Knowledge Exchange and Social Capital for Freshwater Ecosystem Assessments

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The 1972 Clean Water Act (CWA) provided crucial environmental protections, spurring research and corresponding development of a network of expertise that represents critical human capital in freshwater conservation. We used social network analysis to evaluate collaboration across organizational types and ecosystem focus by examining connections between authors of freshwater assessments published since the CWA. We found that the freshwater assessment network is highly fragmented, with no trend toward centralization. Persistent cohesion around organizational subgroups and minimal bridging ties suggest the network is better positioned for diversification and innovation than for learning and building a strong history of linked expertise. Despite an abundance of research activity from university-affiliated authors, federal agency authors provide a majority of the bonding and bridging capital, and diverse agencies constitute the core network. Together, our results suggest that government agencies currently play a central role in sustaining the network of expertise in freshwater assessment, protection, and conservation.

Keywords: freshwater assessment, conservation, social network analysis, Clean Water Act

Freshwater ecological integrity and biodiversity remain under immense and growing pressures as a result of a plethora of human-related impacts (Reid et al. 2018). Spurred in part by dramatic failures of free-market systems to protect valued rivers and lakes, in 1972, the United States passed the Federal Water Pollution Control Act (the Clean Water Act or CWA). This legislation introduced an ambitious mandate to restore and maintain "the chemical, physical, and biological integrity of the Nation's waters" (typically summarized by the term *ecological integrity*). Since that time, substantial conceptual and quantitative research has been focused on defining and measuring ecological integrity, which underlies the protection and restoration of freshwater ecosystems.

A recent synthesis of freshwater assessments since the passage of the CWA revealed that there has been considerable progress toward more consistent, robust, and repeatable assessment practices (Kuehne et al. 2017). Specific signs of advancement included adoption of practices such as more robust site selection, the use of reference conditions, and quantifications of natural versus human impacts on ecosystems. Simultaneously, however, the review revealed recent trends toward desktop (computer-based) assessments exclusively using remotely sensed data and an emphasis on landscape stressors, with less well-defined links to actionable indicators of ecological integrity.

More problematic was that, across all of the assessments reviewed, applicability or a clear connection to management or policy outcomes was often missing, suggesting that this is a crucial challenge for the next generation of assessments (Kuehne et al. 2017). This finding was consistent with work on integrating research into water policy and management in South Africa, wherein Roux and colleagues (2008) documented systemic challenges to establish and sustain intergovernmental and cross-sector collaborations that facilitate development and implementation of freshwater protective policies. A historical segregation between freshwater ecology and freshwater conservation communities may also impede collaborations that could help narrow the gap between research and management (Strayer and Dudgeon 2010).

Disconnects among research, management, and policy are neither new nor unique to freshwater ecosystems (Gibbons et al. 2008). However, the concrete intention of protecting the nation's waters within the CWA offers a well-defined context to examine whether the network of scientific researchers is, in fact, adequately positioned to maximize the management and conservation relevance of future assessments. Along with the need to address important research–management gaps, this research network represents some of the most critical human capital in the public and policy processes that are part of the ongoing maturation and evolution of the CWA (Adler 2013, 2015).

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Social network structure as an indicator of collaboration and knowledge exchange

To evaluate the current status of the freshwater assessment network, we turned to social network analysis as way to understand patterns of collaboration, knowledge exchange, and social capital. Social network analysis (SNA) originated formally in the 1930s and has a long history of use in the social sciences (Borgatti et al. 2009). SNA rests on the assumption that relationships between individuals (or groups) are of critical importance and are the dominant driver of information flows, resource exchange, collaboration, and action. Moreover, SNA approaches are designed to quantitatively measure and compare the structure of relationships, offering insight into questions such as the importance and roles of individuals or groups in a network (i.e., centrality), the extent of cohesion within subgroups (i.e., homophily), and how the connectivity of actors supports or constrains knowledge or resource sharing (Bodin et al. 2006). With a robust history of use, SNA is being increasingly applied in diverse scenarios to bring much-needed social dimensions into ecological and conservation research (Prell and Bodin 2011).

Along with proven applicability, our decision to apply SNA to the freshwater assessment network rests on several circumstances and assumptions. The first is that the scientific concept of assessment of freshwater ecological integrity is stringent enough to identify and examine a majority of the expertise related to this theme. Second, this body of expertise initiated in earnest with passage of the CWA, creating a point at which development of the network can be evaluated. With more than four decades of development, the network is substantial enough to offer insights into patterns of collaboration, past growth, and diagnosis of (likely) future directions. For example, in some networks, influence or power becomes concentrated over time around a relatively small number of individuals or groups (i.e., centralization); centralization may allow efficient coordination of activities by influential actors, but implies they can also act as gatekeepers (Bodin and Crona 2009). Alternatively, networks might grow—or even be fostered to grow—via more diverse collaborations that result in dense networks with low centralization and low levels of homophily (i.e., subgroup cohesion; Johnson et al. 2010).

Most importantly, SNA allowed us to examine the network for evidence of efficient knowledge exchange and strong social capital (i.e., trust, access, learning), which are theoretically and empirically linked with adaptive capacity, collective action, and sustainable management of resources. For example, in a comprehensive study of the effects of the National Estuary Program, Schneider and colleagues (2003) found that the federal program resulted in denser, more connected local networks that integrated more and diverse expertise into policy; furthermore, stakeholders in program estuaries had more positive attitudes toward cooperation and collaboration compared with nonprogram estuaries. Another study of a network of water management municipalities in Quebec, Canada, showed that municipalities were largely indirectly connected (i.e., bridging through governmental and nongovernmental organizations [NGO]), and that connected municipalities implemented more water management activities (Rathwell and Peterson 2012). These and other research have indicated the importance of sustained relationships and network structure to effective natural resource management and conservation (Tompkins and Adger 2004, Pretty and Smith 2004, Ernstson et al. 2008, Fliervoet et al. 2016). Specifically, bonding (i.e., intragroup) and bridging (i.e., intergroup) connections that promote trust, learning, and information sharing are understood to create optimal conditions for collective action (Bodin and Crona 2009).

