Collaborative knowledge mapping to inform environmental policy-making: the case of Canada's Rideau Canal National Historic Site

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Abstract

The Rideau Canal National Historic Site is a complex social-ecological system that connects the Ottawa River and the St-Lawrence River in Eastern Ontario, Canada. As an interjurisdictional waterway, it presents interconnected social-ecological challenges. In this article, we analyze findings from five participatory workshops held with stakeholder groups in the Rideau Canal system. Participants in the workshops co-produced social-ecological relational maps that represent their knowledge and views about determinants of environmental health in the system. The maps were merged by the authors to create an aggregated, collective map grouping all factors that participants perceived as influencing the environmental health of the Rideau Canal. Our analysis focuses on two dimensions of these co-production exercises. First, we use concepts and methods from social-ecological systems and social network analysis to analyze the content of the maps, examining convergences and divergences in stakeholder perceptions of the system and outlining insights into social-ecological linkages that might be relevant for decision- and policy-makers. Most factors cited were social, emphasizing the need for more careful integration of the social and ecological in our understanding of complex historic waterway systems. Second, we examine the value of our workshops, anchored in collaborative systems thinking and network analysis, as a method for eliciting highly variable local knowledge and experiences, and for summarizing these in a consumable form for decision- and policy-makers. We argue that this method facilitates inclusion of various knowledges and perspectives in decision- and policymaking processes and provides pathways to improve social-ecological resilience.

Keywords

Collaboration; knowledge mapping; resilience; social-ecological systems; network analysis; Rideau Canal

1. Introduction

Managing water resources that cross multiple jurisdictions is a major challenge. The existence of multiple governing bodies, as well as stakeholders and rightsholders with varying interests, can hinder effective policy processes and the development of social-ecological resilience. In addition, the uniqueness of freshwater ecosystems makes it difficult to establish universal best practices, emphasizing the need to tailor management and policy decisions to local contexts. Including the knowledge and perspectives of stakeholders and rightsholders in decision-making processes is recognized as a step toward addressing this challenge, although local knowledge should not be extracted but rather co-produced in reflexive and meaningful ways (Klenk et al. 2017). However, there are often many challenges in ensuring meaningful engagement.

This article addresses the need and attendant challenges of including local knowledge and perspectives in environmental decision- and policy-making spaces through co-production in the case of the Rideau Canal National Historic Site (RC) in Ontario, Canada. The RC is a freshwater canal of significant ecological, historical, and cultural importance. Like many constructed waterways, the RC paradoxically presents barriers to conservation (e.g. ecological fragmentation, habitat loss, infrastructure footprint) while also providing opportunities for conservation and improved resilience (e.g. historical and natural conservation initiatives, effective management regimes, conservation-minded economic development) (Lin et al. 2020; Mistry 2020). The RC also has a range of stakeholders with varying perspectives and knowledge that could inform locally relevant environmental decisions and policies.

Knowledge co-production is highly applicable to SESs, because relevant knowledge is held by people embedded in the social-ecological system (Cooke et al. 2021). Co-production is "the collaborative process of bringing a plurality of knowledge sources and types together to address a defined problem and build an integrated or systems-oriented understanding of that problem" (Armitage et al. 2011: 996). While collaboration and co-production are priorities for research funders, barriers such as lack of time and loss of control makes it hard to realize (Morris 2014), underlining the need to investigate methods for effective co-production. Our approach to co-production involved eliciting the perspectives and views of experts and non-experts through knowledge mapping activities, offering an efficient and practical way to improve resilience and inform policy and decision-making (Papageorgiou & Kontogianni 2012; Gray et al. 2014; Özesmi & Özesmi 2004). Resilience is understood as the ability of a system to respond to stressors while maintaining its functions (Berkes 2017). It relates to the importance of adaptive capacity in environmental governance, which can be explored through complex systems thinking that emphasizes the need for diversity, flexibility and strong relationships in management practices (Armitage & Plummer 2010).

We conducted five workshops with RC stakeholders to generate collaborative relational maps of the systemic forces that influence and interact with the environmental health of the RC. Our analysis focuses on two dimensions of these co-production exercises. First, we examine convergences and divergences in stakeholder perceptions of the RC as a social-ecological system, including analysis of a consolidated social-ecological network graph that combines the knowledge co-produced in the five workshops. Second, we discuss two ways in which collaborative systems thinking workshops and social-ecological network analysis is valuable: (1) for eliciting highly variable perspectives and knowledge and summarizing them in a consumable form for decision- and policy-makers and (2) for building resilience in the SES of the RC. Overall, our research highlights the importance of including a range of views to develop a holistic understanding of the RC system, while also recognizing the challenges of participatory governance and engagement. It also addresses the potential of collaborative systems thinking and network analysis to help bridge knowledge-action gaps in social-ecological research. Finally, it has implications for broadening environmental governance and policy by connecting and synthesizing multiple perspectives and knowledges, thus providing narratives and informed paths towards policy action.

2. Collaborative mapping of the Rideau Canal as a social-ecological system

2.1 The case

The RC is a designated UNESCO World Heritage Site, a Canadian Heritage River and a National Historic Site managed by Parks Canada, an agency of the federal government. Canal sections were built to connect pre-existing rivers and lakes, creating a new 200 km navigable pathway that connects the Ottawa River (City of Ottawa) and the St-Lawrence River (City of Kingston) in Eastern Ontario. The system encompasses two watersheds with several lakes and tributaries and passes through 13 counties and townships (Parks Canada 2017). Construction of the Canal was completed in 1832 (Charron et al. 1982) and its ongoing use has been shaped by - and contributes to shape - the environmental health of surrounding ecosystems as well as associated social structures and processes.

Like other inland waterways, the management of the RC must balance multiple usages tied to water level management and water supply, tourism, recreation, conservation, and cultural heritage (Konings & Wiegmans 2016). Conflicting priorities about usage in the cross-jurisdictional context of the RC complicate governance. Additional challenges in the RC and other inland waterways relate to a lack of political will and funding, aging infrastructure, and lack of adaptability (Konings & Wiegmans 2016; Willems et al. 2018). There is also heterogeneity in social and ecological features across the various reaches of the Canal (e.g. inconsistent regulations across municipalities, multiple types of infrastructure, urban or forested shorelines). As a coupled social-ecological system, there are many tensions within the RC such as balancing conservation with recreation and development, as well as controlling the spread of invasive species without harming native species and species-at-risk (Bergman et al. 2021; Mistry et al. 2021; Poulin 2001; Charron et al. 1982). The social-ecological diversity within the system makes it difficult to generate empirical data and scientific knowledge that captures all of the complex dynamics of the waterway. This enhances the need to rely on local and expert knowledge and perspectives to generate integrated and nuanced understandings of the system that can support environmental management and policy-making.

Some research on the environment of the RC has been conducted (Sonnenburg et al., 2009; Walker et al. 2010; Gillis et al. 2010; Stuyt et al. 2015; Agrawal & Jahanandish 2019), but there is a lack of research integrating social and ecological components of the waterway to improve its management (for gaps and opportunities, see Bergman et al. 2021). From 2018 to 2021, researchers from Carleton University, the University of Ottawa and l'Université de Sherbrooke conducted research in partnership with Parks Canada on national historic waterways in Eastern Ontario. As part of this work, the authors facilitated workshops in which participants generated relational knowledge maps of factors influencing the environmental health of the RC. Participants, including residents, users, business owners, regulators, managers, and researchers, provided their perspective and knowledge (local, experiential, and scientific) of the RC.

2.2 Participatory production of knowledge with systems thinking

The literature on environmental management recognizes the importance of participatory approaches and collaboration to build resilience (Perz 2019; Berkes 2017), but participatory approaches have attendant challenges in building trust, engaging participants meaningfully, and dedicating enough time (Bell et al. 2013; Metcalf et al. 2015; Black & McBean 2017; Morris 2014). More specifically, while many methods for collaboration and meaningful engagement exist, few focus on co-production of knowledge that accounts for system dynamics and resilience thinking (Newell & Proust 2012). While relational knowledge mapping and elicitation of mental models are effective methods for understand complex ecological systems (Moon et al. 2018; Jones et al. 2011), mapping exercises can be enhanced through participatory approaches (Gray et al. 2014). We analyze the outcomes of participatory workshops that used the Collaborative Conceptual Modelling (CCM) approach (Newell & Proust 2012; Newell & Proust 2018) to map stakeholder knowledge and perspectives about the RC. This approach provides methods to articulate as well as mesh and extend the participants' individual mental models of a system through mapping and teamwork. This method provides a practical way to develop shared understandings among participants from various professional, cultural, geographic, and disciplinary boundaries (Perz 2019) to support more inclusive decision- and policymaking processes. In fact, shared mental models are useful to create shared pathways to conservation (Moon et al. 2019). The method also helps visualize the complexity of systems along with the challenges they pose for sustainability (Newell & Proust 2018).

