Teams, Networks, and Networks of Networks Advancing Our Understanding and Conservation of Inland Waters*

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Glossary

Hydrologic network Interconnected bodies of water, waterways, and stores of water that comprise the hydrologic cycle.
Network of networks A collection of two or more unique networks, each defined by social, geographic, and temporal boundaries and distinct types of connections (e.g., governance, data gathering, information sharing).
Network A group or system of interconnected people or things (adapted from Oxford Language).
Science of team science The study of the processes by which science teams form, behave, communicate, and carry out scientific research.
Social network analysis Mathematical methods used to characterize the structure of networks in terms of edges (connections) and nodes (social actors such as individuals or organizations).
Social network The self-organizing webs of social actors (individuals, groups, or formal organizations) and the relational connections that bind them. In this article, social (human) networks are defined as groups with 12 or more people. Used interchangeably with "network."
Team science Science that is conducted in a collaborative, interdependent manner among individuals with a wide range of backgrounds, skills, and expertise.
Team A group of 3–11 people who interact and influence each other, are mutually accountable for achieving common goals, and perceive themselves as a social entity (adapted from McShane and Von Glinow, 2010).

Introduction and aim

As scientists across the world are working together to answer complex biological and ecological questions, they are forming larger and larger teams. Often, *teams* and *networks* are used interchangeably, but they are fundamentally unique ideas. Distinguishing between the two can help us understand how to improve the performance of increasingly large and complex scientific efforts. In ecological sciences, networks are used to describe more than large teams: a network is "a group or system of interconnected people or things" (Oxford Language Network, 2021). By this definition, inland waters research, management, and conservation is inherently network-based (Fig. 1), from waterways themselves, to the teams of scientists conducting research, to the policies governing water management. Streams, lakes, wetlands, and groundwater are connected by a network of flowing water as *hydrologic networks*. Human-built infrastructure including drinking water distribution, sewerages, and stormwater management are connected via networks of engineered structures and built infrastructure. Human (social) networks monitor, research, and manage the infrastructure and hydrologic networks. And finally, governance of watersheds, municipalities, states, and nations affect the management function of each of the prior networks (and vice versa).

Consider the Great Lakes basin as a specific example of the network-based aspect of inland waters. Lakes Superior, Michigan, Huron, Erie, and Ontario are connected by a series of waterways including Saint Mary's River, Straits of Mackinac, Niagara River, etc. Built infrastructure such as locks, canals, and water diversions and returns for human use, are distributed across the watershed. Teams at institutions such as Michigan Technological University or the National Oceanic and Atmospheric Administration monitor and research the Great Lakes and connected waterways, and share information through networks such as the Great Lakes Observing System (www.glos.us). Management of the lakes is governed by policy set at the regional, national, or sometimes inter-governmental level. From hydrology to governance, the Great Lakes basin is made up of interacting networks.

Inland waters are inherently *networked*—and the human groups that research and manage them likewise reflect the same network structure. Therefore, these human networks have a particular opportunity to benefit from the understanding of social networks in human collaboration to achieve a goal. Understanding the effective functioning of teams and networks in inland water science will enable the more effective flow of information, resources, coordination, and knowledge creation necessary to address increasingly complex water resources challenges. This article explores the role of teams, networks, and networks of networks in the science of inland waters. Definitions and methods for the development and evaluation of these entities are provided. Case studies from inland waters science are used to illustrate real-world application.

This article sets out to address how to build and maintain *human* networks that can facilitate effective connections between people, knowledge, and data. In recent years, the evidence-based design of collaborative networks and teams in ecological science has increased (Cheruvelil and Soranno, 2018), and the potential effect of this on inland waters is especially great because of the highly networked aspect of inland waters research, management, and conservation. This knowledge must be leveraged to achieve research aims and advancements that would be impossible without crossing disciplinary and institutional boundaries (Fagan et al., 2018).

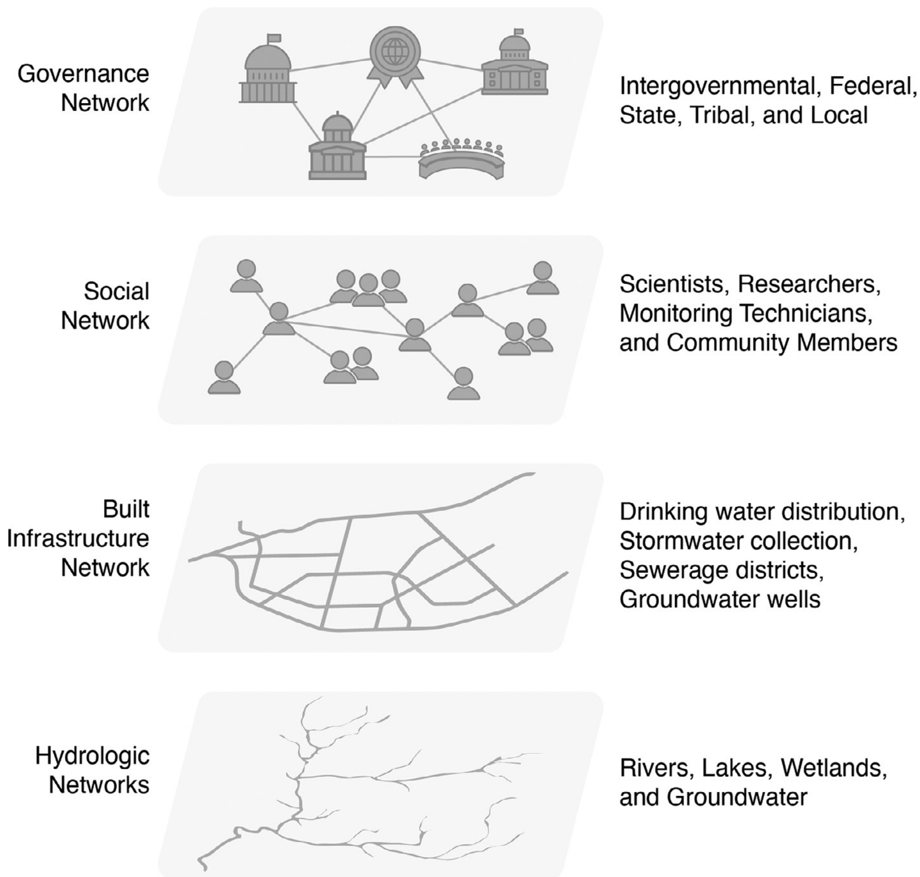


Fig. 1 Network aspects of water, built infrastructure, human (social) networks, and governance networks that relate to them.