In the context of freshwater assessment, connectivity in the form of bonding and bridging ties is likely to promote better management and conservation outcomes because of the time, sustained effort, and relationships required to develop expertise, improve and share methods and practices with others, and have them become integrated into management and policy (Roux et al. 2008). Constraints in the way that research is typically conducted (e.g., dependent on grants, on the basis of short-term collaborations) mean these types of connections may be scarce and uniquely valuable. Given the current freshwater conservation crisis, understanding the status of the network available to address these challenges can help us consider how to optimize and strengthen collaborations in the future (Cross et al. 2002, Vance-Borland and Holley 2011).

Our approach is based on evaluating patterns of shared authorship of peer-reviewed and gray literature publications to depict the strength and direction of collaborations within the network. In a research community, publication is a widespread standard for sharing work and acknowledging expertise of coauthors. Although not every person involved in a project becomes an author and individual publications may be over- or underinclusive, we believe coauthorship is indicative of substantive research collaborations that reflect underlying sharing of ideas, resources, and expertise. We acknowledge in the present article that our synthesis is mainly relevant to North America, and most specifically the United States, where the concept of ecological integrity is prominently enshrined in the CWA and other federal agency mandates (Wurtzebach and Schultz 2016).

Evaluating patterns of collaboration within the research community over time

We identified peer-reviewed and gray literature related to assessment of wetlands, lakes, streams, riparian areas, and watersheds since the passage of the CWA, following protocols outlined by Pullin and Stewart (2006) for systematic review. We applied criteria to limit an initial document pool to systematic and generalizable assessments (see the supplemental material for detailed search protocols and exclusion criteria), retaining a final data set of 111 publications, of which 24% were gray literature. Author names and

Table 1. Descriptive statistics for the individual author network drawn from 111 publications with 437 authors (i.e., nodes).						
Density	Degree (average)	Centralization	Fragmentation	Path length (average)	Components	Component ratio
.02	4.1	.06	.81	3.78	59	0.13

Note: Density is the proportion of observed ties to the total number possible. Degree is the average number of ties for all nodes. Centralization is Freeman's degree centralization, a proportion of a theoretical maximum based on the overall network size. Fragmentation is the proportion of pairs of nodes that are unreachable by any path. Path length is the average number of steps lying between any two nodes that are connected. Components are the number of distinct sets of connected nodes or isolates (i.e., actors with no coauthors). Component ratio is the ratio of the number of components to the total network size.

affiliations were extracted to create a network of individual author nodes symmetrically linked by coauthorship on publications, and a second network of publication nodes (i.e., author groups) linked by shared authors. The network of author nodes (n = 437) was classified on the basis of their organizational affiliation into one of six categories: university, federal government, state government, NGO, local government, or other (e.g., consultancy). To examine cross-ecosystem collaboration, the second network of publications or author groups was classified on the basis of the ecosystem focus of the assessment as stream, wetland, lake, riparian, watershed, or multiple (i.e., more than one type within the same assessment).

Standard network statistics were calculated to evaluate density and fragmentation of the author network; in particular, temporal trends in centralization and homophily of the network were evaluated by calculating Freeman's degree centralization (Hanneman and Riddle 2005) and the *E-I* index (Borgatti et al. 2002), respectively, for each network year. Network graphs using node repulsion were used to visualize connectivity and collaboration across organizational types and ecosystem focus. For each organizational and ecosystem category, we examined measures of centrality associated with influence (i.e., total degree and eigenvector centralities) as well as bonding and bridging strength (i.e., betweenness and eigenvector centralities; Bodin et al. 2006, Bodin and Crona 2009). We then applied contingency analysis to quantify within and between-group ties, also known as bonding and bridging ties. Contingency analysis compares observed ties across categories with an expected number of ties on the basis of multiple permutations; values less than 1 indicate stronger subgroup cohesion than would be expected in a random network (i.e., homophily), and values higher than 1 represent higher than expected rates of collaboration (i.e., heterophily). Finally, to identify and examine characteristics of highly connected nodes in the actor network, we applied core–periphery modeling, which assigns actors to a (dense) core or (unconnected) periphery (Borgatti and Everett 2000). The institutional type and organizational affiliations of actors in the core were examined. All analyses and network graphs were implemented in UCINET (Hanneman and Riddle 2005), and additional details on these methods and metrics can be found in supplemental table 2.

We addressed three key questions with respect to the state of knowledge exchange and social capital for freshwater assessment. First, what are the general characteristics of the network over time, and do these indicate tendencies toward either centralization (i.e., concentration of influence) or homophily (i.e., segregation between groups)? Second, which actors or groups provide the bonding and bridging ties needed to support and maintain knowledge transfer and social capital? Third, to what extent are actors collaborating across organizational types and ecosystems? With this knowledge, we believe it is possible to identify constraints in the network that—if removed—could help improve implementation of freshwater assessments to support positive conservation outcomes both today, and in the future.