Social-ecological systems (SES) is an interdisciplinary concept referring to dynamic, coupled systems in which societal actors and ecological units and subsystems interact through direct, indirect and bidirectional linkages (Glaser et al. 2012; McGinnis & Ostrom 2014; Schoon

& Van der Leeuw 2015). Studying SESs supports improved adaptive capacity and encourages resilience thinking. For example, SESs can act as boundary objects providing a common framework to support effective coordination between actors with different disciplinary and professional backgrounds (Glaser et al. 2012; Hertz & Schlüter 2015). We use social-ecological network methods (Bodin & Tengö 2012) to analyze the relational maps and make recommendations for bridging knowledge-action gaps. This process brings together various actors and presents possible collaborations that build adaptive capacity, thus resilience. In doing so, we attend to power dynamics that shape interactions between science, society, and nature in the context of participatory approaches (Lemos et al. 2018; Van der Molen 2018).

3. Materials and Methods

3.1 Participants

This research obtained approval from the University of Ottawa's Research Ethics Board. Five CCM workshops were held between March and December 2019 near the RC, in the Ontario communities of Smiths Falls and Battersea. Four of those workshops assembled different types of stakeholders (see Table 1) and aimed to gain insight about the environmental health of the RC as a whole. A fifth workshop was organized through action research to address concerns about water quality and was held with a mixed group from the Lower Cataraqui region of the RC (see Mistry et al. 2021).

Purposeful sampling was used to identify "key informants in the field who can help in identifying information-rich cases" (Suri 2011). As we aimed to capture a broad range of views, knowledge and perspectives about the RC, the team generated a large list of potential participants by searching online for non-governmental organizations, environmental groups, community groups, lake associations, businesses, and governmental groups, among others, related to the RC. Researchers and collaborators who have worked in the system for many years also helped identify relevant actors who have limited online presence but play an active role in the system. Academic scientists were colleagues from the research team described in Section 2.1. With the help of collaborators, we produced a tiered list of possible participants that prioritized key informants. We grouped participants for the workshop by stakeholder groups. Participants were invited according to the tiered lists until we recruited a maximum of 15 participants per workshop. Many efforts were made throughout the recruitment stage to engage with Algonquin and Mohawk communities near the RC by using contacts from collaborators and online searches, but these efforts were unsuccessful. A total of 52 individuals participated across the five workshops, with one individual attending both the community and water quality workshop.

During the last step of the knowledge mapping exercise in the workshop, participants were asked to work in pairs. The authors assigned the pairs by observing participants throughout the workshop and pairing people who, based on our knowledge of their affiliation, did not appear to have personal or professional relationships. One group of three was formed in workshops with an odd number of participants.

Workshop	*Community and environmental groups*	*Economic interest groups*	*Academic scientists*	*Government representatives*	*Water quality*
Participants	15	9	9	10	10
Pairs	7	4	4	5	5

Table 1: Number of participants and pairs of participants per workshop.

3.2 Workshops

The main question for the four stakeholder group workshops was "What can be done to maintain or improve the environmental health of land and water in the Rideau Canal?", while the fifth workshop used the same question but substituted environmental health with water quality, due to the specific interest of that group as mentioned above. We organized the workshop around the CCM approach, which draws from systems dynamics and resilience thinking (Newell & Proust 2012; Newell & Proust 2018). We adapted the CCM approach to include four activities that would allow us to identify dominant dynamics in the RC system, to identify leverage points and to develop new shared understandings (Newell & Proust 2012) within a three-hour workshop. The four workshop activities consisted of individual identification of factors which influence environmental health, the creation of a collective timeline detailing how these factors came to be, a knowledge mapping exercise, and a group discussion about leverage points to press for change (for more details on workshop activities, please refer to Supplementary Material 1).

In this article, we focus on the knowledge mapping exercises. Building on previous activities as well as their knowledge and perspectives, participants individually identified the causal relationships among factors relating to the central factor "environmental health" or "water quality". They were asked to add factors around the central factor on a piece of paper, and to connect them with arrows showing the direction of influence, thus creating a systems map representing their mental models of the RC (Newell & Proust 2012; Moon et al. 2019). Next, participants were paired and given a large piece of paper to merge the factors and relationships from their individual maps, thus co-producing knowledge maps and providing opportunities for social learning. One member of each pair described the content of the map with the rest of the group. This mapping exercise generated a total of 25 pair-level maps.

3.3 Analysis

We examine the convergences and divergences across stakeholder views in the maps and analyze a collective map of the RC that aggregates local and expert knowledge. Using MS Excel, we thematically coded the list of factors from the pair-level maps to get a standardized list of factors. Two of the authors reviewed the coding. We also classified factors as either social or ecological. Social nodes included primarily social processes, institutions, and activities such as management and regulations, recreational activities, economic activities, tourism, as well as technologies. Ecological nodes included primarily ecological processes such as biodiversity and species succession. Two of the authors reviewed this classification. Using these factor attributes, we classified relationships between factors in all maps as social ties (social node-to-social node), ecological ties (ecological node-to-ecological node) or social-ecological ties (social node-to-ecological node or vice versa).

We stored data from the maps in MS Excel as 25 unweighted, asymmetric adjacency matrices using binary coding; we coded the presence or absence of a relationship between factors as a 1 or 0. By merging adjacency matrices of pair-level maps from each workshop, we created aggregated workshop-level matrices. When merging these adjacency matrices, we summed the frequency at which participants cited each relationship between the factors to use as the weight of the relationship. We repeated this process with workshop-level matrices to create one aggregated matrix, a collective map.

We used the packages 'sna' (Butts 2019) and 'igraph' (Csardi and Nepusz 2006) in Rstudio, an integrated development environment for the programming language R (R Core Team 2017), to transform the adjacency matrices into networks and generate network measures. Graphs were generated in igraph using the default layout value which calls upon the Fruchterman-Reingold layout, a force-directed algorithm which determines layout according to the forces pulling nodes together and apart from each other (Csardi and Nepusz 2006). This analysis allowed us to describe and compare the structure of relationships between factors across maps (Moon et al. 2019, Giordanno et al. 2017; Gray et al. 2014; Özesmi & Özesmi 2004; Papageorgiou & Kontogianni 2012; Stakias et al. 2013; Mistry et al., 2021). To compare the structure of the maps across workshop groups, we ran one-way ANOVA tests with pair-level data. We also describe differences between workshop maps by using network graphs and measures. The collective map was analyzed through basic network measures and with the Louvain community detection which served to identify communities of factors by maximizing modularity (Smith et al. 2020). The clusters obtained from the Louvain community detection algorithm were used to identify interconnected nodes as distinct clusters of factors. These clusters led to key findings which we used to identify areas of action and create narratives that can be used in policy and decision-making.

4. Findings

4.1 Convergences and divergences in stakeholder views

The co-production exercise in the workshops resulted in 25 pairs of participants, each creating 25 knowledge maps of the RC as a social-ecological system. The maps were converted into networks graphs for analysis. A network is a set of relations between people, concepts or factors. In this case, the network maps represent people's perceptions of causal relationships (herein referred to as ties or edges) between factors that influence the environmental health of the

RC (herein referred to as nodes). Network size refers to the number of nodes in a network, and network density refers to the proportion of actual ties in a network divided by the number of possible ties. A glossary of network analysis terminology is available in Supplementary Material 2.

