

Water governance: new performance measures for diagnosing a watershed organization

by

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Abstract

Collective action problems often impede watershed governance performance, and the need for diagnostic tools to analyze governance performance in the complex network of actors responsible for governing shared waters exacerbates this issue. This research aims to fill this gap by offering new insights into how social network attributes influence a watershed organization's governance performance. Using the Okanagan Basin Water Board network organization as a case study, this research provides a situational context for watershed governance research by exploring the polycentricity literature. Secondly, it examines how exponential random graph models can be employed to evaluate a watershed organization's network performance over time. Finally, it explains how organizational network modelling can be utilized to enhance our knowledge of social capital and watershed governance performance. This research aims to use social network analysis tools based on observed data to diagnose an organization's governance and ecological service delivery performance. An improved understanding of watershed organizational network attributes that contribute to the social capital building, and ecological service delivery will help to enhance organizational governance systems and support our collective responsibility to protect and manage shared and common waters.

Keywords: Watershed, Governance, Network Organization, Social Capital, Polycentricity

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1.0 Introduction

"We have not only a water system but a social system."

Dr. John O'Riordan

(Meeting Minutes: Okanagan Basin Water Board, 1970-11-05, p.6)

Water governance systems are currently not being adequately measured at the watershed level, leaving policymakers unable to make informed decisions. This lack of measurement is a common problem, as anything unmeasured is essentially invisible to policymakers (Coyle, 2019). Despite a desire from Board Directors and elected officials for practical measures that support decision-making in watershed management, few organizations define, track, measure, or apply governance system measures as a resource for decision-support or change management. As someone with more than a decade of experience in watershed governance and management, I aim to address this gap by developing a set of defensible water governance system measures that can support improved decision-making, with a focus on management outcomes such as invasive aquatic species and lake water quality (eutrophication).

A recent survey found that while 93% of British Columbians consider fresh water as their "most precious resource," 84% believe the current water management and decision-making approach in the province is ineffective (Brandes et al., 2016). The impact of eutrophication, floods, and droughts has caused ecosystem crises and even collapse globally, driven by the growing human population and changing climate, which have accelerated the frequency and intensity of freshwater hazards (Folke et al., 2005; Knox, 1993; Pahl-Wostl, 2015a; Rockström et al., 2009; Scheffer et al., 2001). While these are biophysical issues, they are partially rooted in social problems of non-cooperation and unmanaged collective action (E. Ostrom, 2010). Interdisciplinary water governance research is crucial to inform policy changes that can improve watershed governance systems.

This research focuses on a critical aspect of watershed systems, which includes the social-ecological elements within the watershed boundary. When water enters the watershed, it becomes part of this interconnected system until it leaves through consumption or other processes. Fig. 1 provides a conceptual framework for understanding the hydrology and limnology components of the system. In addition, a network of actors in a watershed organization makes decisions that impact the shared waters within the watershed. These decisions are influenced by various network attributes, which this research explores. By analyzing both observed and modelled network relationships, this study sheds light on important aspects of watershed governance, such as centralization, coordination and building networks with local and senior levels of government actors.

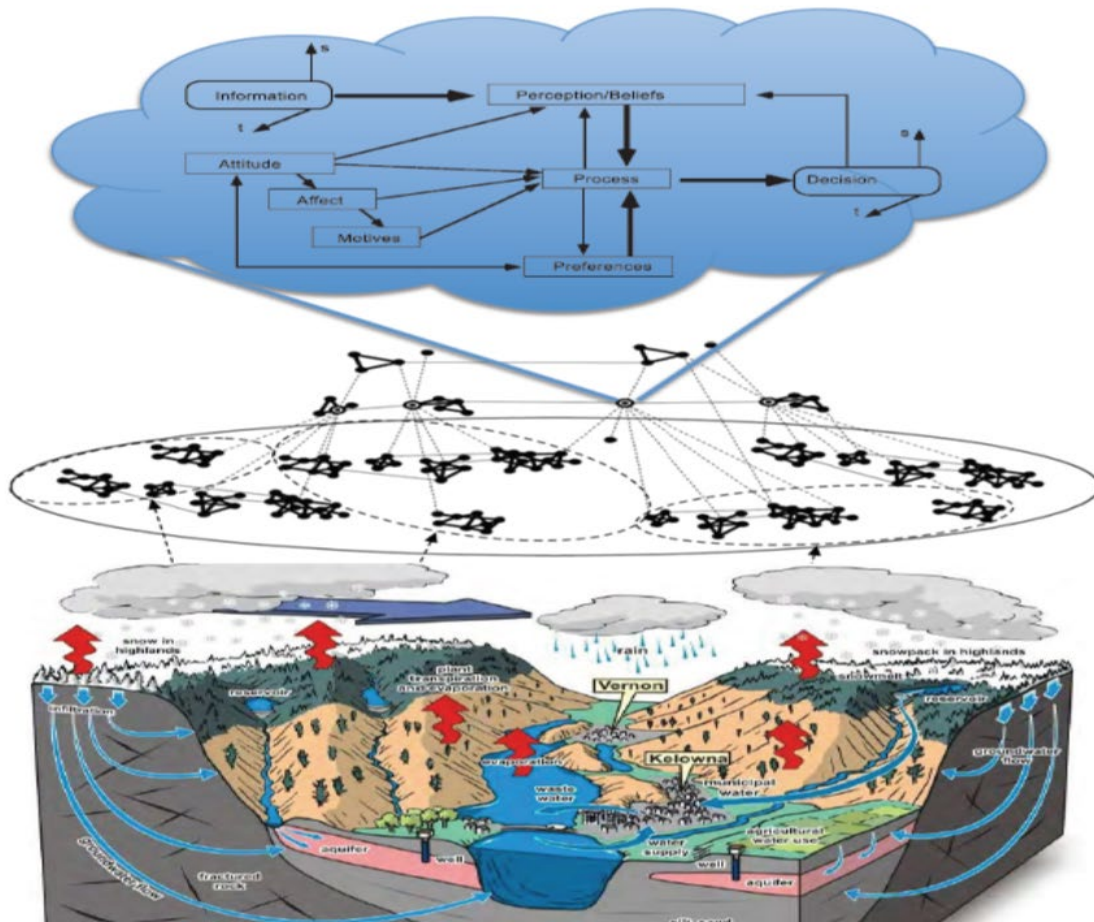


Fig. 1. A conceptual visualization of the social-ecological interactions within a watershed governance system (Jatel, 2022).

Water managers at the watershed level rarely implement water governance performance measures, despite their longstanding availability. However, developing practical and defensible measures could greatly benefit regional watershed organizations like the Okanagan Basin Water Board (Melnichuk, Jatel, & Warwick Sears, 2016) and others. Prior studies of water governance have often relied on expert opinion, but this research takes a different approach by analyzing meeting minutes and social network analytic data to calculate several measures of watershed organization governance. The use of historic meeting minutes as a data source can be highly valuable, providing information about governance system network attributes that can improve both watershed organization performance and ecosystem service delivery.

Water governance is an essential but underfunded aspect of government expenditure. In British Columbia, with a population of 5.2 million people and an annual budget of approximately \$44 billion, water governance and management receive less than 0.001% of the annual provincial budget (Office of the Auditor General, 2013). In contrast, healthcare accounts for 48% of the

government's budget resources, and this number is projected to increase to over 50% in the next decade. Despite limited financial and human resources, this research emphasizes the importance of social network variables such as coordination and centralization in influencing the performance of watershed organizations at the watershed scale. By understanding and utilizing these variables, water managers can improve the effectiveness of their governance systems and promote sustainable ecosystem service delivery.

Water management is a complex issue, involving a network of actors with both formal and informal relationships. However, this network is often invisible, making it difficult to manage. Through the use of social network analysis, researchers can make this network visible and identify the key actors and relationships within it. In this synthesis chapter and accompanying manuscripts, several watershed organizations' social network attributes and their impact on performance outcomes are described. By making these networks visible and measurable, we can better manage our shared waters and ensure their sustainability for future generations.

This research portfolio provides novel insights into a single case study of a watershed network organization, specifically the OBWB. Through the use of an exponential random graph (ERG) model, as well as other statistical analytics, I enhance our understanding of the organizational network structures, also known as motifs, and their impact on organizational performance within the watershed.

Why is this research practical? In a watershed system, the decisions made by individuals and groups have a collective impact on the water supply. As professionals in the field, we encounter these decisions frequently as we develop policies and enforce regulations. However, it can be challenging to translate our understanding of the relationship between network structures and performance into tools that support decision-making. By examining the social network relationships within a watershed organization, this research enhances our understanding of the key factors that impact organizational performance. By shedding light on the often-invisible network of relationships that influence watershed governance, we can better manage our relationship with water.

2.0 Research Background

This section presents the problem statement and contextualizes the research. I list the terms used throughout my research in Manuscript II. I apply the following commonly used definitions (Pahl-Wostl, 2015) throughout this synthesis document:

Water governance is the social function that regulates the development and management of water and provisions of water services at different levels of society and guides water toward a desirable state and away from an undesirable state.

The *water governance system* is an interconnected ensemble of political, social, economic, and administrative elements that perform the function of water governance. These elements embrace institutions as well as actors and their interactions.

Governance systems are not mainly a product of rational design, but researchers characterize them by self-organization, emergence, and diverse leadership in complex networks with many interests and power relationships.

Governance system performance refers to the institutional actors' broader social-ecological goal(s).

2.1 Problem Statement and Context

This watershed governance system research is mainly exploratory. This research looks at several social networks and organizational performance variable relationships. This study contributes to determining practical watershed organization knowledge by

Recognize[ing] which combination of variables leads to relatively sustainable and productive use of particular resource systems operating at specific spatial and temporal scales and which combination leads to resource collapses and high human costs. (Ostrom, 2007, p. 15183)

To effectively measure performance, it is essential to have clear definitions of desired outcomes (Simms & de Loe, 2010). In the context of watershed organizations, I believe that effective performance measures should have several key characteristics. Firstly, they must be based on high-quality data, including longitudinal data. Secondly, they should be able to improve decision-making processes. Finally, they should be linked with organizational performance, and where possible, ecological performance as well. By adhering to these characteristics, we can develop reasonable and effective measures for assessing the performance of watershed organizations.

My manuscript portfolio on governance research addresses three key problem statements in the following ways:

1. There are several distinct polycentricity research communities that are pushing the boundaries of their defined definitions. My research seeks to clarify these definitions and provide a more cohesive understanding of polycentricity.
2. Currently, there is no typology available to categorize a watershed organization's network attributes, which makes diagnosis difficult. My research aims to create a typology to categorize these attributes, making diagnosis more accessible.
3. The relationship between a watershed organization's social network attributes and ecological service delivery programs is not well understood. My research investigates this relationship to provide a better understanding of how social networks impact ecological service delivery.

With a focus on better understanding social network analysis, this portfolio of research papers investigates governance measures that can improve decision-making and delivery of ecosystem service programs for watershed organizations.

2.2 Evolving Context of Watershed Governance

This research adopts a diagnostic approach to analyze watershed governance, focusing on the organization-level of network system arrangements. The study argues that quantitative analysis can help describe system features and their changes over time, leading to improvements in governance and management systems. The argument is particularly relevant to water professionals seeking to implement new change management strategies for watershed governance. In this governance analysis, multiple qualitative and quantitative methods are used to describe the social system under investigation

In recent years, multiple research areas have emerged with different methods and frameworks for diagnosing various aspects of watershed governance, such as systemic, regime, and organizational analysis. In my study, I employed various social network analysis approaches to investigate these three modes of watershed governance. A crucial factor in my research was considering boundary conditions while analyzing the governance system, regime, and organization. This approach provides valuable insights for improving watershed governance systems and addressing complex water-related challenges.

Several bodies of diagnostic research have applied social network analytical methods to improve our understanding of current watershed governance systems. For example, researchers have used social network analysis to enhance our experience of conflict in social-ecological systems (Bodin, García, & Robins, 2020), cooperation in a watershed (Koontz, 2019), institutional fit (Epstein et al., 2015), power dynamics (Morrison et al., 2019), and climate change (Lubell & Robbins, 2021). This research builds on several important works and applies them to diagnosing a watershed organization.

A network organization's performance is a function of nested measurable attributes within a social-ecological system involving three components: (1) *action situations* (E. Ostrom & Cox, 2010; Pahl-Wostl et al., 2012); (2) interaction attributes, and (3) *action situation performance measures*. With the help of a literature review, I identified the state of theoretical knowledge on social-ecological systems, water governance, and governance network analysis. A social-ecological system analysis (E. Ostrom, 2007) provides an important starting point for understanding the influence of different attributes within a given social-ecological system.

Water governance is subject to frequent changes, such as budget, policy, legislation, and leadership, making longitudinal studies crucial to understand their impact on governance performance. However, there is a lack of such studies in the field of water governance (Binder et al., 2013a). Most watershed governance studies are limited to real-time snapshots that may not account for critical contextual circumstances influencing governance performance (Jatel, 2013; Lubell, 2005; Morrison, 2017; Claudia Pahl-Wostl et al., 2012). This study addresses this research gap by analyzing the performance of a watershed network organization over a 50-year period from 1968 to 2017.

2.3 Research Purpose and Objectives

The aim of this research was to reveal the social network attributes of a watershed organization and their influence on performance. This is critical because a watershed organization's performance directly affects the ecological health of shared waters. Our findings highlight the governance indicators of social network and how they can lead to problems such as de-eutrophication (Manuscript II) and invasive aquatic species (Manuscript III). Understanding the connections between social and ecological effects is crucial for improving our approach to water management.

3.0 Dissertation Portfolio Components

I chose to use the Dissertation by Portfolio format because it serves two key objectives. Firstly, it provides an avenue for me to share my research with the watershed community, with the aim of improving the diagnostics of watershed organizations and their leadership performance. Secondly, the portfolio format allows me to collaborate with research experts in my field, such as Dr. Claudia Pahl-Wostl, and expand my network of research collaborators. This would have been less feasible with a traditional manuscript dissertation format. The concluding section of this paper includes a summary synthesis of my research (5.1).

The dissertation portfolio comprises three manuscripts, one of which was written solely by me, while the other two were co-authored. This allowed for valuable collaboration on pertinent questions regarding modern watershed governance.

The three manuscripts presented in this portfolio are as follows:

Manuscript I. Curtailing the Babel Tower effect in water governance polycentricity research literature: A scientometric k-core analysis (Jatel and Pahl-Wostl)

Keywords: polycentricity, scientometric, water governance, k-core, network analysis

Manuscript II. Untapped Potential: The Importance of Social Networks in Evaluating Performance Metrics for Watershed Organizations (Jatel, Pittman, and Pahl-Wostl)

Keywords: watershed, governance, network organization, social network analysis, exponential random graph model

Manuscript III. Exploring changes in 50 years of social networks to improve our understanding of a watershed organization's performance (Jatel)

Keywords: water, governance, indicators, social capital, exponential random graph model, changepoint analysis, social network analysis

Each of the three manuscripts in my dissertation portfolio contributes to my research objectives (as detailed in Appendix A). In the first manuscript, I examine watershed organization governance within the broader context of polycentricity through a scientometric analysis. In the second manuscript, I develop a new exponential random graph model to correlate the likelihood of network characteristics, specifically coordination and centralization and place the case study network organization, the OBWB, within a two-dimensional watershed diagnostic framework (Pahl-Wostl & Kneiper, 2014) that describes the commons-polycentricity of watershed organizations. Finally, in my third manuscript, I investigate the relationship between internal and external variables on the OBWB and changes in network attributes.

3.1 Theoretical Framework

Ostrom's social-ecological system analysis (E. Ostrom, 2009) is a key starting point for understanding the influence of different attributes within social-ecological systems from a diagnostic perspective. Pahl-Wostl and colleagues built on Ostrom's model and developed a water-specific social-ecological model, conducting the first meta-analysis of water governance systems (Pahl-Wostl et al., 2012). The concept of commons-polycentricity has been widely studied and is fundamental to my research, as demonstrated in a book on analyzing and applying polycentricity to governance complexity (Thiel, Blomquist, & Garrick, 2019). Additionally, the application of exponential random graph modelling to complex governance systems (Hileman & Lubell, 2018; Lubell & Robbins, 2021; Lubell, Robbins, & Wang, 2014a) provides crucial theoretical and methodological foundations for my dissertation portfolio.

3.1.1 Collective Action Problem

Collective action problems are at the heart of many complex governance systems (Baldwin, McCord, Dell'Angelo, & Evans, 2018; Koontz et al., 2015; Mark Lubell, Stacey, & Hummel, 2021), posing a challenge to achieving common goals. The concept of collective action refers to the situation where individuals or groups in a society pursue their self-interest rather than the common good, resulting in a suboptimal outcome for all. This is because everyone's self-interested behavior, when taken collectively, leads to outcomes that are worse for everyone involved than if they had worked together towards a common goal.

The issue of collective action is particularly relevant in the context of polycentric governance systems (Thiel et al., 2019), which are characterized by multiple governing units that are

connected by various forms of interaction. These systems present unique challenges to achieving collective action, as each governing unit has its own goals, resources, and incentives that may conflict with those of others. Defining and addressing collective action problems, therefore, is an important theme in the study of polycentric governance systems.

To overcome collective action problems in complex governance systems, scholars and practitioners have proposed various strategies. One approach is to increase communication and collaboration among the different governing units, creating a sense of shared purpose and a willingness to compromise. Another approach is to establish rules and regulations that incentivize cooperation and penalize non-compliance. Yet another approach is to create stronger incentives for individual actors to behave in ways that benefit the common good. Ultimately, the success of these strategies depends on the specific context of the governance system in question, and the willingness of the actors involved to work towards a common goal.

3.1.2 Complex Social-ecological Systems

To better understand water governance systems, Pahl-Wostl's (2015) research employs complex adaptive system (CAS) theory, which is an important aspect of this portfolio. The CAS theory describes how components within a system interact with each other, with a focus on the individuality and diversity of each component, localized interactions, and autonomous processes that lead to nonlinear effects. The theory helps to explain the "system structure" (Pahl-Wostl, 2015c, p. 161) that emerges from self-organization and feedback between emergent macro-level control variables and micro-level interactions. With this theoretical framework, this research aims to explore and diagnose the attributes of a watershed network organization.

The study also builds on the concept that watershed performance is dependent on measurable attributes nested within a social-ecological system consisting of three components. The first component is action situations (E. Ostrom & Cox, 2010; Pahl-Wostl et al., 2012), which are measured by system characteristics. The second component involves interaction attributes within social-ecosystem situations. The third and final component is action situation performance measures (Pahl-Wostl et al., 2012). By understanding these components and how they interact, this research aims to contribute to the improvement of water governance and organizational performance within a watershed context.

3.1.3 Organizational Theory

Watershed organizations are intricate systems composed of actor networks that distribute and allocate decision-making, as stated by Simon (2013). These decision-making networks, made up of interconnected actors, play a critical role in shaping the organization's strategic decisions and daily operations. March and Simon (1993) noted that the likelihood of forming network motifs will have different consequences, affecting the watershed organization's ability to adapt to changes in its structure or other unexpected changes. Simon (2013) argued that during the formative phase of a new organization, some degree of centralization is necessary to secure organization advantages, such as coordination, expertise, and responsibility, but the associated costs of centralization should not be ignored. According to Lubell (2013), the likelihood of an organization forming network motifs reflecting concepts of centralization and coordination has its own set of costs and benefits. Therefore, better understanding an organization's network motifs, the DNA of its social network, and how they change over time can help diagnose the formation and sustainability of watershed organizations and provide practical change management strategies.

3.1.4 Literature Review

This research draws on the strong theoretical foundations developed over the past 50 years in the field of social-ecological systems, water governance, and watershed organizational network analysis, as established by Agrawal, E. Ostrom, Pahl-Wostl et al., Pittman & Armitage, and others. To identify the current state of theoretical knowledge in these fields, I conducted a comprehensive review of relevant literature.

In particular, my review focused on water governance systems and the concept of polycentricity, which has roots in various disciplines such as urban studies, political science, and water governance. The idea of polycentricity has been applied in multiple communities of research, with distinct concepts and applications. Manuscript I provides a systematic review of the literature on polycentricity and its application to water governance, with a focus on the essential aspect of performance as outlined by Pahl-Wostl et al. (2012). By synthesizing and analyzing this literature, this research seeks to deepen our understanding of how polycentric governance systems can facilitate effective water management in complex social-ecological systems.

3.1.5 Rational Actor Theory (RAT)

The use of rational action theory (RAT) in analyzing watershed governance is not a new concept. However, there is a debate among social network researchers regarding its validity and practicality in complex social systems. RAT has been applied to the institutional analysis and development (IAD) framework, which is a social-ecological system. This framework is closely related to game theory (Ostrom & Cox, 2010, p. 455). Similarly, the RAT framework has been used in the "first comprehensive comparative analysis of complex water governance and

management systems" in the context of watershed governance (Pahl-Wostl et al., 2012, p. 24). In this study, I employed linear regression analysis to assess the significance and strength of associations among core governance attributes.

In contrast, some have argued that the application of RAT does not provide a satisfactory account of all human behaviour. And therefore, RAT has a minimal application, especially in bridging the gap between micro (actor) and macro (i.e., organization or regime) social systems (Gross, 1987). This criticism is equally applicable to social network analysis. On the other hand, there is no assumption that the development of organizational social networks provides a comprehensive explanatory model. But instead, the visualization enabled by social network analysis provides new insights into complex actor interactions, cost-benefit actor choices to participate or not, conflict resolution, competition, and cooperation. Developing a longitudinal model of a watershed organization's whole network provides a glimpse into what is often perceived as an opaque network system of actors (Jatel, 2013). It advances our current understanding of meaningful policy and governance advice.

Applying RAT to ecological governance systems presents limitations, and the literature identifies three unresolved challenges. Firstly, the effect of social networks on behaviour remains unclear despite widespread agreement on their importance. Secondly, there is a need for further analysis of multiple social processes that contribute to sustainability and resiliency in watershed governance systems (Levy & Lubell, 2018; Pahl-Wostl, 2009). Lastly, analyzing longitudinal network changes in governance systems is challenging due to the limited availability of network data (Ulibarri & Scott, 2017). To address these issues, a structurally precise network diagnosis quantifies the social drivers of network structures for a watershed organization. A case study of a network of watershed organizations, analyzed through a longitudinal ERG model, enhances our understanding of all three unresolved problems associated with SNA analysis of governance systems. This study characterizes all four components of a network and explores how multi-level government participation influences network attributes such as collaboration, coordination and provincial government actor participation.

4.0 Research Design and Methodology

This section presents my research design and methodology to answer the research questions identified earlier.

4.1 Empiricism

This research adopts a diagnostic approach to understanding watershed organization performance. I used an empirical mathematical model, the ERG model, and a logistic regression model to understand the likelihood and correlation of various aspects of a watershed organization's social network.

I applied mathematical models based on social data to test the hypothesis in each of my three manuscripts. The concepts that I model and measure in this research portfolio include:

Polycentricity is a watershed governance attribute that may be described using a two-dimensional analysis of the likelihood for a network: coordination and centralization. (*Manuscript II*)

Centralization and coordination modelled network attributes of a watershed organization based on social network observations from a two-mode network (OBWB meetings and attendance). (*Manuscripts II and III*)

Horizontal integration (local government), an ERG model result, described the likelihood of local government participation at network organization board meetings. (*Manuscripts III*)

Vertical integration (provincial and federal government), an ERG model result, described the likelihood of provincial and federal government participation at network organization board meetings. (*Manuscripts III*)

Empiricism has enhanced our understanding of watershed organizations and systems for decades, mainly by applying the IAD framework (Koontz, Gupta, Mudliar, & Ranjan, 2015; McGinnis, 2011; E. Ostrom, 2011). This research aims to contribute new knowledge on a small but important aspect of empirical watershed governance performance indicators – that of watershed organization network performance.

4.2 Frameworks

A diagnostic approach may help assess watershed organization performance (Pahl-Wostl 2015, p. 21), thereby enhancing the development of new strategies to address watershed threats, including invasive species and climate change challenges. Water governance performance goals (emergent system-level phenomenon) are explicitly expressed in some situations but are often undefined *a priori*.

Many frameworks help analyze social-ecological systems (Binder, Hinkel, Bots, & Pahl-Wostl, 2013b), such as the human-environment system, management and transition framework (MTF), and the social-ecological system framework. Frameworks used to analyze social-ecological systems vary in their theoretical and disciplinary origin, purpose, and the way they conceptualize the social and ecological systems, interactions, and dynamics. Aligning the appropriate framework to a given research objective is an important consideration. My research objectives support the exploration of social-ecological system changes over time and acknowledge the bidirectional nature of causality between action situation outcomes and governance performance.

The MTF (Pahl-Wostl, Holtz, Kastens, & Knieper, 2010) describes critical variables applied to integrated adaptive water governance and management and provided valuable context to my watershed organization research. It focuses on the watershed level and conceptualizes the social system (society) as a combination of rational choice (IAD framework) and social constructivism (Binder et al., 2013a), leading to a social learning approach. The goal of the MTF is to understand water systems and the transition to adaptive management (Pahl-Wostl et al., 2010). The MTF takes an anthropocentric approach and applies to an analysis-oriented framework. The MTF lends itself to longitudinal studies where the same case study is compared at different periods.

4.3 Data Collection

To analyze the governance systems of the OBWB over a period of 50 years (1968-2017), I gathered data from various sources. To ensure a comprehensive analysis, I measured each action situation every 12 months. It is important to note that performance measures are not always indicative of actual performance and are often used as substitutes. Therefore, estimates must balance validity, ease of measurement, and applicability to support decision making (Kolsky & Butler, 2002). By considering these trade-offs, performance measures can be properly contextualized and applied. Using multiple methods for data collection, such as text analysis and SNA, minimizes the limitations of relying on a single method and provides a more thorough analysis.

4.3.1 *Watershed organization meeting notes (corpora)*

To gather information for my research on the governance systems of the OBWB over a 50-year period (1968-2017), I utilized meeting minute records as a valuable source of data. These records provided me with actor network data, contextual information, insight into the application of new technology, identification of themes and sentiments among board members, and support for actor-network analysis.

To ensure an appropriate research design, I paid special attention to issues of statistical power (Stadtfeld, Snijders, Steglich, & van Duijn, 2018), time lags, variation in within-basin network attributes, and density over time. Specifically, I considered factors such as network size, number of data collection waves, effect sizes, missing data, participant turnover, and procedures for estimating statistical power in my analysis of OBWB meeting minutes.

Using text analysis, I was able to quantitatively analyze over 50 years of meeting notes from the OBWB. To do this, I employed Nvivo software (Bazeley & Jackson, 2013), which supported theme and text analysis, including word frequency analysis to identify key concepts discussed at the OBWB. By utilizing multiple methods to collect data, I was able to reduce the limitations associated with any single method and provide a more robust data analysis.

4.3.2 Social network analysis data

Social network analysis can be a valuable lens to measure how actors engage within and between organizations (Ö Bodin et al., 2019; Örjan Bodin et al., 2016; S. P. Borgatti & Foster, 2003; Lubell, Robins, & Wang, 2014b; Robins, 2015). Social network analysis provides an important, albeit limited, source of information about actor influences on water governance performance (Jatel, 2013).