The freshwater assessment network over time

The individual author network suggests that a diverse and widely distributed array of actors is engaged in assessing freshwater integrity, but that the network is relatively fragmented (table 1). The number of ties relative to the total number possible (i.e., network density) was very low; on average, individuals in this network coauthored with only four other individuals. Correspondingly, Freeman's degree centralization, which ranges from zero if all actors are equally connected to 1 for a network dependent on a single actor, showed that influence is not concentrated. The network has grown unevenly over time, with the fastest growth between 2004 and 2012, and relatively little growth in other periods (figure 1a). However, centralization has consistently declined over time, indicating that with few exceptions, new disconnected or weakly connected components (i.e., separate author groups) have been added more quickly than strongly connected components (figure 1a). Examining the extent to which actors tend to associate only with others in the same organizational type, we found that although the *E-I* index describing the proportion of within-group to between-group ties has been increasing slightly over time, it remains firmly fixed in the zone associated with segregated groups or homophily (figure 1b). Permutation-based testing confirmed that this internal cohesion along organizational lines ($E\text{-}I = -0.39$, $p < .05$) is significantly greater than is expected by chance.

Centrality and collaboration in the freshwater assessment network

The network graph of individual authors (distinguished by organizational affiliation) clearly exhibits a high degree

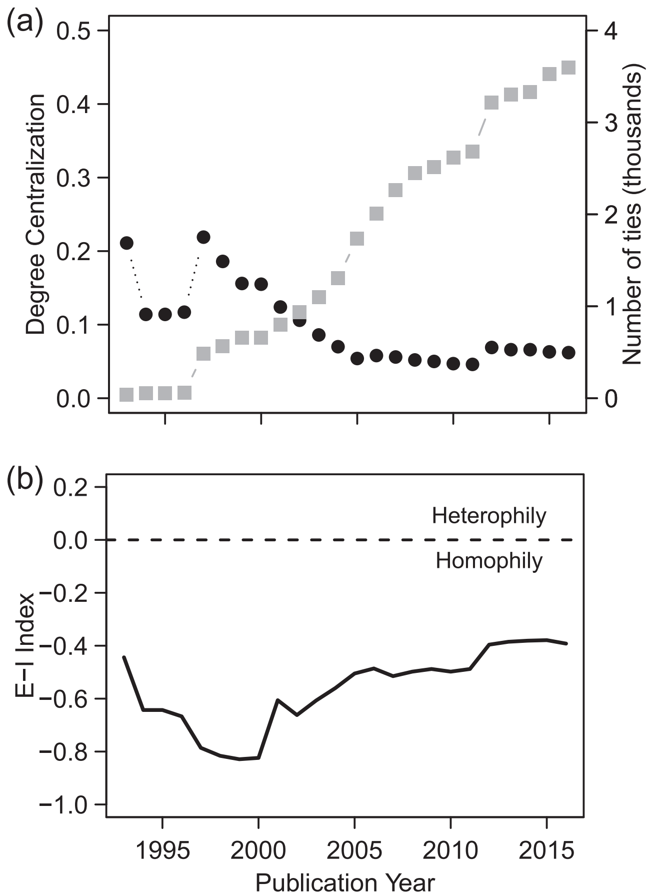


Figure 1. Temporal trend in network characteristics and cohesion within organizational subgroups from 1992 to 2016 (when the number of publications and ties were sufficient for analysis). (a) The cumulative number of ties between actors in the network (the gray squares) and Freeman's degree centralization (the black circles), which describes the concentration or centralization of power across the network as a function of article publication year, and (b) the E-I index of cohesion within organizational types over time; a value of –1 indicates complete homophily, and 1 indicates complete heterophily (the dotted line is at 0).

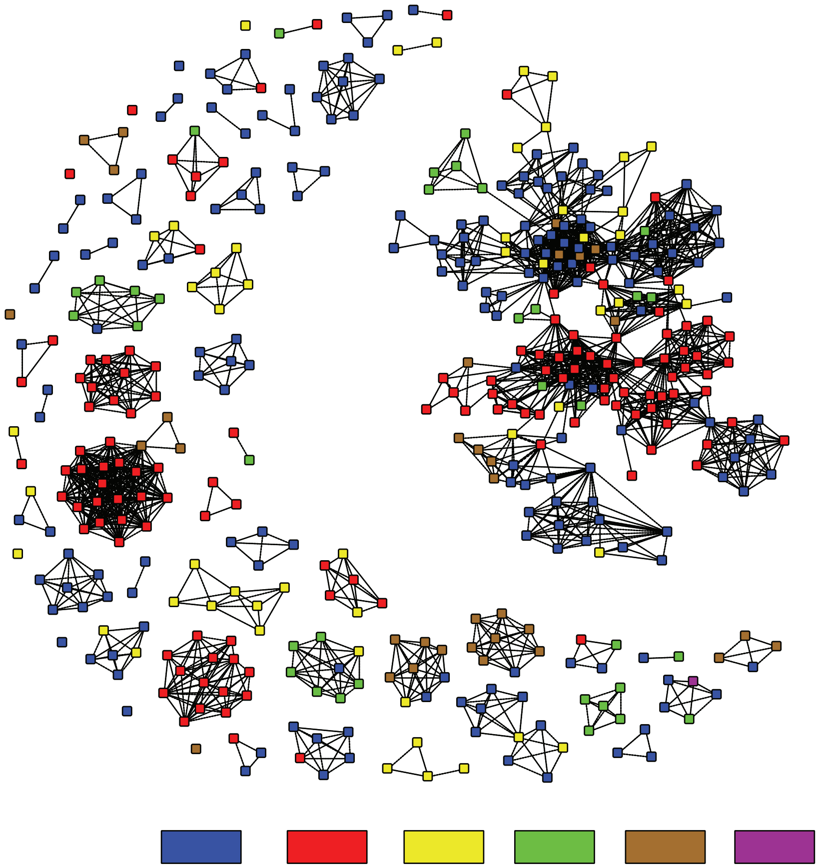
of fragmentation, with one moderately sized connected component and many disconnected components (figure 2). Many components are made up of a single organizational type, consistent with a significant and negative *E-I* index. Although still significant, a less negative *E-I* index of the largest component ($E\text{-}I = -0.25$, $p < .05$) indicates less subgroup cohesion or homophily in the main component than compared to the entire network.