Among the 25 pair-level networks (see Supplementary Material 3), there was a near significant difference among workshop groups regarding the percentage of social and ecological nodes ($F(4, 20) = 2.664$, $p = 0.062$). There was also a significant difference among workshop groups regarding the number of ecological nodes ($F(4, 20) = 3.349$, $p = 0.30$). While most groups had similar proportions of social and ecological nodes at the pair-level, community and environmental groups had less ecological nodes in their maps. Inversely, the water quality pair-level maps included more ecological nodes.

We merged the 25 pair-level networks to create five workshop-level maps and identify convergences and divergences between groups (see Table 2, Figure 1a to 1e and Supplementary Material 4). Workshop-level maps generally had a higher percentage of social nodes compared to ecological nodes. Most workshop-level maps also featured a higher proportion of relationships between social and ecological factors (social-ecological ties) compared to relationships between only social and only ecological nodes (social and ecological ties respectively). Ecological ties account for less than 26% of ties across all workshops. Community and environmental groups strongly emphasized social factors (80.77%) and social ties (55.93%) compared to other groups. The workshop-level map for academic scientists was the most balanced in terms of tie type, closely followed by the water quality workshop which also had the most balanced proportion of nodes. Overall, participants cited social factors and relationships more frequently across all workshops, except the water quality workshop.

Network measure	*Community and environmental groups*	*Economic interest groups*	*Academic scientists*	*Government representatives*	*Water quality*
Network size	52	38	38	36	46
Number of edges	177	120	92	167	244
Network density	0.07	0.09	0.07	0.13	0.12
Percentage of social nodes	80.77	71.05	65.79	63.89	52.17
Percentage of ecological nodes	19.23	28.95	34.21	36.11	47.83
Percentage of social ties	55.93	40.00	36.96	33.53	27.05
Percentage of ecological ties	10.73	10.83	26.09	20.36	26.74
Percentage of social-ecological ties	33.33	49.17	36.96	46.11	46.31
Edgewise reciprocity	0.66	0.47	0.11	0.48	0.41

Number of strong components	10	13	27	7	13
In degree centralization	0.31	0.33	0.29	0.60	0.49
Out degree centralization	0.23	0.13	0.18	0.39	0.49
Betweenness centralization	0.39	0.29	0.11	0.25	0.28
Eigen centralization	0.29	0.23	0.30	0.31	0.26

Table 2: Network measures at the workshop-level

To further compare workshop maps, we can use centrality scores that refers to the level of connectivity of individual nodes. More specifically, in and out degree centrality refers to the number incoming and outgoing ties of a node. As expected, the central factors of environmental health and water quality nodes had the highest combined in and out degree and betweenness centrality scores in their respective workshops. Some factors were cited in all workshop maps: invasive species, climate change, agriculture, boating, water quality, shoreline development and development pressures. Water quality was also a central factor in all workshops, and climate change was central for economic interest groups. Betweenness centrality scores also help identify nodes that act as bridges connecting otherwise disconnected nodes. Tourism and shoreline development were identified as bridging factors in four of the workshop-level maps, while boating, nutrient levels and water quality scores were identified as bridges in three of the workshop-level maps.

There was a significant difference across workshop groups regarding the number of strong components (which are subsets of mutually connected nodes) in pair-level network maps ($F (4, 20) = 3.765$, $p = 0.020$). Figure 1 shows network graphs and is accompanied by descriptions of relationships and network features for each workshop. We use network indicators from Table 2 such as edgewise reciprocity (which refers to the number of mutual ties in a network) and centralization scores (which provide insight about the level of overall connectivity of the entire network) to describe these structural network features.

Figure 1a to 1e: Workshop-level graphs featuring the most central nodes, as determined by a combined rescaled in and out degree centrality score of 0.03 or more. We set a threshold of 0.03 to produce graphs that visually present the dominant nodes and relationships of each workshop map. The centrality score of a node determined node size in the graph, with the most frequently cited nodes having a bigger size. Orange represents social nodes and ties, and green represents ecological nodes and ties. Blue represents social-ecological ties. The width of lines corresponds to weight, that is the frequency at which relationships were cited by participants, while arrows represent the direction of ties.

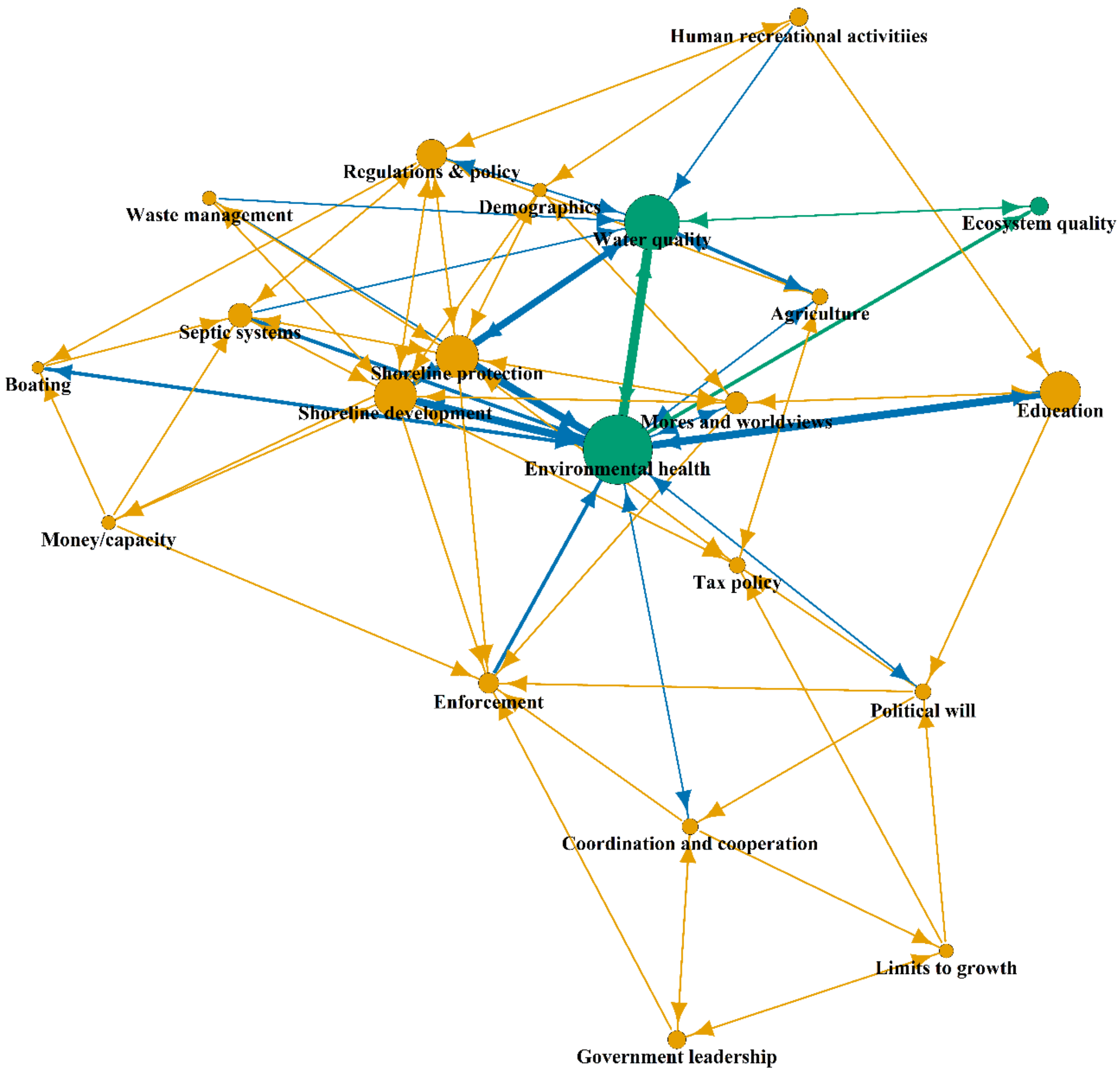

Figure 1a: Community and environmental groups workshop-level network graph.

The community and environmental groups cited more social nodes and those with the highest degree centrality related to human infrastructure (shoreline protection, septic systems), but also values (education, mores and worldviews) and governmental activities (regulations and policy, enforcement, government leadership). Five out of seven pairs perceived the influence of water quality on environmental health, and two pairs saw this relationship as reciprocal. Pairs frequently cited shoreline protection, shoreline development and agriculture as related to water quality and environmental health, thus indirectly connecting these two central factors. Results also show that community groups had the highest edgewise reciprocity, which refers to the number of mutual ties in a network, thus indicating that community groups produced more mutually connected maps.