Network analytics describes several governance performance measures. For example, network motifs (see Manuscripts II and III) provide new insights into the likelihood of network traits being observed, including centralization and coordination. Network attributes were calculated based on two-mode network analysis (Stephen P. Borgatti & Everett, 1997) of actor participants at OBWB meetings. I collected and modelled water governance network data mainly in two standard network software packages, UCINET (S.P. Borgatti, Everett, & Freeman, 2002) and R programming (Goodreau, Handcock, Hunter, Butts, & Morris, 2008).

5.0 Conclusions

This summary portfolio document introduces three new manuscripts with unique research questions (Appendix A) and several mixed-methods applications to help answer them.

5.1 Research Findings

Previously, research involving longitudinal data illustrated that "all events, objects, and states of affairs in the social world are dynamic processes and that time is, therefore, a key category for any appropriate analysis of society" (Rosa & Trejo-Mathys, 2013, p. 1). An improved understanding of Okanagan's watershed network organization resulting from this research supports the development of new diagnostic approaches that reveal fundamental social-ecological interactions pertinent to water and provide appropriate problem framings and strategies (de Loe, 2017).

The network analysis developed through this research portfolio provides new insights into a watershed network organization and its performance over time (Appendix A). Through my analysis, I discovered that polycentricity can be divided into five different research communities, two of which are directly related to watershed governance. The OBWB's governance network transformed over the past 50 years, transitioning from a polycentric structure to one that alternated between centralized rent-seeking and coordination. Interestingly, I found that the likelihood of provincial staff attending Board meetings decreased from 1988-1992, and that there was a shift towards centralization in 2005 that persisted until

2017. These findings suggest that changes in OBWB leadership and restructuring may have influenced the organization's governance approach.

Next, I provide a more detailed summary of the conclusions from each of the three studies in this research portfolio.

In manuscript I, I conclude that a new scientometric analysis of polycentricity research literature, using a k-core community detection method to describe distinct communities, was an improvement in previous studies. Our analysis found five unique and different communities of polycentricity research: urban spatial, European planning, commons, legal, and development. We also found that watershed governance polycentricity was nested in two polycentricity research communities: urban spatial and commons polycentricity.

In Manuscript II, we demonstrate that the OBWB's network governance evolved over time, transitioning from a polycentric governance network to one that oscillated between centralized rent-seeking and centralized coordination. The study contributes to understanding a watershed organization's network governance and performance attributes, providing valuable theoretical and practical insights. This study underscores the importance of social networks and their role in organizational performance, particularly for watershed organizations delivering ecological services.

Manuscript III concludes that based on an ERG model and a statistical analysis, the application of new network indicators, notably anti-centralization and provincial actor participation at meetings were found to be promising new watershed governance indicators. Applying an exploratory framework, a new model describing internal and external variable influences based on network characteristics supported findings of significant changes in the OBWB's network attributes after analyzing 50 years of activity. A shift in the OBWB network from a polycentric to a centralized – coordinated network was observed and partially attributed to a new organizational mandate and change in leadership staff. I conclude that the OBWB, a centralized-coordinated watershed network organization, has network characteristics that contribute to organizational resiliency.

5.2 Synthesis

In this concluding synthesis section, I will address three questions based on my research context, methods, findings, and conclusions. The first question is how my work contributes to the primary debates in watershed governance. The second question is about the value of the new knowledge presented in my research for the scholarship of the domain. The third question addresses how the research findings can be applied to future watershed governance diagnostics.

Governance scholars have observed that "resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist" (Holling, 1973). The present

research emphasizes network attributes and has a practical objective of contributing to water governance theory and achieving specific outcomes, including (1) the formation of new watershed governance organizations, as identified in the British Columbia Water Sustainability Act (2016) and other provinces and states throughout North America, (2) co-management of water between Indigenous and Canadian governments, and (3) improved community-level resilience to climate change.

Saleth and Dinar (2004) identified the importance of institutional and performance linkages, including administrative, legal, and technology implementation. In their social system governance study, they recognized that

the most critical and significant institutional aspects determining institutional water performance are: adequate conflict resolution provisions, legal integration, a healthy dose of centralization within water law, user participation policy, balanced functional specialization, good information, and technology application (p. 311).

This study adds to our understanding of how coordination and centralization influence watershed organization governance and ecological service program delivery. It also contributes to ongoing debates in the literature on watershed governance by presenting new perspectives and findings. Some scholars argue for a descriptive approach to analyzing watershed governance (Plummer et al., 2016), while others advocate for a diagnostic approach (Lubell & Morrison, 2021; Pahl-Wostl et al., 2012). However, relying solely on either approach can lead to challenges such as data availability, oversimplification, and information transparency and quality control. Therefore, I argue that combining both diagnostic and descriptive analyses of watershed governance systems can provide significant value.

Another prominent governance debate in the literature is about applying the concept and definitions of polycentricity to watershed governance performance, urban system transportation efficiency, and legal and political system dynamics, among others. Polycentricity scholars state that

empirical studies have employed definitions of polycentricity that are not entirely consistent with one another and do not capture the full import of the concept as conceived by V. Ostrom et al. (1961), thereby ***impeding systematic theoretical development*** [emphasis added] (Carlisle & Gruby, 2017, p. 2).

Definitions of polycentricity and governance have evolved and vary with discipline. Nobel laureate Elinor Ostrom wrote that "no governance system is perfect, but polycentric systems have considerable advantages given their mechanisms for mutual monitoring, learning, and adaptation of better strategies over time." (Ostrom, 2010, p. 552)

Regarding polycentricity and governance, most practitioners will readily agree that independent, autonomous actors are a necessary condition to describe a governance situation. Where the agreement usually ends, however, is on the question of the suite of "necessary and

sufficient" conditions (indicators) that fully describe a measure of watershed governance polycentricity. Whereas some researchers are convinced that the application of "necessary and sufficient" (Goertz, 2006) conditions, originally used to describe "multi-nucleated" (V. Ostrom, Tiebout, & Warren, 1961) city-unit arrangements, is appropriate for watershed governance situations. Others maintain that a different set of criteria, including coordination "to some extent" (Blomquist & Schroder, 2019, p. 57), is appropriate to describe watershed governance performance. In this study, I apply a new method that uses organization network data to diagnose the centralization and coordination attributes. This research builds on Pahl-Wostl's two-dimensional (centralization and coordination) diagnostic concept of polycentricity.

Social networks are an essential aspect of water governance – complementary to qualitative and other indicator research methods (i.e., OECD water governance indicators and methodology: Mudliar & O'Brien, 2021; Seijger et al., 2018). The use of social network analysis methods to describe governance action situations is not new. For example, a mix of binding and bonding structures provided evidence of the co-occurrence of cooperation and coordination problems, revealing the complexity of governance systems where myriad actors have sometimes aligned and sometimes clashed policy views and preferences (Berardo & Lubell, 2019). Other network studies gained insights about action situation actor cooperation and conflict dynamics (Örjan Bodin et al., 2020, p. 471). Social network analysis provides several statistical (modelled) and descriptive (i.e., motifs, whole network) tools to measure important aspects of an action situation. I argue and describe an action situation network using descriptive and analytic tools.

Our research findings in Manuscript I enhance our understanding of the different communities of polycentricity literature and where we find watershed governance literature, notably urban spatial and commons polycentricity literature.

The impact and contribution of new knowledge gained from this research on the scholarship of watershed organization governance are methodological and pragmatic. Researchers have applied organizational social network analysis to resource-commons problems (Lubell & Morrison, 2021). This research contributes to the growing knowledge of longitudinal case studies of watershed organization governance performance. The application of ERG and other diagnostic models provides a practical methodological framework to help understand how available watershed organization data may offer new insights into governance performance.

The methods for diagnosing organizational networks presented in Manuscripts II and III provide valuable insights into the modelling of watershed network organizations and the relationship between network characteristics and performance. This relationship is often overlooked and rarely analyzed. Manuscript III provides a detailed case study that applies organizational social network analysis to evaluate the performance of a specific program within a watershed organization. Together, these three manuscripts pave the way for new methodological approaches that improve our ability to diagnose and improve watershed organization performance.

This research provides insights into future watershed governance diagnostics by using the Okanagan watershed network as a case study. The study aimed to address three areas of interest: (1) contextualizing watershed organization diagnostics using organizational network observations, (2) assessing organizational network diagnostic tools for measuring organizational network performance, and (3) developing an example of a watershed organization's network attributes to assess various aspects of governance performance. The findings of this research can help improve our understanding of the Okanagan watershed network and inform future watershed governance diagnostics. This research provides valuable new knowledge and insights, including:

- A novel description and characterization of five distinct polycentric research communities
- An understanding of where watershed governance fits within these communities
- A comprehensive characterization of the OBWB network organization and its relationship to a polycentric system
- An improved understanding of the fit of the ERG model to the OBWB network organization data
- New insights into the annual network attributes of the OBWB over a 50-year study period
- A better understanding of how a watershed organization's network characteristics impact organizational performance

To better understand the Okanagan water governance system and develop effective diagnostic approaches, it is essential to have an enhanced understanding of significant social-ecological variables within its context, whether analyzed statistically or descriptively. An improved understanding of the Okanagan water governance system, over time, will support the development of new "diagnostic approaches that reveal key social-ecological interactions pertinent to water [and] provide appropriate problem framings and strategies" (de Loe, 2017). Such an understanding will facilitate the identification of key social-ecological interactions and the development of problem-framing strategies within the framework of water governance theory. Changes to the Okanagan water governance system, as well as other dynamic social systems, are shaped by various system characteristics, as noted by Pahl-Wostl (2015).

6.0 Contributions to Theory and Practice

6.1 Innovative Research Design

In my research portfolio, I explore three governance organization models found in the literature: network, lead, and grassroots association (Provan & Kenis, 2008), with a specific focus on the OBWB network organization (detailed in Manuscripts II and III).

One of the innovations of this research is the use of meeting minutes from a watershed governance organization to generate social network data. Additionally, the application of an ERG model to annual frames derived from the two-mode social network data represents cutting-edge use of new software and faster computing capabilities.

The inclusion of annual data over 50 years is a particularly novel aspect of this research, contributing to a longitudinal social network study. The use of whole-network analytics, including organizational corpora data and exponential random graph modelling, has broad applications for future research on watershed organizations.

6.2 Integrative Approach Linking Theory and Practice

This research portfolio takes an integrative approach, connecting polycentricity theory, social network theory, social-ecological theory, organization theory, and practical organization performance indicators. The aim is to develop insights into the essential network characteristics of a watershed network organization and explore the relationship between network attributes and performance using ERG and logistic regression models. Performance markers examined in this study include attendance at OBWB meetings and changepoints in network characteristics, with a focus on internal and external variables of influence. By linking various aspects of organizational and polycentricity theory and practice, this research provides a diagnostic and exploratory approach that advances our understanding of watershed governance.

7.0 Knowledge Dissemination

Compared to other doctoral programs that prioritize theoretical advancements, the RRU Doctoral of Social Science emphasizes the importance of students' contributions to real-world problems and practical solutions. As part of this focus, disseminating new knowledge is crucial to the doctoral journey.

The three manuscripts in this synthesis portfolio represent the culmination of my doctoral research and have helped me achieve my objective of enhancing my understanding of essential social network attributes relevant to a watershed organization's performance and service delivery. In this section, I will briefly discuss how I plan to disseminate my research findings.

7.1 Publications and Online Access

My ultimate objective is to share my research findings with a wider audience and contribute to the scholarly discourse on watershed organizations and governance. With this in mind, I aim to

publish all three manuscripts included in this dissertation portfolio in reputable peer-reviewed journals within the next 12 months. By doing so, I hope to disseminate my research insights and provide opportunities for future scholars to build on my work and advance the field further.

In addition to publication, I also plan to make my data and exponential random graph model publicly accessible on GitHub and other suitable research data-sharing platforms. This step aligns with the principles of open science and allows other researchers to scrutinize and replicate my findings. Moreover, this will promote transparency and reproducibility, which are crucial for scientific advancement.

To increase the visibility and impact of my research, I will also explore other dissemination channels, such as conference presentations, workshops, and media outreach. For instance, I may present my research findings at relevant academic conferences and engage with stakeholders and policymakers to share my insights and foster dialogue on watershed governance issues. Additionally, I will collaborate with media outlets to ensure that my research findings reach a broader audience, including the general public, who may have a vested interest in the management and sustainability of watershed systems.

7.2 Tracking Impact

To ensure that my research has a meaningful impact, I have developed a plan to track its influence using two sets of metrics. Firstly, I will conduct bibliographic searches and keep track of any publications that arise from this research. This will help me to assess the reach and influence of my work in the academic community.

In addition to academic impact, I also plan to track the practical impact of my research. Specifically, I will monitor the use of network metrics in watershed organizations across British Columbia and Canada. By doing so, I hope to gain insights into how my research has been applied in practice and to what extent it has been useful in improving watershed organization performance.

To achieve this, I plan to establish ongoing relationships with watershed organizations across Canada and work collaboratively with them to apply the findings of my research. I will also seek feedback from practitioners to better understand the challenges they face and how my research can be tailored to meet their specific needs.

Overall, by tracking the academic and practical impact of my research, I hope to ensure that it contributes meaningfully to improving watershed organization performance in Canada and beyond.

8.0 Limitations and Ideas for Future Research

This empirical research on watershed organizations has several limitations that must be considered. Firstly, this study focused on a single organization, which is inherently limited in developing generalizable results. However, it provides a detailed understanding of how social network analysis can be applied to measure performance and metrics modelled on social network analysis to a kaizen-like change management framework. Future research should examine other organizations, such as lead and administrative organizations, to provide different perspectives on performance criteria related to other governance modalities.

Secondly, although the methods of analysis using ERG models are generalizable, the results are specific to the one case study analyzed, and further testing using multiple watersheds is required to improve our understanding of social network and organizational performance relationships. Longitudinal whole-network modelled data can be applied to examine the variation of centralization and coordination between watershed organizations, thus enhancing our understanding of how such data can improve organizational performance. Additional network attributes should also be tested to expand the range of analytical tools at our disposal.

Thirdly, data limitations, especially for longitudinal studies, are problematic. Improved data sources, especially on organizational and ecological performance aspects, would be helpful for future studies.

Fourthly, there is a limitation in knowledge dissemination and application of new findings about network-watershed organization indicators and how organizations may adopt them to enhance decision making. Although publishing the three manuscripts and presenting this work can support watershed organization leaders' adoption of governance diagnostics, additional outreach to organizations interested in improving watershed governance is necessary to address specific local contexts and challenges.

Lastly, future research should involve more watershed governance case studies to provide opportunities to compare governance performance. The application of ERG models using longitudinal data derived from meeting attendance is a method with overall reproducibility. Developing research strategies that integrate watershed organization governance network attributes with change management strategies would further advance the practicality of this research.

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Appendix A. This three-manuscript portfolio includes a summary of research objectives, data, and contributions.

	Manuscript 1	Manuscript 2	Manuscript 3
Research Questions	<p>What does the term “polycentricity” mean across different fields of study, and how can we use scientometric analysis to understand the various communities of research using the term and their conceptualizations?</p> <p>In which communities do we find watershed organization research?</p>	<p>How can we use social network analysis to develop a comparable indicator framework for assessing coordination and centralization in a watershed organization's governance structure?</p>	<p>How can longitudinal trends in network characteristics, as identified through Exponential Random Graph Model (ERGM) analysis inform our understanding of governance performance measures?</p>
Research Objective	<p>Apply a scientometric analysis of polycentricity literature to describe distinct communities within polycentricity literature.</p>	<p>Developing a new typography for diagnosing the polycentricity of a watershed network organization.</p>	<p>An exploratory analysis of internal and external variables relating to changes in network characteristics and subsequently the performance of watershed programs and policy.</p>
Justification for Inclusion	<p>New sociometric analysis based on k-core communities.</p> <p>This study describes where watershed governance fits within the diverse application of the polycentricity concept.</p>	<p>New diagnostic measure for watershed organization polycentricity.</p>	<p>It explores the effects of adopting senior government water management programs on watershed organizations' social network problems in coordinating local and provincial staff.</p>
Data Collection Method	<p>Literature review</p>	<p>OBWB corpora analysis</p> <p>Social network Analysis.</p> <p>ERG Modeling and Average Marginal Effect standardization.</p>	<p>OBWB corpora analysis.</p> <p>Social network Analysis.</p> <p>ERG Modeling and Average Marginal Effect standardization.</p>
Potential Sources	<p>-Google Scholar</p>	<p>Corpora: OBWB meeting minutes (1968–2017)</p>	<p>Corpora: OBWB meeting minutes (1968–2017)</p>

	-Scopus -Microsoft Academic -Crossref		
Task Description	Clarify key governance system measure as it relates to water governance	Develop a new diagnostic standard for watershed organization polycentricity.	Develop a further relational analysis between network attributes and watershed organization program performance.
Independent Variable(s)	Polycentricity journal articles (nodes)	Likelihood of network centralization.	Exploratory analysis applying changepoint analysis on longitudinal social network data including the likelihood of forming two motifs of interest: anti-centralization and provincial tie formation.
Dependent Variable(s)	Citations (edges)	Likelihood of network coordination	Exploratory analysis of internal and external variables.
Post-Test Information?	The context for watershed governance polycentricity	A new measure for longitudinal water governance system polycentricity.	A new performance diagnostic based on ERG model analysis of the watershed organization. Identified change management opportunities to improve OBWB watershed governance performance.
Mode of Data Analysis	Scientometric analysis Social network analysis Principal component analysis K-core analysis	Longitudinal social network analysis Exponential random graph model	Longitudinal social network analysis Exponential random graph model Changepoint analysis

Contributions

Presents findings on how many distinct research communities exist for polycentricity and what they are.

Situates watershed governance polycentricity.

A new diagnostic measure of watershed organization polycentricity

Improved understanding of water governance organization's change management and the impacts of provincial programs adopting to watershed organizations.

Appendix B. Quantitative governance research scan

Date	Researcher(s)	Model	Independent variable(s)	Dependent Variable(s)	Key Findings	Future Research Direction
2008	Andersson and Ostrom	Logistic Regression	Financial transfers from central to municipal government in NR governance	% of municipal government personnel working with natural resource management (NRM).	(1) Central funding and meeting with NGOs and CBOs enhanced both dependent variables.	Longitudinal data develops dynamic analyses of how local institutions respond to local contexts and affect ecological processes.
			Political pressure from local community-based organizations	View of natural resource governance as a political priority by the mayor	(2) Municipal income influenced NRM personnel but not NRM priorities	Valuable data on governance outcomes
			Non-government organizations working on NRM		(3) Decentralization, population density, and education: no influence on dependent variables.	Controls for the influences of natural and socioeconomic processes that shape outcomes.
					(4) Each additional meeting with NR staff with CBOs and NGOs provokes a 0.5% increase in the proportion of municipal teams dedicated to NRM.	

Date	Researcher(s)	Model	Independent variable(s)	Dependent Variable(s)	Key Findings	Future Research Needs
2018	Baldwin et al.	Qualitative analysis	<p>Polycentric governance</p> <p>Overlapping governance</p> <p>Coordination mechanisms among CWP, WRUAs and WRMA.</p> <p>Water governance component functions: water allocation, compliance monitoring, sectioning of violations, and conflict resolutions</p>	<p>Collective action (several indicators):</p> <p>Presence of a water rationing agreement between CWPs</p> <p>Compliance with the agreement</p> <p>Information sharing across governance levels</p> <p>Perceived trust between actors at different governance levels</p>	<p>Collective action is occurring in the basin</p> <p>Features associated with polycentricity (1) overlapping authority and (2) coordination mechanisms between actors - are critical drivers of collective action.</p>	

Date	Researcher(s)	Model	Independent variable(s)	Dependent Variable(s)	Key Findings	Future Research Needs
2018	Omori and Teorero	one-way analysis of variance (ANOVA), mixed-level logit regression	(1) User group characteristics (2) Project site characteristics (3) User group institutional arrangements (4) individual farmers' characteristics and participation in collective actions	Tramline status (operational or nonoperational) [binary dependent variable]		
2019	Pittman and Armitage	ERGMs	Network building blocks	Observed network	Importance of considering centralized actors and core teams in governance networks and representation from the state. Improved consideration of latent (hidden or concealed) capacity	

Date	Researcher(s)	Model	Independent variable(s)	Dependent Variable(s)	Key Findings	Future Research Needs
2012	Pahl-Wostl et al.	Multiple linear regression		System performance	<p>Confirm the importance of vertical and horizontal coordination for system performance .</p> <p>Polycentric systems are more adaptative and have a higher overall performance .</p>	



Appendix D. Summary of journal article manuscript publication details.

	Manuscript title	Author(s)	Link to academic journal	The rationale for selection of a journal as a target publication outlet	Journal's submission guidelines	Submission requirements met
i.	Curtailing the Babel Tower effect in water governance polycentricity research literature: A new scientometric k-core analysis	Jatel, N. Pahl-Wostl, C.	Ecological Indicators https://www.sciencedirect.com/journal/ecological-indicators	Open Access Journal: Ecological Indicators is an open access journal with no publishing charges (No APC Charge).	https://www.sciencedirect.com/journal/ecological-indicators	Yes
ii.	<i>A new social network diagnostic framework measuring centralization and coordination of a Canadian watershed organization over 50 years of activity</i>	Jatel, N. Pittman, J. Pahl-Wostl, C.	Journal of Environmental Management https://www.journals.elsevier.com/journal-of-environmental-management	Transformative journal with publications on similar research logic and methods.	https://www.journals.elsevier.com/journal-of-environmental-management	Yes
iii.	Measuring the network social capital of a Canadian watershed organization: New (modelled) social network water governance indicators	Jatel, N.	Canadian Water Resources Journal https://www.tandfonline.com/toc/tcwr20/current	A Canadian peer network of watershed managers.	https://www.tandfonline.com/action/authorSubmission?show=instructions&journalCode=tcwr20#preparing-your-paper	Yes

DOAJ website (open access): https://doaj.org/search/journals?ref=homepage-box&source=%7B%22query%22%3A%7B%22query_string%22%3A%7B%22query%22%3A%22water%20governance%22%2C%22default_operator%22%3A%22AND%22%7D%7D

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Title: Curtailing the Babel Tower Effect in water governance polycentricity research literature:
A scientometric k-core Analysis

Authors: Nelson Jatel and Claudia Pahl-Wostl

Abstract:

Polycentricity, a concept described by Michael Polanyi in 1951 and later developed by Vincent Ostrom and his colleagues in 1961, has emerged as a powerful tool for analyzing social systems such as governance, transportation, urban-centre development, and law. In this study, we aimed to explore the diverse research communities that use the concept of polycentricity and understand where watershed governance polycentricity fits within this interdisciplinary landscape. To achieve our research goals, we employed a multi-method approach, combining network analytics and hierarchical k-core clustering, to map the communities of polycentricity literature. Our results identified five distinct communities of polycentricity literature, two of which included water governance polycentricity. By mapping out these research communities, we aimed to foster conceptual consistency, reduce conceptual misuse, and facilitate the theoretical development of water governance polycentricity. Our findings highlight the diverse applications of polycentricity in various fields and emphasize its potential to describe essential features of a watershed governance system. This study contributes to our understanding of the complex dynamics of polycentricity and provides a framework for analyzing the multi-level, multi-sectoral governance systems essential for addressing environmental challenges. Overall, our research underscores the importance of interdisciplinary approaches in addressing complex social issues and lays the groundwork for future research on polycentricity in water governance.

Key Words: polycentricity, scientometric, water governance, k-core, network analysis

Findings:

- (1) Using scientometric analysis, we show five distinct polycentricity communities of literature based on our citation database, Google Scholar. These five polycentricity communities are Urban spatial, European planning, Commons, Legal, and Development.
- (2) Water(shed) governance literature was found in two communities of polycentricity literature: urban spatial polycentricity and commons polycentricity.
- (3) Methodologically, k-core hierarchical classification was a reasonable method to establish distinct communities of literature within the polycentricity literature network.

Introduction

Polycentricity, a concept with multiple definitions, has evolved and describes different ideas developed by researchers from various disciplinary communities. Concepts with several meanings are subjected to "conceptual stretching" and the "Babel Tower effect" (Baleghizadeh & Naeim, 2011). This effect, based on the Genesis origin myth, describes how people speaking different languages could not communicate with each other. Understanding the diverse perspectives on polycentricity can enhance comprehension and help more effective collaboration across the research community.

In general terms, polycentricity often refers to a system or structure with multiple centers of power or decision-making. This can refer to various levels of the organization, from cities to countries to global governance structures. Polycentricity is often contrasted with a monocentric or single-centred system. Polycentric systems are often characterized by their ability to adapt to local conditions and preferences and their potential for promoting diversity and innovation. However, they can also be more complex and challenging to coordinate than monocentric systems.

Polycentricity has garnered increasing attention in the literature (see Appendix 1) in several research arenas, including social-ecological system analysis (Berkes 2017), urban studies (Dühr et al., 2010, Green 2007), city development patterns (Kloosterman and Musterd, 2001), and law (Richardson et al., 1990). For example, Nobel laureate Elinor Ostrom (2010) wrote, "No governance system is perfect, but polycentric systems have considerable advantages given their mechanisms for mutual monitoring, learning, and adaptation of better strategies over time." In a separate arena of research, urban development scholars have written, "the concept of balanced and sustainable polycentric development has become one of the hallmarks of the emerging field of European spatial planning" (Shaw & Sykes, 2004). Multiple definitions of polycentricity have resulted in distinct conditions, necessary and specific to a given discipline and ontology, leading to conceptual homonyms (Goertz, 2006). To gain a deeper understanding of how the meaning of a word evolves, it's helpful to conduct a thorough analysis incorporating qualitative and quantitative methods, including historical grammar (Malkiel, 1957). With "the concept's multi-disciplinary genealogy" (Thiel et al., 2019, p. 5), mapping the various communities found in published literature supplies a practical visualization of how the concept is defined from different perspectives. We posit that a better understanding of the delineation of research communities that use distinct definitions of polycentricity can contribute to minimizing the Babel Tower effect.

Scientometric analysis of polycentricity literature

Scholars have applied scientometric analysis of polycentricity to address the Babel Tower effect (van Meeteren et al., 2015), dividing researchers into linguistic groups unable to understand one another. This earlier scientometric analysis applied Louvain's modular method to find community boundaries. Louvain's method is imperfect in finding the boundary conditions of research communities in the literature, partly because the algorithm's output depends on the order in which a researcher analyzes the nodes (Blondel et al., 2008), thus making it impossible to reproduce. In contrast, this study contributes to the polycentricity literature by implementing a network analysis and k-core method to find polycentricity community boundary conditions in the broader polycentric literature. We generate a

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birds-eye view of the polycentricity literature network and a new classification of its distinct communities. Furthermore, after mapping the distinct communities of polycentricity research, we are interested in understanding where watershed governance research is situated within the network of polycentricity literature communities.

Applying a scientometric analysis to map the concept of polycentricity can help better understand the concept's different conceptualizations and evolution over time. It can find the essential authors, research institutions, and research fields that have contributed to developing the concept and the interdisciplinarity of the research. Moreover, it can show knowledge gaps and opportunities for future research that can contribute to a more comprehensive understanding of polycentricity. This approach can also help to show the communities of researchers working on different aspects of polycentricity and help communication and collaboration between different research communities, integrating the interdisciplinary understanding of polycentricity. Overall, scientometric analysis can supply valuable insights into the evolution, application, and interdisciplinarity of the concept of polycentricity, which can contribute to a better understanding of this complex concept.