On the basis of average centrality metrics for each organizational type, we found that actors in federal agencies—despite being fewer in number than university-affiliated actors—had the highest total degree, betweenness, and eigenvector centralities. Therefore, individuals affiliated with federal agencies tended to have more coauthors, were most often the shortest path between other actors, and were connected with other nodes displaying high centrality. As a whole, these high centralities suggest that federal agency actors play important roles in the network as coordinators, knowledge brokers, and by providing bonding and bridging ties (Bodin et al. 2006, Bodin and Crona 2009). Secondary importance varied between actors affiliated with NGOs, universities, and other (i.e., consultancies) organizations, depending on the specific centrality metric being measured (figure 2).

We next applied core–periphery modeling to identify and examine characteristics of those core or most densely connected actors. Not all organizational types were represented in the set of core actors, which was composed of only 24 federal (18.5% of all federal actors), 7 state (13.5%), and 11 university (6%) affiliated actors. The core network was further decomposed into specific institutional affiliations, of which fourteen were represented (figure 3). The prominence of the US Environmental Protection Agency (EPA) and the US Geological Survey in the core freshwater assessment network is expected. However, other federal agencies that are less commonly associated with freshwater assessment and conservation were also well represented, indicating the diversity of agencies with mandates and resources to help tackle freshwater assessment research. In particular, National Park Service actors were prevalent in the core network, second only to the EPA; this appears to be largely because of the work of a regional office containing a few well-connected actors that have sustained work on multiple large-scale assessments over time. The presence of some state agencies and universities in the core network also indicates important aggregations of assessment expertise in some states (e.g., California Dept. of Fish and Game) and academic institutions (e.g., Penn State University). We believe these cases are highly illustrative of the way in which assessment expertise accrues not only from recognized federal programs (e.g., the EPA) but also from the entrepreneurial efforts of local actors and research groups that are able to marshal resources and sustain commitment to assessment research over time.

When we examined connections between ecosystem-based author groups (i.e., the publication network), we found that the large majority (48%) of assessments focus on stream ecosystems, followed by wetlands, watersheds, lakes, riparian, and multiple ecosystems (figure 4). Despite this highly uneven representation, all ecosystem types appeared in the connected portion of the publication or author group network. Author groups that focused on lake ecosystems were indicated as important nodes in the network, with the highest centralities across all three metrics. Author groups in stream and wetland ecosystems were also relatively well connected on the basis of all centrality metrics, whereas groups that investigated multiple, watershed, and riparian ecosystems held more peripheral positions (figure 4).

Contingency analysis of within and between-group ties illustrated patterns of collaboration across the organizational



	University	Federal	State	Other	NGO	Local
	n=186	*n=130*	*n=52*	*n=35*	*n=33*	*n=1*
Degree	7.8	13.1	5.6	5.5	8.1	4.0
Betweenness	116.5	182.2	74.7	21.0	51.0	0.0
Eigenvector	0.33	2.65	0.20	0.47	0.10	0.00

Figure 2. Network graph with actor nodes colored as one of six organizational types; an increased line weight indicates multiple collaborations between actors. The average total degree, betweenness, and eigenvector centralities are calculated for the actors affiliated with each of the organizational types.

actor network and the ecosystem publication network (table 2). We found that organizational within-group ties were higher than expected, reflecting subgroup cohesion that is consistent with the overall negative *E-I* index (table 2a). This tendency toward within-group collaboration was fairly similar for all organizational types, although it was lowest for university and highest for state-affiliated actors (table 2a). Collaboration between different organizational types was consistently lower than expected; exceptions to this pattern (i.e., where the observed to expected ratio (O/E) approaches or exceeds 1) were university–state interactions and local–university or local–other interactions.

As with the organizational actor network, author groups working in different ecosystem types also exhibited tendencies toward ecosystem-based cohesion (table 2b). However, unlike with organizational types, higher than expected magnitudes of cross-ecosystem collaboration were also observed, particularly between lake–stream and lake–watershed groups (consistent with the higher centralities of lake author groups). Author groups working on watershed and riparian assessments had the lowest rates of both within and between-group collaborations, reflecting their low centralities in the network.

Implications of organizational and ecosystem-based fragmentation

With this synthesis, we sought to understand the state of knowledge exchange and social capital in the network of expertise related to assessment of ecological integrity for fresh waters. We examined growth of this network over time as an indication of likely future trends as well as organizational and ecosystem-based cohesion to explain patterns of collaboration (and conversely, fragmentation). It is worth reiterating that, in assuming that knowledge exchange and social capital stem largely from relationships between individuals or organizations, SNA evaluates conservation problems very differently from a traditional scientific view whereby knowledge is shared by dissemination of publications and products. However, ample evidence from the literature demonstrates that sustained relationships are a critical foundation for effective integration of research into management and conservation processes and policies.

As with any network analysis, there are individuals whose involvement or participation in the network is not captured (e.g., Fischer et al. 2014, Horning et al. 2016). A publication network based on coauthorship naturally will not include every contributor; in fact, many assessment projects explicitly acknowledge other formal and informal participants (e.g., advisory boards, individuals that provided advice or support). The true network is therefore larger, with more individuals in the periphery, and has some additional bridging and bonding ties that are not captured in the present article. However, we believe this is more an issue of scale than pattern, and that the publication network represents and illustrates the overall trends in intra- and interorganization and ecosystem-based collaboration.