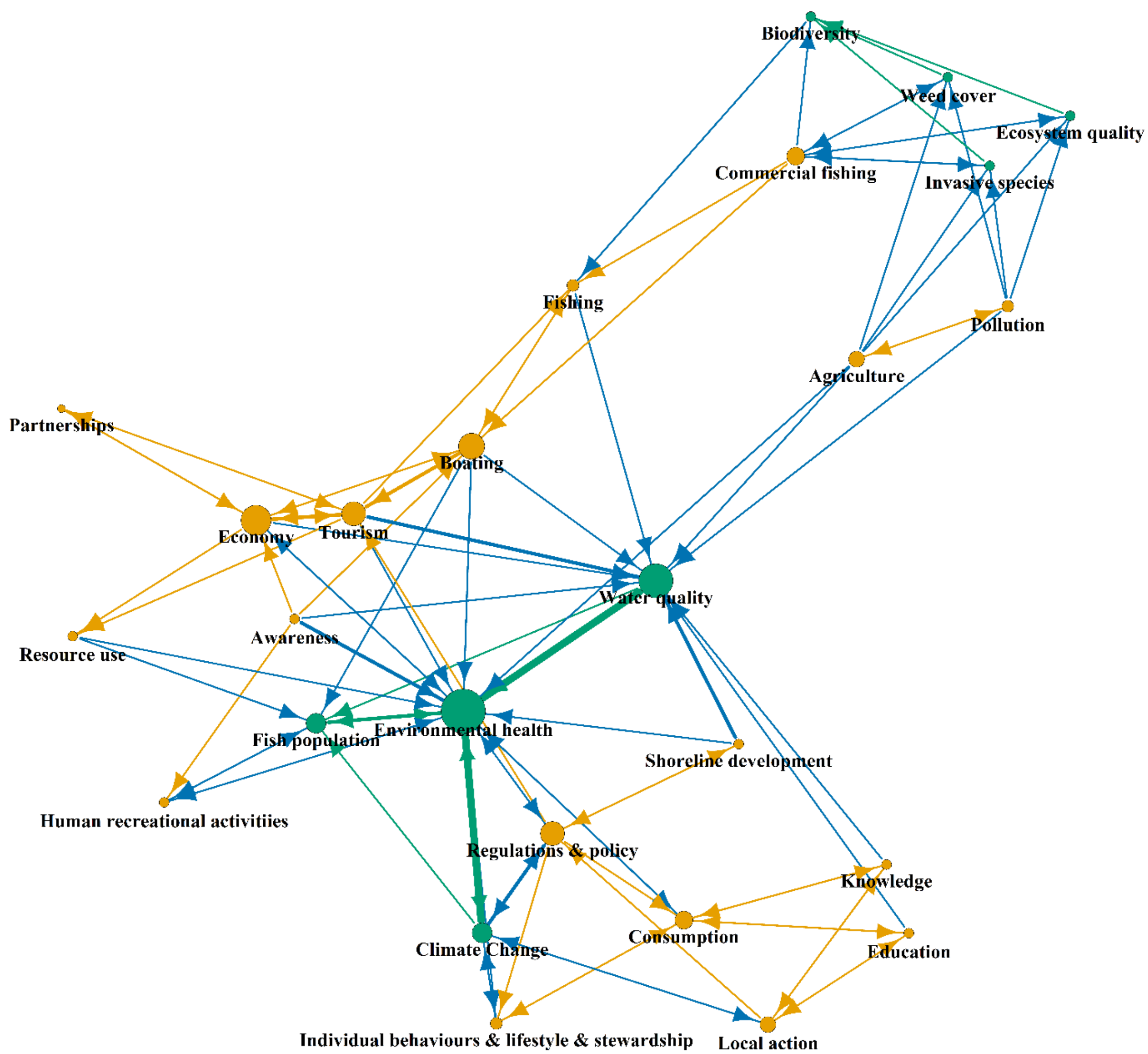

Figure 1b: Economic interest groups workshop-level network graph.

Economic interest groups had a more balanced view than community and environmental groups. Nodes with highest degree centrality related to human behaviour and decisions (boating, tourism, commercial fishing, agriculture, local action, regulations and policy), economic values (economy, consumption) and ecological factors (climate change, fish population). All pairs linked water quality and climate change to environmental health. Some also acknowledged the reciprocity of the relationship between climate change and policy. Although there are distinct clusters of social and ecological factors, there are many social-ecological ties, many which relate to economic activity.

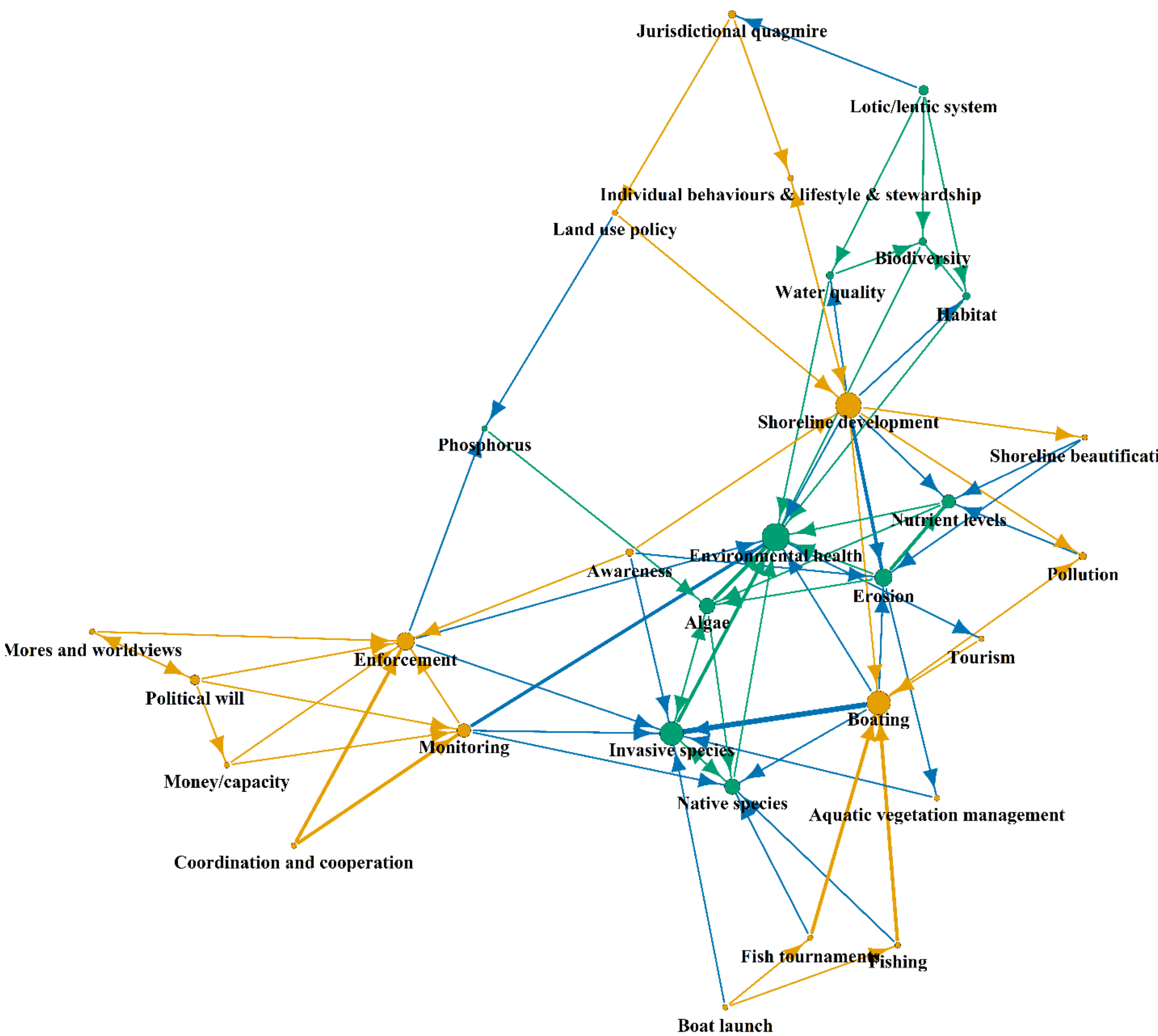

Figure 1c: Academic scientists' workshop-level network graph.

