human activities on these ecosystems has increased over time, reaching a point where most of these systems are highly degraded (Kauffmann et al., 1997; Millennium Ecosystem Assessment, 2005; European Environmental Agency, 2012). The outcomes of continuous human intervention in European rivers have caused a loss of function and environmental services (Elosegi et al., 2010). Thus, plans and actions regarding rivers not only affect natural and economic river resources, but also social assets (Millennium Ecosystem Assessment, 2005; Hommes et al., 2009). This legitimises the need for sustainable fluvial management and ecological restoration.

Frequently, various social actors present different scopes to address fluvial issues and contribute their different perceptions to assess and solve problems (Eshuis and Stuiver, 2005; Rinaudo and Garin, 2005). Therefore, to develop socially concerned and sustainable river practices, a participatory process should be established that, allows the stakeholders: (a) to work together to define the criteria for sustainable management, (b) evaluate alternatives, (c) set priorities and restrictions, (d) recommend technologies, (e) pro-
pose policies and (f) monitor and evaluate impacts (Johnson et al., 2001; Giordano et al., 2005; Rinaudo and Garin, 2005).

To assist in the development of a river management plan based on both public participation and expert knowledge, we propose the use of Fuzzy Cognitive Maps (FCMs) as a semi-quantitative model tool as provides a structured, simple and inexpensive way to model overall fluvial systems through a soft evaluation of the relationship between different concepts and factors interpreted by stakeholders (Giordano et al., 2005; Papageorgiou et al., 2009; Malek, 2017; Paolisso and Trombley, 2017).

Therefore, the present study aims to 1) explain the FCM as qualitative methods to model a fluvial system; 2) analyse the scope of expert knowledge in the development of multi-user decision-making models; and 3) apply the FCM in a case study of a Mediterranean fluvial management.

2. Material and methods

2.1. Fuzzy cognitive maps

FCMs constitute a structured modelling technique that can be used in complex systems (Papageorgiou et al., 2009). Predictions on systems performance are made through a semi-quantitative or semantic assessment of the relationships between concepts (Papageorgiou and Kontogianni, 2012). A FCM can be described as a qualitative model that portrays how a given system operates (Özesmi and Özesmi, 2004). The qualitative model is derived by describing the system in terms of its component variables and the causalities among these variables (Park and Kim, 1995).

An FCM is a directed network (i.e., digraph) composed of nodes or concepts that are used to describe system behaviour and edges that represent the causal links between concepts. Each concept (node) has a state variable that varies from 0 to 1 and it is associated with an activation variable (i.e., 0 means no-activate and 1 means activate), and each link has an associated real number or weight variable from -1 to 1 that reflects the relationship "what-if" between concepts (Papageorgiou and Kontogianni, 2012). With the fitted connection weights, a FCM connection matrix is encoded from each FCM as deeply described in Banini and Bearman (1998).

These maps can be obtained by asking people to define the variables of the system and to identify relationships among these variables using "what if" rules to justify the cause and effect relationship in each connection inferring a semantic weight for each connection (Stylios and Groumpos, 2000, 2004; Papageorgiou and Groumpos, 2005). This information can be facilitated by filling out questionnaires, interviewing people, checking on scaled semantic attributes or drawing arrows of different width on a concept map (Özesmi and Özesmi, 2004).

The construction of a FCM requires the input of human experience and knowledge of the system under consideration. Thus, FCMs integrate the accumulated experience and knowledge concerning the underlying causal relationships among factors, characteristics and components that constitute the system (Papageorgiou and Kontogianni, 2012).

This tool is considered to be a semi-quantitative method because the quantification of concepts and links can be interpreted in relative terms (Kok, 2009).

The main elements of a FCM are nodes or concepts \{C1, C2, ..., Cn\}; directed edges (CjCk, etc.) as a set of directed arcs that represent the relationship (positive or negative) between concepts; adjacency matrix (Ec = ec) as a matrix that contains the values of each relationship (the values belong to the interval from -1, conversely correlated, and 1, directly correlated) and state vector \( A = (a_1, a_2, ..., a_n) \) where \( a_n \) is a real number between 0 and 1, from which the categorical concept status is obtained: 1 activate or 0 no-activate (Kok, 2009; Papageorgiou and Kontogianni, 2012).