We found that the network of actors with expertise in freshwater assessment is highly fragmented, and there is little indication that centralization is increasing with time. This is an important finding as it reflects that disconnected or weakly connected components are consistently added more quickly than strongly connected components,

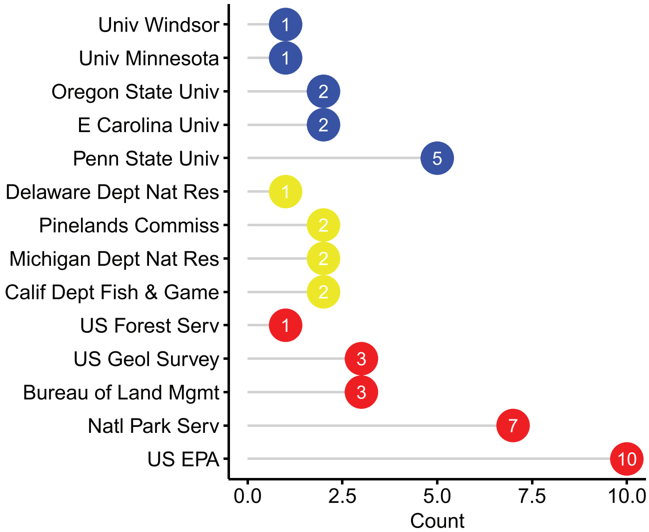


Figure 3. The number of actors affiliated with each of the fourteen agencies or institutions identified as part of the core network (n = 42 actors) on the basis of core–periphery modeling in UCINET.

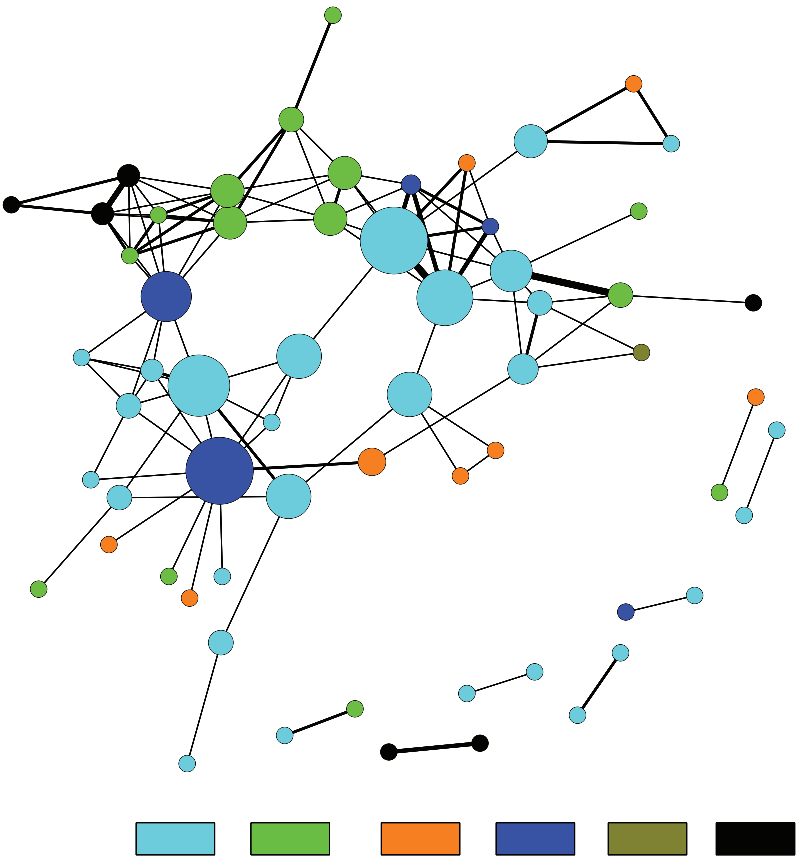
suggesting an emphasis on diversification and innovation, rather than learning and building a strong history of linked expertise (Bodin et al. 2006). Although innovation is a natural (and desired) feature in research communities, as a dominant trend it may not lead to improved management relevance and a better integration of science into freshwater policy (Roux et al. 2008). We also found that cohesion around organizational types appeared to be a persistent feature of the network, with only slight indications that collaboration across these boundaries is increasing over time.

Despite overall fragmentation, we found encouraging signs of cross-ecosystem exchanges when examining the network of author groups. Interestingly, the small number of author groups that focused on lake ecosystems (only 5% of all publications) was especially influential and provided important bridging (i.e., between group) as well as bonding (i.e., within-group) ties. This can partly be attributed to a high proportion (5 of 6 lake assessments) being in the connected portion of the network. However, more broadly, we believe this is because of the fact that lakes are assessed relatively infrequently compared to other ecosystem types, and are also considered to integrate watershed and stream health; professionals that assess lakes likely tend to develop expertise in these other areas as well. Author groups working in streams and wetlands are also associated with higher rates of bonding and bridging ties than those working in watershed, riparian, and multiple ecosystem assessments.