The basics of teams, networks, and networks of networks

Before a discussion of the formation, maintenance, and attributes of teams, networks, and networks of networks, it is useful to briefly define these entities and the relationships between them.

Readers will be familiar with the concept of a *team*: a group of people who interact and influence each other, are mutually accountable for achieving common goals, and perceive themselves as a social entity (adapted from McShane and Von Glinow, 2010). In this article, a team is defined as a group of more than 2 and less than approximately 12 people (Box 1). Teams have long been used in the pursuit of science. The *science of team science*-the study of how science teams form and operate-has come out of two primary fields: organizational psychology and translational medicine. The science of team science has been an area of investment and active research since the late 1990s (Stokols et al., 2008; Hall et al., 2018). Although theories and knowledge of teams have developed in parallel in these fields, they agree on this: trust, communication, data and resource sharing, accountability, and cooperation are essential to reaching shared goals.

This article considers networks generally (e.g., interconnected waterways or coordinated data collection systems), but focuses most on *social networks,* within which humans or organizations are connected. Social networks are the self-organizing webs of social actors (individuals, groups, or formal organizations) and the relational connections that bind them. Although the structure of social networks has long been studied by the fields of anthropology and sociology, recent advances in computing have made it possible to study complex social networks in increasing detail and led to the development of more specialized sub-fields and breadth of fields using network analytic methods. Network analysis can be used to measure the formation, structure, performance, and resilience of networks of networks through time (Wang, 2016; Hall et al., 2018).

In practice, entire networks can make connections with other networks by forming new and beneficial connections between individuals across networks. This results in a network of networks, or a collection of two or more unique networks, each defined by social, geographic, and temporal boundaries and distinct types of connections.

Hereafter, teams, networks, and networks of networks are considered entities along a continuum of size (number of individual actors) and structural complexity (connections relating individuals). The value of the relationships between people is determined by the alignment of the connections with the objectives of the team, network, or network of networks.

Teams

What is a team?

Many drivers of change in inland waters-climate warming, pollution, hydrologic modification, and restoration-are large, complex, and interconnected; thus, responding to these changes requires broad interdisciplinary expertise. At the same time, advances in technology and data collection, compilation, and harmonization have given us more information about water than ever before (Cheruvelil and Soranno, 2018). These facts have contributed to the rise of *team science* in limnology-science that is conducted in a collaborative, interdependent manner among individuals with a wide range of backgrounds, skills, and expertise.

The potential for transformative science is maximized in research teams where individuals from different domains integrate their collective knowledge into new ideas and methods that go beyond those of an individual discipline (Stokols et al., 2008). The need for innovation across disciplines and the rise in team science is reflected by the increased funding of multi-principal investigator proposals for centers and research that are inter- or trans-disciplinary (National Science Foundation, 2013).

Sharing and integrating information across disciplines requires an environment of learning, and openness to learning requires trust (Tebes et al., 2014; Salazar et al., 2012). Successful and sustainable teams, therefore, are those teams that foster psychological safety–the shared belief among team members that interpersonal risk (e.g., proposing novel or risky ideas, asking clarifying questions, expressing lack of knowledge) will not come at a price (Edmondson, 1999). Psychological safety and trust are essential for team members to maintain the ability to interact and influence one another, to practice accountability, and to feel a part of a social entity.

Defining a successful scientific team is somewhat elusive, as the number of publications or citations are not holistic measures of success; success includes the effects on *science* and the *individual.* Morale and commitment to the team are additional ways to measure success; team members with high morale are committed to the cause and willing to do the work necessary for successful outcomes (He, 2012). Below are suggestions for how to foster these characteristics in your own science teams.

Methods for effective teams

Trust is the foundation of successful social connections (i.e., human relationships) that foster creativity, information exchange, and scientific advancements. Teams can intentionally build trust over time by creating shared experiences and by offering training in the interpersonal skills required to create positive relationships. Hierarchical relationships are inherent in many science teams, but activities that foster empathy or demonstrate diverse abilities and communication styles can build psychological safety among members with different amounts of power.

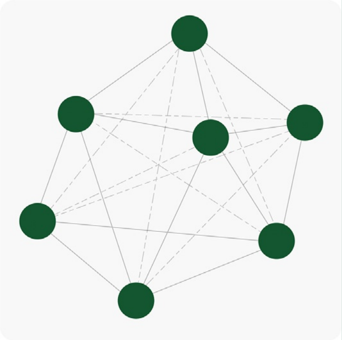
The ability of teams to perform a variety of tasks is not related to the maximum or mean individual intelligence, but rather on features like social intelligence (Woolley et al., 2010). Emotional intelligence or social sensitivity can be built through open discussions and recognition of differences in personalities, philosophies, backgrounds (Cheruvelil et al., 2014), and by practicing

Box 1 What differentiates a team from a network?

Everything from a tight-knit group of five scientists to a large, multi-institutional collaboration with hundreds of contributors might be called either a "team" or a "network." We want to distinguish between the two terms and focus our discussion on how viewing large teams as networks can help improve their management and development. All teams can be characterized as a network, but many networks are not teams because they may or may not be striving for a common goal, may not have a shared identity, and the boundaries of membership are less clearly defined. Because of a diversity of meanings and cultural context for the terms "team" and "network," it is important to technically define and distinguish between a team and a network.

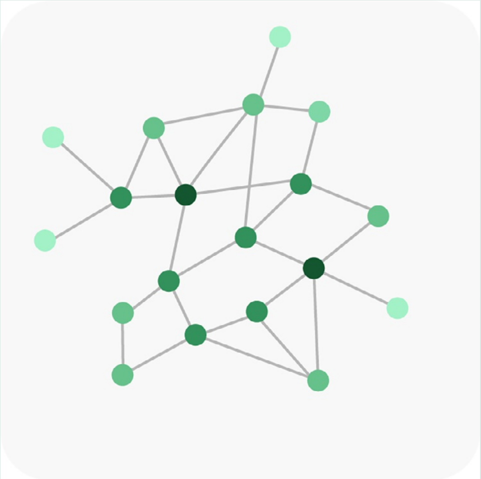
Small groups, something less than 12 people, have the advantage of being able to more easily keep all members engaged, maintain communication between all members, and create clear roles and responsibilities for members.