2.2. Graph theory and FCM

Cognitive maps are compounds of a large number of variables (one per concept) that have many interconnections and feedback cycles. The direction and numbers of relationships between variables produce three types of concepts: transmitter concepts, receiver concepts and ordinary concepts (Eden et al., 1992; Harary et al., 1965). The type of variables in a map is important, because the map shows the relationships among these variables and facilitates an understanding of its structure (Özesmi and Özesmi, 2004).

Graph theory indices provide a way to characterize FCM structures by means of three indices: outdegree, indegree and the centrality index (Özesmi and Özesmi, 2003, 2004).

2.3. FCM development process

Once the stakeholder and/or expert group interviews were conducted, we obtained an individual FCM from each participant. These individual cognitive maps were augmented and additively super-imposed (Kosko, 1987, 1986) to generate the aggregate map (Fig. 1). There are a number of different methods to aggregate the individual maps (van Vliet et al., 2017), each has advantages and disadvantages. In this case, each individual map was combined to generate a group or social map (Mouratiadou and Moran, 2007). For that, each individual matrix was augmented and added, producing a single matrix that represents the FCM. Then, the final aggregated FCM was obtained by normalizing each adjacency matrix element according to the number of experts who supported it, k, and their decisional weight, \( p_i \) (Eq. (1)) (Banini and Bearman, 1998):

\[
E_c = \sum_{i=1}^{k} p_i E_i / k
\]

Where \( k \) represents the number of experts interviewed; \( p_i \) is the decisional weight of the expert \( i \), where \( \sum_{i=1}^{k} p_i = 1 \); \( E_i \) is the aggregated connection matrix, and \( E_i \) is the connection matrix written by the expert \( i \). The use of decisional weight \( p_i \) for calculating each adjacency matrix element allows a freedom degree for generating new scenarios under different social contexts.

The FCM involved an iterative technique, in which each state variable \( a_{ci} \) changed its value. Each iteration corresponded to a given interval step, and the value of each item in the current iteration was computed based on the values of the preceding items in the previous simulated iteration. Due to the iterative nature of this process, the system represented by a FCM changes over time as: a) a new steady state at equilibrium, b) an un-converged state and c) a periodic loop of states (Curia and Lalvále, 2011). To facilitate the system convergence in each iteration the values of the state vector were filtered by an activation function. According to Bueno and Salmeron (2009), there are mainly four activation functions that determined the activation level of each concept. Among them we have chosen a sigmoid function (Eq. (2)), used in other studies that apply FCM (Stylios and Groumpos, 1999).

\[
f(x) = \frac{1}{1 + e^{-m(x-\beta)}}
\]

Where \( m \) is a real positive number (as a general rule, the higher \( m \) the safer the convergence), \( \beta \) is the numerical threshold from dividing each variable into ten activation level (i.e., \( p = 1/10, 2/10, 3/10, \) and so on), and \( x \) is the value of the state variable at a determined iteration. If the variable value is lower than the lowest threshold, \( x < \beta \), the filter \( f(x) \) produces a number close to 0 (implying no activation) while if the variable value is higher, the result will be 1 (implying activation). In scenario simulation this concept division in ten pieces produces a more sensitive response
on output variables, and then a more graduated policy can be simulated. This procedure is applied to keep the status variable as a categorical variable which facilitates convergence. In addition, this graduated method offers the possibility of developing easily comparative analysis between scenarios in a complex decisional environment (Bueno and Salmeron, 2009).

2.4. Simulation process

The FCM was used to analyse the system behaviour by running simulations and to determine future possible management scenarios, which can serve to guide environmental managers in the decision-making process regarding the objective system (e.g., the river system). Simulations were made by multiplying the initial state vector \( \{A_1\} \) by the adjacency matrix of the aggregate FCM \( \{E_c\} \), where \( A_1 \) is a row vector of size 1xN, with N being the total number of variables (Tan and Ozesmi, 2006).