Watershed governance polycentricity

Watershed governance is one area of research that has applied the concept of polycentricity. Inadequate governance hinders adaptation to the changing climate (Hamilton & Lubell, 2019; Knox, 1993) and threatens water ecosystems (Domisch, Amatulli, & Jetz, 2015; Lewis & Maslin, 2015; Rockström et al., 2009). Watershed governance research considers this context of growing social and ecological uncertainty and variability, emphasizing the need for effective governance systems to address these challenges. For instance, measures of polycentricity have been shown to contribute to generally high-performing governance systems, specifically in the context of climate change adaptation (Pahl-Wostl et al., 2012). Moreover, polycentric governance systems have enhanced specific water governance performance, including cooperation, conflict resolution, and competition (Koontz, 2019). Scholars have also examined the influence of polycentric governance on collective decision-making within water actor networks (Berardo & Lubell, 2016). Moreover, watershed governance polycentricity is described as a critical social function regulating the development and management of water and providing water services at different levels of society, guiding the resource towards desirable outcomes and away from undesirable ones (Pahl-Wostl, 2015).

We apply scientometric analysis to situate watershed governance polycentricity within the broader polycentricity literature to reveal distinct communities of scholarship that have developed around the concept. By exploring these communities' methods, theories, and research questions, we can better understand how scholars in different fields have approached the concept of polycentricity and how they have applied it to study watershed governance. This will help us show gaps in our understanding of water governance polycentricity and potential areas for future research and collaboration. As the meanings of polycentricity and governance have evolved over time and across different communities, our systematic review of the literature on polycentricity will help us identify the different branches of evolution that have occurred and where research on water governance fits in. It is worth noting that the

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problem of "conceptual stretching" has been discussed in detail (van Meeteren, Poorthuis, Derudder, & Witlox, 2015), underscoring our approach's importance in supplying clarity and understanding in this area.

In this paper, we have divided the contents into three distinct sections. First, we provide a detailed description of the methods we used for our analysis. We employed a multi-method approach to differentiate between the various communities of polycentricity literature. Next, we present the outcomes of our analysis. Finally, we discuss our findings and draw conclusions based on our research, highlighting the importance of our study.

Methods

In our study of the polycentricity literature, we employed a range of multi-disciplinary methods to analyze the network of scholarship and its communities of interest. Our approach involved exploring four scholarly search engines and choosing to use one, developing a database of literature citations, and applying hierarchical cluster analysis to show distinct communities of interest within the broader network. By employing these methods, we aimed to supply a comprehensive analysis of the polycentricity literature and shed light on the various communities of scholarship that have developed around the concept.

Developing a citations database

To find the most suitable web-based bibliographic search engine for our scientometric analysis, we analyzed four academic research search engines - Google Scholar, Microsoft Academic, Scopus, and Crossref (see Appendix 3 and 4). While other databases, such as Web of Science, PubMed, and Semantic Scholar, were available for analysis, they yielded low search engine results for "polycentricity."

According to Kumar and Choukimath (2015), Google Scholar is a popular source of bibliometric data for scientometric-based analysis. However, some researchers have noted limitations and reproducibility issues with Google Scholar (Gusenbauer & Haddaway, 2020). While some argue that it is inappropriate for primary analysis, others suggest that it democratizes citation analysis, provides broader academic access, and is a more comprehensive source of citations (Martín-Martín et al., 2021). A study by Harzing and Van der Wal (2008) found that Google Scholar and the combination of Web of Science (WoS) and Scopus had a high correlation. Google Scholar offers advantages such as a full-text search option and open-access content, features not available in Scopus (Gusenbauer & Haddaway, 2020). Although there are challenges with repeatability and location independence, Google Scholar offers broader access to academic works, including books, academic thesis publications, and conference proceedings. The authors of the text used an off-the-shelf software program to retrieve and analyze academic sources to build their Google Scholar search engine citations database (Harzing, 2007). We summarized the RepOrting standards for Systematic Evidence Syntheses (ROSES) flow diagram in Appendix 5.

Overall, while there are limitations to the Google Scholar database, it offers distinct benefits and advantages over other databases, making it a valuable resource for this analysis. After reviewing the

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literature and our primary search engine data (see Table 1), we decided to use Google Scholar for our scientometric analysis as it had strong support from the literature as well as the highest number of papers (n = 997) and citations (n = 24,504) compared to other search engines. Previous scholars noted that Google Scholar is a “major and popular source of bibliometric data for Scientometric-based analysis” (Kumar & Choukimath, 2015, p. 158).

Network analysis

Social network analysis can be used to analyze networks of research articles. Citation network analysis has been used to map the connections between articles and authors, identify key concepts and trends, and track the development of a field over time. For this study, we analyzed the polycentricity literature, including published works represented as nodes and associated citations represented as network edges. We used R software to use these defined nodes and edges as input data for our network analysis (Adhikari & Dabbs, 2017; Core Team, 2013). Overall, social network analysis provides a powerful tool for analyzing and understanding research networks and can help researchers identify new research directions, collaborations, and opportunities.

Principal component analysis (PCA)

Principal Component Analysis (PCA) is a popular statistical technique used in exploratory data analysis and predictive modelling (Rytsarev et al., 2019). It involves computing the principal components of a collection of network nodes and transforming every assertion expressed in terms of coordinates relative to one basis into an idea expressed in terms of coordinates relative to the other basis (Morchid et al., 2014).

In this study, we employed PCA to compare various network variables in the polycentricity literature, including in-degree, coreness, eigenvector, total-degree, closeness, and out-degree. The objective was to identify the most relevant variables to use in our cluster analysis and better understand the dynamics of polycentricity in watershed governance systems.

Our PCA analysis allowed us to reduce the complexity of the network data and identify essential variables that capture the underlying variation in the polycentricity literature. By reducing the dataset's dimensions, we could easily visualize and interpret the relationships between the various network variables and their impact on the overall network structure.

Our findings highlight the importance of in-degree and coreness as the most influential variables in determining the polycentricity of watershed governance systems. By understanding the key factors contributing to the emergence of polycentricity in governance networks, we can develop more effective delineation between research communities.

Cluster analysis – k-cores

Earlier scientometric analyses of polycentricity have sought to minimize the Babel Tower effect by dividing researchers into linguistic groups, unable to understand one another (van Meeteren et al., 2015). To overcome the limitations of Louvain's modular method, we apply a k-core hierarchical

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classification technique to enhance our ability to find community boundaries corresponding to k-core selected categories (Alvarez-Hamelin et al., 2005). This method enables us to produce a new "map" of polycentricity communities in the research literature and differentiate distinct communities of scholarly interest.

We applied a partitioning method using k-cores of our polycentric literature network for the classification and analysis of multivariate observations. A k-core decomposition of a network graph is "a maximal connected subgraph in which every vertex is connected to at least k vertices in the subgraph. K-core decomposition is often used in large-scale network analysis, such as community detection" (Sariyüce et al., 2013, p. 433). There are five classes of clustering methods or partitioning methods: k-means (Appendix 6-9), hierarchical clustering (Appendix 16), density-based clustering, model-based clustering, and fuzzy clustering (Sai Krishna et al., 2018). Researchers commonly use K-core decomposition in other disciplines, such as ecology and genetics. This method helped answer two central research questions. First, what is the correct number of communities? Furthermore, how can we differentiate distinct communities of scholarly interest? Based on the k-core analysis, we produce a new "map" of polycentricity communities in the research literature.

In contrast, van Meeteren et al. (2015) study applies a different, less reproducible method to distinguish community boundaries. We argue that the k-core hierarchical classification technique (Alvarez-Hamelin et al., 2005) although a more computationally resource-intensive approach compared to previous clustering efforts, enhances our ability to find community boundaries corresponding to k-core selected categories in a reproducible way.

Research efforts have been made to calculate k-cores (Alvarez-Hamelin et al., 2005; Cui et al., 2014; Sariyüce et al., 2013). Using R software (Core Team, 2013) analytic tools, we visualize k-means clusters and apply a "process for partitioning an n-dimensional population into k sets based on a sample" (MacQueen, 1967, p. 281). K-means clustering can classify observations into k-groups based on their similarity. Analysts represent each group by the mean value of points, known as the cluster centroid (Montresor et al., 2011). The k-core of a graph is the largest subgraph in which every vertex is connected to at least k other vertices within the subgraph. Core decomposition finds the k-core of the chart for every possible k (Cheng et al., 2011). This method allowed us to differentiate our research communities within the broader polycentricity literature network.

The k-means algorithm requires users to specify the number of communities to generate. We visually explored six k-core values of our polycentric literature (Appendix 9). Although this visual assessment tells us where delineations occur between clusters, it does not tell us the optimal number of groups.

Determining the number of K-core communities

Partitioning clustering methods, like k-means, require specifying the number of clusters generated. K-means clustering is one of the most well-known partitioning methods. It involves defining sets using the total within-cluster variation, which measures the compactness of the clusters to ensure it is

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optimized. We aim to answer questions like “What makes this cluster unique?” and “Which clusters are like one another?”

We first apply the Elbow Curve method to evaluate our polycentric network of communities (Bholowalia & Kumar, 2014; Humaira & Rasyidah, 2020). Probably the most well-known method for exploring community composition, the Elbow Curve method applies the sum of squares at each number of clusters to calculate and graph the network. The aim is to look for a slope change from steep to shallow (an elbow) to determine the optimal number of clusters. The Elbow Curve method (Appendix 13) is helpful because it shows how increasing the number of collections contributes to separating the groups meaningfully, not marginally. This method is inexact but still potentially helpful.

A helpful tool to analyze network k-cores is the R package “NBClust” (Charrad et al., 2014). The NBClust package provides 30 indices for determining the number of clusters. It presents the best clustering scheme for the results obtained by varying all combinations of several groups, distance measures, and clustering methods (Appendix 10). The NBClust analysis corroborated other single methods, such as the elbow method, to describe the optimal number of polycentricity literature communities or clusters (Appendix 10-15). Moreover, we conduct a clustering validation exercise applying other methods to evaluate the results of a clustering algorithm (Halkidi et al., 2001).

Text analysis

We analyzed the metadata from each article, including author, publication date, and article titles, using the qualitative analysis software Nvivo (QSR, 2020). We present the results of the word cloud analysis in Appendix 17-24 and a summary of our text and coded theme analysis in the results section.

Next, we report on our results.

Results

Since the late 1990s, there has been a significant increase in annual citations that used “polycentricity” in their title (Appendix 1) with various definitions (Appendix 25). This section summarizes our results from a bibliographic survey and network analysis of polycentricity literature. We used the standard search engine, Google Scholar (see Appendix 1), to generate bibliographic data. Using network analytics, we group “communities of literature” based on common citations.

Bibliographic search engine results

On October 29, 2021, we searched for “polycentricity” using four widely used bibliographic search engines: Google Scholar, Microsoft Academic, Scopus, and Crossref. The results of our search are summarized in Table 1. Interestingly, our review revealed significant variations between the scholarly research databases, showing that each database may be more suitable for specific research goals or questions.

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Table 1. Summary of search engine results for “polycentricity” as of October 2021.

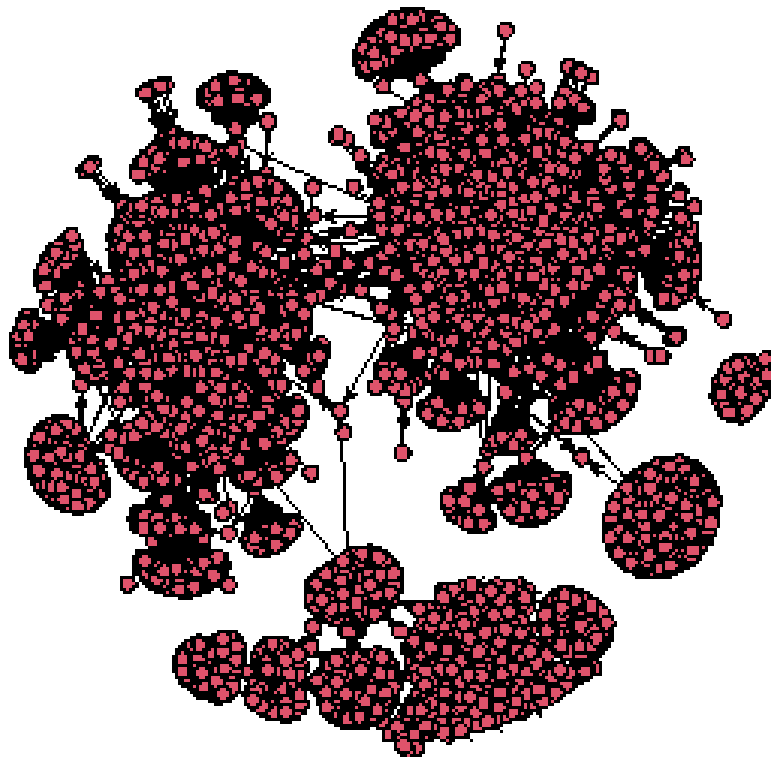
	Google Scholar	Microsoft Academic	Scopus	Crossref
Publication years	1967–2021	1937–2021	1981–2020	1996–2021
Citation years	54	84	40	25
Abstract	Partial	Yes	No	Partial
Papers	997	621	200	288
Citations	24,504	17,453	12,415	3,955
Citations/year	454	208	311	158
Citations/paper	25	28	62	2
Age-weighted citation rate	3323	2,283	1,662	608
Authors/paper	1.9	2.2	1.0	1.9
Hirsch h-index	75	71	58	35
Egghe g-index	142	126	100	59
PoP hl, norm	57	52	58	24
PoP hl, annual	1.1	0.6	1.5	1.0
Fassin hA-index	27	22	17	11

Table 1 summarizes the search engine results for "polycentricity" as of October 2021. The table shows each search engine's publication years and citation years, the number of papers and citations found, and the citation rate per year and per paper. The table also displays the age-weighted citation rate, authors per paper, Hirsch h-index, Egghe g-index, PoP hl (norm and annual), and Fassin hA-index for each search engine. Microsoft Academic has the highest number of citation years and Crossref has the lowest number of citation years. Google Scholar has the highest number of papers and citations found. Scopus has the highest citations per paper and age-weighted citation rate, while Crossref has the lowest citations per paper and age-weighted citation rate. Google Scholar has the highest Hirsch h-index, Egghe g-index, PoP hl (norm and annual), and Fassin hA-index.

Network analysis results

We developed a network analysis framework for the whole network of polycentricity citations. We show a network map of polycentricity literature in Figure 1. Each node stood for a literary work (article or book), and each edge stood for a reference or citation found in the original work.

Figure 1. The network map of polycentricity literature was found on the Google Scholar database (October 29, 2021). The red dots are Google Scholar articles analyzed. Edges are literature citations.



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Figure 1 is a network map that visualizes the polycentricity literature found on the Google Scholar database as of October 29, 2021. The red dots represent the analyzed Google Scholar articles, and the edges represent literature citations. The map shows several distinct clusters of literature, each with its own set of closely connected articles. These clusters are interconnected through several literature citations, indicating that there is a significant overlap between the different clusters. The visualization allows for a quick overview of the literature. It highlights the relationships between different articles, making it easier to show the most influential and relevant works. We present a summary of several whole-network attributes in Table 2.

Table 2. Network properties of recent polycentricity citations.

Network attributes	Network
Nodes (vertices)	7,355
Directed	TRUE
Edges	10,896
Density	0.0002

Table 2 shows the network properties of recent polycentricity citations. The network has 7,355 nodes (vertices) and is directed. There are 10,896 edges, showing several connections between the different nodes in the network. The network's density is 0.0002, which means that the network is sparse, with only a tiny percentage of possible connections present. Overall, these network properties suggest that the polycentricity literature is complex and interconnected, with many articles cited and being cited by others in the network.

Next, we analyzed the total number of citations and the network degree of each node (Figure 2). A summary of network metrics and their characteristics, including their contribution to the two-dimensional k-core analysis, are presented in Appendix 6-8.

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Figure 2. A graph of the degree value. Each node reflects the number of citations from the primary polycentricity articles. In this study, the node degree measures sources in each piece reflected as network edges.

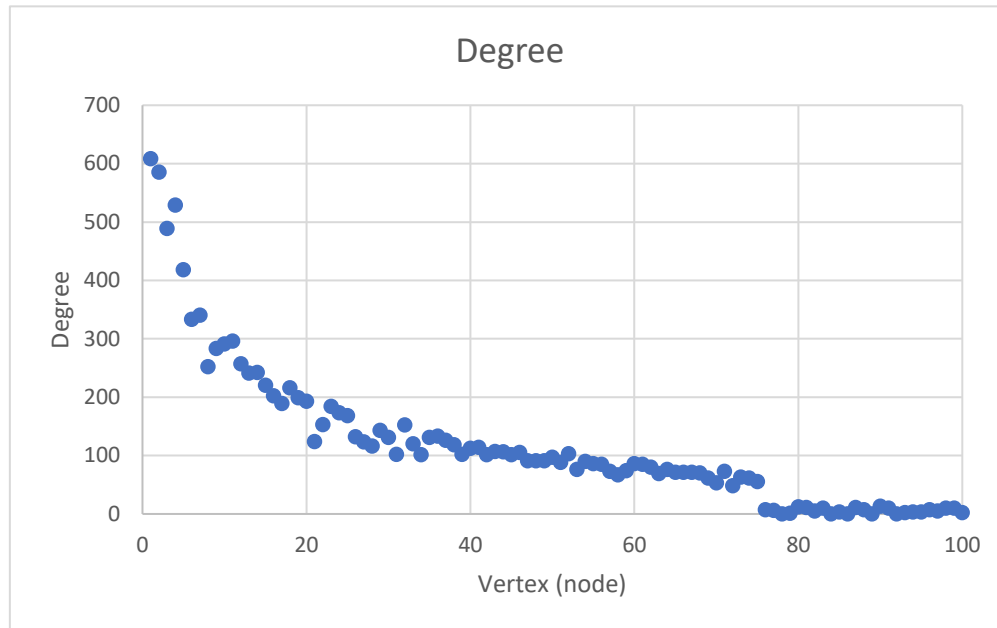


Figure 2 is a graph that shows the degree value of the primary polycentricity articles. Each node in the graph represents the number of citations the primary article has received, and the node size corresponds to the number of articles citing it. The edges between the nodes represent the connections between articles based on their citation relationships. The graph shows several highly valued articles, showing that many others have cited them. These articles are likely to be meaningful and influential in polycentricity. Visualizing the degree value of primary articles helps show the most influential and well-cited articles, providing a valuable tool for researchers to explore the literature and discover new avenues for their research.

We examined all 997 documents in Google Scholar for their citation linkages and found that more than 80% of the citations were concentrated in the top 27 primary articles. Beyond these, we noticed a decline in the number of citations to other reports, with a second drop occurring after the top 75 most cited articles, as depicted in Figure 2. As a result, we excluded primary reference documents with no citations, resulting in 397 articles published between 1975 and 2021. We then created a database of the citations from these 397 primary articles, forming a network of 7,355 documents in the polycentricity literature.

With the entire network of articles and citations described and found, we turn our analysis to show clusters of pieces standing for distinct communities of polycentricity research and knowledge generation.

Finding communities of knowledge within the network of polycentricity literature

In this study, we conducted a comprehensive network analysis to gain insights into the dynamics of polycentricity in watershed governance systems. To summarize our findings, we present a PCA diagram in Figure 3, which illustrates the critical node information from our analysis.

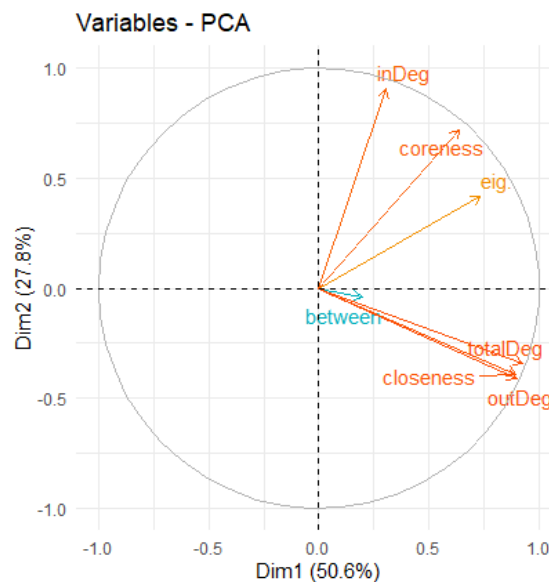
To better understand the network, we explored several ego-network indicators, including eigenvector centrality, closeness, coreness, out-degree, in-degree, all-degree, and betweenness, as detailed in Appendix 6. Our analysis revealed two dimensions that accounted for over 78% of the network variance, as shown in Appendix 7.

The variables that contributed most significantly to the first dimension, as outlined in Appendix 8, were total degree (24%), out-degree (23%), closeness (23%), and eigenvector centrality (15%). These variables indicate the network's structure and connectivity and suggest that the nodes with a high total degree, out-degree, closeness, and eigenvector centrality play a crucial role in the overall functioning of the network.

For the second dimension, the contributions from our ego-network measures included in-degree (41%) and coreness (25%). This dimension reflects the extent to which nodes are connected to other highly central nodes and the level of influence these nodes exert on the network.

Overall, our findings shed light on the complex interplay of different factors contributing to the emergence of polycentricity in watershed governance systems. We can develop more effective policies and interventions to promote sustainable water management by identifying the key variables that shape the network structure and dynamics.

Figure 3. Social network variable attributes PCA analysis.



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PCA is a powerful statistical technique that helps us show hidden linear patterns in a dataset and express them in terms of a lower-dimensional dataset without losing crucial information (Sanò & Medina, 2012). In our study, we used PCA to visualize and assess the network metrics of our polycentricity literature dataset.

We examined two aspects of our analysis: firstly, we investigated which network variables were included in the k-core analysis, and secondly, we explored how each of the network indicator variables contributed to different dimensions of the k-core analysis.

By leveraging PCA, we were able to gain a deeper understanding of the complex network structure of our dataset and show the critical variables that shape it. Our study highlights the importance of using advanced statistical techniques such as PCA to analyze complex datasets and extract meaningful insights that can inform policy and decision-making.

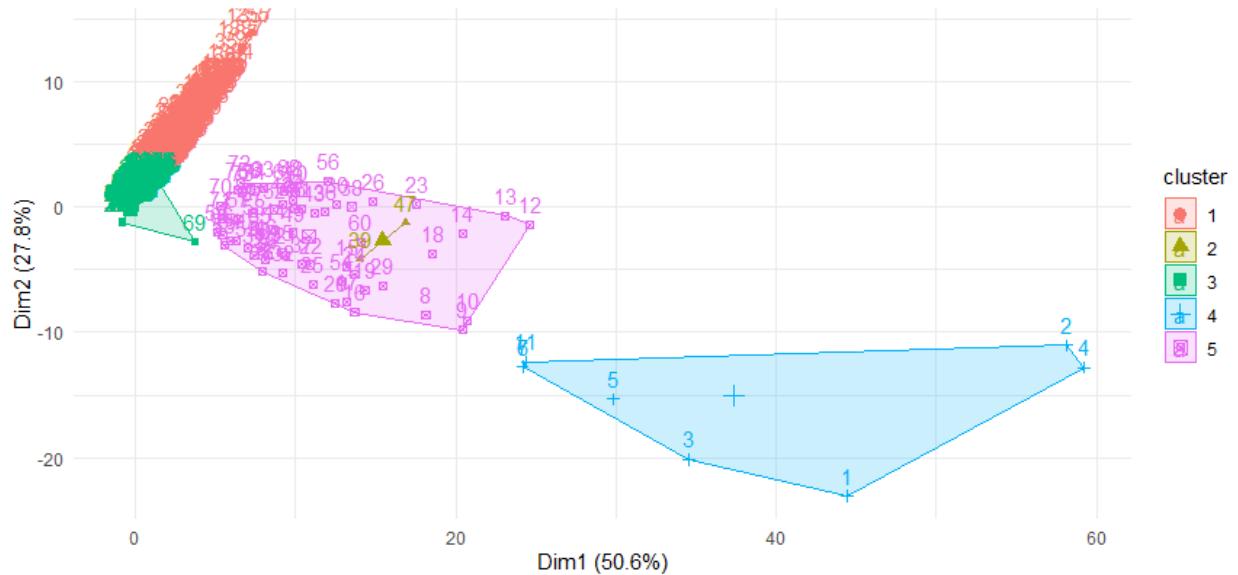
k-core communities

In October 2021, we conducted a k-core community analysis to show distinct communities within our Google Scholar database search results for polycentricity literature. This method enabled us to group our data based on different levels of communities and supplied several options for analysis.

To find the optimal number of k-clusters for our analysis, we examined six k-core classifications and used statistical tests, including the Elbow Curve method and NBClust analysis. Our results revealed five distinct communities of polycentricity literature, as shown in Figure 4.

Our study highlights the effectiveness of the k-core approach in analyzing complex networks and showing distinct communities, especially when compared with other methods such as Louvain's modular method. These findings can inform future research on polycentricity and help researchers gain a deeper understanding of the various applications of this concept in different fields, including governance, transportation, urban-centre development, and law. Our study underscores the importance of using advanced statistical techniques to analyze complex datasets and show meaningful insights that can inform policy and decision-making.

Figure 4. A visual summary of k-core community clustering of contemporary polycentric literature.



- 1. Urban spatial (red) | 2. European Planning (yellow) | 3. Commons (green)**
4. Legal (blue) | 5. Development (purple)

Figure 4 is a visual summary of k-core community clustering of contemporary polycentric literature. The visualization shows five distinct clusters, each with a different colour and labelled with a thematic keyword. The clusters are identified as follows:

1. Urban spatial (red)
2. European Planning (yellow)
3. Commons (green)
4. Legal (blue)
5. Development (purple)

The clusters stand for highly related articles and share common citation patterns, indicating that they are part of a broader thematic area within the polycentricity literature. This visualization provides a quick overview of the main thematic areas within the polycentricity literature and can be used to identify the most influential works within each cluster. Next, we show in Table 4 the most referenced articles in each of the five groups of polycentricity.

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Table 4. Classification of polycentricity communities with a summary of findings from article title text analysis, coded theme analysis, and influential scholars from each of the five k-core clusters.