Academic scientists cited many ecological factors that had high degree centrality (invasive species, erosion, native species, algae, nutrient level, lotic/lentic system), but they also considered human behaviour (shoreline development, boating, enforcement, monitoring, political will). Most pairs mentioned the influence of boating on invasive species, and some linked fishing and fishing tournaments to boating. The influence of algae, invasive species and monitoring on environmental health was also identified. This network graph shows a relatively proportional view of social, ecological and social-ecological ties with some clustering. Overall, network indicators suggest that academics co-produced the most fragmented view of the RC with distinct clusters formed of connected factors (highest number of strong components, low number of edges, low score of density, low edgewise reciprocity, and lower centralization scores).

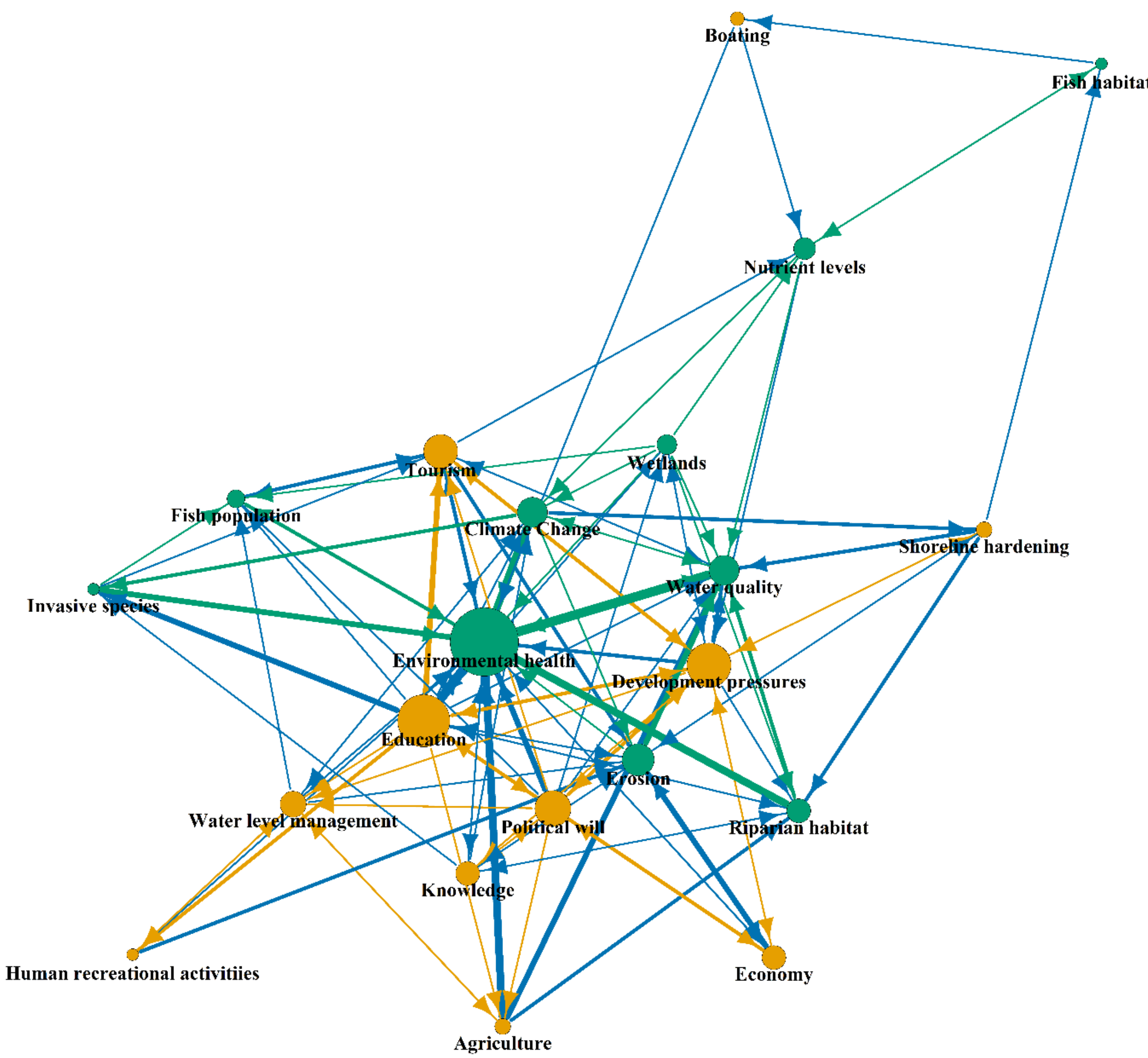

Figure 1d: Government representatives' workshop-level network graph.

Human actions and decisions (education, development pressures, political will, tourism, water level management) had the most ties in the government representative workshop, but some biophysical indicators were also central (erosion, climate change, water quality). All pairs linked education and water quality to environmental health. Agriculture, climate change and riparian habitat were also recognized by most pairs as influencing environmental health. A higher proportion of social-ecological ties in this network graph shows an integrated view of environmental health. Network indicators suggest that government representatives perceived dense connections among factors with the smallest number of separate clusters (highest network density and in degree centralization score, as well as the lowest number of strong components).

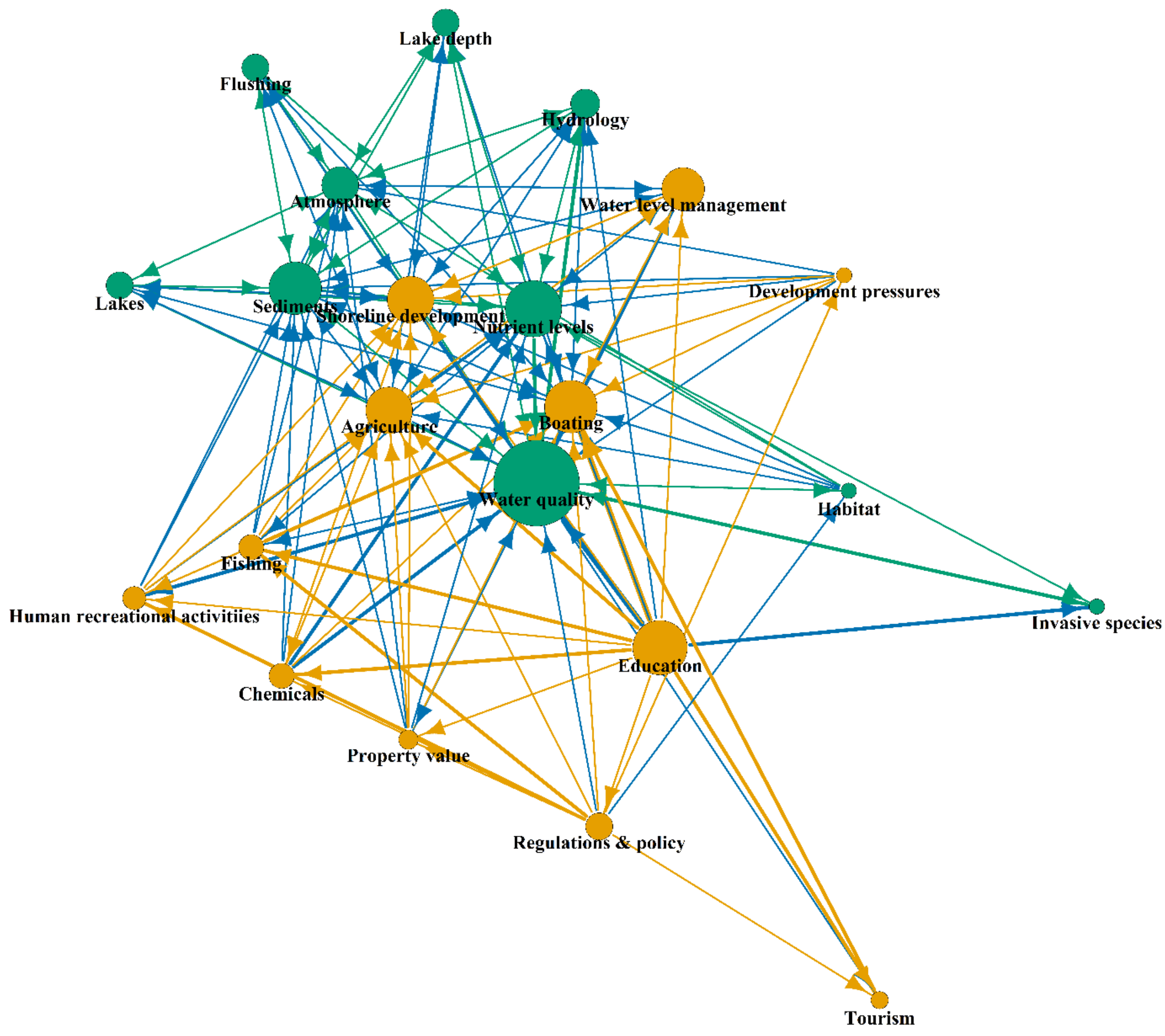

Figure 1e: Water quality workshop-level network graph.