The process of simulation begins when we assign a value of 1 (i.e., activate concept) to each variable. Based on the collective expert/stakeholder knowledge, each activated concept contributed its weight to activate its descendent concepts; then, these concepts are free to interact with others concepts (Papageorgiou and Kontogianni, 2012). In each iteration, the filter function was applied, which produced a new state vector with \( \{1\} \) activated concepts and \( \{0\} \) no-activate concepts. If a concept has an activation value of 0, this concept would not contribute at the next iteration, whereas an activation value of 1 would represent the contribution at the next iteration.

The next step was to obtain responses on management scenarios by asking “what-if questions to determine the state of the system that would be developed under different conditions or if different policy options were implemented (Kosko, 1987).

3. The case study area

Esla River is a tributary of Duero River on its right bank, located in the Iberian Peninsula (Fig. 2). It has a basin area of 16026 km², a length of 287.83 km and an average of 5066 hm³ annually (CHD, 2015).

Two large reservoirs are located along the river. The Riaño is on the river’s source, with a maximum capacity of 650 hm³ and an area of 817.51 km² (CHD, 2015). Ricobayo is near the mouth of the Esla River in the Duero River. Ricobayo has a maximum capacity of 1179 hm³ and covers an area of 159.52 km² (CHD, 2015). The presence of these dams conditioned the river’s natural flows regime, changing the natural pattern of the river downstream from the dams with an increase of water availability in summer, coinciding with irrigation season. The presence of the Alto de Payuelos, Cea-Carrión, Curueño-Porma and Páramo Bajo channels plays an important role in the Esla River basin regulation (CHD, 2015).

This fluvial system supplies water to a total of 278,000 people, including the city of León; to an irrigation area of 97,000 ha; to three fish farms; and to the refrigeration system of the Robla thermal power plant. In addition, 19 hydroelectric plants are present, with a combined capacity of 451 MW and an average production of 1115 GWh. A marked increase of irrigation demand is expected (CHD, 2015).

4. Application of FCM to Esla River basin

An FCM was applied to model the perception of a group of experts in river issues to develop a future Esla River management plan. The FCMs were obtained by seven in-depth interviews conducted in group sessions with experts in fluvial ecosystem and water resources who acted as representatives of the river authority, municipalities, farmers and hydroelectric enterprises. We believed that a sample of seven expert interviews was manageable and sufficient to draw conclusions.

At the beginning of the interviews, the participants were given an A4 sheet containing a number of variables that were predefined by the authors to serve as a guideline to the participants as depicted in Table 1. These predefined variables were selected from the REFORM EU project (www.reformrivers.eu), where a conceptual river system scheme was created showing the main interactions.
between pressures, processes, states, impacts and response variables in European rivers (OECD, 1993; EEA, 2012). This conceptual scheme was made after a deep review process of scientific documents and publications that explicitly reported causal effects between river pressures and biological responses in fluvial systems (García de Jalón et al., 2013; Lorenz, 2015).

The participants were also provided with a table that had a rating scale of 10°, numbering from −5 to 5, by which they could describe any type of connection between the variables (Table 2). The weights of the connections were added when answering the following question: “Do you think that variable x is affected by or affects any other variables?” (Mouratiodou and Moran, 2007).

To analyse the structure of the map according to the graph theory, important FCM indices such as indegree, outdegree and centrality were calculated in R (Kolaczyk and Csárdi, 2014). The simulation of different management scenarios was also calculated with the Fuzzy Cognitive Mapping & Modelling software tool (Bachhofer and Wildenberg, 2010) (freely available in www.fcmappers.net). The variables with the highest centrality, indegree and outdegree are depicted in Table 4.