Community	Community Name	Text analysis of citation titles (Count, weighted %)	Authors of top citations	Water and watershed (Count, coverage %)
1	Urban spatial	Urban (116, 3.9%)	Duhr et al., 2010 (521)	Water (7, 0.1%)
		Spatial (72, 2.5%)	Hillier, J. 2017 (444)	Watershed (1, 0.03%)
		Spatial (286, 0.9%)	Burger & Meijers, 2012 (384)	Water governance (4, 0.2%)
		Structure (49, 1.7%)	Green, N., 2007 (384)	Watershed governance (1, 0.06%)
		Development (46, 1.6%)	Carlisle & Gruby, 2019 (259)	
2	European Planning	European (3, 15.8%)	Davoudi, S. 2003 (736)	Water (0)
		Planning (3, 15.8%)	Shaw & Sykes 2004 (88)	Watershed (0)
		Spatial (3, 15.8%)		
		Agenda (1, 5.2%)		
		Metropolitan (1, 5.2%)		
3	Commons	Urban (951, 1.5)	Berkes, F., 2017 (5532)	Water (272, 0.2%)
		Governance (873, 1.4%)	Ostrom, E., 2010 (4037)	Watershed (23, 0.03%)
		Spatial (487, 0.8%)	Folke et al., 2002 (3986)	Water governance (63, 0.2%)

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		Case (399, 0.7%)	Liesbet & Gary, 2003 (3469)	Watershed governance (4, 0.01%)
		Social (399, 0.7%)	Birkland, T. 2019 (2650)	
4	Legal	Legal (6, 13.4%)	Richardson et al., 1990 (96)	Water (0)
		Law (4, 8.7%)	Griffith D., 1981 (72)	Watershed (0)
		Pluralism (4, 8.7%)	Sinha, S., 1993 (46)	
		Analysis (1, 2.2%)	Griffiths, J., 1995 (42)	
		CBD (1, 2.2%)	Zahle, H., 1995 (21)	
5	Development	Development (10, 2.8%)	Kloosterman & Musterd, 2001 (846)	Water (0)
		Legal (9, 2.5%)	Gordon & Richardson, 1996 (667)	Watershed (0)
		Policies (8, 2.0%)	Ostrom, V. 1999 (402)	
		European (7, 2.0%)	McGinnis, 1999 (392)	
		Spatial (7, 2.0%)	Coffey and Shearmur, 2002 (287)	

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Table 4 summarizes the findings of the classification of polycentricity communities. The table lists five k-core clusters: Urban spatial, European Planning, Commons, Legal, and Development. The table provides information about text analysis of citation titles, authors of top citations, and water and watershed coverage percentages. The table shows that the Urban spatial community focuses on urban and spatial development, while the European Planning community primarily focuses on European planning and metropolitan areas. The Commons community is focused on governance, spatial planning, and social cases. The Legal community is focused on legal pluralism, while the Development community is focused on policies and development. Finally, the table shows that no communities have significant coverage of water or watershed-related topics.

Our analysis of the citation relationships within the polycentricity literature found five distinct communities, as shown in Figure 4. However, we found that these communities varied in size and supplied different insights into how polycentricity has been developed and defined across various disciplines.

Table 5. k-core communities and a corresponding number of articles found in each community.

K-core	1	2	3	4	5
Given name	Urban spatial	European Planning	Commons	Legal	Development
No. Citations	4427	2	6961	8	64
(%)	(39)	(0.02)	(61)	(0.07)	(0.6)

Table 5 shows the number of articles found in each of the five k-core communities found in the study and the corresponding number and percentage of citations within each community. The Commons community had the highest number of citations (6961 or 61%), followed by the Urban Spatial community (4427 or 39%). The European Planning community had only 2 citations (0.02%), while the Legal and Development communities had 8 citations (0.07%) and 64 citations (0.6%), respectively.

Of note is our k-core analysis, which revealed that clusters one (Urban Spatial) and three (Commons) share closer citation networks than they do with cluster four (Legal). These finding sheds light on the interconnections between different aspects of polycentricity research and highlights the importance of considering multiple perspectives when studying this concept.

By supplying a more nuanced understanding of the citation relationships within the polycentricity literature, our study contributes to the broader literature on complex networks and interdisciplinary research. These insights can inform future research on polycentricity and related concepts, such as

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governance, urban development, transportation, and law, ultimately advancing our understanding of how these systems function and evolve.

Next, we focus on situating water governance literature within the five communities of polycentricity literature.

Water Governance in polycentricity literature

To gain deeper insights into the polycentricity literature and find the study of watershed governance, we employed a k-core cluster analysis. We sorted our database based on k-core cluster scores and thoroughly examined each cluster to find articles about water(shed) governance. To better understand the key themes and concepts associated with each polycentricity community, we created word clouds that display the most often used terms in the article titles (see Appendix 17-23). By analyzing these terms, we could characterize the five communities and present our findings in an easy-to-read format in Table 4. This method supplied a comprehensive overview of the literature, allowing us to show the communities where the study of watershed governance is most prominent and better to understand the key themes and concepts within each community.

Through our analysis, we discovered that the concepts of water governance are embedded in two communities of interest in the polycentricity literature, namely Urban spatial polycentricity and Commons polycentricity. This finding is consistent with our prior knowledge of the water governance literature. It is a valuable contribution to the knowledge base of water(shed) scholars looking to connect different research areas. Our analysis is beneficial in bridging the gap between urban spatial polycentricity, commons polycentricity, and water governance research by highlighting literature citations associated with our field of interest.

In the next section, we provide a discussion about our research results.

Discussion

In this study, we aimed to use scientometric analysis to explore how polycentricity has been applied in water governance and to show the various communities of scholars who have studied this concept. By examining these communities' methodologies, theories, and research questions, we can better understand how polycentricity has been approached and used in the study of water governance. This analysis will help us find gaps in our understanding of polycentric water governance and opportunities for future research and collaboration. Since the meanings of polycentricity and governance have evolved over time and across different communities, our systematic review of the literature on polycentricity also highlights the different paths of development and where research on water governance fits into this broader field.

Sociometric analysis is a powerful technique for examining social relationships and network interactions. It is instrumental in understanding the concept of polycentricity, which involves the distribution of power and authority across multiple centers. By analyzing the relationships and interactions between authors in a network of published work, sociometric analysis can provide insights into the interconnectedness and cooperation between centers within the network. This information is crucial for

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understanding how a concept like polycentricity is applied across multiple centers and its implications for the functioning of the network. Sociometric analysis can reveal the level of conceptual cohesion between centers and help us identify areas where cohesion between research communities is low. Overall, sociometric analysis is a valuable tool for understanding the complex dynamics of polycentric literature networks.

Our analysis uncovered five distinct communities of polycentricity research: Urban Spatial, European Planning, Commons, Legal, and Development. We have represented these communities as branches of knowledge in Figure 5, which we constructed using network analysis and k-core community clustering. This scientometric approach allowed us to show and visualize the different groups of polycentricity literature. Our findings supply valuable insights into the diverse nature of polycentricity research and highlight the distinct communities of practice around this concept (see Figure 5). The representation of these five communities of polycentricity knowledge reflects the breadth and depth of research that has been conducted on this topic.

Figure 5. Branching knowledge tree representation of the five communities of polycentricity research.

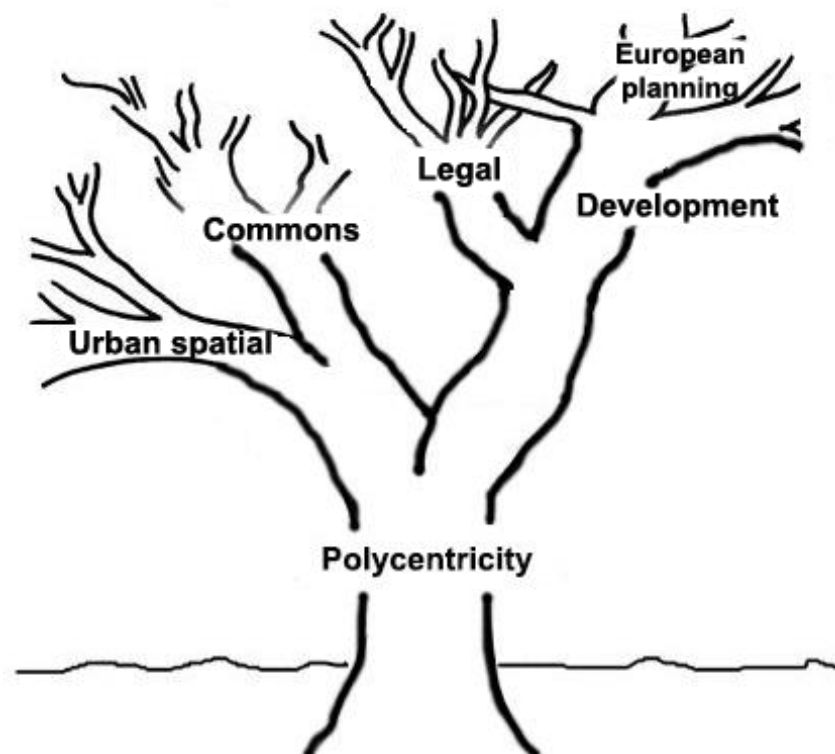


Figure 5 is a visual representation of a branching knowledge tree showing the five communities of polycentricity research. The tree is divided into five main branches, each representing a different community of research: Urban spatial, European planning, Commons, Legal, and Development. The size of each branch indicates the number of articles published on each topic, with larger branches representing more articles. The tree provides a visual overview of the different topics and subtopics

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within each research community and can be used to identify the most popular and influential areas of study. Understanding the unique communities within the field of polycentricity is crucial for researchers to collaborate effectively and share knowledge across disciplines. The concept of polycentricity has evolved significantly over time, resulting in various normative, descriptive, and diagnostic definitions, including constitutional structures, power dynamics, and effective coordination methods.

To supply a glimpse into these definitions, we present three examples from our literature review analysis in Table 6, which highlight distinct aspects of polycentricity in the Legal, Urban Spatial, and Commons communities (for a more comprehensive list, see Appendix 25). These examples offer valuable insights into the diverse branches that have contributed to developing polycentricity and its relevance to different research communities. By examining these communities and their unique perspectives, researchers can better understand polycentricity as a concept and its applications across a wide range of fields.

Table 6. Examples of three evolutionary branches of the concept of polycentricity with different ideas and applications in other research communities (social frameworks).

Community of research	Legal	Urban spatial	Commons
	Legal polycentricity is a situation that is many-centred, with interacting points of interest – each crossing of strands in a distinct center for distributing tensions. (Fuller & Winston, 1978, p. 395)	Urban spatial polycentricity uses spatial models that operate at a fine scale in which individual agents of a population move, grow, and decline through processes of decision-making incorporating positive feedback (Batty, 2001, p. 636) Planners use functional polycentricity to describe urban centers in planning policies. Urban centers are a network of internationally accessible metropolitan regions and their linked hinterland (towns, cities, and rural areas of varying sizes). (Green 2007).	Commons polycentricity refers to multiple governing authorities at differing scales, and each unit within a social-ecological system exercises considerable independence to make norms and rules within a specific domain. Participants in a polycentric system have local knowledge and constantly learn (Ostrom 2010).

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Table 6 presents three examples of the different evolutionary branches of polycentricity and their applications in various research communities. The Legal branch is defined as a situation with many interacting points of interest, while the Urban Spatial branch uses spatial models that incorporate decision-making processes. The functional polycentricity in the Urban Spatial branch describes urban centers in planning policies. On the other hand, the Commons branch refers to multiple governing authorities at different scales, with each unit exercising considerable independence to make norms and rules within a specific domain. The participants in this branch have local knowledge and are constantly learning. These examples supply insight into how polycentricity has evolved and its relevance to different research communities.

Social scientists have described polycentricity using various disciplinary, ontological, and epistemological lenses. Polycentricity scholars remind us that

empirical studies have employed definitions of polycentricity that are not entirely consistent with one another and do not capture the full import of the concept as conceived by V. Ostrom et al. (1961) thereby **impeding systematic theoretical development** [emphasis added]. (Carlisle & Gruby, 2019, p. 22)

Carlisle and Gruby (2017) emphasize that conceptual homonyms create frequent impediments. Furthermore, researchers observed that

polycentricity is plagued by inherent contradictions and assumptions and that some significant gaps in knowledge remain...The emergent benefit of certain types of polycentricity has been alluded to in the literature but is yet to be systematically explored and exploited by analysts and practitioners. (Morrison et al., 2019, p, 2,6)

Our analysis has shown that polycentricity has developed and been defined differently across various research communities. We present our detailed findings on the five distinct polycentric communities to shed light on this. In the following sections, we highlight some of the characteristics of each community.

Urban spatial polycentricity

Urban spatial planning is one of the largest polycentricity research communities, accounting for 39% of the analyzed literature. This community has extensively studied polycentricity in urban centers, which has resulted in well-developed concepts and theories, including discussions of morphological and functional polycentricity. Scholars in this field compare the relationships between cities, examine the networks of flows and cooperation between urban areas of different scales, and focus on analyzing the social factors that affect urban centers, such as traffic, transportation, electricity grids, and water infrastructure. This community's research has contributed to the evolution of the concept of polycentricity and has produced significant publications on theoretical and methodological considerations. Scholars have identified two significant elements of polycentricity - morphological and relational - and continue to focus on its application as an analytical concept. As a result, this active research arena has led to significant publications (Halbert, 2008; Hanssens, Derudder, Van Aelst, & Witlox, 2014; Li, Zhu, & Wang, 2019; Meijers, Hoogerbrugge, & Cardoso, 2018; Sarkar, Wu, & Levinson, 2019; Yue, Qiu, Xu, Xu, & Zhang, 2019; Zhao, Derudder, & Huang, 2017) on the theoretical and methodological aspects of polycentricity in urban spatial planning.

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Polycentricity in urban centers has been a well-developed concept in urban geography, arising from studies describing polynucleated city systems and urban landscapes (Batty, 2001). Discussions of morphological and functional polycentricity (Burger & Meijers, 2012) have been central to this community's dialogue and contextual arguments. Scholars in this field compare the relationships between cities and examine the networks of flows and cooperation between urban areas of different scales. *Functional polycentricity*, an analytical concept rather than a normative one, is a significant aspect of this community's research, as it enhances our understanding of urban centers and their social factors, such as traffic and transportation (Yingcheng et al., 2019), electricity grids (Buchmann, 2017), and water infrastructure (Porse, 2018).

European planning polycentricity

The European planning polycentricity community is a significant subset of the polycentricity literature and closely relates to the Development polycentricity community. Despite its growing influence on spatial policy discourse, the exact meaning of polycentricity in this context is still difficult to pinpoint (Davoudi, 2003). Researchers in this cluster argue that polycentric development has become a defining feature of European spatial planning and serves as a conceptual framework for understanding interconnections and interdependence (Shaw & Sykes, 2004). This community continues to explore a range of political, economic, and geographic considerations within the European spatial planning field.

The European planning polycentricity community is a significant branch of the polycentricity literature, closely related to the Development community. Despite its increasing influence on spatial policy discourse, the precise meaning of polycentricity in this context stays elusive (Davoudi, 2003). Scholars in this group argue that polycentric development is a defining feature of European spatial planning and serves as a conceptual framework for understanding interconnections and interdependence between different regions and cities (Shaw & Sykes, 2004). This community continues to delve into various political, economic, and geographical factors within the European spatial planning domain.

One significant contribution from this community is the idea of "multi-level governance," which acknowledges that various levels of governance, including local, regional, national, and European, all play a role in shaping spatial development policies. Scholars in this community also recognize the importance of networked governance, which emphasizes the need for coordination and cooperation between different actors, including public and private institutions, civil society organizations, and community groups, to achieve effective spatial planning outcomes (Healey, 2004).

Furthermore, scholars in this community continue to explore the role of polycentricity in promoting sustainable development and social cohesion. They argue that polycentric development can help to reduce spatial inequalities and promote economic growth in peripheral regions, while also preserving natural resources and promoting social inclusion (Böhme et al., 2014). This research community's active and ongoing contributions to the polycentricity literature highlight the significance of polycentric development as a framework for understanding and promoting sustainable spatial development in the European context.

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Commons polycentricity

A diverse body of literature characterizes this group of researchers and is heavily influenced by the works of Nobel laureate Elinor Ostrom. Dr. Ostrom's research on the water industry in California and her collaboration on polycentric systems for governing metropolitan areas led to a common framework consistent with game theory, which advanced knowledge of common-pool resource systems. Researchers have developed several frameworks within this community, including the institutional analysis and development framework and the management and transition framework, to analyze social-ecological strategies.

A central research topic in this community is social-ecological governance (Thiel et al., 2019), and scholars have made significant progress in understanding the complexities of social-ecological systems. For instance, previous studies have shown that central governance systems limit adaptive capacity within a water governance system (Pahl-Wostl and Knieper, 2014). Researchers have demonstrated that polycentric systems enhance adaptive water governance systems. The Westmill Co-Op wind farm project in England (Ostrom 2010) is an excellent example of a commons polycentric governance system that supported collaboration and coordination, resulting in a net reduction of GHG emissions.

This community is also interested in examining Indigenous knowledge and learning opportunities to form a community of knowledge holders (Berkes, 2017). Overall, the research in this community has provided valuable insights into social-ecological governance and demonstrated the potential of polycentric systems in enhancing adaptive water governance systems.

Legal polycentricity

Legal polycentricity refers to legal issues that involve adjudication and arbitration. Scholars in the field, such as Finck (2014) and Fuller & Winston (1978), have discussed this concept. Some legal scholars argue that polycentric disputes are unsuitable for adjudication, as said by King (2008).

Legal polycentricity has also been used in international legal theory and modern human rights law to describe a global, pluralist approach to the nature of law. This approach considers diverse civilizations, as highlighted by Garcia (1996). Scholars in this field have raised concerns about whether the current legal system, which has local origins, can meet the challenges of international society, as further discussed by Garcia (1996).

In simpler terms, legal polycentricity refers to legal issues that involve resolving disputes through adjudication or arbitration. Some legal experts believe such disputes cannot be resolved effectively through traditional methods. Additionally, legal polycentricity has been used to describe a pluralistic approach to the nature of law, which considers diverse civilizations. However, there are concerns that the current legal system, which has local origins, may not be able to meet the challenges of a global society.

In jurisprudence, legal philosophy, legal polycentricity is a concept that emphasizes the diversity and conflicting nature of values within the legal system. Sinha (1993) describes legal polycentricity as the belief that the best values are many and incapable of being harmonized into one singular vision. This

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concept highlights the intricate nature of legal systems and the difficulties in finding unified approaches to resolving disputes and defining legal values. Overall, legal polycentricity underscores the complexity of the legal system and the need to appreciate the diversity and multiplicity of legal values.

The legal polycentricity community is based on "polycentric tasks" as described by Fuller and Winston (1978, p. 394). Petersen and Zahle (1995) delve into legal polycentricity and its practical applications in their text. Moreover, polycentricity has been used to describe entire legal systems. For example, the Chinese legal system is referred to as "radically polycentric" due to the lack of a single source of ultimate authority, as pointed out by Clarke (2005, p. 65). In essence, the legal polycentricity community draws from the idea of polycentric tasks, which emphasizes the need for multiple decision-making centers in legal systems. Additionally, polycentricity can also be used to describe legal systems where no single source of ultimate authority exists, such as in the Chinese legal system.

The polycentricity cluster primarily focuses on legal studies and includes economic and urban geographic studies. Within this legal polycentricity community, various research disciplines show the interdisciplinary nature of polycentricity research and highlight the diverse literature available. Therefore, legal polycentricity is not confined to legal studies alone but extends to other fields that share its principles. The interdisciplinary nature of this community emphasizes the need for collaboration across different research areas to gain a holistic understanding of polycentricity. This approach encourages researchers to explore polycentricity from multiple perspectives and to gain insights from various fields.

(Urban landscape) Development polycentricity

A small but notable community within the polycentricity literature focuses on urban landscape development. Within this cluster, polycentricity refers to either intra-urban patterns of population and economic activity clustering, as seen in cities like Los Angeles, London, and Paris, or interurban patterns, as seen in the Dutch Randstad and the Padua-Treviso-Venice area in northern Italy (Kloosterman & Musterd, 2001).

This polycentricity research community contributes significantly to various fields, including spatial analysis, demography, economy, and planning. By examining the patterns of urban development and the clustering of population and economic activity, this community supplies insights into the complex dynamics of modern urban landscapes. Therefore, the interdisciplinary nature of this research community provides a holistic understanding of the complexities of urban development and contributes to knowledge in various fields.

This group uses the concept of polycentricity to describe the clustering patterns of population and economic activity within or between urban areas. Their research significantly contributes to spatial analysis, demography, economy, and planning. Scholars argue that metropolitan areas can be governed effectively using polycentric arrangements involving multiple decision-making centers and bureaucratic organizations.

However, unlike the Commons polycentricity, this community of scholars mainly focuses on social systems, particularly governments, and does not typically consider ecological commons. To describe the

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political systems that involve multiple decision-making centers, an alternative term, *multinucleated political systems* (Ostrom et al. 1961), has been suggested as an alternative to polycentric political systems.

Therefore, the use of polycentricity in urban landscape development research supplies insights into the dynamics of metropolitan areas and the role of governance in managing them effectively. However, it is essential to recognize the limitations of the concept and explore alternative terminologies that may be more suitable for contexts.

This research community views society, particularly metropolitan areas, as polycentric systems. They argue that polycentric arrangements, characterized by multiple decision-making centers and bureaucratic organizations, can perform as efficiently as fully integrated systems with a single governing unit. Scholars argued that “no prima facie grounds existed for expecting less efficient performance from polycentric arrangements than from a fully integrated system with one governmental unit having exclusive jurisdiction over any particular metropolitan area” (V. Ostrom, 1999, p. 52).

Their research explores the governance patterns in metropolitan areas and how these political systems, with multiple centers of decision-making and bureaucratic organizations, produce public goods and services. They aim to provide insights into the management and governance of metropolitan areas to ensure the effective delivery of public goods and services to the community.

Now that we have explored the five clusters of polycentricity literature, we focus on how watershed governance fits into this diverse and intricate field.

Water governance and polycentricity

Polycentricity is considered a crucial concept in designing water governance systems, as several contemporary authors in the water governance literature have pointed out. The application of polycentricity theory in studying social-ecological and watershed governance systems has yielded a range of studies, some aimed at supplying a descriptive understanding of polycentricity. In contrast, others look to show the factors that shape its form. This is especially pertinent in water governance (Schröder, 2018).

Polycentricity theory is crucial in designing governance systems within the water governance literature. Contemporary authors in this field use polycentricity theory to describe social-ecological and watershed governance systems (Thiel, 2017). Some studies supply a descriptive understanding of polycentricity (Thiel and Moser, 2019), while others identify the explanatory factors that shape it (Pahl-Wostl, 2015). To clarify the operationalization of polycentric governance in water governance, recent research has summarized five definitions of polycentricity (Schroder, 2018). These definitions highlight the importance of defining good or problem specificity and boundary conditions, especially relevant in water governance.

Our analysis of polycentricity research takes a unique approach by combining social network analysis and k-core analysis to show five distinct communities within the literature. This method builds upon earlier scientometric analyses of polycentricity and supplies a more nuanced understanding of this

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multidisciplinary research. By examining these k-core communities, we can differentiate between various branches of polycentricity research, such as the Urban spatial research community, which introduced functional polycentricity (Green, 2007), and those that used functional polycentric governance systems to describe institutional features (Carlisle & Gruby, 2018). This analysis is essential for reducing confusion and misinterpretation of terminology and improving our comprehension of polycentricity research.

In the following section, we compare our analysis to previous scientometric studies and discuss how these findings help us better understand the different communities of polycentricity.

Contributions to scientometric analysis of polycentricity

To supply a comprehensive understanding of the diverse aspects of polycentricity theory and the evolving literature, we have found five distinct research communities. These communities contribute to the field with models from legal and commons literature, each with unique perspectives. To better visualize our findings, we compare our analysis with an earlier study by van Meeteren et al. (2015). Table 7 highlights the differences between the two scientometric analyses of polycentricity.

Table 7. Comparison of study results with a scientometric analysis.

Study title	Pacifying Babel's Tower: A scientometric analysis of polycentricity in urban research	Scientometric analysis of polycentricity: Networked communities of research interests
Study authors	(van Meeteren et al., 2015))	Jatel and Pahl-Wostl, 2023
Bibliographic database	Scopus	Google Scholar
Nodes (preliminary search)	509 (polycentricity*)	795 (polycentricity)
Nodes (first-degree nodes)	11,000	16,500
Edges (citations)	20,000	24,500
Community determination method	Louvain's modularity method (like ANOVA)	K-core hierarchical analysis method
Challenges	The algorithm's output depends on the order in which an analyst considers the nodes (Blondel et al., 2008, p. 4)	Computationally resource intense. Several communities need to be identified as <i>ex-ante</i> .
Scope / Improvement	Meta-study of academic literature in urban studies.	Analysis of broader contemporary academic literature. Enhanced reproducibility.
Number of communities	8	5
Community names	Governance, Inter-regional, Inter-urban, World City, Economic Geography, China, Intra-urban, Commuting	Urban spatial, European planning, Commons, Legal, Development

Table seven compares two studies on polycentricity in urban research: one by van Meeteren et al. (2015) and the current study. Despite using different bibliographic databases and community determination methods, the studies discovered different numbers and names of polycentricity research communities. The first study identified eight communities, while the second study showed five. The second study claimed improved reproducibility and analyzed a broader range of contemporary academic literature. Both studies met computational challenges, and while the first study used Louvain's modularity method, the second used the K-core hierarchical analysis method. The table supplies a concise summary of the similarities and differences between the two studies.

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Future research directions

The findings of this study suggest several avenues for future research. First, further exploration of the two distinct communities of polycentricity literature that engage with watershed governance could supply a deeper understanding of the application of polycentricity in this context. Second, continued efforts to develop reproducible methods for differentiating communities of polycentricity literature could lead to improved communication and collaboration between researchers working with this concept. Additionally, applying the k-core community composition analysis to other concepts with multiple definitions could supply valuable insights into the state of research within these fields. Finally, future research could explore the implications of stretching the concept of polycentricity in the literature and the potential consequences of blurring essential distinctions between definitions, theory, and application.

Practical implications

The scientometric study on polycentricity and watershed governance has several practical implications. First, it can inform scholars and practitioners about the current state of the literature on polycentricity and the distinct communities of research that engage with watershed governance. This can help researchers show gaps in the literature and develop new research questions that can contribute to a better understanding of polycentric governance in watershed management. Second, the study highlights the importance of developing a reproducible method for differentiating communities of literature. This can enhance communication and collaboration among researchers from different disciplines and communities. Third, the study supplies a valuable tool for policymakers and practitioners interested in implementing polycentric governance in watershed management. The findings can help them show the most relevant and up-to-date research on polycentric governance and watershed management. They can also use this information to design more effective policies and management strategies. The study has practical implications for advancing knowledge, improving communication and collaboration, and informing policy and practice in polycentric governance and watershed management.

We answer our research question, how can we differentiate distinct communities of scholarly interest, using scientometric analysis to find and analyze the different disciplinary definitions of polycentricity, and how do different research communities engage with polycentricity? By examining the similarities and differences in published works across various fields, this study supplies a better understanding of polycentricity and how it is applied across different disciplines. This knowledge can enhance communication and collaboration between research communities and inform policy and decision-making related to social-ecological systems, urban development, and governance. Overall, this research highlights the importance of a multidisciplinary approach to studying complex concepts like polycentricity and the potential benefits of using scientometric analysis to explore research communities and their conceptualizations.

Conclusion

In this manuscript, we analyze the citations available using a Google Scholar literature review for polycentricity. We apply a network analytic and k-core community analysis method to analyze the reference literature citations and show five communities of research that apply different evolutionary branches of the concept of polycentricity. We find this analysis method very helpful in contextualizing a research area of interest—water(shed) governance—within the backdrop of multiple research communities applying the concept of polycentricity.

This study helps defuse the Babel Tower effect through an improved understanding of distinct concepts, alerting scholars to several differences between polycentricity research communities. Multiple methods are applied to enhance our understanding of the polycentric literature network. First, applying k-core supplies a valuable and reproducible method to differentiate distinct communities within the literature. Further, we provide examples of each of the five distinct communities, with implications to theory and practice. Reflecting on the results of this study, we see that a scientometric analysis of an academic literature network of journal articles, such as Google Scholar, supplies a valuable method to reduce the stretching of a multi-disciplinary concept, such as polycentricity, as they continue to develop and evolve through time.