Within networks, subgroup cohesion may facilitate efficient development of specialized expertise (Bodin and Crona 2009). Despite the goal of providing protection in a unified way under the CWA (i.e., the nation's waters), regulatory pathways for protection and restoration differ on the basis of the type of freshwater ecosystem. For example, although monitoring of streams and lakes is typically linked with controlling pollutants for water *quality*, protection of wetland habitat loss is determined by an assessment of *function* (Hauer and Smith 1998, Copeland 1999). Depending on the region, riparian areas may be protected as wetlands under the CWA, under state or regional policies and regulations (e.g., Northwest Forest Plan, Chesapeake Bay Critical Area Act), or may be largely unprotected (Brinson et al. 2002). Despite justification for ecosystem-based cohesion, there are still benefits to be gained from cross-ecosystem exchange, including efficiency (i.e., not reinventing the wheel), sharing effective assessment methodologies, and enhancing outreach and implementation practices. Our results do suggest some potential opportunities to improve bridging ties. Rates of collaboration with riparian and watershed author groups (i.e., typically emphasizing indicators on the basis of remotely sensed landscape factors) indicate stronger barriers to collaboration compared to their counterparts working in lake, stream, and wetland ecosystems. These barriers may be caused by legitimate divisions, such as the specificity of suitable indicators (Dale and Beyeler 2001) or differences in the way these assessments are used and applied (Tulloch et al. 2015). However, segregation may also spring from challenges in bridging expertise (e.g., incorporating remote sensing with more traditional approaches; Gergel et al. 2002, Dauwalter et al. 2017), and historical aquatic–terrestrial divisions (Fausch et al. 2002, Soininen et al. 2015). We recommend closer examination of the riparian and watershed ecosystem subgroups for opportunities to improve knowledge exchange and social capital.

We find less justification for the observed cohesion within organizational types. Indeed, the fact that the CWA is a federal law enacted largely through state and local jurisdictions suggests an urgent need for communication, collaboration, and planning across those sectors (Scholz and Wang 2006, Roux et al. 2008). Similarly, although NGOs rarely play a direct role in management of natural resources, they can be a powerful force for advocacy and policy reform. Finally, freshwater resources often cross multiple jurisdictions, which should also promote higher rates of cross-sector collaboration (e.g., Angradi et al. 2009, Stein et al. 2009). Instead, our results suggest that the majority of freshwater assessment research activity is accomplished by actors within single organizational types. It is worth noting, however, that university-affiliated actors showed the greatest tendency to break with this trend, as was reflected by relatively high between-group O/Es in the contingency analysis and the lowest within-group O/E (table 2a).

We believe our evidence of organizational homophily—though perhaps improving slowly with time—reflects persistent constraints in research collaborations. These constraints are likely to begin from the outset of projects, which may be through agency program funding (usually limited to that agency's use) or through application for project funding. Collaboration on funding proposals can be difficult, both



	Stream n=48	Wetland n=28	Watershed n=14	Lake n=6	Riparian n=4	Multiple n=11
Degree	2.02	2.11	1.00	5.50	0.50	1.73
Betweenness	34.06	15.76	4.71	76.32	0.00	4.09
Eigenvector	0.025	0.071	0.008	0.108	0.003	0.061

Figure 4. Network graph with publication (i.e., author group) nodes colored according to the ecosystem focus of the assessment; 49 author groups that were unconnected (i.e., isolates) have been removed to improve clarity. The nodes are sized by their betweenness centrality, and an increased line weight indicates multiple ties between author groups. The average total degree, betweenness, and eigenvector centralities are calculated for the publication nodes affiliated with each of the ecosystem types.

policy have emphasized the importance of social processes to build communication pathways and trust (Roux et al. 2008, Gibbons et al. 2008). Conscious efforts to increase substantive cross-sector collaborations could be a realistic interim goal toward improving management relevance and application of freshwater ecosystem assessments.

Social capital and the future of freshwater assessment, protection and restoration

More than four decades since its passage, the CWA is an evolving piece of legislation (Adler 2013, Doremus and Tarlock 2013). Even the definition of the foundational phrase "the Nation's waters" is still under bitter dispute in legal and regulatory contexts (Adler 2015, Colvin et al. 2019). Similarly, although assessment methods have indeed progressed, new methodological possibilities and challenges will continue to arise and require evaluation for their potential to improve (or derail) assessment of ecological integrity (Kuehne et al. 2017). When we consider the CWA as a strong but evolving protection for fresh waters, the urgency for participation and coordinated input of experts becomes increasingly apparent. Our results suggest that the network, which is characterized by a high degree of fragmentation, is not optimally positioned for collective action to meet these challenges.

However, a major strength of a network analytic approach is being able to differentiate overall activity (of actors or groups) from those actors that connect and sustain the larger body of expertise.

in having to share scarce funding among added partners and even practical problems in moving funding between organizations. For workers in agencies and NGOs, ability to lend substantial time or expertise to projects outside a strict mandate can be challenging even assuming adequate funding. Finally, collaborations are simply easier within a single organization or research group, in which actors are likely to have existing relationships and share goals, resources, and even customs (Lachapelle et al. 2003). Despite these very real issues, our findings reveal that the status quo has resulted in a somewhat bleak outlook for development of the diverse, connected network of expertise that is urgently needed to protect freshwater ecosystems and biodiversity (Strayer and Dudgeon 2010). Prior evaluations of ways to improve integration of research into management and

Actors with high centralities tend to participate in more relationships and connect more actors, thereby facilitating knowledge transfer and resource sharing (Bodin and Crona 2009). Despite the numerical dominance of university-affiliated actors in the network, we found that actors associated with federal agencies had the highest centralities, exhibited similar (or higher) rates of cross-sector collaborations, and formed the majority of actors in the core network. Depending on the centrality metric being considered, actors in state agencies, NGOs, and consultancies had comparable importance as university and federal actors. Despite low numerical representation, state agency actors composed nearly as large a component of the core network as university actors. In the freshwater assessment arena, these results may reflect the relative stability of federal, state, and even NGO

Table 2a. Observed and expected (O/E) ties within (gray shading) and between (no shading) subgroups of actors affiliated with different organizational types.