### Table 1

Table 1

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross barriers, dams and weirs</td>
<td>Set of artificial barriers that prevent or obstruct the natural water flow</td>
</tr>
<tr>
<td>Natural water flow regime</td>
<td>Water flow in natural conditions</td>
</tr>
<tr>
<td>Water quality</td>
<td>Physicochemical status of surface and ground waters</td>
</tr>
<tr>
<td>Sediments dynamics</td>
<td>Erosion, transport and sedimentation balance in natural conditions</td>
</tr>
<tr>
<td>Agro-forestry production</td>
<td>Agricultural and livestock farming in river banks and floodplains (presumably water abstractors)</td>
</tr>
<tr>
<td>Urban uses, infrastructures</td>
<td>Presence of human structures near the river that alter the natural river dynamic</td>
</tr>
<tr>
<td>Continuity and width of riparian landscapes</td>
<td>Riparian vegetation in a continuous strip</td>
</tr>
<tr>
<td>Socioeconomic aspects</td>
<td>Influence of human activities on river ecosystems</td>
</tr>
<tr>
<td>Riparian vegetation</td>
<td>Vegetal species associated with the riparian ecosystem and their quantity and quality</td>
</tr>
<tr>
<td>In-stream communities</td>
<td>Fish and other animal species populations living in around the river canal</td>
</tr>
<tr>
<td>Hydroelectric production</td>
<td>Alteration of the river ecosystem due to the existence of hydroelectric power plants</td>
</tr>
<tr>
<td>River connectivity (longitudinal, lateral and vertical)</td>
<td>Connectivity of riparian ecosystem</td>
</tr>
<tr>
<td>Bank conditions</td>
<td>Alteration of river banks</td>
</tr>
</tbody>
</table>

### Table 2

Interpretation of the causal relationships between variables.

<table>
<thead>
<tr>
<th>Strength connection by interviewer</th>
<th>Sign and strength of relationship (linguistic weight)</th>
<th>Interpreted crisp weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>−5</td>
<td>Negatively very strong</td>
<td>−1</td>
</tr>
<tr>
<td>−4</td>
<td>Negatively strong</td>
<td>−0.8</td>
</tr>
<tr>
<td>−3</td>
<td>Negatively medium</td>
<td>−0.6</td>
</tr>
<tr>
<td>−2</td>
<td>Negatively weak</td>
<td>−0.4</td>
</tr>
<tr>
<td>−1</td>
<td>Negatively very weak</td>
<td>−0.2</td>
</tr>
<tr>
<td>1</td>
<td>Positively very weak</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>Positively weak</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>Positively medium</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>Positively strong</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>Positively very strong</td>
<td>1</td>
</tr>
</tbody>
</table>

### 5. Results

#### 5.1. FCM outcome

The number of variables in the seven individual FCMs was 13, while 46.57 ± 26.42 connections (±SD), on average, were observed
Natural water flow regime

Cross barriers, dams and weirs

Fig. 3. Aggregated FCM of the Esla River.

Table 3
Comparison of the values between individual maps and collective FCM.

<table>
<thead>
<tr>
<th>Index</th>
<th>Individual FCMs</th>
<th>Aggregated FCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of maps</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Variables</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Number of connections</td>
<td>46.57 ± 26.42</td>
<td>114</td>
</tr>
<tr>
<td>Connections/variables</td>
<td>1.58</td>
<td>8.77</td>
</tr>
<tr>
<td>Density</td>
<td>0.124</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Table 4
Variables with the highest centrality, indegree and outdegree.

<table>
<thead>
<tr>
<th>Centrality (Influential)</th>
<th>Indegree (Receiver or state)</th>
<th>Outdegree (Transmitter or driver)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross barriers, dams and weirs</td>
<td>Riparian vegetation</td>
<td>Cross barriers, dams and weirs</td>
</tr>
<tr>
<td>Riparian vegetation</td>
<td>In-stream communities</td>
<td>Natural water flow regime</td>
</tr>
<tr>
<td>Natural water flow regime</td>
<td>River connectivity</td>
<td>Agro-forestry production</td>
</tr>
</tbody>
</table>

As seen in Fig. 3, arrows mean the causal-effect relationships and nodes symbolise concepts. The continuous lines represent positive relationships while dotted lines represent a negative relationship. The most influential or central variable was “Cross barriers, dams and weirs” as many arrows come in and come out from this node. The most affected variables (i.e., receivers) by others are (in order) “Riparian vegetation”, “River connectivity”, “Sediment dynamics”, “Continuity and width of riparian landscapes”, “In-stream communities”, “Water quality”, “Bank conditions” and “Socio-economic aspects”.