Two of the five polycentricity research communities reference water and watershed governance: Commons polycentricity and Urban spatial polycentricity. This creates a potential Babel Tower effect, although the distinction between water governance, in the first instance, involves social-ecological systems. At the same time, the latter concept is focused on urban system interactions. Both communities of polycentricity literature supply valuable perspectives, enhancing communications between and among multi-disciplinary researchers and practitioners.

Future analysis may address interesting questions that appeared in this analysis. For example, we chose one of four bibliographic repositories, Google Scholar, a database influenced by many algorithms, including earlier computer searchers by a researcher. Future research may apply this similar network and cluster analytics to enhance our understanding of complex terms applied differently in inter-disciplinary arenas and evolve through time.

To sum up, the meaning of polycentricity differs across various research communities, and there is no universal definition for this concept. To better understand how polycentricity applies to water governance, we traced the term's history and explored its etymology. Through a Google Scholar review and a network analytic and k-core community analysis method, we found five distinct research communities that use polycentricity differently. Two of these communities, Commons and Urban Spatial, offer valuable perspectives on watershed governance. Moving forward, scholars could receive help from a comparative or longitudinal approach to examine the evolution and performance of polycentric systems over time. Past studies have shown that adaptive water governance systems can receive help from polycentric approaches, while central governance limits their adaptive ability. By referring to the etymological roots of polycentricity, researchers can better apply the concepts found in the Commons and Urban Spatial communities to communicate polycentricity in watersheds.

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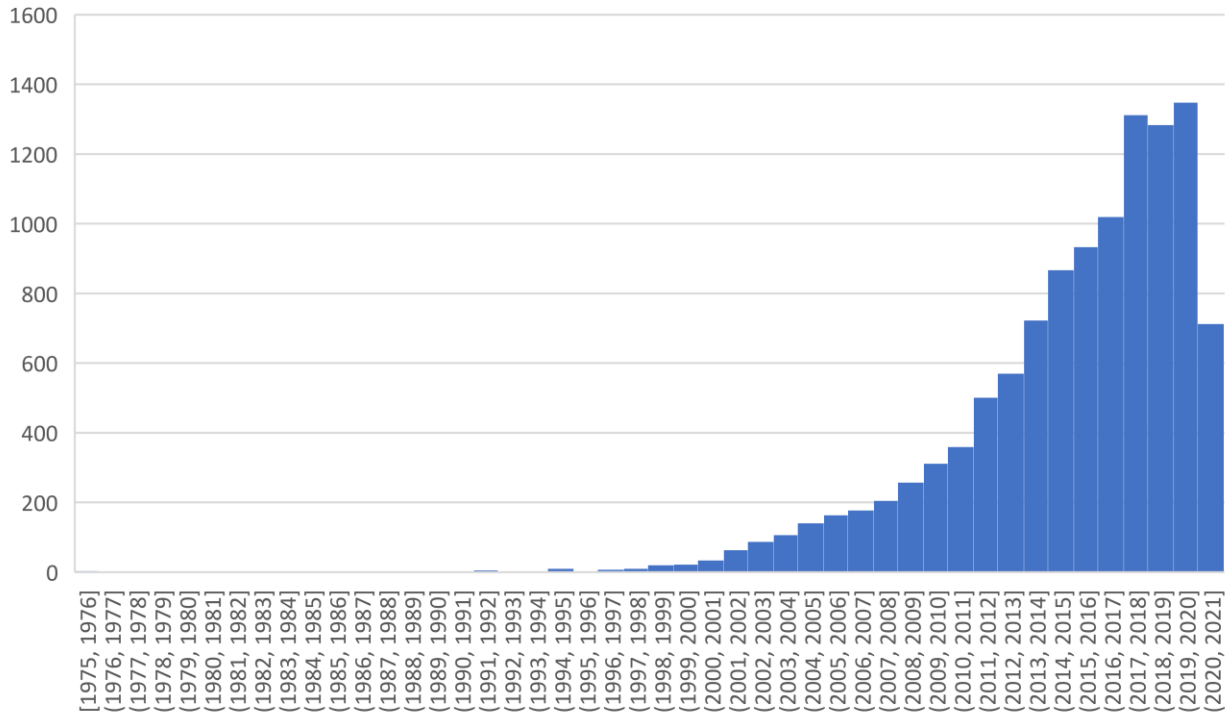
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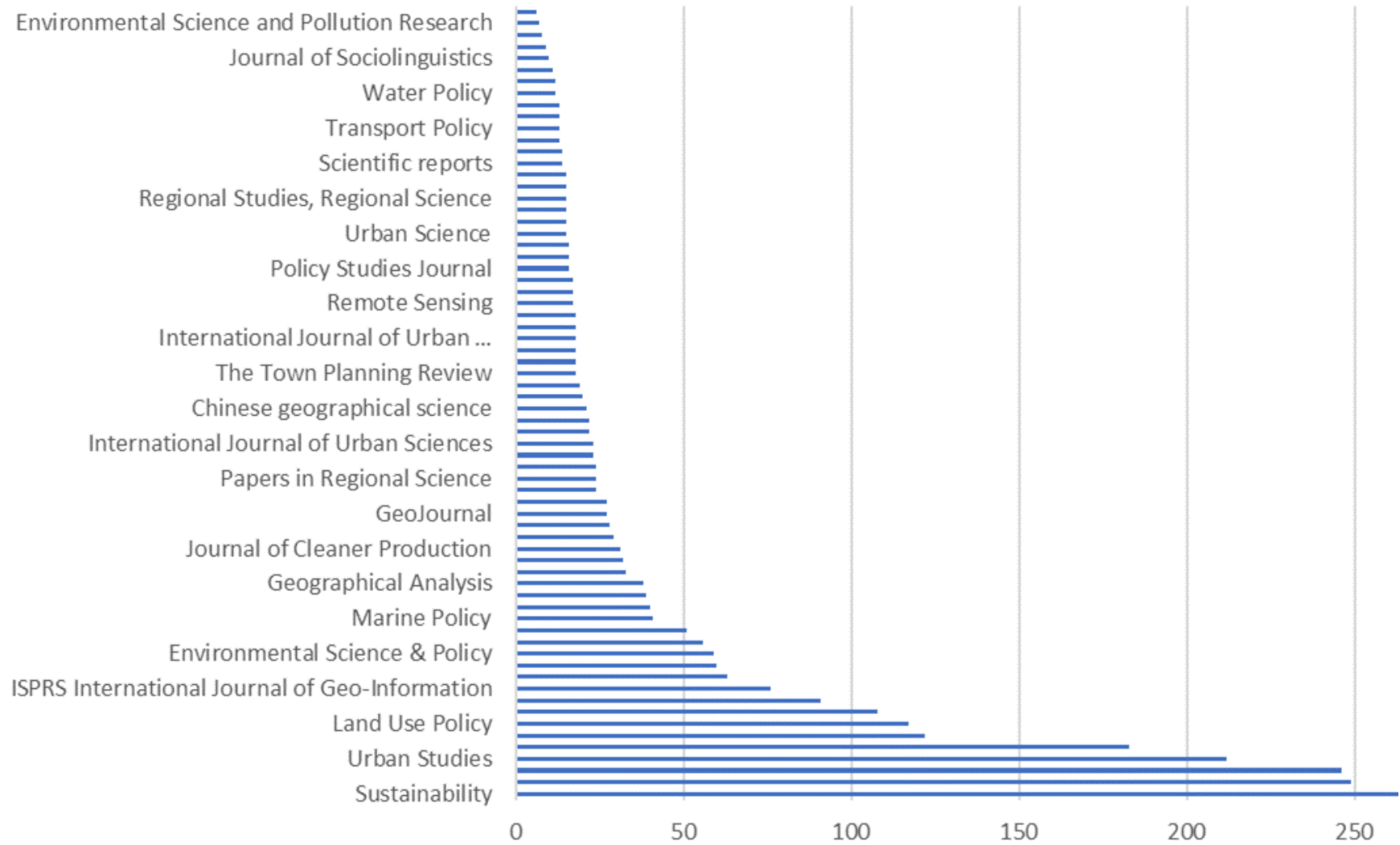
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Appendix 1. The histogram of annual citations of polycentricity (n = 11,286) was found using Google Scholar.



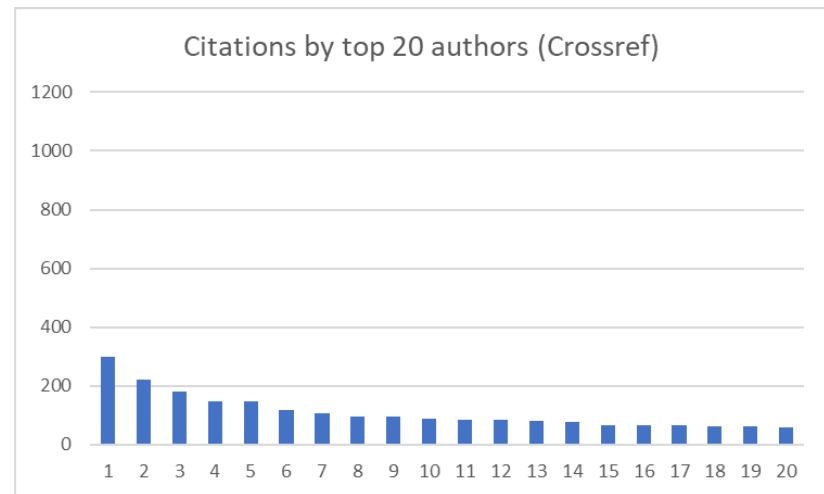
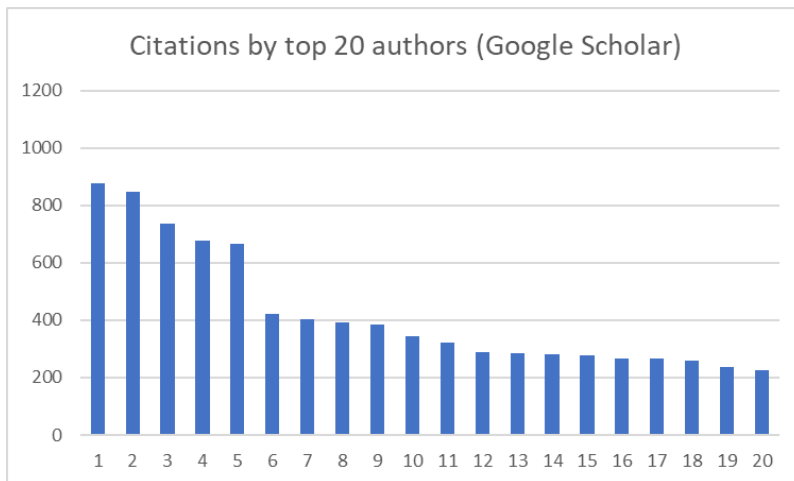
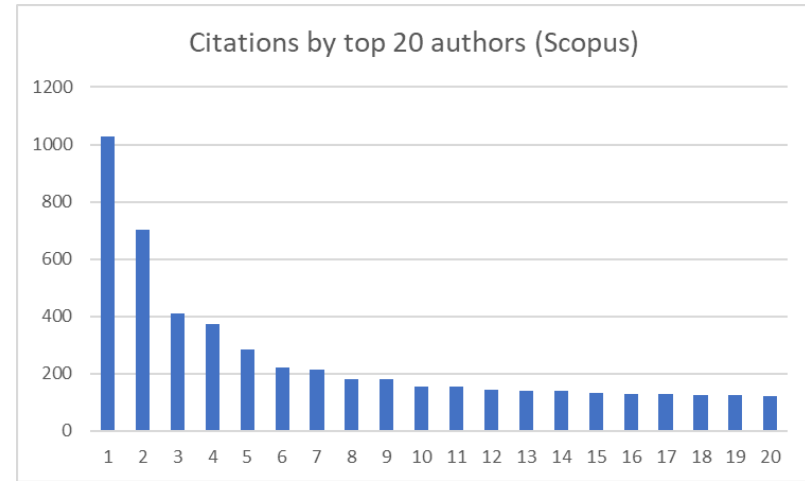
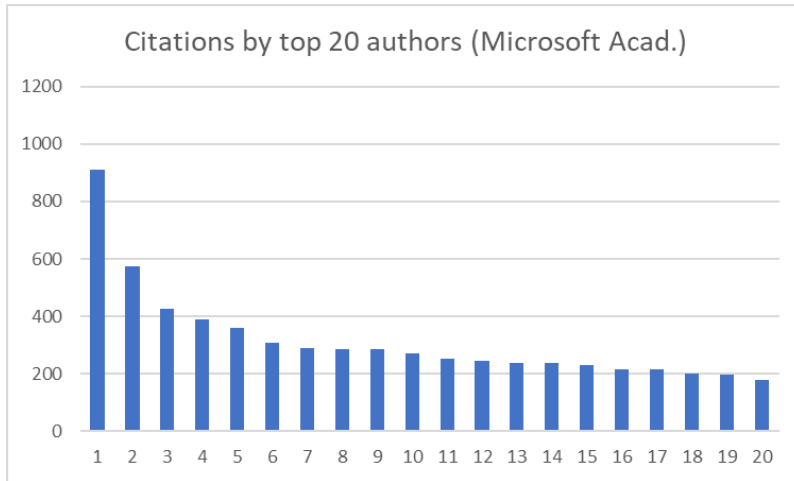
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Appendix 2. Journals based on the frequency of polycentricity citation using the Google Scholar search engine (n = 997).



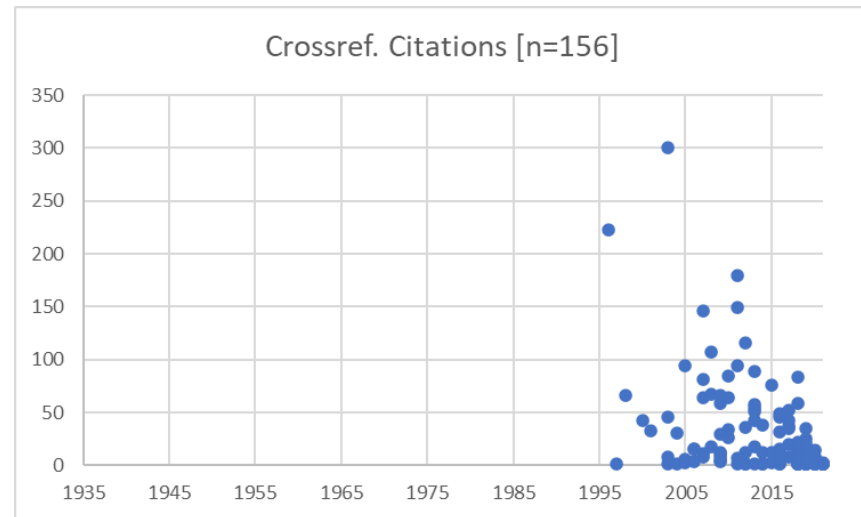
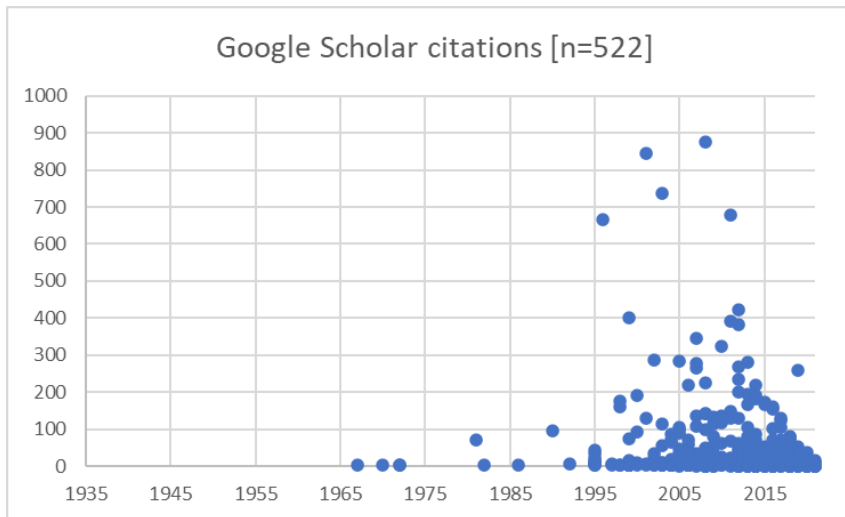
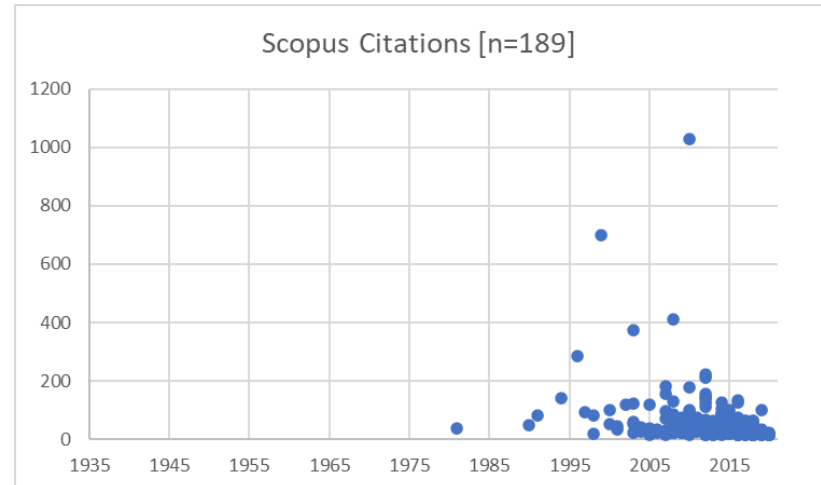
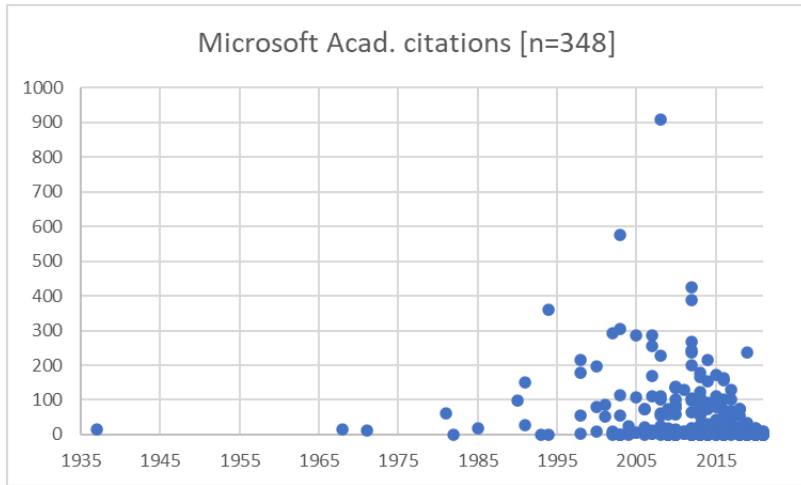
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Appendix 3. Top 20 listings in four search engines. Several total citations per journal article.



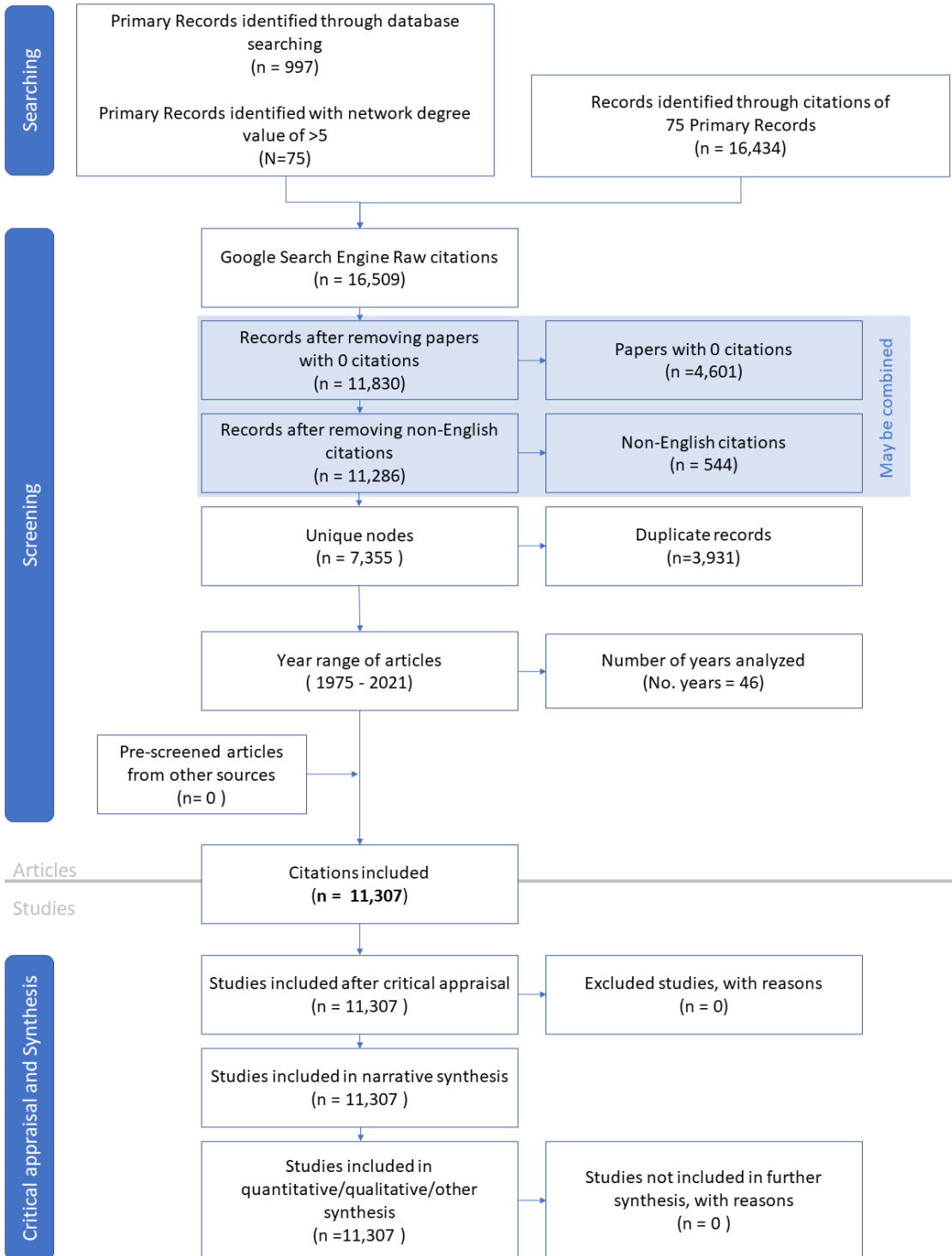
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Appendix 4. Comparison of four search engines and the term “polycentricity” in journal articles (blue dots) and their associated total citations (x-axis) over time.



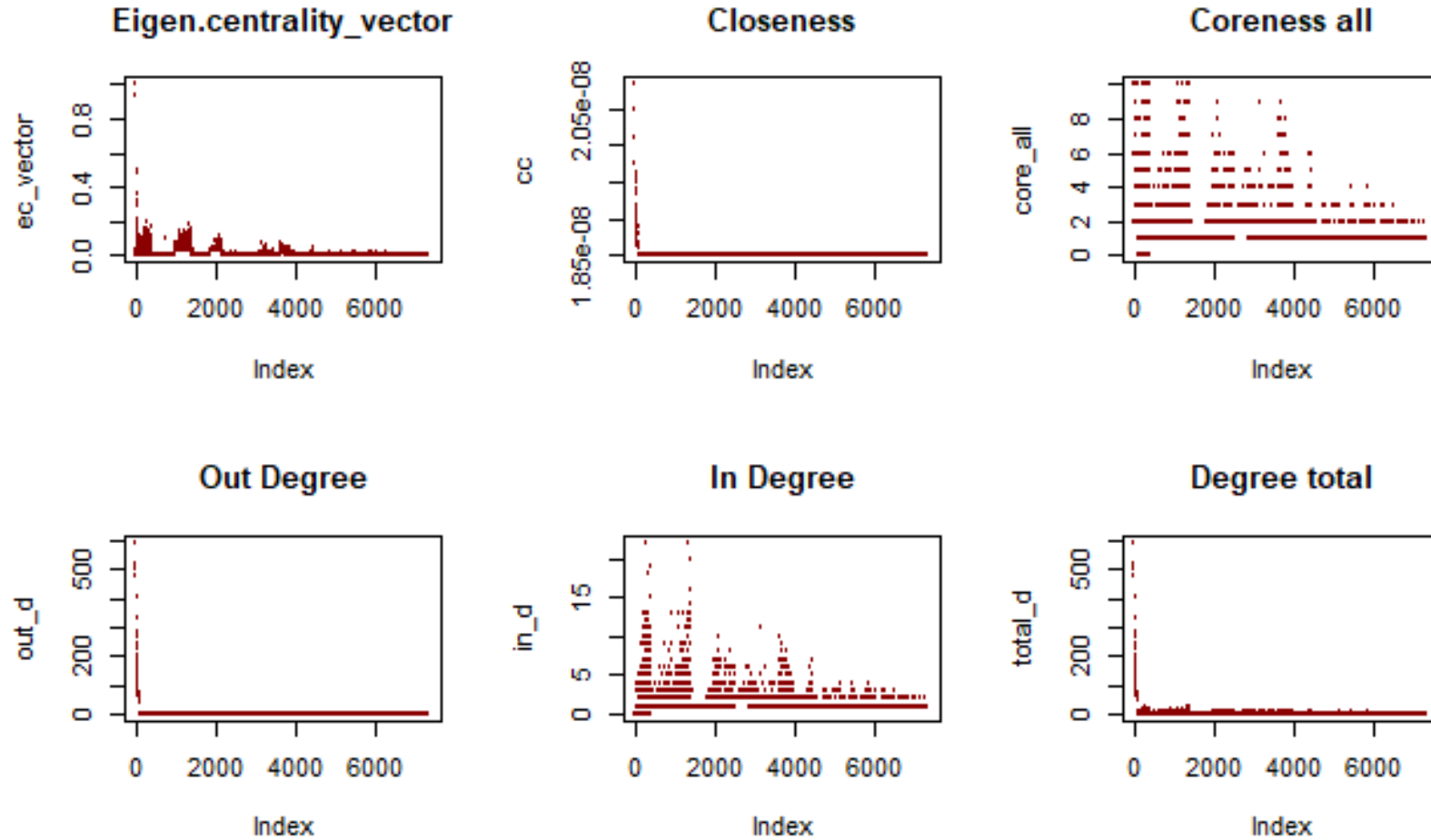
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Appendix 5. ROSES Flow Diagram (Haddaway et al., 2017): Polycentricity search results - Google Scholar (2021-10-29).