Nodes with the most ties in the water quality workshop included both biophysical factors that directly relate to water quality (nutrient levels, sediments) and human behaviours that are perceived to influence these factors (education, boating, shoreline development, agriculture, water level management). Many pairs linked climate change and education to water quality, and education to boating. This network graph features many social-ecological ties where human actions influence biophysical indicators. However, social and ecological nodes are mostly located on opposite ends of the network, which indicates less direct connections. Overall, the water quality workshop-level map presents a densely connected map by featuring some of the highest in and out degree centralization scores and a high network density.

4.2 Collective-level map

The collective network was created by aggregating workshop-level maps, thus representing the knowledge and perspectives of all groups (see Supplementary Material 5 for the full map, tie list and node list). It has a lower network density than workshop-level maps due to ties being spread over a high number of nodes (see Table 3). The collective map is skewed towards social factors (70.54%) but is more balanced in terms of types of ties, with most ties connecting social and ecological factors (41.94% are social-ecological ties). Beyond environmental health and water quality, the most frequently mentioned factors include education, boating, climate change, invasive species, agriculture, shoreline development, tourism, and regulations & policy. The first four were cited in all five workshops. Overall, 26.79% (30) of factors were mentioned by four or more pairs of participants (out of 25), which indicates that around three quarters of factors were not frequently mentioned by participants.

Network measure	*Collective map*
Network size	112
Number of edges	689
Network density	0.06
Percentage of social nodes	70.54
Percentage of ecological nodes	29.46
Percentage of social ties	39.33
Percentage of ecological ties	18.72
Percentage of social-ecological ties	41.94

Table 3: Network measures for the collective map.

Factors that are well-connected in the map (high degree centrality) include education, shoreline development, boating, nutrient levels, water-level management and erosion. Following environmental health and water quality, education, shoreline development, boating, nutrient levels, water-level management, erosion, tourism and coordination and cooperation were the top bridging nodes in the collective-level map. Most pairs in all workshops cited water quality as influencing environmental health. Other more frequently cited relationships across workshops include the influence of shoreline development and agriculture on water quality, as well as the influence of boating, climate change, invasive species and education on environmental health. As can be seen in the full map figure (Supplementary Material 5), the network structure in the collective map is mostly formed by one cluster with some nodes being slightly less connected to the core of the network. The center of the cluster presents a mix of social-ecological ties, with social factors and ties at the periphery. Few ecological factors and ties are at the periphery, indicating that while they are more directly connected and better integrated in the network.

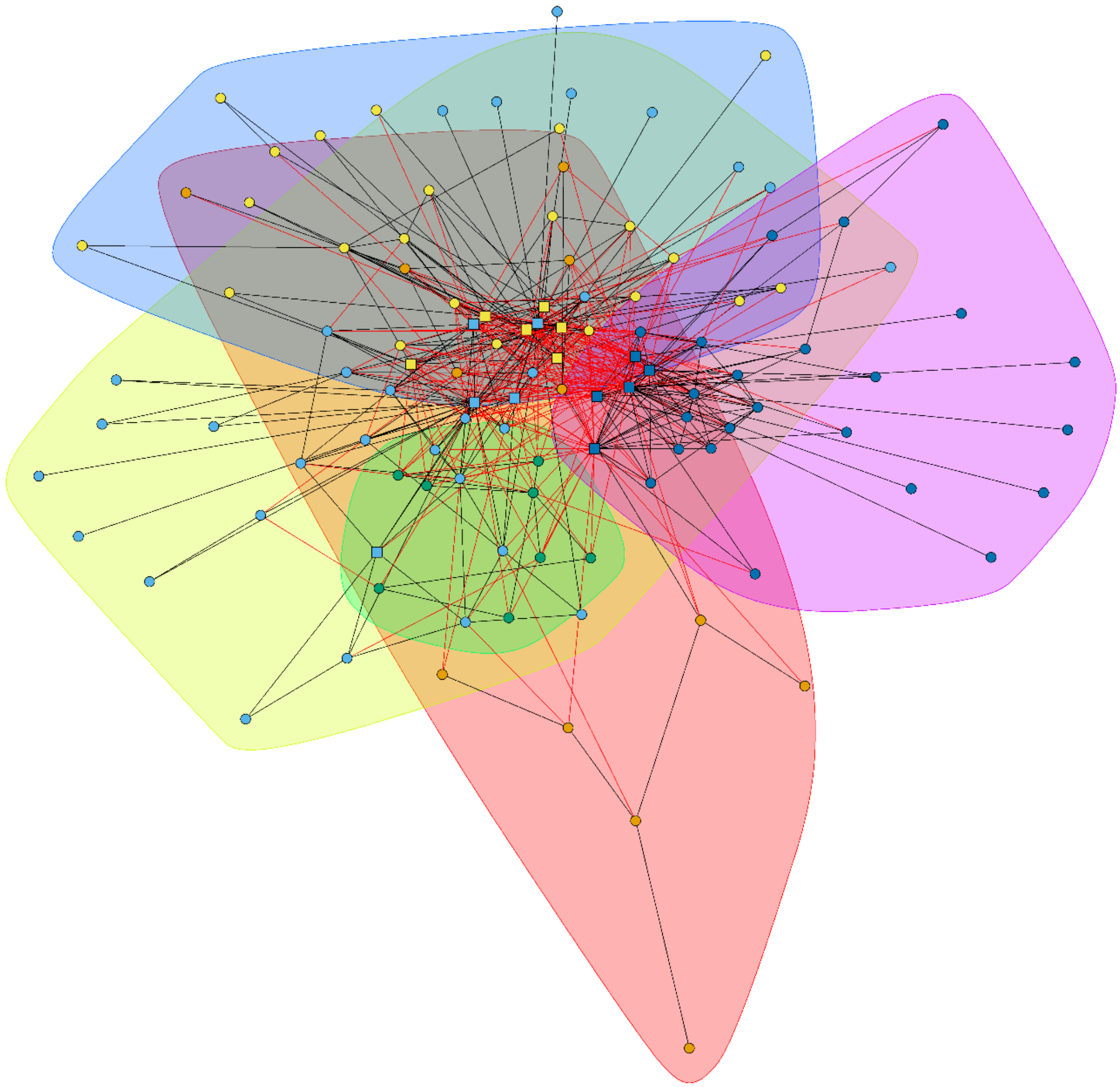

Figure 2: Collective-level network graph with results from the first round of Louvain community detection algorithm, which identified 5 main clusters (distinguished by color for visual convenience: blue, yellow, green, red, and pink).

Figure 2 presents results from the first round of the Louvain community detection algorithm which identified five main clusters. The Louvain community detection algorithm was applied again to the main clusters which had more than 20 nodes. This second iteration identified 13 clusters whose core findings are described in Table 4 (see Supplementary material 6 for individual graphs). These clusters encompass all nodes from the collective-level network, though only 31.35% of all ties are represented in the clusters. We can see that half of the clusters formed around social ties (six clusters), and only one formed around ecological ties. Six social-ecological clusters were also identified. Table 4 also describes some narratives that can be told from the core findings.