Small work groups (teams) have the maximum number of connections per actor. Every actor has a connection to all other actors. This makes them unique networks because all nodes connect directly to each other.



The ideal size for a work team is 5–7 people because as teams get larger, they require more complex coordination and are more likely to become less productive because of social loafing (Forsyth, 2009). As small groups grow, dynamics begin to shift, and once teams get beyond 5–7, they often break into sub-teams of 3–6 members. As teams grow beyond half a dozen or so, they start to display new patterns, where members begin to work more closely with some members than others, have less frequent communication with the entire group, and have more complex work plans. It is at this stage that the concept of a network and the application of social network analysis to understand structure and function become useful.

Larger work groups (networks) have variation in the number of connections per actor. Actors have connections with one to five other actors. Darker shaded nodes indicates higher degree (number of connections with other nodes).



As the complexity of inland waters science grows, so too does the size and complexity of the groups needed to address them. With greater group size, network patterns begin to appear. In the networks that take on complex projects, much of the actual work tends to get accomplished in smaller work groups (or teams). Even though the social entity is a large network, the work group is likely to be a small team of 3–6 people where all members know each other, interact frequently, and have a well-defined scope of work in which each member has clear roles and responsibilities. The team or work group is a building block of the larger network structure.

Although the threshold at which a group transitions from a team to a network will vary, in this article a specific threshold is given. We distinguish and define *teams as groups of fewer than approximately 12 people and networks as groups of approximately 12 or more people* because increasing group size reduces the ability of individual members to interact with, influence, and hold accountable every other member, and to perceive belonging to the group.

reflexivity through sharing personal experiences and perceptions (Read et al., 2016). Allowing time to build personal connections and interpersonal skills will motivate commitment to the team and foster trust that all members are working toward the success of the team.

Box 2 Social network analysis.

Social network analysis uses mathematical methods to characterize the structure of networks in terms of edges (connections) and nodes (social actors, such as individuals or organizations). Network analysis is also referred to as graph theory (Wasserman and Faust, 1994).

A group of any size greater than three can be analyzed according to the methods below; however, we make a case in this article that more meaningful distinctions in network structure begin to appear when the number of actors in the group exceeds approximately 12.

Average Degree: In any network, degree is the number of edges (connections) that exist for a node (actor). The average degree describes the network as the average number of edges per node, or connections per actor, in the network. Higher levels of average degree are associated with more robust networks (Martin and Niemeyer, 2020).

Centralization: Networks that have a few actors with very high degree (many connections), while most of the network has actors with low degree (few connections), are described as having high centralization. These types of network graphs have a star-like structural pattern.

Closure: One common trait of networks is whether, in any triad, all three possible connections exist (a closed triad). Closure measures the proportion of all closed triads present as compared to all potential closed triads.

Degree Distribution: The degree distribution refers to whether connections among actors are evenly spread across actors in the full network, or whether some actors have very high degree (many connections) while others have very low degree (few connections).

Density: The proportion of connections that exist in a network to all possible connections that could theoretically exist. Smaller networks generally have higher density than larger networks.

Reciprocity: The likelihood of mutuality, or bi-directional, positive actions within a social network. When positive actions occur in both directions between two actors. Reciprocity is an important factor in building and strengthening sustained social connections.

Although diversity in the experiences and information each member brings to the team can foster creativity and interactions among group members that boost team performance (Hoever et al., 2012), diversity in values can create conflict and division of team members that creates an environment of distrust and low team performance (Jehn et al., 1999). Successful teams are both diverse and socially sensitive enough to manage their own diversity. Consider and make efforts to balance diversity in career stage, member incumbency (60–70% incumbent), domain expertise (>1 person per domain), communication mode, and viewpoints (Cheruvelil et al., 2014).

To feel invested in a team, members must have a shared understanding of team purpose and goals, and how they directly contribute to success (Bennett et al., 2018). Successful execution of science by a team depends on clear roles and responsibilities, management of tasks, and a means of accountability. The approaches used to manage and accomplish work can vary greatly within and across disciplines and cultures, and guidance for collaborative scientific management approaches have been defined (e.g., collaborative manuscript management sensu Oliver et al., 2018). The management approach selected will in turn influence how roles and responsibilities are assigned and tracked, which is essential for an accountability.

Effective communication allows the sharing and building of knowledge and trust, but can be difficult to establish and maintain, especially in new teams. Establishing communication includes establishing group norms (e.g., taking turns in group discussion and normalizing disagreement); effective meeting logistics that support all members seeing and hearing one another clearly; and the use of break-out groups to increase participation and engagement. Effective communication also includes having difficult discussions, and which can be enhanced by practicing skills related to recognizing and managing conflict (Read et al., 2016). The combination of shared expectations, optimizing the meeting logistics, and training in facilitation or conflict resolution all support effective communication and increase the likelihood of success of science teams.

Team science in inland water research

The need for team science in inland waters research is becoming more prevalent given an increasing number of disparate data sources, expanding spatial and temporal scales of interest, and new cross-scale and cross-system integrative approaches. Likewise, team science as an explicit research focus within limnology is also growing increasingly common.

Within the lake-centric part of limnology, the science of team science is being practiced and contributed to through graduate student training programs (Read et al., 2016), collaborative approaches to scientific writing (Oliver et al., 2018), the formation and maintenance of high performing science teams (Cheruvelil et al., 2014); recommendations around scientific reward structures (Goring et al., 2014); and around data collection and macrosystems ecology (Soranno et al., 2015).

Within river and wetland research, team science is less prevalent. However, new collaboratives around data sharing, such as a global network of intermittent rivers, have made mention of the importance of team science for accomplishing their goals (Datry et al., 2016). What is evident is that inland water research is moving into an era of being purposeful about the formation of these teams.

Team case study: Projections of climate change effects on Lake Tanganyika (CLEAT)

CLEAT is a transdisciplinary collaborative team with a goal of understanding how climate affects the East African Lake Tanganyika, the fisheries sector, and to make projections and recommendations for long-term sustainability. The project was funded through the Ministry of Foreign Affairs of Denmark. An initial team was formed for the proposal, but the team configuration and membership evolved through time, which proved both a strength and a challenge to accomplishing project goals. A major challenge was bringing people together from different cultures, most of whom had not worked together, nor on this lake, before.

Structure of the team: *International, multicultural, medium*
- 13 individual members from three countries.
- Small core leadership team of three people.
- 23% early career scientists.
- Limnologists, modelers, fisheries consultant, social scientists.