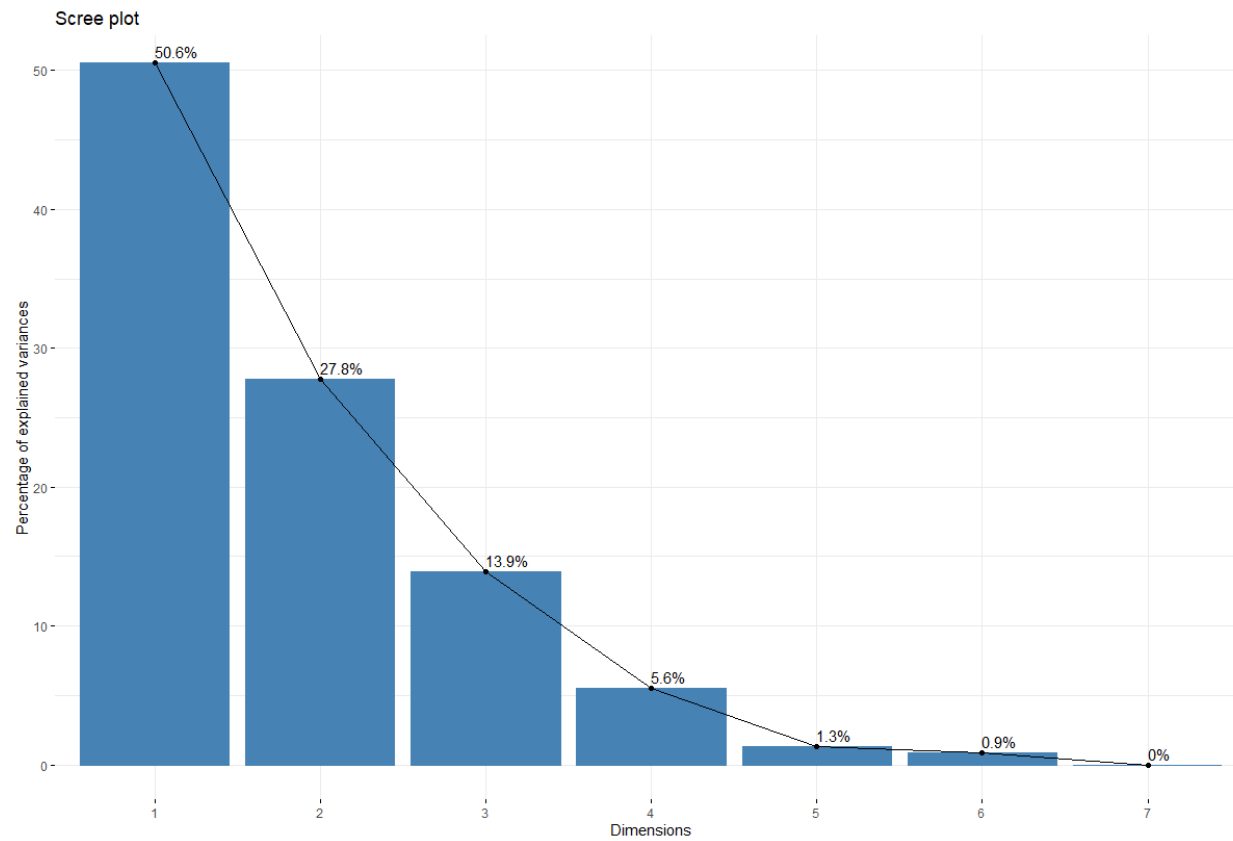
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Appendix 6. Analysis of network statistics for polycentricity literature network.



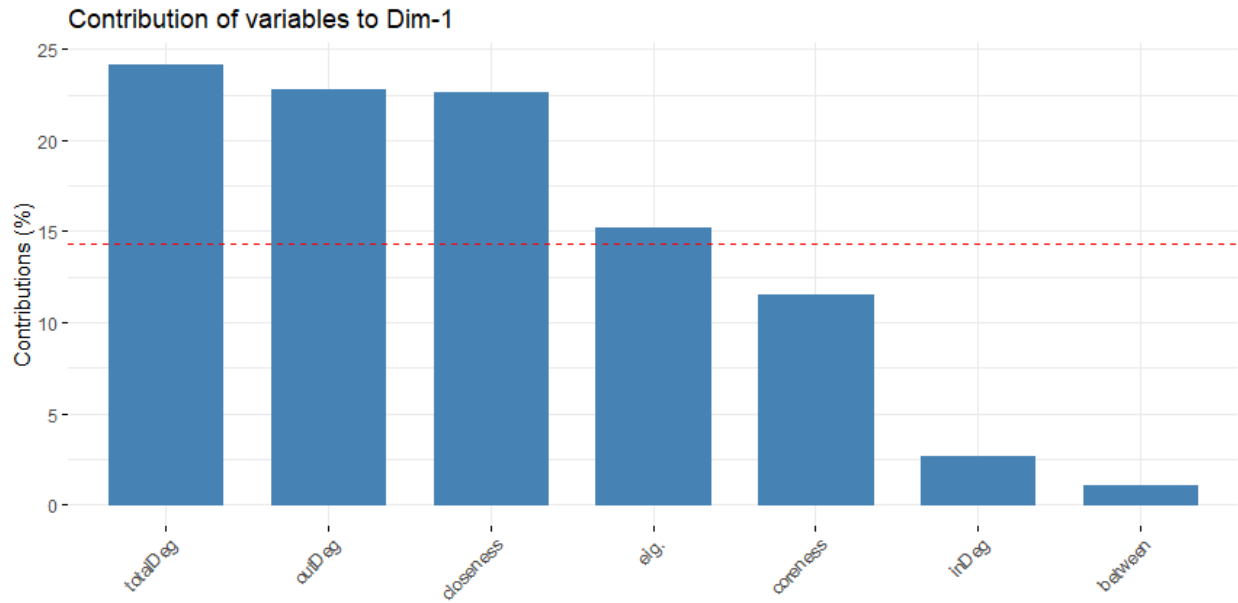
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Appendix 7. Visualize eigenvalue variance. Over 78% of the variance is captured in the first two dimensions.

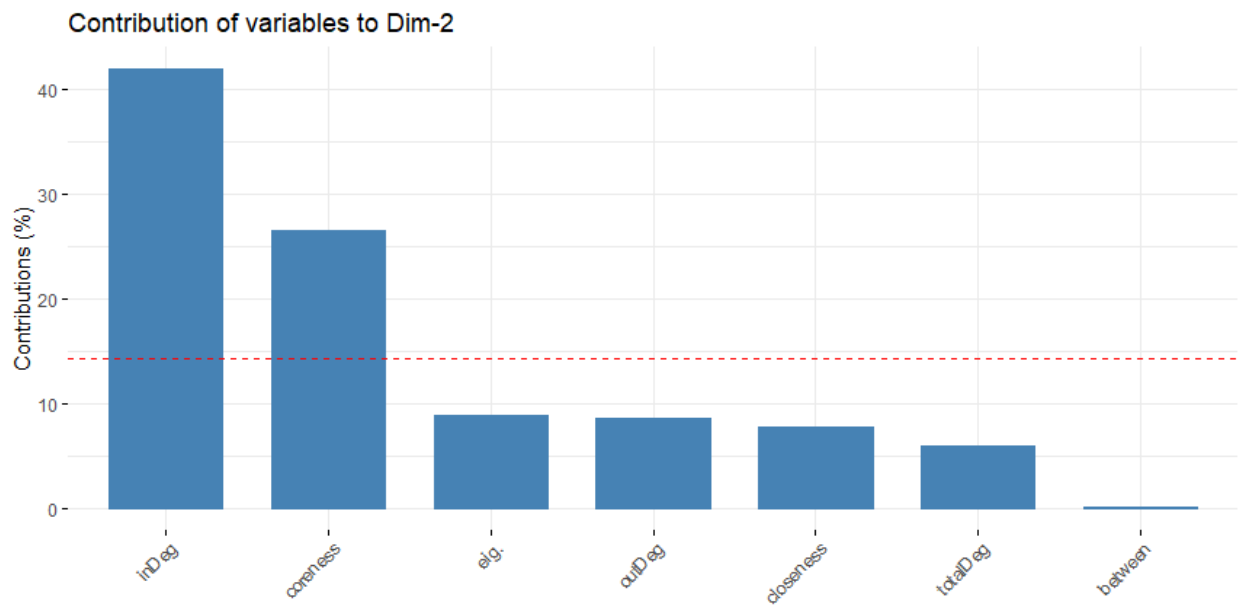


Appendix 8. Contribution toward variables to dimensions 1 and 2.

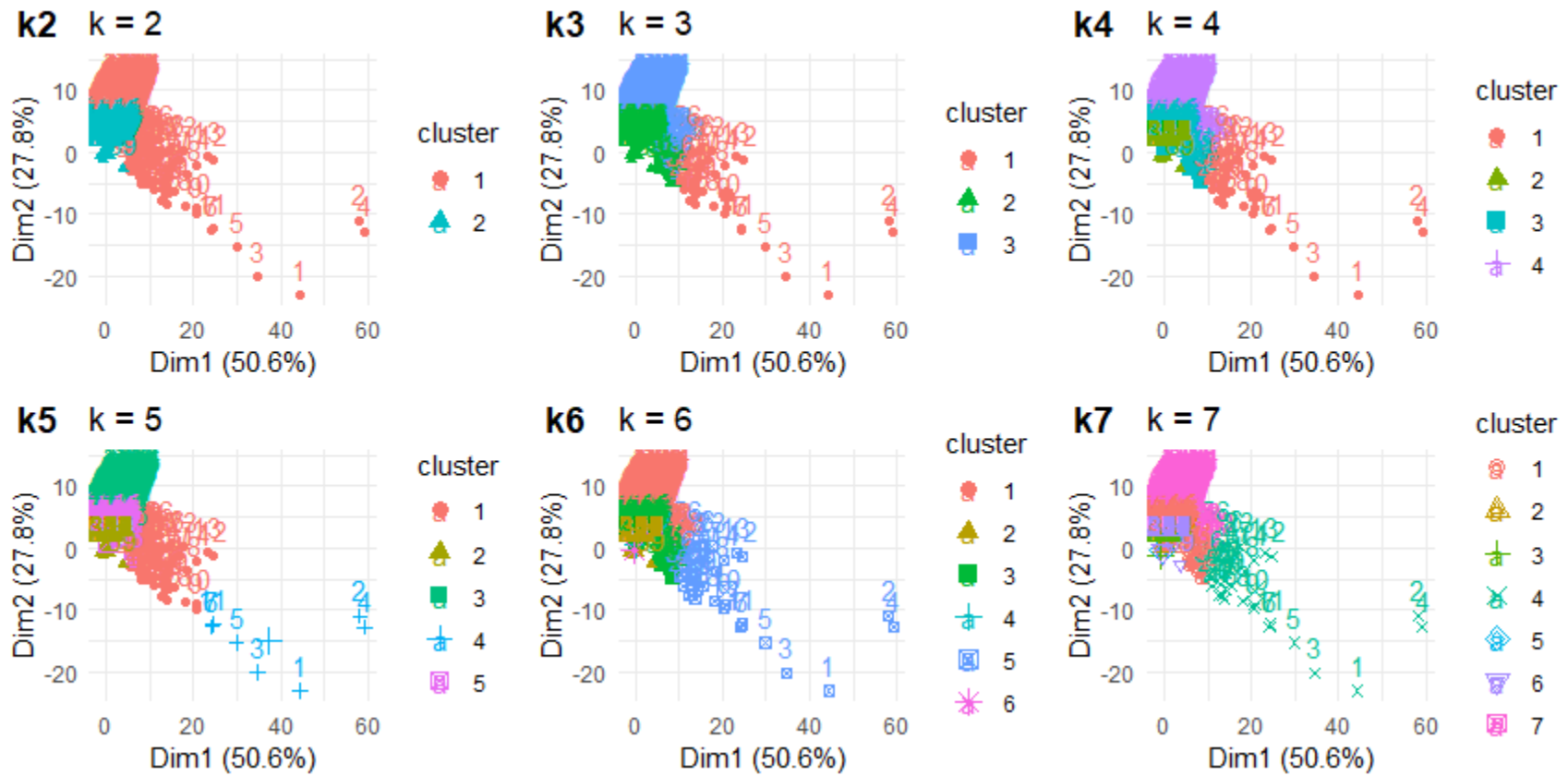
A.



B.



Appendix 9. A review of how contemporary polycentricity literature groups into communities based on the number of k-cores. We explore 2–7 k-core communities.



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Appendix 10. R software output from **NBClust analysis**. We used the “Mcuitty” method and “euclidean” distance settings for this analysis.

* Among all indices:

* 5 proposed two as the best number of clusters

* 5 proposed three as the best number of clusters

* 11 proposed five as the best number of clusters

* 1 proposed six as the best number of clusters

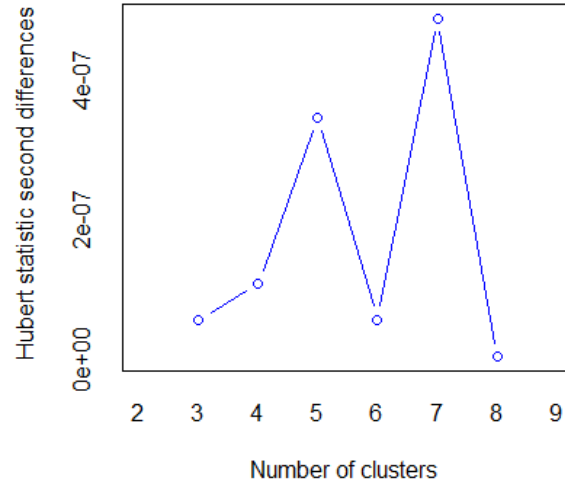
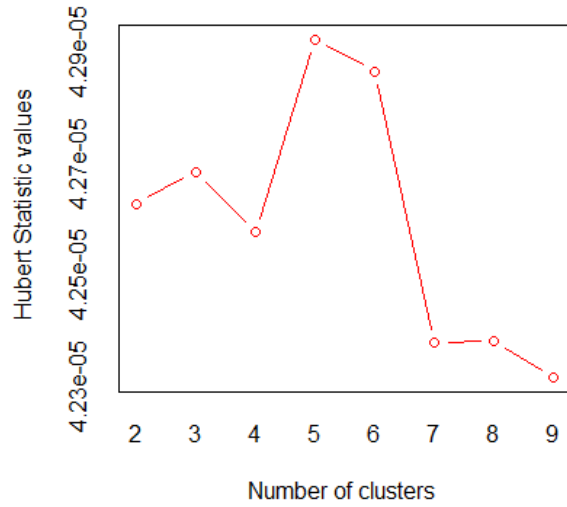
* 1 proposed nine as the best number of clusters

***** Conclusion *****

*** According to the majority rule, the best number of clusters is 5.**

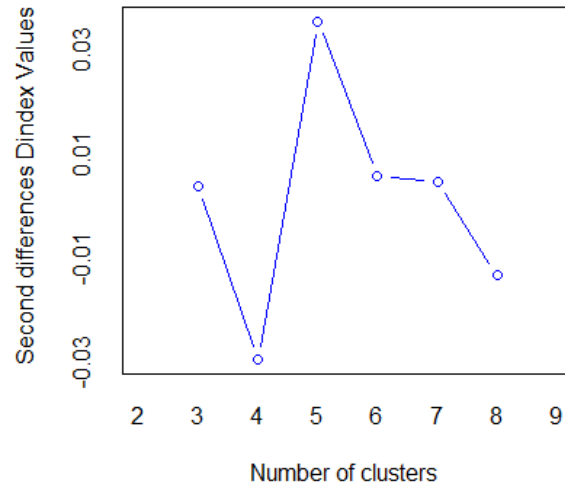
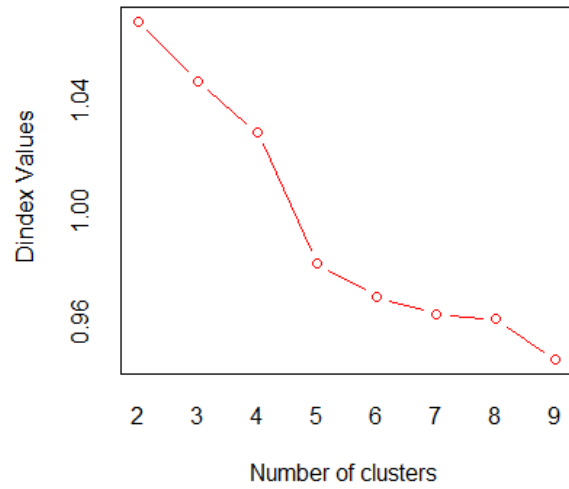
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Appendix 11. The Hubert index is a graphical method of determining the number of clusters. In the plot of the Hubert index, we seek a significant knee that corresponds to a substantial increase in the value of the measure, i.e., the significant peak in the Hubert index second differences plot.



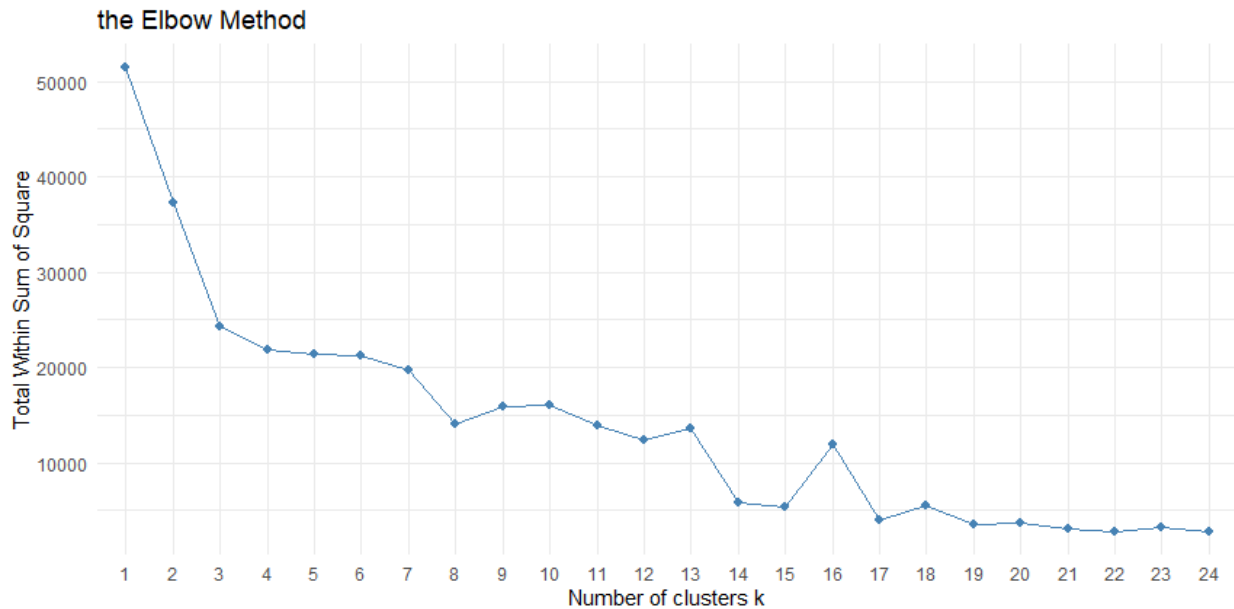
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Appendix 12. The D index is a graphical method of determining the number of clusters. In the plot of the D index, we seek a significant knee (the significant peak in the D index second differences plot) that corresponds to a substantial increase in the value of the measure.



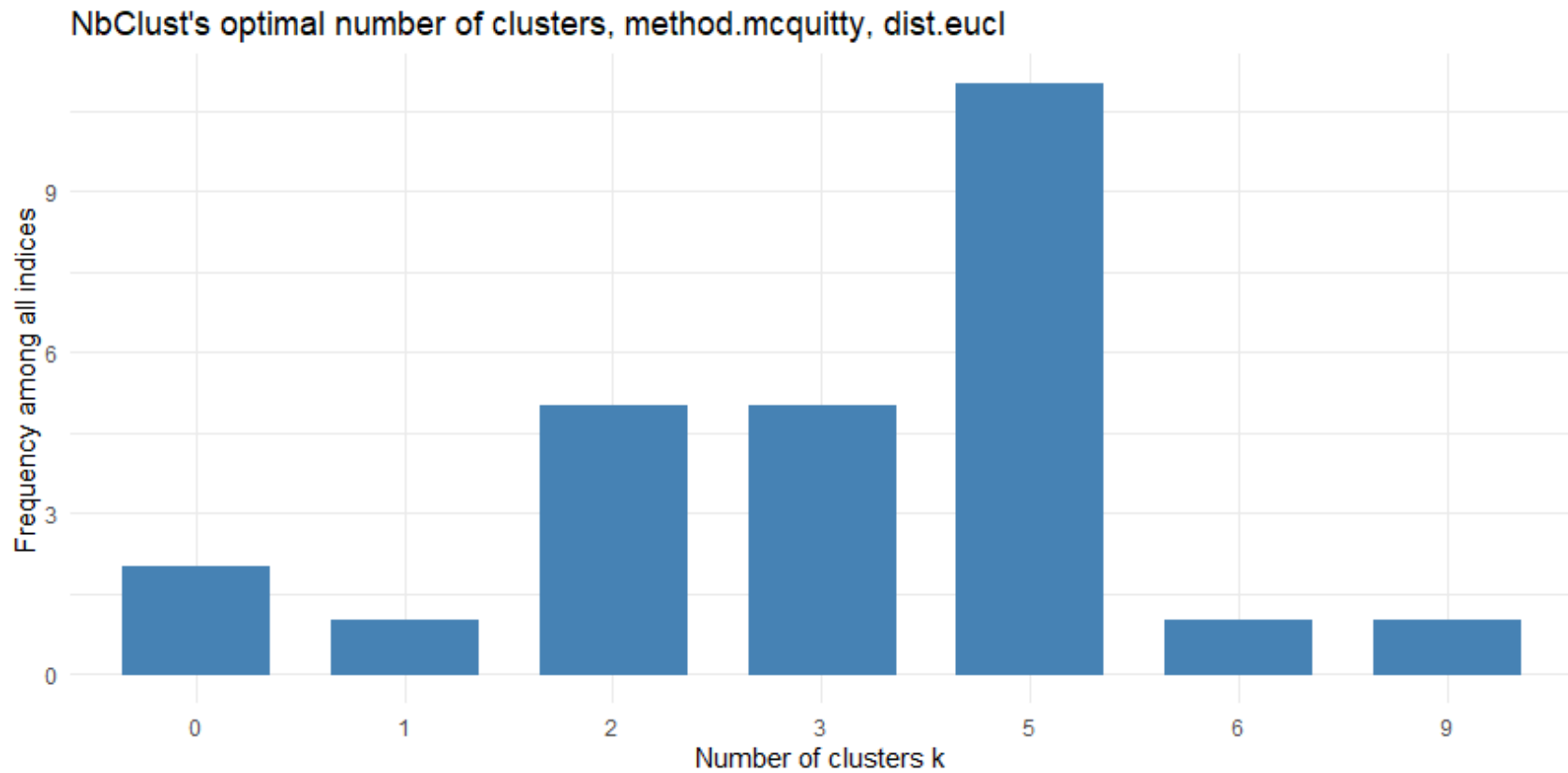
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Appendix 13. The **Elbow Curve method** analyzes how many *k*-core communities best describe contemporary polycentricity bibliographic data. Probably the most well-known method is the elbow method, in which the sum of squares at each number of clusters is calculated and graphed, and the user looks for a change of slope from steep to shallow (an elbow) to determine the optimal number of clusters. This method is inexact but still potentially helpful.



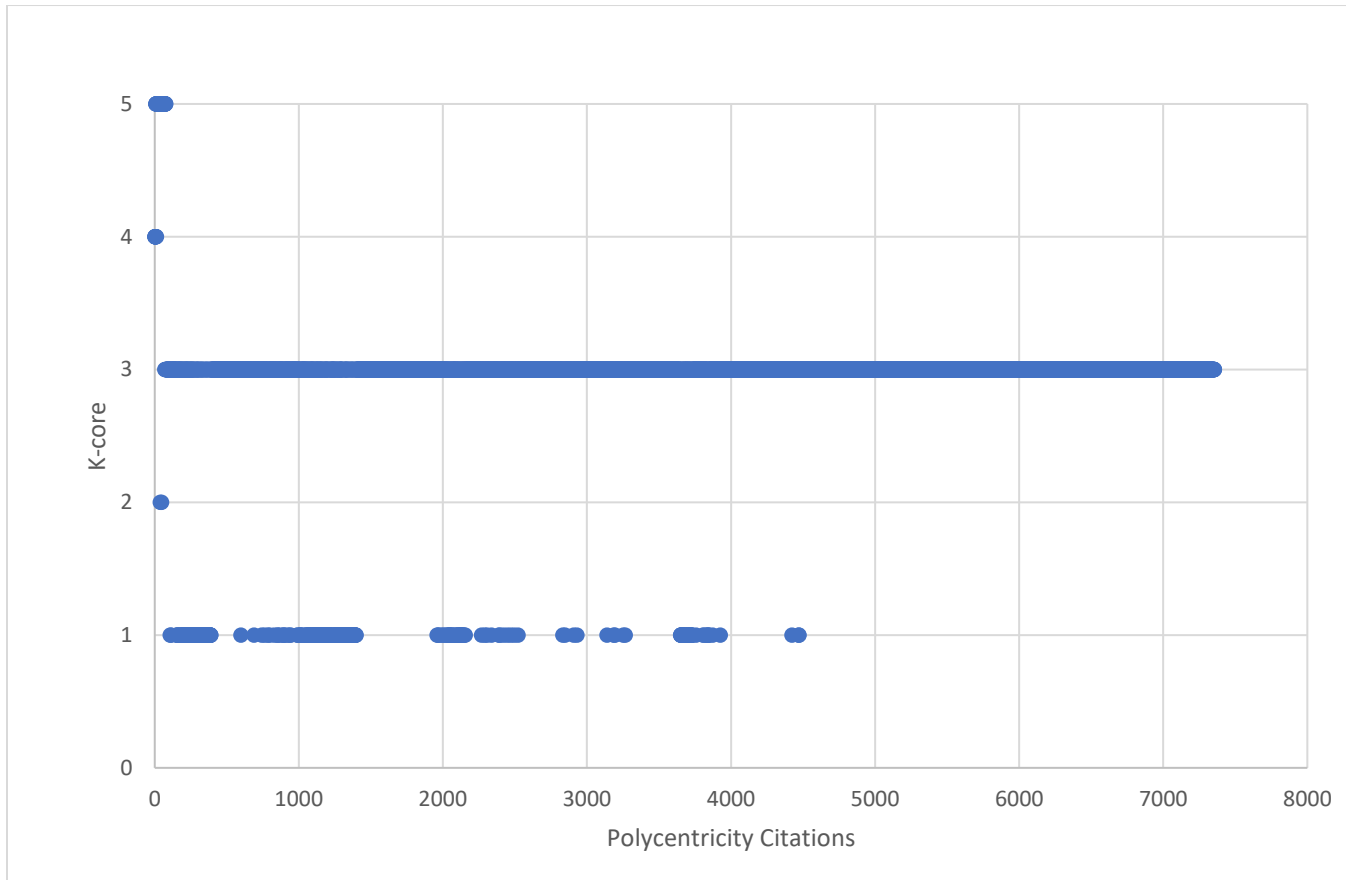
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Appendix 14. NbClust package of 30 indices for determining the appropriate number of clusters. We used the Mcquitty method and the Euclidean distance measures. Consensus results indicate five clusters optimize k-core.