Cluster	*Classification*	*Narratives derived from the knowledge and perspectives found in the collective-level map*
1 Red	Social-ecological	Commercial fishing is perceived to impact turtle distribution, ecosystem quality and weed cover, and indirectly biodiversity. Jurisdictional quagmire is also seen as being influenced the RC's construction (led by Colonel By in the 1830s), and influences land-use policy and phosphorous.
2.1 Yellow	Social	Coordination and cooperation acts as a bridge between multiple nodes and was frequently cited as influencing enforcement, monitoring and common vision. Broader social trends – such as placing limits on growth, making the environment a financial priority, and consumption – relate to individual behaviour and government actions like leadership and stewardship. Individual behaviours and enforcement are perceived to be especially influential.
2.2 Yellow	Mostly social	Education is central to this cluster and highlights related social factors such as actors related to education (e.g., Conservation Authorities, lake associations) and mechanisms that can influence education (political will and involvement, engagement, mores and worldviews, and awareness, which can be influenced by new technologies).
2.3 Yellow	Social-ecological	This cluster features environmental health. There are social ties between local action (like pesticide use), fish management, global actions, and regulations. Regulations act as a bridge, indicated by high betweenness centrality, between social actions and environmental health. Some biophysical indicators interact through ecological ties like native and invasive species, algae, and climate change. Climate change is seen as influencing and influenced by both environmental health and regulations.
3 Green	Social	This cluster centers around shoreline protection. It is tied to waste management and hospitality (which are both influenced by social media), and there are bidirectional relationships between shoreline protection and tax policy, septic systems, money and capacity, and demographics.
4.1 Blue	Social-ecological	Development pressures are influenced by knowledge, shoreline hardening and vegetation cover, while influencing municipalities and riparian habitats.
4.2 Blue	Mostly social	Boating influences boat launches and public access; it was frequently seen in a bidirectional relationship with fishing. Lock activities influence both boating and aquatic vegetation management, which would otherwise not be linked.
4.3 Blue	Social-ecological	Recreational activities mediate the relationship between aquatic ecosystems, fish populations and fish tournaments through reciprocal

		relationships. Fish populations are influenced by boating and fishing regulations as well as resource use and fish tournaments, which influence resource use, forming a feedback loop. Resource use mediates the relationship between rural infrastructure and development regulations.
4.4 Blue	Mostly social	Economy is seen as influencing and being influenced by tourism and erosion, and tourism also influences erosion. Partnerships are in bidirectional ties with economy and tourism. Community influences both tourism and cottages, with cottages influencing erosion.
5.1 Pink	Mostly ecological	Nutrient levels are influenced by property values (the only social node of this cluster) and biophysical factors like lake depth, sediments, atmosphere and lakes.
5.2 Pink	Social-ecological	Canal construction influences shallow zones in the waterway, which influence turbidity.
5.3 Pink	Social-ecological	Water quality is at the core of this cluster and is influenced by ecological factors like buffer zones, while influencing ecosystem productivity. It is also directly tied to many social factors like road salt, artificial lakes, water traffic, storm water management, pollution, agriculture and water-level management. This can inform recommendations such as focusing on dams and chemicals through water-level management and agriculture to directly and indirectly influence water quality.
5.4 Pink	Mostly social	Shoreline development influences municipal funds, and there is a bidirectional relationship between habitat and shoreline development, showcasing a social-ecological tension.

Table 4: Core findings among Louvain clusters presented as narratives. The color specified with the cluster number refers to the associated colored clusters in Figure 2.

5. Discussion

5.1 Insights for governance of the Rideau Canal

Working towards conservation and building social-ecological resilience requires an understanding of the complex dynamics that shape systems, as well as the diversity of perspectives and knowledge that people hold about these systems (Moon et al. 2019; Gray et al 2012; Furman et al. 2021). The findings show these diverse perspectives and knowledge and reveal that there are shared and divergent assumptions about environmental health in the RC (Moon et al. 2019). The network maps are dynamic cognitive representations of reality based on life experience, perceptions, and worldviews, also known as mental models (Jones et al. 2011). Co-developing such mental models in natural resource management can help identify similarities and differences in actors' perceptions of environmental issues, integrate these different perspectives through social learning, and create collective representations of a given social-ecological system (Jones et al. 2011). These elements are essential for effective adaptive co-management because they build resilience by facilitating dialogue among stakeholders to collectively identify potential leverage points and form narratives to inform education and policy- and decision-making (Berkes 2017). This work is also novel in the context of the RC, thus providing the basis for future investigation of this dynamic waterway system.

A main finding is that social factors were overemphasized in the network maps. Most groups conceptualize the RC as an SES where more than half of the factors are social, which demonstrates that challenges to sustainability and environmental wicked problems "tend to be societal problems, rather than technical problems" (Berkes 2017: 7). Another significant finding is the different number of strong components between groups, which indicates that there are differences in the mental models of community groups, economic interest groups, academics, government representatives and the water quality workshop participants when conceptualizing the RC as a SES. Differences between groups were expected since social and psychological factors such as environmental attitudes, socio-demographics, and environmental knowledge and concerns are known to influence perceptions of the environment and social-ecological systems (Guo et al. 2018).

Community and environmental groups cited a higher proportion of social factors compared to other groups which could be attributed to higher levels of community involvement. Mental models are influenced by life experiences (Jones et al. 2011; Furman et al. 2021) and social interactions (Bustan 2016). For example, participation in the preservation of watersheds was tied to solidarity and attending to the interests of a group (Bustan 2016), supporting the insight that community groups perceive more social factors than other groups.

Although the academic scientists and water quality workshops had the most fragmented workshop-level maps, they also had the most balanced view of the system in terms of social-ecological ties. The mental model of academics may be influenced by their training and the reductionist approach science takes to study the environment and empirical phenomena (Gallagher 2018). Academics are also generally more familiar with the concept of SES than other groups, and preexisting knowledge of the concept is likely to have shaped their mental models of the RC as a system composed of distinct social and ecological components (for example, see Bergman et al. 2021). The fragmented representation demonstrates the utility of using SES as a boundary object in collaborative mapping exercises to foster interdisciplinary work and provide a holistic view of a complex SES (Hertz & Schlüter 2015). The fragmented view of the RC by academics may also be contextualized by the theory on the strength of weak ties, which refers to the idea that a person with many weak ties has greater access to a variety of novel, non-redundant information sources (Granovetter 1973; Aral 2016). Out of the participating groups, the academics are the least embedded from other actors and thus feature fewer weak connections within the RC system (e.g. they operate in thematic academic circles rather than RC-based community and management circles). As mentioned, they also present more homogenous views than other groups (e.g. scientific reductionism and prior understandings of SESs). This provides them with a less diverse pool of knowledge to draw from when generating mental representations of the RC, therefore present a simpler schema than the other groups, such as community groups who produced densely connected maps.

The water quality workshop demonstrates that focusing on a narrow topic with a mixed group of knowledgeable stakeholders may lead to more precise outcomes and balanced representations of social and ecological factors (Mistry et al. 2021). The mixed group also explains the fragmentation in the map as differences in environmental perceptions are expected between people who have different lived experiences and social characteristics (Moon et al 2019; Jones et al 2017; Furman et al. 2021; Guo et al. 2018). While individual mental models and conceptual maps are only partial representations of a system, collaborative participatory mapping and the aggregation of shared mental models generated more complete representations of water quality in the Lower Cataraqui and the RC system (Jones et al. 2011; Gray et al. 2014).

The collective map allowed us to identify key factors and areas of action to maintain and enhance environmental health in the RC. Unsurprisingly, regulations and policy were frequently cited in the maps, revealing the reflexive potential of our method. Informing decision-making processes with the resulting narratives (see Table 4 for examples) about the possible roles of policy in the RC system creates space for nuanced discussions and structured decision-making when seeking to update, renew or rethink these policies (Gregory et al. 2021; Moon et al. 2019). Our findings provide multiple pathways for consideration which aligns with the iterative dimension of adaptive management, thus building resilience in the RC system (Berkes 2017).