Rules of the team: *Collaborative, transdisciplinary science*
- Leadership provided by small core of senior scientists.
- The scientific challenges and unique location motivated team participation.
- Project policies were collaboratively developed early and emphasized values, outlined authorship expectations, and had guidelines for data sharing.
- Emphasis was on building community through inclusiveness, communication, flexibility, and transparency.
- Entire team in-person meeting and social activities were important for building trust and social connections at the beginning of the project.

Outcomes of the team: *Publications, new fisheries policies*
- Multiple scientific publications.
- International media coverage of project.
- Engagement with policy makers and local organizations; additional non-project scientists and graduate students became involved directly or with related projects.

Networks

What is a (social) network?

A social network is a self-organizing web of social actors (individuals, groups, or formal organizations) and the relational connections that bind them. Because peer reviewed publications are increasingly produced by larger groups (Wuchty et al., 2007) distributed across more institutions (Jones et al., 2008) and political boundaries (Wagner et al., 2015), it can be useful to consider social network analysis and network properties to understand and improve group function.

The overarching structure of connections in a network determines how easily information or resources can flow or pass through a network, which then influences the ability of the network to accomplish work like creating new knowledge or coordinating collective action (Henry and Vollan, 2014). Network traits are defined by the pattern of connections between social actors (also referred to as nodes), and determine how easy it is for networks to share and create knowledge, adopt new knowledge, and coordinate for collective action (Henry and Vollan, 2014; Krebs and Holley, 2006; Phelps et al., 2012).

Network structures arise out of a variety of constraints, both physical and social, and are determined by the purpose of the network and the actions of individuals comprising it (Phelps et al., 2012; Marin and Wellman, 2011). Network structures are also shaped by individual choices and behaviors: actors may position themselves in a centralized role in order to retain or withhold information or power, or in order to aggregate information for the benefit of the outer actors or groups (Barabási and Albert, 1999; Henry, 2011). Social actors are more likely to form connections with those closer in geographic proximity, to other actors that are similar, and to actors that are connected to other actors (Barabási and Albert, 1999; Guimera et al., 2005; McPherson et al., 2001; Jasny et al., 2019). Network structures are also influenced by the social rules of engagement (e.g., normative expectations to share data freely) or required relationships (e.g., student committee membership), or the knowledge-based tasks networks have formed to achieve (Box 3) (Marin and Wellman, 2011). For example, when funders require a memorandum of understanding among a group of local agencies in order to be eligible to receive funding, the funder is making an intentional play to create network connections between a diverse set of actors. Individuals and organizations are only able to maintain a limited number of connections, and therefore, as new members join, existing connections may drop off or become less frequent connections, thus changing the patterns of connections in the network.

Box 3 Knowledge-based tasks for networks.

Network structures have differential effects on the ability of the network to accomplish various *knowledge-based tasks*:

- Flow of information or resources across the network
- Adoption of knowledge from one field of practice to another
- Integration of knowledge across fields
- Creation of new knowledge or innovation
- Solving complex problems
- Engaging in coordinated action
- Building capacity to mobilize for and engage in collective action

Table 1 illustrates how network structures change based on degree, density, centralization, closure, and modularity. These structures have varying opportunities and challenges for collaboration, knowledge sharing, and team performance (Table 1). See *Further Reading* for more detailed descriptions of how network structures enable or hinder creation, transfer, and adoption of knowledge and build capacity for coordinated or collective action.

Methods for effective networks

The considerations for forming effective teams also apply to forming effective networks. As in teams, trust is the foundation of network connections and plays a central role in the formation of relationships in a network, thus influencing the network structure (Phelps et al., 2012). Trust is the basis for the formation of individual connections, larger subgroups, as well as how knowledge and resources flow through a network (Levin and Cross, 2004). In addition, social network analysis can be used to help networks evaluate their capacity for knowledge-based tasks (Box 3) over time and understand how established processes and norms are supporting or degrading the intended network structure and achieving network tasks.

Some tasks are well suited to be parallelized and performed simultaneously, and in this case, the network structure and the assignment of work can be optimized to support this work. Research tasks such as data collection, data aggregation, modeling, and writing tasks may be best completed by a number of sub-groups (or *teams*) within the network and coordinated by a few lead scientists. Mapped as a network, this would resemble the hub-and-spoke network, where the lead scientists are acting as the hubs between teams.

When the goal of a network is to share and integrate knowledge, or create new knowledge and innovations, then a higher density core-periphery network may be more suitable. Consider the intensive, multi-day scientific events known as "annual retreats" or "workshops," where the goal is to integrate past work, iterate on knowledge, and create or revise a group vision that might be held by dozens of participants. These multi-day events could be used to cultivate greater density in the network and cultivate trust and team identity, by maximizing the opportunities for all network members to share information and to encourage the formation of social connections among participants.

When networks seek to make progress with specific tasks such as modeling or data analysis, while simultaneously advancing knowledge and innovation, then the network communication structure should allow for frequent within-team communication, with less frequent (but regular) opportunities to seek advice and share preliminary results. The corresponding network structure that optimizes both for accomplishing independent, parallelized, or sequential tasks, while advancing knowledge generation, is a multi-hub network.

Social network analysis can be used to strategically intervene when parts of a network—or single actors—fail. If a single actor becomes overwhelmed with requests for time or advice and is unable to perform their tasks because of collaboration overload (Cross et al., 2016), then that actor may become a limiting factor to achieving shared goals. In network structure, this would appear as high centralization, and the solution to this would be to encourage new connections to form to reduce the degree (number of connections) that are reliant on a single actor in order to accomplish their work.