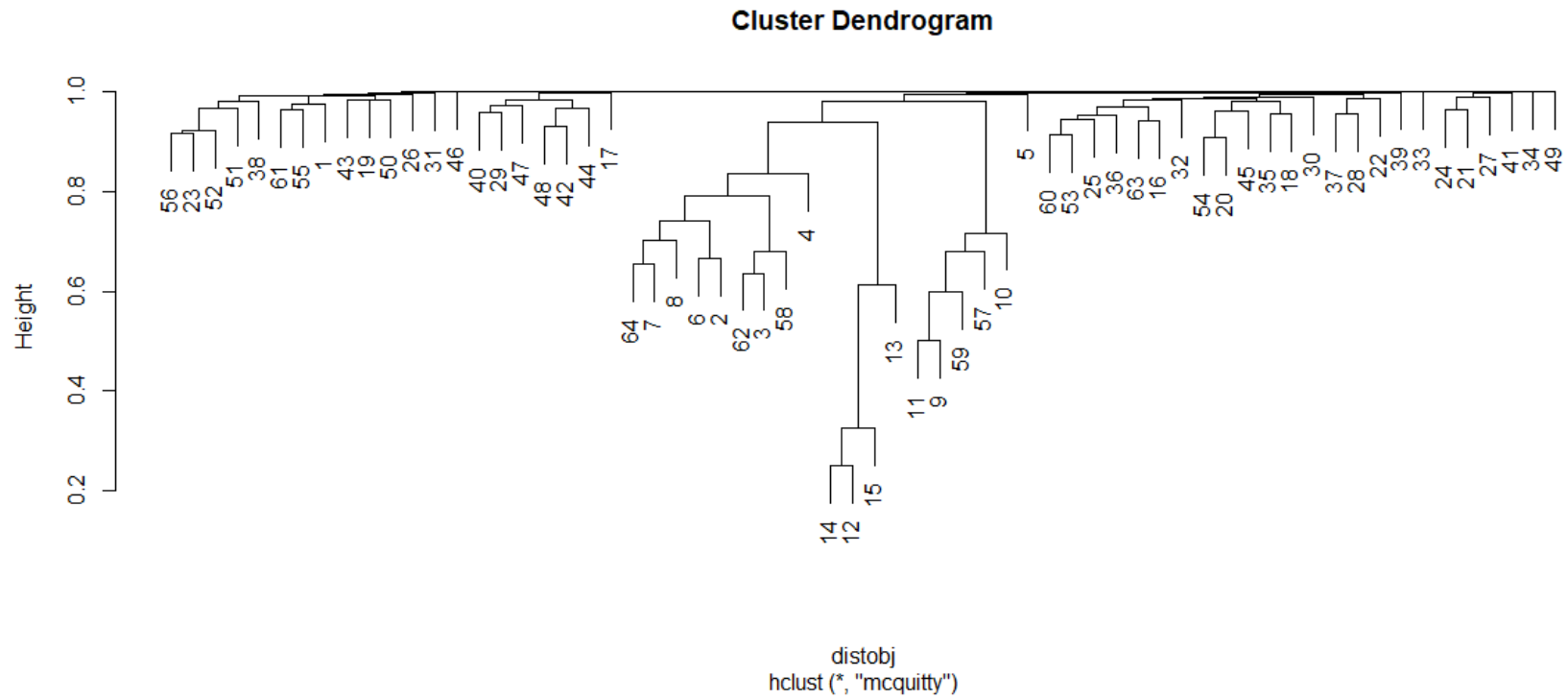
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Appendix 15. Cluster statistics: Polycentricity citation count using Google Scholar.



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Appendix 16. Cluster dendrogram of polycentricity citation literature from Google Scholar (Mcquitty method).



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Appendix 18. K-core community 2: **European planning polycentricity.**

application
reflections agenda interpretation
practice **planning**
tool **european** normative
concept **spatial** briefing
analytical

Manuscript I.

Appendix 20. K-core community 4: **Legal polycentricity.**

transformation
reference
special monocentric regulation
theory note dogmatics nodes unity
multiple disintegration legislation
values danish law city importance
jurisprudence cbd legal analysis nutshell
euthanasia pluralism evaluating
integration divergence national version
notes fragmentation property
residential philosophy

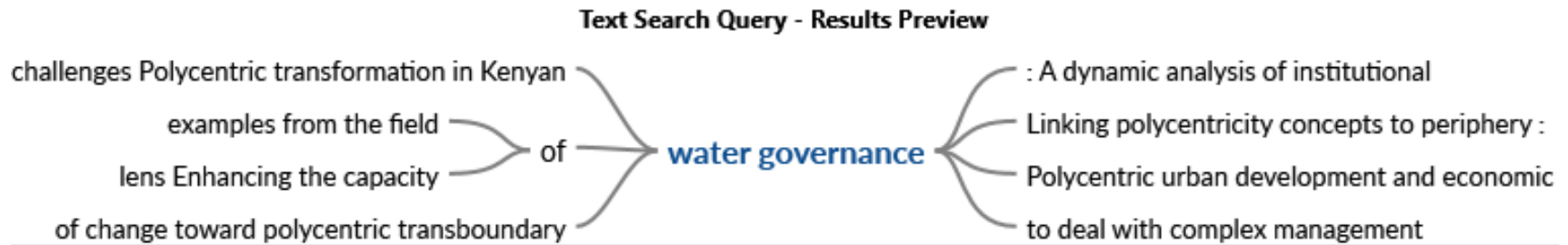
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Appendix 21. K-core community 5: Development polycentricity.



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Appendix 22. Word tree for the phrase water governance. K-core 1: **Urban spatial polycentricity**.

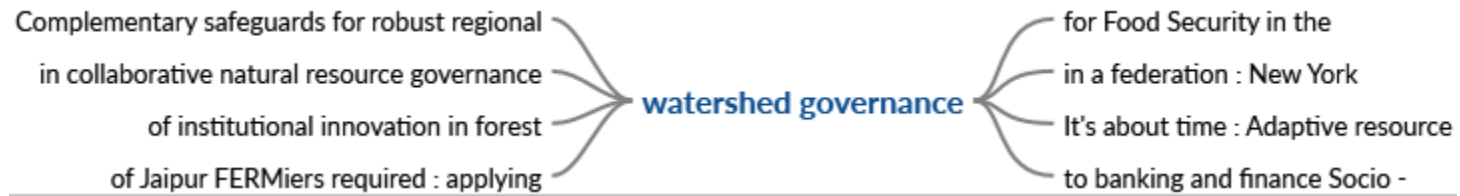


Appendix 23. Word tree for the phrase water governance. K-core 3: Commons polycentricity.



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Appendix 24. Watershed governance word tree. K-core 3: **Commons polycentricity**.



Appendix 25. Definitions of polycentricity are used to describe commons water governance.

Year	Author(s)	Definition
1951	Polanyi	(1) a network of “pin-points” (nodes: people or organizations) connected through relational ties that are simultaneously influenced by systemic perturbations represented by the totality of ego and whole network displacements, (2) social tasks expressing self coordination, and (3) performance achieved by automatic mutual adjustment.
1961	Vincent Ostrom et al.	Applying (1) many autonomous units formally independent of one another, (2) Choosing to act in ways that take account of others, and (3) Applying processes of cooperation, competition, conflict, and core resolution.
2008	Andersson et al.	Seeks to unleash the ingenuity and stimulate the creativity of political entrepreneurs. It is a system that is structured so that actors within the system are given opportunities for institutional innovation and adaptation through experimentation and learning.
2010	Ostrom	Multiple governing authorities characterize polycentric systems at differing scales rather than a monocentric unit (see Ostrom, 1999). Each unit within a polycentric system exercises considerable independence to make norms and rules within a specific domain (such as a family, a firm, a local government, a network of local governments, a state or province, a region, a national government, or an international regime). Participants in a polycentric system can use local knowledge and learn from others engaged in trial-and-error learning processes. As larger units get involved, problems associated with non-contributors, local tyrants, and inappropriate discrimination can be addressed, and significant investments are made in new scientific information and innovations.
2012	Pahl-Wostl	The idea of polycentricity (R3) is that power is distributed without loss of coordination. To capture this idea in a single index is difficult but was done here by considering two elements. First, we ask if power is distributed to multiple centers with horizontal coordination. Second, we ask if there is decentralization with authority and capacity to act at lower levels. The variable R3 was calculated based on the following indicators: (1) multilevel structure of domestic water legislation and subsidiarity, (2) actor-network: vertical coordination (government), horizontal coordination (government), the role of local governments, and (3) centralization: one level one actor, degree of centralization, technical capacity and economies of scale, legal obligations and responsibility.
2012	Aligica and Tarko	A structural feature of social systems of many decision centers has limited and autonomous prerogatives and operates under an overarching set of rules. It consists of: (1) an assortment of decision centers, (2) an Institutional/cultural framework (overarching system of rules), and (3) Spontaneous order and evolutionary competition. Requires three parameter conditions: (A) Active exercise of diverse opinions, (B) Autonomous decision-making layers, and (C) Incentive compatibility: alignment between rules and incentives.

2015	Marshall	Polycentricity should be understood generally as an attribute of polycentric governance arrangements rather than, more specifically, of polycentric governance systems. Polycentricity describes Complex Adaptive Systems (CAS). Entities should exhibit considerable or substantive <i>de facto</i> autonomy from each other. Coherence is a necessary attribute of polycentric governance systems, but it is not in itself sufficient. The principle of subsidiarity contributes to polycentric governance system performance.
2017	Morrison	Polycentrism is a model of governance that actively steers local, regional, national, and international actors and instigates learning from experience across multiple actors, levels of decision making, and temporal scales. Its most prevalent conceptualization is a non-hierarchical set of interactions between public and private actors operating at various levels (e.g., supranational, national, and subnational) without a predominant central authority. A polycentric system comprises many autonomous units that are formally independent of one another, both of which choose to act in ways that take account of others through self-organized processes of cooperation and conflict resolution.
2017	Berkes & Fikret	Literature often uses polycentric systems characterized by multiple and overlapping jurisdictions at different levels. Polycentric systems often have several governing authorities rather than a single one.
2017	Mathias	Maintaining a polycentric system means here satisfying constraints defined by network metrics. The critical issue relies on a trade-off between the transaction costs (for developing and maintaining networks) and the benefits of the partnerships (Lubell et al. 2002).
2017	Carlisle and Gruby	As formulated by [V. Ostrom et al. (1961) ...Thus, we propose the following two attributes of a polycentric governance system: (i) multiple, overlapping decision-making centers with some degree of autonomy: (ii) choosing to act in ways that take account of others through processes of cooperation, competition, conflict, and conflict resolution. We, therefore, propose that the best way to envision a polycentric governance system is not as a tidy and static network of discrete, connected decision-making centers. Instead, it is a dense and evolving web of decision-making centers – some transitory and other relatively fixed-and supporting actors from diverse sectors and domains.
2017	de Loe and Patterson	It is characterized by multiple decision centers and multi-level (e.g., local, regional, national, global) governance systems.
2018	Oberlack et al.	Social-ecological systems, Governance, tele-coupled systems, Networks of Action.
2018	Villamayor-Tomas	Four key aspects of polycentricity are coproduction, local self-governance capacity, subsidiarity, and coordination (Aligica & Tarko, 2015).
2019	Fischer & Maag	In polycentric governance systems, actors have to decide strategically to which forums they want to allocate their scarce resources to maximize their benefit. Actors in polycentric governance systems can rely on many channels to influence collective action decision-making.

2019	Berardo and Lubell	The term polycentricity continues to encompass the three core attributes identified by Ostrom et al. (1961, p831). Multiple governing authorities characterize polycentric systems at different scales rather than monocentric ones.
2019	Biddle and Baehler	To stay true to the most influential formulation of polycentricity (V. Ostrom et al., 1961, V. Ostrom, 1991), Carlisle and Gruby (2017, p. 6) have captured the combination of independence and interdependence that characterizes polycentricity in two defining attributes: the presence of “multiple, overlapping decision centers with some degree of autonomy” and the tendency of those centers “to act in ways that take account of [other centers] through processes of cooperation, competition, conflict, and conflict resolution.”
2019	Morrison et al.	A polycentric system comprises multiple governing authorities at different scales that do not have a hierarchical relationship but are engaged in self-organization and mutual adjustment (Ostrom, 2010).
2019	Baltutis and Moore	Initially conceived by Polanyi (Polanyi 1951, as cited in Aligica and Tarko 2012) and further developed by Ostrom et al. (1961), the concept of polycentric governance has been used as a lens and guiding principle to analyze a diversity of management and governance issues, including common-pool resources (Ostrom 1990, McGinnis 1999, Mostert 2012), urban and regional planning (Salet and Savini 2015), decentralized regulatory regimes (Black 2008), forest governance (Nagendra and Ostrom 2012), and climate governance (Ostrom 2010, Jordan et al. 2015).

Untapped Potential: The Importance of Social Networks in Evaluating Performance Metrics for Watershed Organizations

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Abstract

In the 21st century, the relationships between people are crucial to the success of watershed organizations. However, social networks must be better understood when evaluating an organization's performance metrics. This study focuses on the Okanagan Basin Water Board (OBWB), a Canadian public network organization responsible for managing the watershed by local governments. The OBWB provides various services, including the Sewage Facilities Assistance grant program, which significantly impacts the ecosystem by improving water quality and reversing lake eutrophication. To understand the social network attributes of the OBWB, the study employs a modified watershed governance network framework, focusing on two attributes: centralization and coordination. A standardized exponential random graph model is applied to identify the likelihood of forming network motifs representing these attributes. The study's structural network analysis provides valuable insights into the strategic aspects of organizational social capital building. Our findings suggest that the OBWB's network governance evolved, transitioning from a polycentric governance network to one that oscillated between centralized rent-seeking and centralized coordination. The study contributes to understanding a watershed organization's network governance and performance attributes, providing valuable theoretical and practical insights. This study underscores the importance of social networks and their role in organizational performance, particularly for watershed organizations delivering ecological services.

Keywords: watershed, governance, network organization, social network analysis, exponential random graph model

Research Implications/Key Findings

1. Two-mode network data and a two-dimensional grid were used to analyze 50 years of board meeting data from the Okanagan Basin Water Board (OBWB) to explore the evolution of its network governance.
2. The OBWB's network governance evolved, transitioning from a polycentric governance network to one that oscillated between centralized rent-seeking and centralized coordination.
3. Two outliers were identified in the network's attributes in 2017 and 1992, and changes in the organization's core governance functions and external environment were found to have influenced the evolution of its network governance. The study highlights the usefulness of two-mode network data and the two-dimensional grid approach in characterizing network governance attributes. It may be valuable to other organizations facing similar challenges in evolving their governance structures.

Introduction

The importance of watershed organizations in ecosystem service delivery cannot be overstated; these organizations act as crucial bridging entities between multiple levels of government and other social actors. To ensure optimal performance, it is essential to understand the structure and dynamics of the social networks within these organizations. This paper explores how social network analysis can be used to gain insights into the coordination and centralization among actors within a watershed organization's network, ultimately contributing to improved watershed governance performance.

Watershed organizations play a crucial role in ecosystem service delivery by bridging organizations between various levels of government and other social actors (de Loë, 2009; Folke, Hahn, Olsson, & Norberg, 2005). Social capital is critical to a watershed organization's network-building efforts (Coleman, 1994). To improve watershed governance performance, gaining insights into the structure and dynamics of the organization's social networks, including the level of coordination and centralization, is essential. Social network analysis is a powerful tool that can help identify critical actors, relationships, and communication channels within the network. This analysis can also identify potential gaps or bottlenecks in the network that may hinder communication and collaboration, providing opportunities to strengthen relationships and improve organizational performance. By utilizing social network analysis, we can better understand critical aspects of an organization's network governance system, enabling us to pinpoint significant characteristics and trends that drive organizational success. Ultimately, social network analysis can enhance our understanding of the social dimensions of watershed governance and provide valuable insights to guide decision-making and policy development.

To truly comprehend the effectiveness of organizations like the OBWB, which local governments created to improve decision-making and water quality in a complex social-ecological governance system, we require practical tools to assess their impact and guide strategic decision-making. Unfortunately, such tools are currently scarce. To aid in our analysis of the OBWB, which functions as a network organization in a watershed governance system, we have outlined vital concepts in Table 1, which are used to help answer our research question and support the framework for our study.

Table 1. Summary of applied definitions in this study.

Term	Definition	Source
Action situation	Individuals (acting on their own or as agents of formal organizations) interact, thereby jointly affecting outcomes that those actors differentially value.	McGinnis & Ostrom, 2014
Exponential random graph model	ERGMs are statistical models for social network structure that has significant potential to help us understand processes that occur at different levels in the formation of social ties and individual outcomes.	Lusher et al., 2020
Governance regime	An intermediate layer between government and the state influencing control and authority;	Bressers & Kuks, 2013

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	includes institutions, actors, and social structures.	
Motifs	The prevalence of specific micro-level configurations that appear in a social network.	Bodin et al., 2019a
Polycentric governance	The institutional analysis emphasizes how people develop and use institutional arrangements to try to order their interactions with one another and address problems.	Thiel, Blomquist, & Garrick, 2019
Policy network structures	A meso-level variable in a general framework of a policy system that links macro-level institutional arrangements to micro-level individual behaviour and overall system properties to policy outputs and outcomes.	Lubell et al., 2012
Polycentric systems	Composed of multiple subsystems and internal variables within these subsystems at multiple levels analogous to organisms consisting of organs, organs of tissues, tissues of cells of proteins, etc. In a complex social-ecological system, water and governance systems are relatively separable but interact to produce outcomes at the system level. Feedback affects these subsystems, their components, and other larger or smaller social-ecological systems.	Ostrom, 2009
Social networks	Connectedness is central to modern human life—social structures limit or enable social action. Networks have always been major to our survival and well-being.	Light & Moody, 2020
Watershed governance system	The interconnected ensemble of political, social, economic, and administrative elements that performs the function of water[shed] governance. These elements embrace institutions as well as actors and their interactions.	Pahl-Wostl, 2015b

As part of the effort to better understand the social dimension of watershed governance, several governance diagnostic studies have provided new insights into the governance of social-ecological systems, including studies on European watersheds (Pahl-Wostl, 2015b), power relationships (Morrison et al., 2019), and sea-level rise adaptation (Lubell et al., 2021). Scholars of social-ecological systems identify that one crucial long-term goal is to

...recognize which combination of variables tends to lead to relatively sustainable and productive use of particular resource systems operating at specific spatial and temporal scales and which combination tends to lead to resource collapses and high costs for humanity (Ostrom, 2007, p. 15183).

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Governance diagnostic studies have provided insights into the value of distinguishing between horizontal and vertical coherence where,

a key task of social network analysis has been to invent graph-theoretic properties that characterize structures, positions, and dyadic properties (such as coherence or connectedness of the structure) and the overall shape (i.e., distribution) of ties (Borgatti, Mehra, Brass, & Labianca, 2009, p. 894).

Efforts to understand how different network structures, for example top down compared with polycentric systems, have been the topic of research for the past three decades (Ostrom, 2009, Pahl-Wostl & Kneiper, 2014, Lubell and Robins, 2021). Empirical studies to enhance our understanding of these social-ecological governance systems is an area of active research.

To help understand these complex systems, several new models have been applied to polycentric system analysis. For example, the application of fuzzy logic (Pahl-Wostl & Kneiper, 2014), ERG models (Lubell & Robbins, 2021; Lubell, Robins, & Wang, 2014a), and the institutional analysis and development (IAD) framework (Koontz, Garrick, et al., 2019; Koontz, 2006), have been applied to improve our empirical understanding of watershed network-governance systems. These studies have enhanced our knowledge of diagnostic measures that influence good governance and ecological service delivery success. However, the use of metrics for freshwater governance indicators in Canada is low (Dunn & Bakker, 2011). Several challenges in developing empirical studies for complex watershed organizations include, data limitations, setting appropriate boundary conditions, and often a dual-directional cause-effect response between governance performance and ecological signals are ongoing research efforts.

In Canada, several water-governance systems have been analyzed (Armitage, De Loë, & Plummer, 2012; Brisbois & de Loë, 2015; Plummer, Armitage, & de Loë, 2013; Simms & de Loe, 2010), but practical management tools to assess, diagnose, and benchmark the performance level of a watershed organization and strategic change management are limited. Scholars have recognized that evaluation tools for effective governance systems (de Loe & Patterson, 2017) can enhance decision-making.

In this study, we focus on two important watershed governance indicators, coordination, and centralization. Centralization is a concept that has been dominant to several governance arguments. For example, Marshall (2015) distinguishes two concepts of polycentricity; polycentric arrangements that do not include the existence of an overarching set of rules that coordinates interactions between the authorities and those that do have overarching rule sets.

In addition to centralization, coordination is an essential indicator of a polycentric arrangements. Previous research has identified coordination as a core governance function (Jiménez et al., 2020) that influences positive policy outcomes (Vaas, Driessen, Giezen, van Laerhoven, & Wassen, 2017). Governance scholars note that "without coordination, the distribution of power and authority and overlapping responsibilities of the different decision-making centers may lead to uncoordinated and contradicting actions with loss of effectiveness and efficiency" (Pahl-Wostl & Kneiper, 2014, p. 141). There is a need for coordination among different authorities of an organization.

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Within the Canadian governance system, watershed organizations are nested within layers of provincial, federal, First Nation, and international water governance systems, each exercising different degrees of influence. Watershed governance in Canada is a shared responsibility between multiple levels of government and with differing degrees of delegation of authority, where "under Canada's Constitution Act, responsibilities for water was divided between the federal-provincial governments, with the provinces having the most direct responsibility" (de Loe & Kreutzwiser, 2007, p. 88). Legal water scholars observe that "no one level of government can provide a complete framework for protecting water resources...this fragmentation of jurisdiction has led to regulatory gaps, policy vacuums and management by crisis" (Muldoon & McClenaghan, 2007, p. 246).

Scholars have identified that evaluation tools for effective governance systems can enhance decision-making. We extend this reasoning to analyze purpose organizations such as the OBWB, which local governments develop to support decision-making and improve water quality in a complex social-ecological governance ecosystem. This highlights the need for practical tools to assess the performance of such organizations and guide strategic decision-making.

Research question

In this study, we ask the research question ***how can we use social network analysis to develop a comparable indicator framework for assessing coordination and centralization in a watershed organization's governance structure?*** It is relevant to the current context of watershed management, and it aims to address a significant gap in knowledge by exploring how social network analysis can be used to develop a comparable indicator framework. The question focus is on the use of social network analysis to assess coordination and centralization in a watershed organization's governance structure. The question is also feasible, as social network analysis is a well-established research method in the field of network science. By answering this research question, we have the potential to generate new insights and knowledge, and it is significant, as understanding the coordination and centralization in watershed governance can lead to more effective management practices. Finally, the research question is measurable with appropriate research methods, and is ethically sound. Overall, this research question has the potential to contribute to the advancement of knowledge in the field of watershed management and governance.

To answer our research question, we build on a previously developed governance system typology originally used to analyze water governance at a national watershed level (Pahl-Wostl & Knieper, 2014), to one that will be used to analyze a single watershed organization's network attributes (Fig. 1). This previous research describing a centralization/coordination matrix (Figure 1) was developed by Pahl-Wostl and Knieper (2014) to describe governance regimes at the national level, in contrast to this single watershed level applied to this research and is a practical starting point to analyze a watershed organization governance system. A new network-governance system typology is proposed (Figure 1) providing a modified qualitative analysis tool to diagnose a watershed governance system based on modelled social network data from a watershed organization.

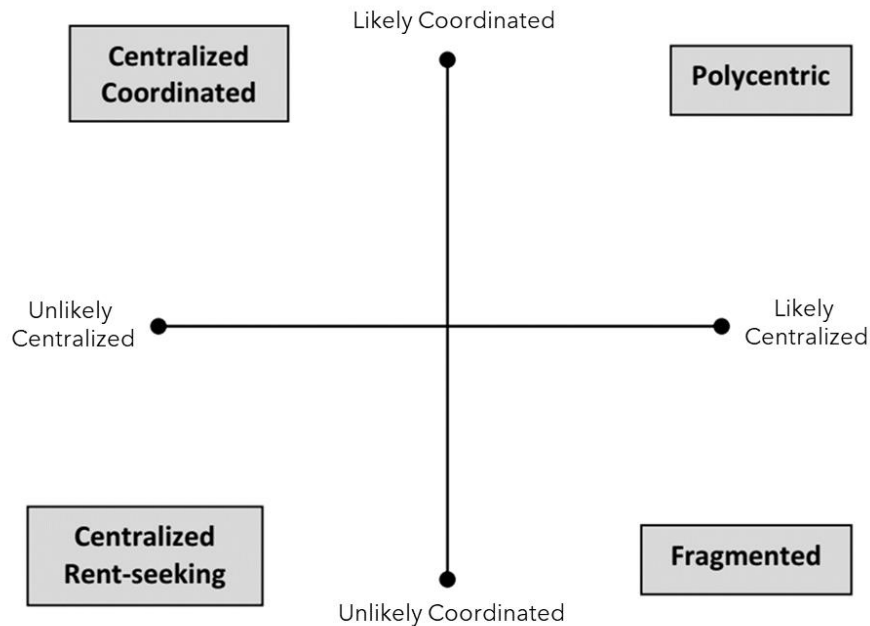


Fig. 1. Categorization of the governance system in a two-dimensional power distribution grid and degree of coordination/cooperation. The shaded corner boxes denote the ideal-typical configuration based on a watershed regime topology (Pahl-Wostl & Knieper, 2014).

Drawing on the work of Pahl-Wostl and Knieper (2014), we aim to address two important research questions. Firstly, using a two-dimensional analysis of governance systems, we seek to determine which category our case study network organization falls under, namely centralized-coordinated, polycentric, centralized rent-seeking, or fragmented. Secondly, we aim to investigate how this categorization is indicative of the organization's governance performance. Through answering these questions, we hope to test the effectiveness of a new watershed governance indicator framework that relies on social network data.

The rest of this paper is organized as follows: The methods section explains how we collected data and developed the ERG model and introduces the two-dimensional typography we use to analyze the OBWB network organization case study and address our research questions. Next, we present our findings from the ERG model and the OBWB 50-year maximum likelihood estimates (MLEs), using the two-dimensional typology. We then discuss our findings from our new longitudinal ERG model analysis of a network organization, and offer concluding remarks, including directions for future research.

Methods

This study follows a mixed methods approach to analyze a Canadian network watershed organization's social network building effort. We analyze the core governance issues discussed at public OBWB board meetings.

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This analysis reflects three phases of activity. First, we observed and collected organizational network data. We modelled the network data second. Third, we modelled and contextualized the network data within a new comparative analysis typology.

Case study geographic setting and context

This study applied a case study approach to analyze a Canadian watershed organization, the Okanagan Basin Water Board (OBWB). The OBWB is a suitable watershed organization case study because it is an excellent example of "purpose departmentalization" (March & Simon, 1993, p. 48). It was created jointly by the three Okanagan regional districts and operated as a single department with the specialized and focused task of solving water problems (Melnychuk, Jatel, & Warwick Sears, 2016). Within this broader context of watershed governance, the OBWB has emerged as a local government-based system, lacking authority but creating a structure for knowledge generation through scientific and social studies (Marr & Prince, 1974), resource mobilization, and policy framing.

The Okanagan basin is a semi-arid watershed located in south-central British Columbia, Canada (Fig. 2.), spanning a length of 200 km and has an area of 8,000 km². The Okanagan basin is an international Canadian–US watershed and identified as an area of tremendous biological and ecological significance, expressing one of Canada's most endangered ecosystems supporting desert-adapted species found nowhere else in Canada (Iverson, Curran, Fleming, Consultants, & Haney, 2008). In addition to the compelling bi-physical location of the OBWB, the Okanagan basin was chosen, in part, as the test case for developing a governance model of a network watershed organization because of the readily available access to over 50 years of meeting minute corpora.