	University	Federal	NGO	Other	State	Local
University	1.46	0.41	0.43	0.32	0.84	0.85
Federal		3.87	0.29	0.37	0.46	0
NGO			2.48	0.44	0.56	0
Other				4.63	0.09	1.51
State					5.22	0
Local						n/a

Note: The values of O/E are based on permutation-based contingency analysis in which values below 1 indicate lower than expected rates of collaboration and values above 1 indicate higher than expected rates of collaboration. “n/a” is used where the numbers of ties were too few for analysis.

Table 2b. Observed and expected (O/E) ties within (gray shading) and between (no shading) subgroups of author groups working in different ecosystem types.

	Stream	Lake	Multiple	Wetland	Watershed	Riparian
Stream	1.45	3.41	0.00	0.41	0.57	0.57
Lake		3.63	1.65	2.27	2.60	0.00
Multiple			3.96	1.59	0.00	0.00
Wetland				2.31	0.14	0.00
Watershed					0.60	0.00
Riparian						0.00

Note: The values of O/E are based on permutation-based contingency analysis in which values below 1 indicate lower than expected rates of collaboration and values above 1 indicate higher than expected rates of collaboration.

and consulting groups, which allow for consistent emphasis on assessment, development and sharing of expertise over time, and relationship building. Our results do not dismiss the importance of university-affiliated actors, but simply suggest that these are not the most prevalent source of bonding and bridging capital.

The critical role of government agencies in linking the freshwater assessment network is one of the most important implications of this work. Despite a perception that the primary role of government is regulation and enforcement, our analysis suggests a unique capacity for government agencies to provide long-term bonding and bridging functions that support knowledge transfer and social capital of the larger network. We believe that this results from the relative stability of federal and state institutions, which includes not only access to programmatic funding, but technical resources (e.g., data and website infrastructure) and staff with ability to support long-term processes. Indeed, from their work on improving cross-sector collaborations, Roux and colleagues (2008) specifically noted that the short-term nature of most applied research and policy work did not allow for the development of the social processes that led to integration of science into management policies.

Our results are also consistent with other analyses that have specifically examined the contribution of federal agencies to natural resource governance, finding similarly central roles in connecting diverse stakeholders, facilitating knowledge exchange, and supporting development of local networks (Schneider et al. 2003, Fischer et al. 2016, Fliervoet et al. 2016). However, these and other research efforts have also noted the dilemmas that arise when networks have to rely on central actors or institutions, which can include restriction of creativity (Roux et al. 2008), gate keeping (Bodin and Crona 2009), or vulnerability to increased fragmentation if those actors are lost (Fliervoet et al. 2016). This may be particularly true for state and federal agencies, that are subject to political pressure to alter priorities as well as the threat of having programs cut or being periodically shuttered (Thompson 2005). The recent extended federal government shutdown is a vibrant reminder of the way in which that role is vulnerable to public opinion, economic factors, and political climate.

Even with these constraints, we recommend that recognizing and capitalizing on the central roles that government (and other nonacademic) institutions can play offers the most effective means to help bolster local networks and build connectivity of the network as a whole (Schneider et al. 2003). Our work indicates that this may be possible, in that clusters of regionally focused expertise (e.g., state and some universities) have arisen over time, and seem to be strengthened by their connections with national or federal institutions. These clusters of expertise appear to arise primarily from the entrepreneurial efforts of actors and research groups that manage to develop and maintain cross-sector and cross-jurisdictional relationships, and then use these to help sustain their work over time. We recommend that a focus on continuing to build and maintain these types of national–regional collaborations will help improve the long-term capacities for knowledge exchange and social capital in freshwater assessment, management, and conservation.

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Supplemental material

Supplemental data are available at *BIOSCI* online.

References cited

Adler RW. 2013. The decline and (possible) renewal of aspiration in the Clean Water Act. Washington Law Review 88: 759.

Adler RW. 2015. US Environmental Protection Agency's new Waters of the United States rule: Connecting law and science. Freshwater Science 34: 1595–1600.

Angradi TR, et al. 2009. A bioassessment approach for mid-continent great rivers: The Upper Mississippi, Missouri, and Ohio (USA). Environmental Monitoring and Assessment 152: 425–442.

Bodin Ö, Crona B, Ernstson H. 2006. Social networks in natural resource management: What is there to learn from a structural perspective? Ecology and Society 11: 2.

Bodin Ö, Crona BI. 2009. The role of social networks in natural resource governance: What relational patterns make a difference? Global Environmental Change 19: 366–374.

Borgatti SP, Everett MG. 2000. Models of core/periphery structures. Social Networks 21: 375–395.

Borgatti SP, Everett MG, Freeman LC. 2002. UCINET for Windows: Software for Social Network Analysis. Analytic Tecnologies.

Borgatti SP, Mehra A, Brass DJ, Labianca G. 2009. Network analysis in the social sciences. Science 323: 892–895.

Brinson MM, et al. 2002. Riparian Areas: Functions and Strategies for Management. National Academy of Sciences.

Colvin SA, Sullivan SMP, Shirey PD, Colvin RW, Winemiller KO, Hughes RM, Fausch KD, Infante DM, Olden JD, Bestgen KR. 2019. Headwater streams and wetlands are critical for sustaining fish, fisheries, and ecosystem services. Fisheries 44: 73–91.

Copeland C. 1999. Clean Water Act: A Summary of the Law. Library of Congress.