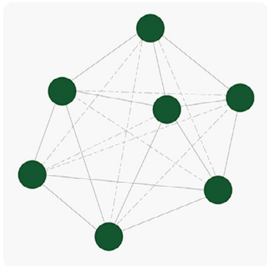
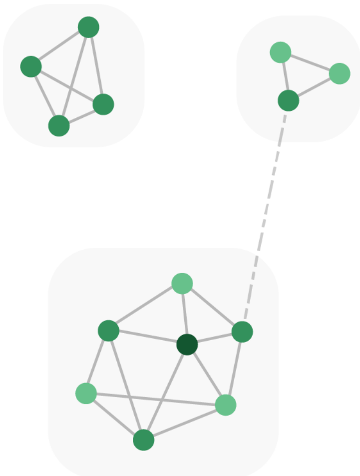
Networks in inland waters research

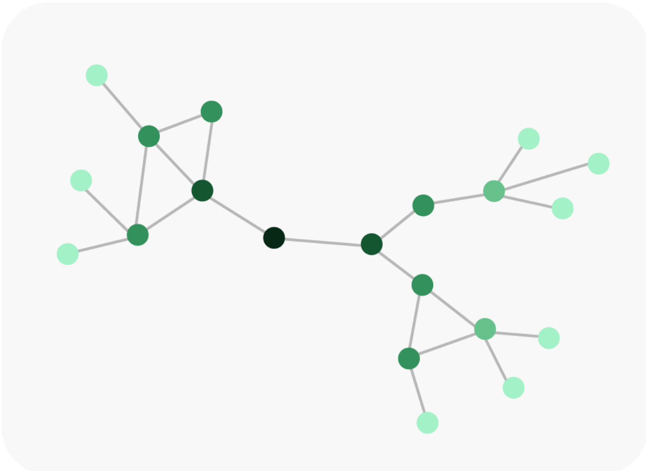
As the scale and scope of scientific research has expanded, so too have a variety of networks that focus on aquatic systems. Many of these networks share overarching research objectives but vary in their approach to accomplish knowledge-based tasks, which is in turn reflected in the network structure. Three tasks that aquatic networks appear to focus on singularly or in combination include (1) coordinated data collection and flow of information, (2) creation of new knowledge, and (3) building and engaging in collective action.

Networks designed around consistent data collection tend toward a decentralized hub-and-spoke model (Table 1), in which data sharing is the primary connection between actors, and governance and resource sharing from a central actor sustains the network. Government-sponsored inland waters networks in the United States that are designed for coordinated data collection and information flow include the National Ecological Observatory Network; U.S. Environmental Protection Agency National Aquatic Resources Assessments of lakes, streams, and wetlands; and the U.S. Geological Survey (USGS) National Streamgage Network. Information flow and communication occurs in support of the task of data collection. Information content from data collection flows from the less connected, outer actors toward the central actors, and governance (e.g., protocols, standards) tends to flow from the central actors to the outer actors. These networks have a strong emphasis on gathering data rather than on knowledge integration or new knowledge creation. Highly managed protocols and coordinated sampling lead to high quality datasets that are comparable across space and time, which facilitates data analyses by users of the network data.

In contrast, networks focused on creation of new knowledge tend to have core-periphery structures (Table 1), and the connections that bind the actors exist to optimize communication and resource sharing. An example of such a network is the Global Lake Ecological Observatory Network (GLEON; see case study below). These networks have more emphasis on bringing people together to integrate knowledge globally and for the creation of innovations in aquatic science and technology. The structure of the network, for which connections between actors are based on voluntary and non-standardized communication and resource sharing, heavily relies on trust. Knowledge networks with core-periphery structure may evolve more rapidly through time as compared to data collection networks, as new teams are created, new social connections are formed, and others senesce. Community-built tools and open science approaches are complementary to the core-periphery network structure and are a hallmark

Table 1 Definitions, idealized example structures, attributes, and real-world examples of teams, networks, and networks of networks. Darker shaded nodes have higher degree (number of connections with other nodes), while lighter shaded nodes have lower degree.

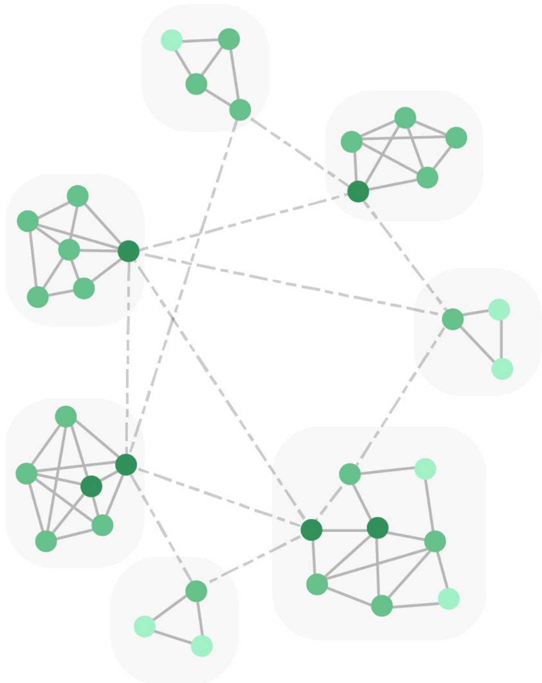
Name, size, and description, idealized structure	*Traits and ideal uses (see Box 2 for definitions of traits)*	*Examples*
Team: 3–11 people; small, tight knit collaborative group. 	Average Degree: Moderate (3–6) Density: Moderate (>0.50) Closure: High (>0.60) Reciprocity: High (>0.50) Centralization: Low Modularity: Low Well-defined scope and objectives that can be accomplished by a small group	Projections of Climate Change Effects on Lake Tanganyika Team (CLEAT, see case study below)
Isolated Teams: More than 12, collection of small teams of variable size. No ties or very weak connections across teams. 	Average Degree: Low-moderate (1–3) Density: High within teams, low across full network Closure: High within teams, low across network Reciprocity: High within teams, low across network Centralization: Low within teams Modularity: High Work completed by separate teams, requires little coordination	Co-author teams contributing separate articles to a journal issue

Small Network: A single network including12–24 members in which all individuals have at least one connection. 	Average Degree: Low-moderate (1–3) Density: Low Closure: Low Reciprocity: Low Centralization: Moderate Modularity: Low-moderate	Grant-funded team with several co-investigators and their labs, requiring strong integration between groups
Centralized Network (Baran, 1964). Variable size, larger than 12 Also known as a *hub-and-spoke network* (Krebs and Holley, 2006). 	Average Degree: Low Density: Low Closure: Low Reciprocity: Low Centralization: High Modularity: High Used when a high level of coordination or standardization between actors is needed. The key feature of this network is the power held by the two key actors and the lack of connectivity among other actors. The hubs control information flow out to the edges of the network. This is an efficient network (e.g., emergency response) but vulnerable if either of the hubs is taken out of the network or intentionally limits information flow	U.S. Geological Survey National Streamgage Network National Science Foundation National Ecological Observatory Network U.S. Environmental Protection Agency National Lakes Assessment

(*Continued*)