There was strong consensus across all workshops on the influence of water quality on environmental health, indicating the need for action in this area. Other areas of action cited in all workshops were education, boating, climate change and invasive species, some of which are also the most connected factors in the map: education, shoreline development, boating, nutrient levels, water-level management and erosion. Many social factors (education, shoreline development, boating, water-level management, erosion, tourism, coordination and cooperation) play a bridging role connecting factors across the system, highlighting the role of human actions as potential leverage points (or problems) tied to biophysical indicators of environmental health like nutrient levels and erosion. Insights from network analysis and the relationships among factors can be used to prioritize action in the RC by identifying precise pathways of action.

This paragraph provides an example of how the map can be used to identify areas of action and pathways to support resilience. There was consensus across workshops about the need to consider education, it was also a central node and a bridge in the system. In alignment with the environmental education literature (Ardoin et al. 2020), it can thus serve as a leverage point to improve social-ecological resilience in the RC. The relationships in the collective map reveals specific realms of activities or behaviours that education should target like agriculture, boating, consumption, development, enforcement, fishing, recreational activities, landscaping, tourism, septic systems and water-level management. The collective map also reveals key actors of education in the system, Conservation Authorities and lake associations, who should be supported by decision- and policy-makers.

Our analysis of the collective map presents combined insights from expert and local knowledge as concise and precise narratives that can inform policy- and decision makers (Table 4 and Supplementary material 6 for the respective maps). The network analysis also revealed consensus on the need for coordination and cooperation in the governance of the RC system. This mapping exercise provides a starting point for governmental collaborators who can use the results to highlight priority pathways for their respective jurisdictions and test mutually reinforcing solutions based on intersecting pathways (Newell & Proust 2012). Such an exercise is especially important to build resilience for the RC system considering it features jurisdictional quagmire (Mistry 2021, Bergman et al. 2021) which presents significant governance challenges that can impede adaptive co-management (Armitage et al. 2009; Folke et al. 2005).

5.2 Implications for decision- and policymaking

Research has shown that modelling and mapping of SESs in participatory approaches helps to bridge disciplines and support decision-making (Anderies 2002; Glaser et al. 2012; Rounsevell et al. 2012; White et al. 2018; Giordano et al. 2017; Gray et al. 2012; Gray et al. 2014; Özesmi and Özesmi 2004; Papageorgiou and Kontogianni 2012; Stakias, et al. 2013). We used both quantitative thresholds (network measures) and qualitative information (the factors and the relationships between them) to provide evidence and derive narratives of system-wide interactions that can inform policies in the RC. Our research process provides a practical way for both local and scientific knowledge and perspectives to inform decision-making in a context where interconnections in large waterway systems are difficult to investigate empirically, particularly where there is limited empirical data on the SES (Bremer et al. 2020). This approach also provides a meaningful way to engage with key actors and foster social learning (Mistry et al. 2021; Berkes 2017; Moon et al. 2019; Jones et al. 2017).

The outcomes of these workshops underscore the need for careful thinking to effectively mobilize collaboration to improve environmental governance and research (Perz 2019). The mapping exercise in pairs to lead discussion on areas of action contributes to shared understandings of multiple perspectives among participants and development of holistic solutions (Mistry, 2020). This method provides a way for researchers, governments, local groups and businesses, among others, to come together early on in engagement and consultation processes in order to understand how systems-thinking can be used to tackle complex problems, especially in the context of policy-making (Glaser et al. 2012). While the workshops enabled the authors and participants to strengthen their relationships with other disciplines, locals and government representatives in the RC, iterative approaches and ongoing relationship-building can improve the quality of outcomes over time (Young 2020).

This method is also a starting point to address power imbalances between local and expert knowledge by considering epistemological pluralism: each form of knowledge stems from different worldviews which are equal and valid (Miller et al. 2008). However, there are limits to this method of knowledge co-production and the extent to which it addresses specific power imbalances as well as broader power dynamics. Our findings show that outcomes of this workshop remain anthropocentric as participants mentioned more social nodes. The workshops also had a limited number of participants who were selected by the authors, showing that collaborative processes remain limited by logistics (e.g. how many people can feasibly participate in each workshop) and relational power dynamics (e.g. who is given the opportunity to participate) (Young 2020). For example, Internet searches could only identify groups with enough capacity and resources to organize an online presence, and no more than 15 participants could attend each workshop. Though demographics were not recorded, the authors also acknowledge there was a skew towards men and an older population. Additionally, the authors are still working on building ties with Indigenous communities in the area surrounding the RC system so their perspectives could not be included. As such, this work represents the views of Canadian settlers. Future research must consider if and how formal systems thinking, and relational approaches could be mobilized to rebuild conversations and relationships with Indigenous communities in the RC and other regions of the world.

Despite these limits, the workshop and network analyses have value in aggregating various stakeholder knowledge, framing it in ways that include both social and ecological factors, and providing findings that can serve as evidence to support policy and decisions, especially in the absence of empirical data. The aggregated, collective maps are tools that can help find points of agreement across participants and present combined knowledge in concise forms to governments. This can serve to articulate more nuanced and accurate narratives of social-ecological systems that are informed by those who know the system best with the goal of sustaining and maintaining social-ecological systems. This type of process advances collaborative governance efforts and builds resilience and adaptive capacity by developing relationships and co-producing knowledge representations of the system that otherwise would be fragmented and underutilized in management of the RC (Berkes 2017; Moon et al. 2019).

While discussions are ongoing with government representatives on how they can integrate these tools in management of the RC, we present three suggestions. First, decision- and policy-makers could use findings from workshop-level maps (section 4.1) to identify similarities and differences in the knowledge, perspectives and priorities of different groups. This can inform engagement and communication strategies for different actors who have distinct interests, priorities, and understandings of the RC system. In addition, decision-makers and policy-makers could use the various network visualizations in the paper and supplementary materials as a way to engage stakeholders, rights-holders and staff where there may be tensions or conflict and to initiate discussion about system-wide management of the RC. Second, decision-makers and policy-makers could use the network statistics, for example the centrality scores of factors in the collective map, to identify collective priorities and areas of action. Key priorities and pathways to action can also be identified by looking for factors who score highly in different types of centrality scores (ex. degree centrality which refers to direct connections and betweenness centrality which refers to bridging capacity). Finally, the key findings and narratives derived from the knowledge mapping exercise present consumable information to act on social-ecological tensions in the RC system. These narratives could be integrated in education initiatives, new policies and strategic planning.

This work has implications for policy as a means, not an end, to improve the collaborative nature of governance in complex systems. In fact, governments should pay more attention to the people's perceptions of the environment, coordination among multiple groups and entities that have different knowledge and perspectives, and demands for effective and meaningful participation to collectively improve the implementation of environmental policy and regulations in order to build resilience in both governance the RC and within the SES itself (Liu 2021; Young 2020). Our findings and methods provide ways to meet these needs as it (1) co-produces local and expert knowledge in a way that includes both social and ecological factors and enhances social learning, (2) aggregates and presents this knowledge in a consumable form for policy-makers, and (3) generates specific recommendations on various social-ecological issues. While more work remains to efficiently integrate participatory co-production and knowledge mapping of mental models in decision-making about the RC, we offer many pathways forward for decision-makers in the RC and elsewhere to use these tools to work towards resilient social-ecological systems.

6. Conclusion

The RC is a complex waterway that is difficult to manage. Conducting participatory workshops with various groups of stakeholders allowed us to capture local and expert perspectives and knowledge in a way that accounts for both social and ecological tensions. Systems thinking and network analysis methods allowed us to analyze the knowledge maps that represent the mental models of participants to aggregate various perspectives and mobilize various knowledges in a way that can inform policy, decisions and the overall governance of the RC. The collective map allowed us to identify priority areas of action through consensus across stakeholder groups, and areas where further deliberation may be required.

This tool has potential for representing social-ecological knowledge and paving the way for meaningful inclusion of various knowledges in decision- and policymaking processes through iteration. Conducting subsequent CCM workshops with increasingly refined questions and different groups of participants could bring clarity and precision to the priority pathways for action. As such, we suggest that future research using these methods include multiple instances of mapping and target specific concerns (e.g., the water quality workshop) where additional deliberation and knowledge could fill knowledge gaps on the interconnections between social and ecological components of complex systems. This research provides a practical method for decision- and policy-makers to integrate disciplinary and professional silos which can result in informed policy and management strategies that balance social and ecological priorities while simultaneously building adaptive capacity and resilience.

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