Cross R, Borgatti SP, Parker A. 2002. Making invisible work visible: Using social network analysis to support strategic collaboration. California Management Review 44: 25–46.

Dale VH, Beyeler SC. 2001. Challenges in the development and use of ecological indicators. Ecological Indicators 1: 3–10.

Dauwalter DC, Fesenmyer KA, Bjork R, Leasure DR, Wenger SJ. 2017. Satellite and airborne remote sensing applications for freshwater fisheries. Fisheries 42: 526–537.

Doremus H, Tarlock AD. 2013. Can the Clean Water Act succeed as an ecosystem protection law? George Washington Journal of Energy and Environmental Law 4: 46.

Ernstson H, Sörlin S, Elmqvist T. 2008. Social movements and ecosystem services: The role of social network structure in protecting and managing urban green areas in Stockholm. Ecology and Society 13: 39.

Fausch KD, Torgersen CE, Baxter CV, Li HW. 2002. Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes. BioScience 52: 483.

Fischer AP, Vance-Borland K, Burnett KM, Hummel S, Creighton JH, Johnson SL, Jasny L. 2014. Does the social capital in networks of "Fish and Fire" scientists and managers suggest learning? Society and Natural Resources 27: 671–688.

Fischer AP, Vance-Borland K, Jasny L, Grimm KE, Charnley S. 2016. A network approach to assessing social capacity for landscape planning: The case of fire-prone forests in Oregon, USA. Landscape and Urban Planning 147: 18–27.

Fliervoet JM, Geerling GW, Mostert E, Smits AJM. 2016. Analyzing collaborative governance through social network analysis: A case study of river management along the Waal River in the Netherlands. Environmental Management 57: 355–367.

Gergel SE, Turner MG, Miller JR, Melack JM, Stanley EH. 2002. Landscape indicators of human impacts to riverine systems. Aquatic Sciences 64: 118–128.

Gibbons P, et al. 2008. Some practical suggestions for improving engagement between researchers and policy-makers in natural resource management. Ecological Management and Restoration 9: 182–186.

Hanneman RA, Riddle M. 2005. Introduction to Social Network Methods. University of California, Riverside.

Hauer FR, Smith RD. 1998. The hydrogeomorphic approach to functional assessment of riparian wetlands: Evaluating impacts and mitigation on river floodplains in the USA. Freshwater Biology 40: 517–530.

Horning D, Bauer BO, Cohen SJ. 2016. Missing bridges: Social network (dis) connectivity in water governance. Utilities Policy 43: 59–70.

Johnson JC, Christian RR, Brunt JW, Hickman CR, Waide RB. 2010. Evolution of collaboration within the US long term ecological research network. BioScience 60: 931–940.

Kuehne LM, Olden JD, Strecker AL, Lawler JJ, Theobald DM. 2017. Past, present, and future of ecological integrity assessments. Frontiers in Ecology and the Environment 15: 197–205.

Lachapelle PR, McCool SF, Patterson ME. 2003. Barriers to effective natural resource planning in a "messy" world. Society and Natural Resources 16: 473–490.

Prell C, Bodin Ö, editors. 2011. Social Networks and Natural Resource Management: Uncovering the Social Fabric of Environmental Governance. Cambridge University Press.

Pretty J, Smith D. 2004. Social capital in biodiversity conservation and management. Conservation Biology 18: 631–638.

Pullin AS, Stewart GB. 2006. Guidelines for systematic review in conservation and environmental management. Conservation Biology 20: 1647–1656.

Rathwell KJ, Peterson GD. 2012. Connecting social networks with ecosystem services for watershed governance: A social ecological network perspective highlights the critical role of bridging organizations. Ecology and Society 17: 24.

Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PT, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ. 2018. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biological Reviews 94: 849–873.

Roux DJ, Ashton PJ, Nel JL, MacKay HM. 2008. Improving cross-sector policy integration and cooperation in support of freshwater conservation. Conservation Biology 22: 1382–1387.

Schneider M, Scholz J, Lubell M, Mindruta D, Edwardsen M. 2003. Building consensual institutions: Networks and the National Estuary Program. American Journal of Political Science 47: 143–158.

Scholz JT, Wang C-L. 2006. Cooptation or transformation? Local policy networks and federal regulatory enforcement. American Journal of Political Science 50: 81–97.

Soininen J, Bartels PIA, Heino J, Luoto M, Hillebrand H. 2015. Toward more integrated ecosystem research in aquatic and terrestrial environments. BioScience 65: 174–182.

Stein ED, Fetscher AE, Clark RP, Wiskind A, Grenier JL, Sutula M, Collins JN, Grosso C. 2009. Validation of a wetland rapid assessment method: Use of EPA's level 1-2-3 framework for method testing and refinement. Wetlands 29: 648–665.

Strayer DL, Dudgeon D. 2010. Freshwater biodiversity conservation: Recent progress and future challenges. Journal of the North American Benthological Society 29: 344–358.

Thompson Jr BH. 2005. Conservative environmental thought: The Bush administration and environmental policy. Ecology LQ 32: 307.

Tompkins EL, Adger WN. 2004. Does adaptive management of natural resources enhance resilience to climate change? Ecology and Society 9: 10.

Tulloch VJ, et al. 2015. Why do we map threats? Linking threat mapping with actions to make better conservation decisions. Frontiers in Ecology and the Environment 13: 91–99.

Vance-Borland K, Holley J. 2011. Conservation stakeholder network mapping, analysis, and weaving. Conservation Letters 4: 278–288.

Wurtzebach Z, Schultz C. 2016. Measuring ecological integrity: History, practical applications, and research opportunities. BioScience 66: 446–457.

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