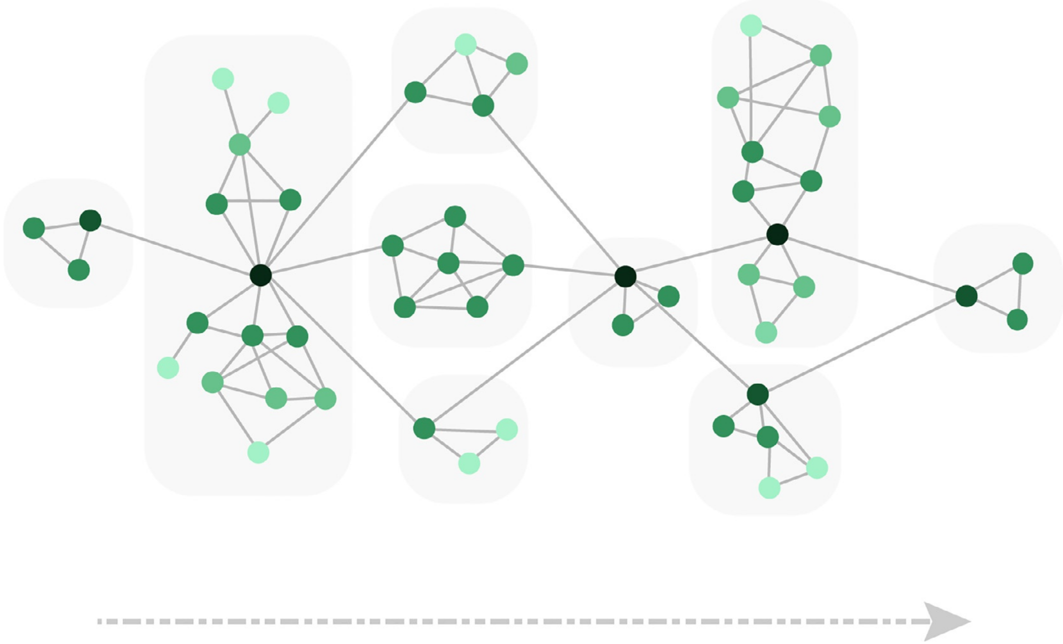
Table 1 (Continued)

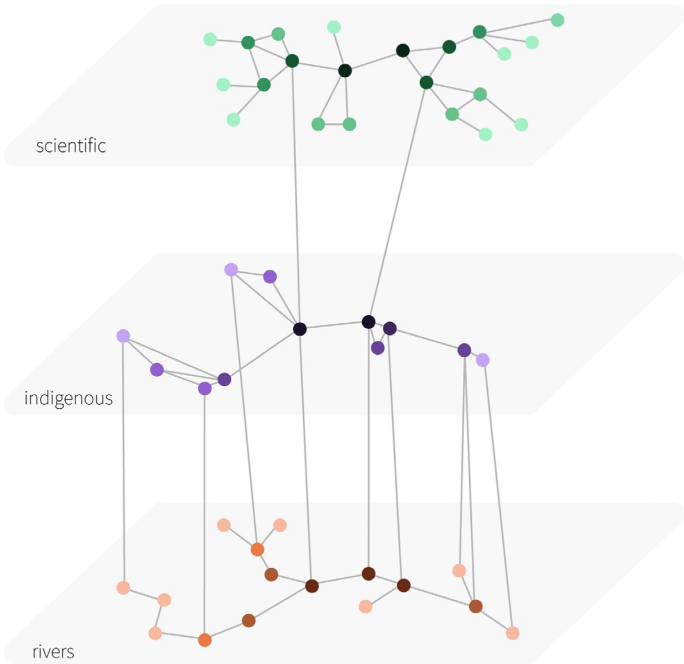
Name, size, and description, idealized structure	*Traits and ideal uses (see for definitions of traits)*	*Examples*
Decentralized Network: Variable size, larger than 12 Also known as a *multi-hub network* (Krebs and Holley, 2006) 	Average Degree: Low Density: Low Closure: Low-moderate Reciprocity: Low Centralization: High Modularity: Moderate This kind of network may be formed initially for data collection or a more centralized, standardized purpose, but evolves to decrease centrality and increase density and closure. This network has a higher capacity to share knowledge and resources and be more resilient to loss of one of the hubs because there is more closure and less centralization (Baran, 1964)	National Science Foundation Long Term Ecological Research
Core-periphery: Typically two dozen or more, tightly connected core with sparse connections to the outside members (Borgatti and Everett, 2000). 	Average Degree: Low in periphery too high in core Density: High in core, low in periphery Closure: High in core, low in periphery Reciprocity: High in core, low in periphery Centralization: Moderate-high Modularity: Variable These networks are more resilient (due to the dense connections in the core), represent network maturity, and may improve the coordination capacity of the network (Krebs and Holley, 2006; Csermely et al., 2013) Useful for knowledge generation and innovation. Due to the centralization and density in the core, this type of network has increased capacity to move knowledge and resources across the network, coordinate collective action, and be resilient to change (Csermely et al., 2013)	Global Lake Ecological Observatory Network

Small world networks: Small, densely connected groups with sparse connections between groups. 	Average Degree: Moderate (especially within sub-groups) Density: Low across full network, high within clusters Closure: Low across full network, high within clusters Reciprocity: Low across full network, high within clusters Centralization: Moderate-high Modularity: High Used to coordinate and share information across sparsely connected teams or communities. Weak ties connect the groups to each other	American Society of Limnology and Oceanography

(*Continued*)

Table 1 (Continued)

Name, size, and description, idealized structure	*Traits and ideal uses (see for definitions of traits)*	*Examples*
Multi-team systems: A few dozen to hundreds of members, teams operate in parallel, and each has a unique focus and scope, but are all contributing to common overarching scope. Teams may be doing work that is dependent on the results from other teams, as indicated by the arrow 	Average Degree: Moderate (especially within sub-groups) Density: Low across full network, high within clusters Closure: Low across full network, high within clusters Reciprocity: Low across full network, high within clusters Centralization: High Modularity: High Used with a large and complex scope of work, requiring either specialization within small teams, or distribution of a large scope of work over many teams. The work of all teams contributes to a larger goal than the scope of each individual team. We define a multi-team system as a *network of networks* because of the separation of teams which may vary in size, network structure, and coordination with the larger goals of the network	Human Genome Project

Multi-level networks: Layers or levels represent unique types of network connections.  	All network metrics (average degree, density, closure, reciprocity, centralization, and modularity) vary across the layers. Typically, contacts between layers are highly centralized and not highly dense, but this too varies by the purpose of the network connections across layers. Used to connect existing networks to each other. Each network has a unique purpose and types of ties (e.g., monitoring, governance, ecological). The structure of each layer is determined by its mission and context, ties are formed between layers to facilitate creation of something no layer can accomplish alone	Indigenous Observation Network

of some inland waters networks (Read et al., 2018). New connections built within this type of network are critical to developing new users of data and tools.