The most central variable was “Cross barriers, dams and weirs”. This variable had a strong effect on the other variables (outdegree of 6.54), and they were affected by an indegree of 0.4. The variables were ordered according to their centrality, as shown in Fig. 4 and Table 4.

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The variables that greatly affected other variables (outdegree > indegree) (i.e., transmitters or drivers) were “Cross barriers, dams and weirs”, “Natural water flow regime”, “Agro-forestry production”, “Urban uses”, and “Hydroelectric production”, whereas the opposite situation was for “Riparian vegetation”, “River connectivity”, “Sediment dynamics”, “Continuity and width of riparian landscapes”, “In-stream communities”, “Water quality”, “Bank conditions”, and “Socio-economic aspects” (Table 4).

6. Scenario simulations

First, the steady state of the Esla River system was obtained before considering any fluvial management action. The steady state vector characterized the system according to the panel of experts, actors and stakeholders’ knowledge. If a concept was reinforced by a policy, the state vector would change, and the effects would be measured as a difference of the value of the concepts. To determine the steady state, we ran a FCM process starting with an initial state vector A0, with all variables set to 1 (Fig. 5), and after convergence an equilibrium or steady state vector was obtained. Then we ran a battery of simulations with different activation levels (i.e., from 0 to 1 by 0.1) for some specific concepts to generate different restoration scenarios (Fig. 6).
Expectedly, “Cross barriers” was the most central variable, because this concept was an artificial element that altered further natural river conditions and affected many of the socio-economic variables. Next, the most central variables, such as “Riparian vegetation” and “Natural water flow regime”, were the natural variables that were currently affected by anthropic activities in the Esla River Basin.

As Fig. 5 shows, socioeconomic variables had higher initial values than most of the environmental variables, because the Esla River, like most Mediterranean rivers, is a system that is heavily degraded by anthropogenic activities (EEA, 2012). Therefore, socioeconomic variables had a very high initial value, despite not being the most central variables in our knowledge map. Otherwise, the “Natural water flow regime” showed a low value in our steady state system, due to the strong influence that other variables with high outdegree values, such as “Cross barriers” or “Agroforestry production”, had on the system.

The importance of the generation of simulation scenarios was to measure the change experienced by the variables from their steady state values. Therefore, we fairly accurately measured and...
quantified the effects of different actions applied to the management of the Esla River. In our study, we aimed to determine the results of simulating variables with high outdegree values regarding variables with large indegree values, because we considered the importance of regulating the effects of the strong variables and how most sensitive variables reacted when changes were made.

Once the effects of simulating the main high outdegree variables were determined, different management scenarios were developed based on the simulation of one of the system variables or several variables together. These scenarios included: 1) the increase in the presence of dams due to the requirements of agricultural uses and 2) the increase of river connectivity, especially longitudinal connectivity. The objective was to measure the degree to which the variables changed from their steady state values. A negative value indicated a reduction in the variable state compared with the initial conditions, while a positive value reflected an increase in the variable state (Tan and Özsesmi, 2006).

6.1. Scenario 1: increment the presence of transversal barriers

This scenario simulated the effects of increasing the number of cross barriers (dams and weirs) in the river. We expected the decrease of natural water flow, which meant that there was an alteration in the sediment balance. The longitudinal connectivity of the river also decreased due to the discontinuity generated by the presence of new obstacles. On the contrary, we expected the agro-forestry production, infrastructures, hydroelectric production and socioeconomic aspects to increase.

6.2. Scenario 2: increment of river connectivity

This scenario simulated the effects of increasing the river connectivity of the Esla River. We expected the decrease in the presence of artificial barriers and, therefore, an increase in natural water flow regime, sediments dynamics, riparian vegetation, riparian landscape continuity, in-stream communities and bank conditions.