Finally, there are networks that focus on data collection, knowledge creation, and building capacity for collective action. The National Phenology Network has a focus on data collection and information sharing, but also on building the capacity to mobilize community scientists for collective action in support of the network's goals. Quality control of data is less emphasized as compared to the hub-and-spoke model described above. In contrast, the Long Term Ecological Research (LTER) network model not only functions as a hub-and-spoke network, but also incentivizes connections between different actors (LTER sites) via targeted cross-site funding. In this model, distributed place-based research stations collect high-quality, standardized data that are used primarily for pre-identified locally scaled research questions but the data are also publicly accessible. Within each location, knowledge creation, communication, and trusting social connections comprise the network connections.

Network case study: Global Lake Ecological Observatory Network

The Global Lake Ecological Observatory Network (GLEON) is a grassroots network of scientists, sensors, and data. The network has been funded by the U.S. National Science Foundation and various private foundations over time. GLEON is a core-periphery network that seeks to integrate knowledge across fields, create new aquatic science knowledge and innovations, and provide an optional platform for data sharing. GLEON seeks to enable connections between as many members as possible; however, also has a more sustained core of members with higher density, and with more sustained participation in the network through time.

Structure of the network: *Core-periphery*
- 500 individual members from 49 countries.
- 30% students.
- 60 member *lakes* from 34 countries on six continents.
- Members from academic, public, non-governmental and private institutions.

Rules of the network (excerpted from https://gleon.org/about/vision-and-mission): *Educational, collaborative, scientific*
- Steering Committee, Student Association, and Collaborative Climate Committee guide the long-term strategy, student services, and collaborative culture and practices of the network.
- Annual meetings rotate geographically to encourage new membership.
- Interdisciplinary lake science.
- Foster an empowered, diverse membership and facilitate informality, collegiality, and collaboration.
- Spark curiosity and share ideas, expertise, and data.
- Use transparency in decision-making, communication of results, tools, and products.
- Prioritize professional development of members.

Outcomes of the network: *Global lake research, technical and scientific advances, team-science fluent membership*
- Open data and community-built tools (Read et al., 2018).
- Effective pipeline for student training and career opportunities.
- 329 publications attributable to network collaborations between 2005 and 2020.
- Technical innovation resulting from GLEON-based collaboration between private sector and academia, driven by research needs.
- Training in team science (Read et al., 2016), sensor technology, data processing, and modeling skills.
- International networks for future opportunities (jobs, research collaborations).
- Appreciation for different cultures.

Networks of networks

What is a network of networks?

Beyond teams and networks, science frequently requires building connections between networks with different purposes and disciplinary alignment (e.g., monitoring, governance, analysis). These are networks of networks: interconnected networks where each layer is a unique network defined by social, geographic, and temporal boundaries and distinct purposes, e.g., governance, data gathering, information sharing. Networks of networks are often called multilevel networks (Lazega and Snijders, 2015; and see Table 1).

All of the knowledge about teams and networks described in previous sections also applies to the structure of networks of networks, but networks of networks are recognized to have uniquely transformative capabilities, and are being invested in by scientific agencies as a growth area (e.g., National Science Foundation AccelNET program).

By definition, networks of networks are interconnected by a small number of connections across networks; this structure makes them more vulnerable to the loss of those cross-network connections.

Methods for effective networks of networks

The process of forming networks of networks varies greatly depending on the networks that need connections to each other. Because networks of networks are composed of networks and teams, and rely on connections between actors through which knowledge and resources are shared, we speculate that the best practices for teams and networks also apply to networks of networks. However, in addition to the previous guidance, we hypothesize that the time needed for leadership and maintenance of key connects (cross-team, cross-network) scales proportionally with the complexity of the network.

Small world networks are an emergent property of human communities: because no explicit effort or design is required to build a small world network, the only prerequisite is a minimum number of individuals with opportunities to interact and form connections. In contrast, multi-team systems are used under moderate to highly organized circumstances, and in some cases to achieve very specific, coordinated outcomes where the work of one team is dependent on the previous work of another (see Table 1).

Multilevel networks form when independently-created networks become connected by relationships between individuals *across* networks; thus, these network of networks structures can be formed only when two or more networks already exist, and then become connected. The way that meaningful connections across networks are made and sustained are studied most frequently in the fields of environmental governance and resilience (Hahn et al., 2008; Hileman and Lubell, 2018). Thus, theories and applied knowledge about how best to design, manage, and study networks of networks are just beginning to appear in the literature (Brass and Borgatti, 2019; McGee et al., 2019). One of the unique features of networks of networks is that where any individual network structure might be resilient, the dependency of networks of networks on a small number of inter-network connections can make them vulnerable (Das et al., 2017). Because networks of networks are connected by actors, the loss of key actors or a connection can create a cascading failure. Networks of networks that have strong interdependent coupling may be less resilient than individual networks.

Support and training for the development of networks of networks can be found through organizations sponsoring inland waters research, including the National Socio-Environmental Synthesis Center or the USGS Powell Center.

Networks of networks in inland water research

Multi-team systems may be the most common form of networks of networks found in inland waters research. At this time, direct study of multi-team systems pursuing inland waters research objectives is not available, but it is likely that this network of network structure is present in the aquatic sciences: most natural science researchers in Norway conduct about 20% of their work in what would be described at least as multi-team systems (Kyvik and Reymert, 2017).

Multi-level networks can also be found in the field of inland waters. As a Federal agency, the USGS is a model of a national network of networks, as it incorporates a diverse set of networks including the National Water Quality Monitoring Network, the National Streamgage Network, the National Phenology Network, and others which have direct relevance for aquatic science; but the network of networks also features looser affiliation with other networks within USGS including volcano and earthquakes observatories. These networks within a network have been created within a bureaucratic framework and under an earth-science mission; largely, connections between the network are informal and consist of information sharing between a small number of individuals each embedded within one of the networks.