7. Discussion

7.1. Characteristics of the variables

The variables of our aggregated FCM were all ordinary, meaning that causal relationships existed among these variables. However, certain variables had high values in their outdegrees, suggesting that specific variables strongly influenced the system and could be considered to be drivers ("agroforestry production", "urban uses", "cross barriers" and others) or pressures (disturbance of "natural flow regime") according to the DPSIR classification (i.e., Drivers, Pressure, State, Impact, Response) (OECD, 1993; EEA, 2012). The drivers, as variables that will be less affected by changes in the system, are ideal candidates to manipulate the system (van Vliet et al., 2017). This driver concept may produce environmental effects on the structure and functioning of the river (Garcia de Jalón et al., 2013), which was mostly reflected on the high indegree variables considered to be state variables (i.e., "river connectivity", "continuity and width of riparian corridor", "riparian vegetation" and "in-stream communities") that were related to abiotic or biotic ecosystem conditions (Garcia de Jalón et al., 2013). In summary, the values of the variable’s indegree and outdegree were important in determin-
Fig. 7. Effects of simulating several concepts in our aggregated FCM. We simulated a decrease in the transmitter concepts “Cross barriers” (1), “Agroforestry production” (5) and “Urban uses, infrastructures” (6), while there was an increase in the “Natural water flow regime” (2), and we obtained the relative effects on the other variables: “Water quality”(3), “Sediments dynamics” (4), “Continuity and width of riparian landscapes” (7), “Socioeconomic aspects” (8), “Riparian vegetation” (9), “In-stream communities” (10), “Hydroelectric production” (11), “River connectivity” (12), and “Bank conditions” (13). The results depicted the percentage of change from the steady state in two different simulations: from a worst scenario for natural conditions (dark coloured bars) to the best scenario for natural conditions (light coloured bars) and the tendency among both scenarios.

7.2. Aggregation process, steady vector and general issues

This study explored the use of the FCM as a tool for simulating fluvial ecosystem responses and forecasting concept trends. Some drawbacks can be found during the aggregation process where the individual maps are combined into a general one. The existence of new methodologies recently published for map aggregation can be combined with previous simpler aggregation methodologies; however there is no consensus on how to best construct the aggregated FCM (van Vliet et al., 2017). Despite, the aggregate FCM was used in this research to reach the steady state vector by activating start concepts and then obtaining responses by solving a system of filtered linear equations. Adjacent matrix coefficients were estimated as an average of the individual expert’s values, and standard error can be also estimated for each coefficient. This provided an estimate interval and a significance level to evaluate the FCM explicative power (Shmueli, 2010; Shmueli and Koppius, 2011). In addition, keeping adjacency matrix for each representative expert allows making weighted averages based on different social composition. For instance, a change toward a more “ecologist” concerned society can be model by an increment in the weight of ecologist representative, conversely, a more “productivist” society shall be model by higher loading for farmer and landowners.

In the Esla River FCM, the steady state vector showed an ecosystem that was greatly influenced by human activity, in which the economic and social variables presented high network influence, even though their centrality indices were relatively low. Meanwhile, the essential elements for the proper functioning of this ecosystem, as a “natural flow regime”, showed very low values that were affected by anthropogenic variables.

7.3. Simulation of management scenarios

The aggregate cognitive map can be considered an a priori model of the analysed ecosystem. When an expert made their FCM, it is supposed to apply their full knowledge along with the accessible information. The methodology was based on the comparison of different steady state vectors obtained from different activation vectors composed of a different set of activated variables, by different action levels of activate levels or both. The interpretation of the simulated scenarios in the present study was that the results should be interpreted in a qualitative, rather than a quantitative, manner (Tan and Özesmi, 2006). Despite this, FCMs are a promising structuring tool in the scenario development (van Vliet et al., 2012).
7.3.1. Scenario 1: increment the presence of transversal barriers

This scenario simulated an increment in the placement of new artificial barriers in the Esla River (Fig. 7). The highest indegree variables were greatly affected by the increment in the value of this variable, whose outdegree was the highest of the entire system. The width and continuity of the riparian corridor would be affected, because the river regulation involves fundamental changes in the flow and sediment transfer, which were the main factors in fluvial morphodynamic changes (Church, 1995). The trend of an increase in agricultural land in the study area corresponded to the need to build more water storage structures that would alter the ecosystem downstream of its location (Ward and Stanford, 1983, 1995; Petts and Gurnell, 2005, 2013; Vörösmarty et al., 1997). As shown in Fig. 6a, the presence of riparian vegetation would be reduced downstream of the dams (Nilsson et al., 1991; Andersson et al., 2000; Merritt et al., 2010; Merritt and Wohl, 2002, 2006). Fig. 6a also shows that in-stream communities were not immune to the further fragmentation of the river. A strong impact on species migration and diversity was due to the effect of artificial barriers (Kingsford, 2000; Cote et al., 2009; Jager et al., 2001). Clearly, the hydrological connectivity would be greatly altered by the existence of dams (Ward and Stanford, 1983, 1995, 2006; Segurado et al., 2013, 2014). Pringle (2003) argued that "hydrologic connectivity is essential to the ecological integrity of the landscape, and reduction or enhancement of this property by humans can have major negative environmental effects".

7.3.2. Scenario 2: increment of river connectivity

This scenario simulated a situation in which an increase of river connectivity was achieved due to the intervention of other variables ("Cross barriers", "Agroforestry production", "Urban uses, infrastructures", etc.), which caused a hindrance to the natural connectivity of the river (Fig. 7). According to the idea of the multiple dimensions of fluvial connectivity (Ward, 1989), the measurements made in this simulation were aimed at diminishing the importance of the variables that generated a disturbance in one or more of the river connectivity dimensions. Variables such as "agro-forestry production" and "urban uses" would be reduced from their initial values due to an increase in the interactions of the river channel with the adjacent riparian system and the floodplain, improving the exchanges of nutrients and organic matter (Ward, 1989).

Special efforts to improve the longitudinal dimension of connectivity should be considered, as it determines several vital ecological processes (Ward, 1989; Tockner et al., 1998; Lucas et al., 2001). The reduction of the disconnection generated by artificial barriers lead to a progressive increase in the water flow regime, which could be the most important measure to recover the riverine ecology, and it needs to be implemented first in a fluvial restoration process (Lorenz et al., 2015). The variable "in-stream communities" increased its value parallel to an increment in the connectivity value due to the longitudinal connectivity restoration having positive impacts on fish species, especially in migratory species (Segurado et al., 2014).

For these reasons, all of the approaches that were oriented to enhance the unions between habitat patches (in this case, river segments separated by artificial barriers) should be applied in conservation planning (Eróz et al., 2011).

8. Conclusion

The present river management will produce a future response on the river ecosystem which should be forecasted. The use of FCMs to determine the behaviour of Esla River and possible future management scenarios was useful in building a model based on the available knowledge of how a complex system was perceived, because more detailed information may not be available. This methodology dealt with the connections between the ecological and social concepts of an ecosystem. FCMs are subject to limitations due to their semi-quantitative approach. Nevertheless, they were proven to be suitable for organizing complex ecosystem models, in which concepts and the causal relationships between them could be determined. The analysis of how variables with high outdegree values affected variables with high indegree values was valuable for quantifying the effects of the impact over the most sensitive variables and for determining the behaviour of the system. The simulations suggested that to develop an effective fluvial management plan according to the experts involved in the process, a reduction in the effects of the artificial barriers that leads to an increase of the naturalization of the river system is necessary.

Stakeholder participation is the primary component of the FCM methodology. In this case, the reviews of seven experts regarding river issues provided a clear description of how the river ecosystem worked together. Expanding the use of this methodology to other stakeholders, such as local residents, consumer associations or ecologists, for further research and studies will be essential. However, more research is needed on the process of aggregating individual maps into a single map to prevent that the perceived knowledge on their individual map by each stakeholder are underlined on the final map.

Therefore, we determined that FCMs were a good tool for decision making and could be a suitable methodology for generating simulations of future policy scenarios aimed to develop realistic fluvial restoration works and better conservation strategies.

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References


García de Jalón, D., Alonso, C., González del Tango, M., Martínez, V., Gurnell, A., Lorenz, S., Wolter, C., Rinaldi, M., Belletti, B., Masselman, E., Hendriks, D,