In contrast, the Indigenous Observation Network (ION; see case study below) is a multi-level network that has been created under a less formal setting: ION links an intertribal watershed council with a standardized community-based monitoring network and an indigenous knowledge network; this network of networks is designed for the co-production of new scientific knowledge. This multi-level network relies heavily on social relationships between a small number of individuals who span the three network layers.

The Consortium of Universities for the Advancement of Hydrologic Sciences, Inc. (CUASHI) is a network of networks that incorporates international partners and emphasizes integration of knowledge, creation of new knowledge, and data sharing. CUASHI's goal is to catalyze water-related research across institutions and disciplines. Institutions, rather than individuals, are members; currently there are more than 140 member institutions, with 20% from outside the United States. CUASHI primarily maintains infrastructure to support collaborative research and data sharing, but also provides training opportunities and hosts an annual meeting.

In the aquatic sciences, there is a growing demand for the creation of networks of networks beyond the naturally occurring small world networks, to multi-level networks in which layers are connected through formal linkages that can serve as "force multipliers and connectors to advance science." Recent investments by the NSF (e.g., the U.S. National Science Foundation's AccelNet Program and Coastlines and People Program) focus on connecting people, rather than infrastructure, in recognition of the importance of human relationships for creating networks of networks. The goal is to bring together networks that might not normally interact because the scientific context differs substantially. This approach is gaining ground within the aquatic sciences, with calls to strengthen connections between remote sensing scientists and limnologists to better understand lake ice dynamics, for example (Sharma et al., 2020).

Network of networks case study: Indigenous Observation Network

The Indigenous Observation Network (ION) is a multi-level network of networks that connects scientists, community monitoring groups, and indigenous knowledge networks. The ION links community-based water-quality and permafrost monitoring programs that produce data from the Yukon River Basin in the United States and Canada. The Yukon River Inter-Tribal Watershed Council (YRITWC), an Indigenous non-profit organization, collaborates with the USGS, and the University of Alaska-Fairbanks to implement the ION. The ION was first established in 2006 to measure baseline water quality in the Yukon River Basin and has continued to collect hundreds of surface water samples annually to track effects from changing climate and land use. Today, ION has sampled >200 sites across the Yukon River Basin spanning the United States and Canada.

Structure of the network of networks: *Multi-level*

- Yukon River Inter-Tribal Watershed Council represents 76 Tribes and First Nations located in the Yukon River Basin that have signed the inter-tribal accord.
- USGS and YRITWC have agreed to collaborate on monitoring and science activities through a memorandum of understanding.
- U.S. Environmental Protection Agency—Indian General Assistance Program (EPA-IGAP) funds the surface water sampling of community members in the United States that participate in the program.

Rules of the network of networks: *Quality and conservation*

- Tribes and First Nation members of the YRITWC are the governing body committed to preserving and protecting the environmental quality of the Yukon River.
- Standardized training, field methods, quality assurance, lab analysis, and data publication is practiced across sites and by all community technicians.
- YRITWC consults with participating members on new site selection.
- Outside access to community members and collaborators is restricted by USGS and YRITWC project personnel so as to avoid stakeholder fatigue.

Outcomes of the network of networks: *Co-production of knowledge, conservation, and community engagement.*

- Research on long term water quality trends and other climate change effects experienced by Indigenous communities (Toohey et al., 2016).
- Demonstrated the generation of accurate, precise, and reliable water quality data by Indigenous community-based monitoring network.
- Provides rich opportunities for USGS engagement with Indigenous stakeholders.
- Provides opportunities for students and community members from traditionally underrepresented groups to engage in science, technology, engineering, and math (STEM) activities.
- Communities have greater trust in ION data than that collected by other entities because it is being collected by community members (Wilson, 2017).
- The ION allowed for deeper integration of Indigenous Knowledge with western science to understand climate change effects on this relatively under-studied (from a scientific perspective) region (Herman-Mercer and Schuster, 2014) by building long term trusting relationships.
- Communities have used the ION program to establish baseline monitoring and assessment required to establish conservation districts that further the YRITWC goal of preserving the environmental quality of the Yukon River.

Conclusion and synthesis

Trust is essential to the formation of human relationships, and these relationships in turn are the basis of meaningful connections in teams, networks, and networks of networks. Communication, data sharing, resource sharing, and coordination are impossible without trust; and without those functions, groups at all levels of organization cannot accomplish knowledge-based tasks including sharing and integration of knowledge, innovation, collective action, and more. The intentional formation of teams and networks, informed by the literature on the science of team science and social network analysis, can result in more productive and sustained performance. Creating and maintaining successful teams, networks, and networks of networks is dependent on both the structure and the culture of the entity.

Increasing the commonly-understood attributes of high performing teams and the ideal uses of various network structures will allow societies, universities, government agencies, and funders to improve team science and network building. A reward structure that recognizes and values the successful creation of teams and networks to accomplish inland waters research can incentivize more emphasis of team and network development in inland waters research. Because many reward structures focus on the products rather than the processes of team science, training for the social-emotional skills required to lead or participate in successful teams, networks, and networks of networks are not commonplace in natural and physical sciences graduate programs, and there are multiple generations of inland water science professionals working in teams or networks without such training. Outside of a few specialized graduate training programs that are limited in size and offered irregularly (e.g., NSF Research Traineeship program, GLEON), there are no common pathways for inland water professionals (particularly those outside of graduate school) to receive training geared toward improving team science outcomes.

At the writing of this article, networks of networks remain the least understood of the entities examined in this article. However, as humans face ever increasing global-scale environmental challenges related to water quality and availability, new connections across communities, research, governance, and management groups could help minimize the societal and environmental effects.

An understanding of the basis of teams, networks, and networks of networks, which all rely on robust, trusting human connections, will be essential to adapting to a changing planet. Inland waters research—and geosciences more broadly—can benefit from the knowledge acquired through social science research, and the integration of this to team and network formation; and we hope that this knowledge will contribute to meeting the global environmental challenges facing inland waters today.

Knowledge gaps

- Methods for developing and maintaining specific network structures and rules of engagement to accomplish various knowledge-based tasks.
- The effect of transdisciplinarity and convergent science on teams, networks, and networks of network structure and function.
- Methods for development and maintenance of multi-level networks and networks of networks.
- Rules of engagement for networks and networks of networks of various structures and purposes.
- Best practices for evaluating the success of teams, networks, and networks of networks outside of product-based metrics.

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Team Science

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