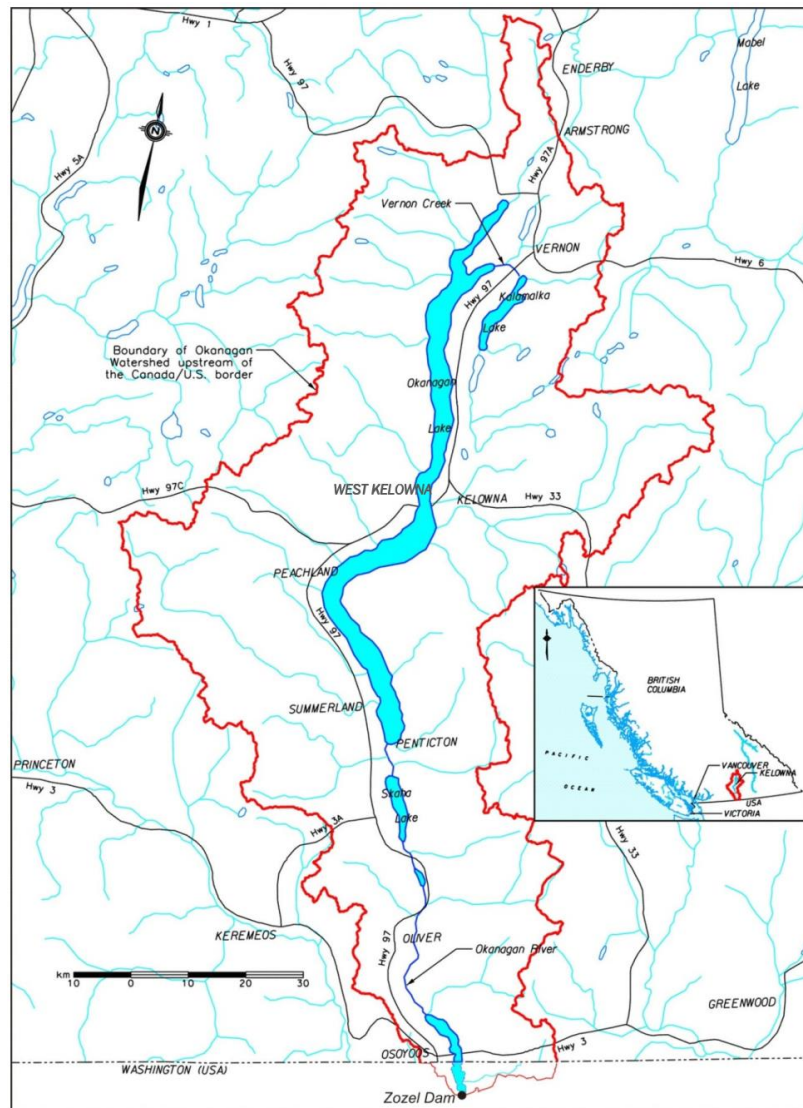


Fig 2. Map of the Okanagan basin, located in the western province of British Columbia, Canada. The Okanagan is a sub-basin of the international Canada-US Columbia basin (OBWB, 2016, p. 30).

The OBWB is a watershed organization founded through the issuance of supplementary Letters of Patent to promote the shared water interests of Okanagan communities (OBWB, 2016) by the three regional districts of the Okanagan valley. The OBWB, as a network organization, is mandated to explore water science and support the local Okanagan government's management of climate change-related risks. The British Columbia government (Minister of Municipal Affairs) issued the supplementary-Letters-Patent under Section 138 of the Municipalities Enabling and Validating Act, granting the formation of the OBWB in 1970. We characterized a year of OBWB meetings as an action situation (Pahl-Wostl, 2015b; Pahl-Wostl, Holtz, Kastens, & Knieper, 2010, p. 575).

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The Okanagan watershed underwent several widespread problems in the late 1960s (Nordin, 1983; Wagner & White, 2009). It faced significant eutrophication in the mid-1960s, resulting from increased human sewage and agriculture fertilizer run-off (Saether, 1980).

In this watershed governance case study, the Okanagan population has increased significantly (Fig. 3) over the 50-year study period. The people of the Okanagan have tripled every 30–40 years since 1940 (Jensen & Epp, n.d.), with a recorded 2016 Canadian federal census population of 362,000. Over the same period, the nutrient loading entering local valley bottom lakes decreased substantially (Fig. 3), partly due to the OBWB's incentive Sewage Facilities Assistance grant program (<https://www.obwb.ca/sfa/>). Significant water quality degradation was due partly to unconsolidated septic fields (Marr & Prince, 1974).

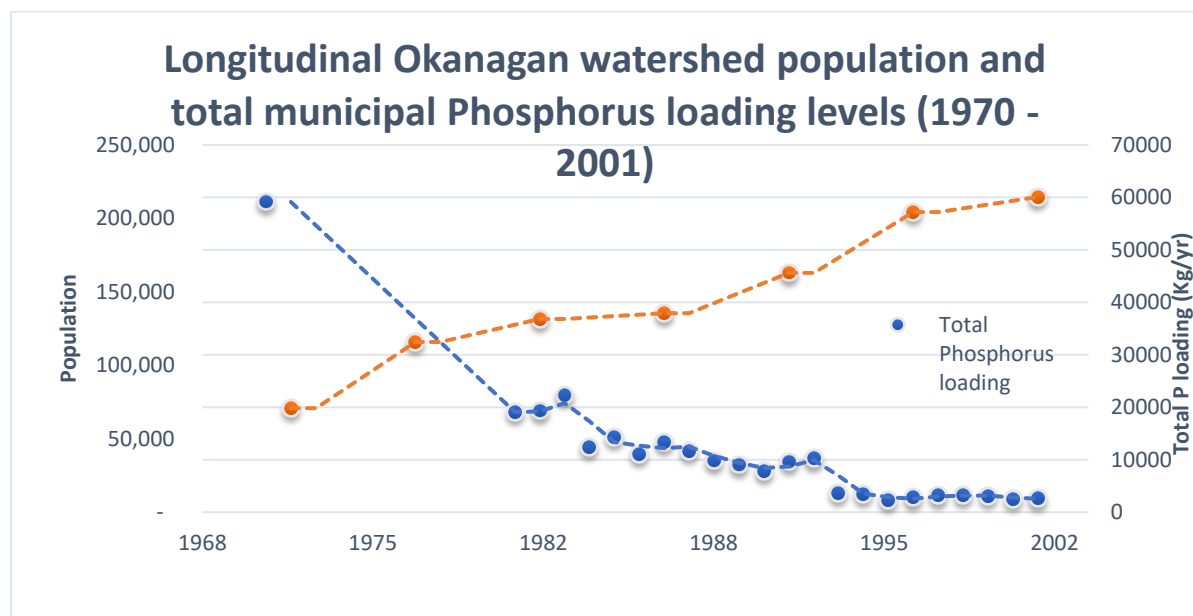


Fig 3. Longitudinal analysis of water quality (phosphate) in Skaha Lake, a mainstream Okanagan Lake, compared with population growth during the same time.

Assessing the network governance performance of a watershed organization is challenged, in part, because not all organizations play the same function within the broader watershed governance system. The literature distinguishes at least three types of watershed governance organizations - shared, lead, and network-organization (Lubell, Jasny, & Hastings, 2016; Provan & Kenis, 2008). While some studies emphasize the importance of leadership organizations (Lubell, Robins, & Wang, 2014b; Lubell, Stacey, & Hummel, 2021; Sayles & Baggio, 2017), the Okanagan Basin Water Board (OBWB) would be classified as a network organization, defined as "a separate administrative entity set up specifically to govern the network and its activities" (Provan & Kenis, 2008, p. 236). Although the analysis of network watershed organizations is relatively rare in the literature, as compared to case studies of lead organizations (Lubell et al., 2021) and broader regime-level analyses (Pahl-Wostl, 2015), they significantly influence watershed governance outcomes.

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Corpora text analysis

To build our ERG models and analysis of governance themes, we used information from OBWB public meeting minute corpora detailing actor attendance, actor affiliation, and meeting discourse content. We accessed meeting-corpora from the publicly available website www.obwb.ca/minutes (June 2021).

Corpora data is a rich source of information providing actor network data, contextual data, information on the application of new technology, identification of themes, and sentiment of board members, thus supporting several network analyses. We used the software package Nvivo 3 to organize, code, and analyze our text data.

Social network analysis

Social network analysis "has become a core analytic technique across a range of social scientific disciplines" (Light & Moody, 2020, p. 7), but data for any model development are usually limited. There are two types of social network analysis: ego network analysis and whole-network analysis (Light & Moody, 2020). Ego network analysis takes a connectionist approach with a primary focus on the relationships between actors and how these relationships support diffusion across the network. The connectionist process, or "small-world" research approach, provides insights into the rate of information sharing or disease transmission (Light & Moody, 2020).

Alternatively, we apply a positional or whole-network analysis approach focused on relational patterns known as motifs within actor networks. Researchers identified actor centralization and coordination as important social network variables influencing social-ecological outcomes (Örjan Bodin et al., 2016; Borgatti et al., 2009; Cross, Borgatti, & Parker, 2002; Kilduff & Brass, 2010; Light & Moody, 2020; M. Lubell & Robbins, 2021; March & Simon, 1993). We collected and modelled our data as a two-mode network (Everett & Borgatti, 2013), with meetings and actors grouped into annual meeting panel data sets.

Exponential Random Graph (ERG) model

We paid particular attention to the choice of model parameters and the application of motifs to improve our understanding of watershed network building. The ERG model's essential logic lies in evaluating a structural statistic's quantile concerning a baseline distribution on the set of possible structures (Butts, 2008). As a statistical model, an ERG model permits inferences about whether, in our network of interest, there are significantly more (or less) reciprocated ties or motifs formed, for instance, than we would expect (Lusher, Koskinen, & Robins, 2013). We wrote the general form for an ERG model (Light & Moody, 2020) as follows:

$$\Pr(Y = y) = \exp(\vartheta^T g(y, X)) / \kappa(\vartheta)$$


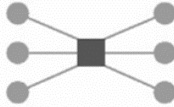
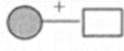
Where the Y term is the random variable for the state of the network (with realization y), the $g(y)$ term is a vector of model statistics for network y . The ϑ term is the vector of coefficients for those statistics. And the κ term represents the quantity in the numerator summed over all possible networks, typically constrained to be all networks with the same node set as y .

The ERG model equation that we apply to this analysis is as follows:

$$\text{ERGM} = \text{edges} + \text{gwb1degree}(0.4) + \text{b1factor}(\text{government: local, provincial})$$

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We provided a summary of our ERG Model parameters in Table 2. To analyze ERGMs, we applied the R software package "Statnet" (Handcock et al., 2019). The general application for Statnet modelling "is generative: micro-level processes are proposed (via the model) to reproduce the macro-level network structure and tested to the goodness of fit" (Morris, Handcock, & Hunter, 2008, p. 14). We used Statnet to generate Monte Carlo MLE based on our observed data. We tested the MLE models using Statnet's goodness-of-fit statistics, which we summarize in Appendix 1. The ERGM model statistics (Appendix 1) show that the indicator fit within this social network model of the 1969 OBWB governance system panel data is relatively good, except for forming new modelled ties with federal government actors. The poor statistics relating to national government actors are due to the small number participating in the network and the frequency with which they attended OBWB meetings.

Effect	Configuration*	Description
<i>Motif characteristics</i>		
	Edge	
Likelihood of forming a new edge, given observed network data.		Given the formation of a new tie, the likelihood is to attend a watershed organization's board meetings.
Likelihood of forming Anti-centralization motifs [Centralization]	GWB1degree 	Likelihood of actor coordination, with the addition of a new tie. The term adds one network statistic to the model equal to the weighted degree distribution with decay controlled by the decay parameter (set at 0.4) for nodes in the first mode of a bipartite network. This motif describes coordination and learning via open structures (M. Lubell & Robbins, 2021).
<i>Actor characteristics</i>		
Likelihood of forming new actor ties. [Coordination]	B1Factor.org("type") 	The tendency of a tie forming with an actor belonging to a specified organization (i.e., local or provincial government). This statistic assesses the number of times an actor with that attribute appears in an edge without other organization types.

*(Wang, Sharpe, Robins, & Pattison, 2009)

Table 2. Summary ERG model parameters (Handcock et al., 2020).

The study applied a statistical method known as geometrically weighted degree (GWD) to measure the distribution of connections among actors in a network (A Levy, 2016). Network centralization – the tendency for edges to accrue among a small number of popular nodes – is a

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key network variable in many fields, and in ERGMs it is primarily modelled via the geometrically-weighted degree (GWD) statistic (Snijders et al. 2006; Hunter 2007). GWD statistics have been referred to as "anti-centralization" network measures (Lubell & Robbins, 2022), and I applied the same logic to this study. A negative coefficient of GWD suggests a centralization tendency, while a positive coefficient indicates a more dispersed network. This method aimed to understand better OBWB's network structure and how it may have influenced its governance performance over time. The result of this variable reflects the overall tendency of network dispersion where a negative coefficient indicates "a strong centralization tendency." The application of the anti-centralization motif is supported by previous research (Lubell & Robbins, 2022; Ren et al., 2023).

This study also employed a categorical nodal attribute, referred to as B1Factor, as a second motif of interest. B1Factor statistics were commonly used to identify the number of occurrences of a node with a specific attribute (i.e., provincial actor) in an edge (M. S. Handcock, Hunter, Butts, Krivitsky, et al., 2020). This attribute was incorporated into the Exponential Random Graph Model (ERG model) as a predictor variable, as described in Equation 1. The ERG model was used to estimate the likelihood of a new edge formation, given the predictor variables selected, including the B1Factor attribute.

Standardizing ERGM outputs

To compare network characteristics over time or between organizational cases, it is crucial to standardize Exponential Random Graph Model (ERG) panel data (Duxbury, 2021). To achieve this, we built upon previous research that has developed ERG models (Robins et al., 2007) and a topological framework for analyzing longitudinal social networks (Uddin et al., 2015). However, comparing panel data modeled using ERG can be problematic due to the dynamic nature of network characteristics and the variations in network size and density present in the observed data. To address this issue, we calculated the Average Marginal Effect (AME) for each ERG model Markov Chain Monte Carlo (MCMC) output (Duxbury, 2021). This standardization procedure allows for a more accurate understanding of the dynamics of network characteristics in organizations over time and enables the comparison of ERG panel data.

Results

Next, we describe the multi-method social network analysis. Building on observed two-mode network data derived from OBWB meeting note corpora, we applied an ERG model to each annual action situation of the network organization.

Our modeled results are visually presented in Fig. 4 showing annual MLE values for the two network variables of interest, the likelihood of anti-centralization motif formation and provincial actor attendance.

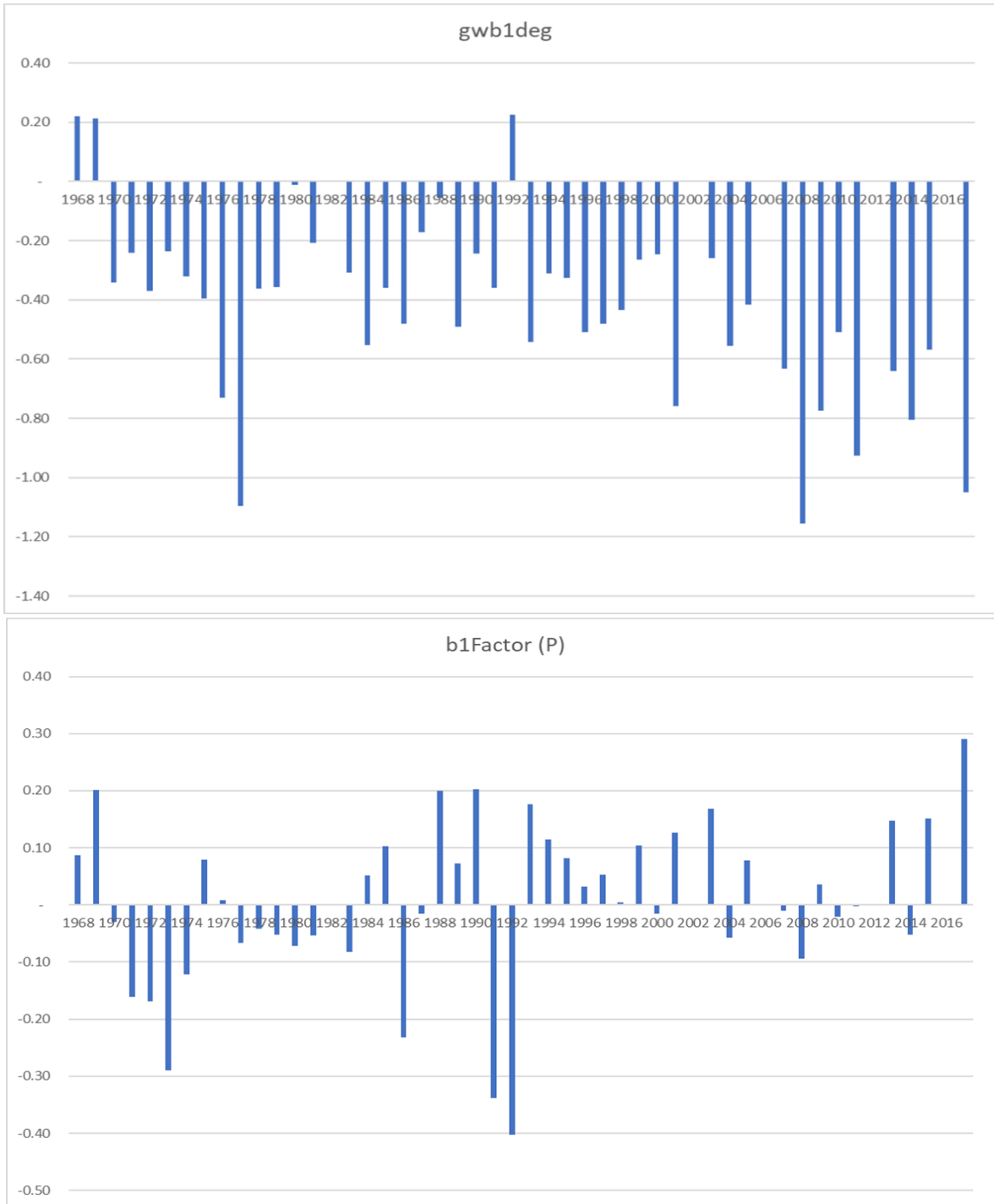


Fig. 4. Summary of 50 years of standardized ERG model maximum likelihood estimate (MLE) data for network indicators of anti-centralization (gwb1deg) and coordination (provincial attendance).

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The graph in Figure 4 displays the standardized annual MLE values for the modeled governance motifs. Each bar on the graph represents an annual action situation, where we studied the two-mode network that represents the meetings and the actors' attendance. Using the ERG model, we analyzed the likelihood of forming anti-centralization motifs within a given year of observed network data from OBWB board meetings to determine the level of Board centralization. A negative anti-centralization value suggests a more centralized network, while a positive anti-centralization value indicates a decentralized or multi-centered network.

With MLE calculations in hand, we characterized this data using a two-dimensional grid of distribution of power or decentralization (x-axis) and degree coordination (y-axis). This two-dimensional grid distinguishes four governance configurations: polycentric, fragmented, centralized-coordinated, and centralized rent-seeking (Pahl-Wostl & Knieper, 2014).

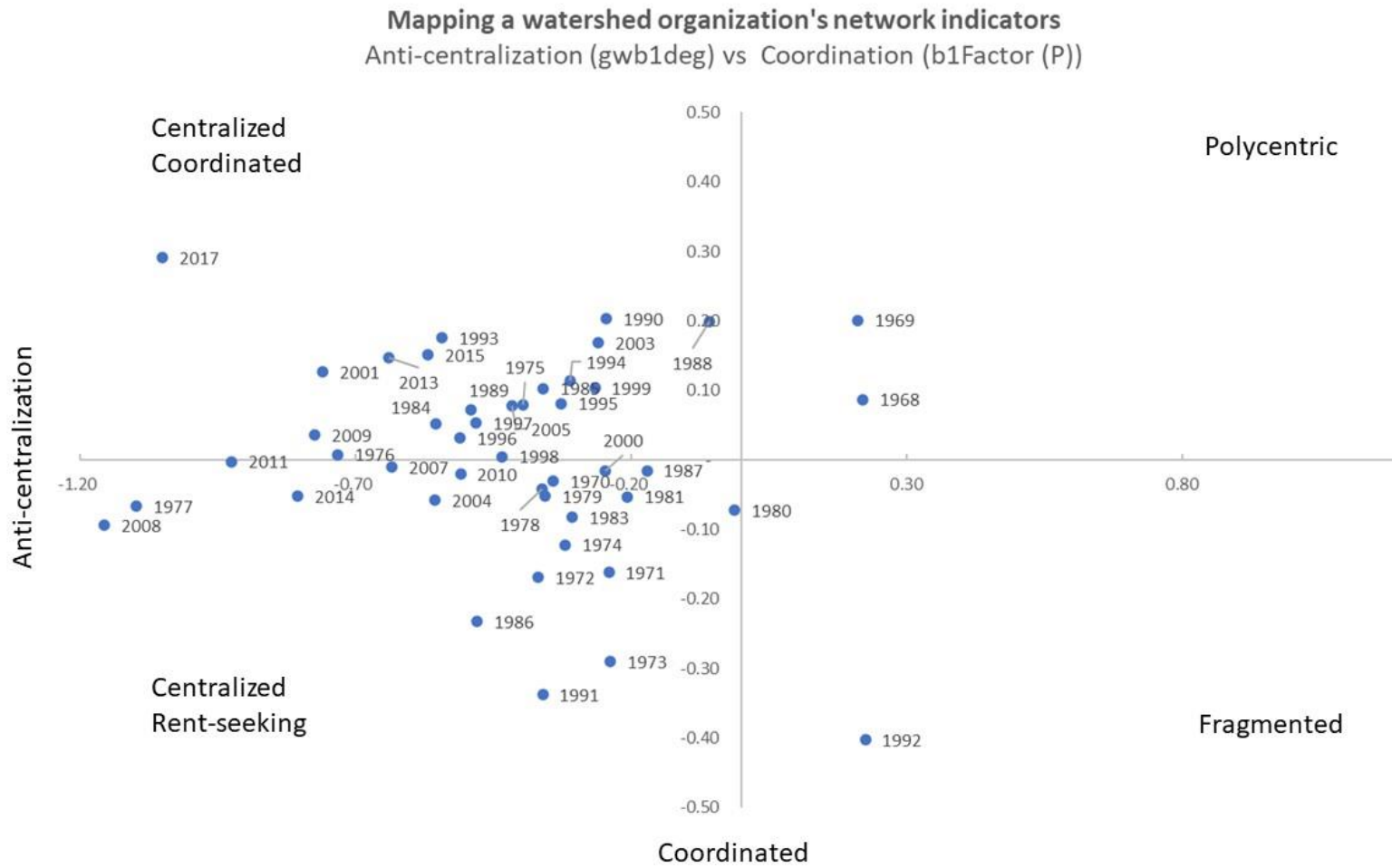


Fig. 5. A two-dimensional governance typology shows anti-centralization and coordination network attributes. Values for annual OBWB coordination and we plotted centralization maximum likelihood estimates (MLE) within the typology and colour-coded by the decade of modelled data.

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We have identified two outliers in our analysis. The first one occurred in 2017, where the network action situation indicated a highly centralized and coordinated network structure. The second outlier occurred in 1992, where the network expressed characteristics of being highly fragmented.

The OBWB has played a crucial role in performing "core governance functions" (Pahl-Wostl, 2015, p. 45), including policy framing, conflict resolution, rulemaking, knowledge generation, and resource mobilization. We have summarized our results in Table 3, indicating that the OBWB has exhibited network characteristics falling within each of the four prescribed governance categories during different years (action situations). As the OBWB matured, the network attributes expressed during a year of Board meetings evolved from a polycentric governance network to one that oscillated between centralized rent seeking and centralized coordinated.

Period (or outlier)	Characterization (Network properties)	No. of observations
1968-1969	Polycentric	2 of 2
1970's	Centralized rent seeking	7 of 9
1980's	Mixed (centralized rent seeking & centralized coordinated)	
1990's	Centralized coordinated	8 of 9
1992	Fragmented	1 of 1
2000's	Mixed (centralized rent seeking & centralized coordinated)	
2010's	Mixed (centralized rent seeking & centralized coordinated)	
2017	Centralized coordinated	1 of 1

Table 3. Summary of decadal trends and outliers observed in 50 years of standardized ERGM watershed organization (OBWB) network data.

Discussion

Through this section, we present our main findings, compare, and contrast our results with those of previous studies, and highlight the broader implications of our research. To ensure a logical flow of information, we first summarize our main findings and their significance. We will then draw on previous research in the field to contextualize our results and discuss their implications for future research and practice.

Main findings and significance

The findings from our analysis of 50 years of OBWB board meeting data provide valuable insights into the evolution of network governance within this organization. Our study used two-mode network data to model the OBWB's network attributes, and we characterized the data using a two-dimensional grid of distribution of power or decentralization and degree coordination. This two-dimensional grid allowed us to distinguish four governance configurations: polycentric, fragmented, centralized-coordinated, and centralized rent-seeking.

Our analysis revealed that the OBWB's network was polycentric during its formative years, which indicates a high likelihood of provincial actor participation and the formation of anti-centralization network motifs. As the organization matured, its network attributes evolved from a polycentric governance network to one that oscillated between centralized rent seeking and centralized coordinated. This transition occurred mainly during the 1970s, when the network became more centralized and rent-seeking, with a focus on resource mobilization.

In the 1980s, the network displayed mixed attributes, including both centralized rent seeking and centralized coordination. During this period, the OBWB played an important role in policy framing, conflict resolution, and rulemaking. The network then transitioned towards a more centralized and coordinated network during the 1990s, with a focus on knowledge generation and policy implementation. This trend continued into the 2000s and 2010s, where the network displayed mixed attributes of centralized rent seeking and centralized coordination.

Our analysis also revealed two outliers in the network's attributes. The first outlier occurred in 2017, where the network displayed a highly centralized and coordinated structure. The second outlier occurred in 1992, where the network expressed characteristics of being highly fragmented.

Answering our research question required building on previous work and developing a new typology to analyze a single watershed organization's network attribute. Figure 1 shows the governance system typology that we developed based on the centralization/coordination matrix developed by Pahl-Wostl and Knieper (2014) for higher-level governance regime analysis. Our modified qualitative analysis tool provides a framework for diagnosing a watershed organization's governance system based on modeled social network data. Using this framework, we identified two additional research questions to explore. The first question asked what category our case study network organization falls under based on a two-dimensional governance system analysis: centralized-coordinated, polycentric, centralized rent-seeking, or fragmented? The second question focused on how the categorization reflects an organization's governance performance. By answering these questions, we were able to test several aspects of this

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new watershed governance indicator framework based on social network data. Ultimately, our research has the potential to contribute to the advancement of knowledge in the field of watershed management and governance by providing a comparable indicator framework for assessing coordination and centralization in a watershed organization's governance structure.

Overall, our study demonstrates the usefulness of two-mode network data and the application of a two-dimensional grid to characterize network governance attributes. Our findings suggest that the OBWB's network governance has evolved over time, reflecting changes in the organization's core governance functions and the external environment. The study's insights may be useful to other organizations facing similar challenges in evolving their governance structures.

Findings in relation to previous research in the field

The findings from this study build upon previous research in the field of network governance and provide new insights into the evolution of network governance within the Okanagan Basin Water Board (OBWB). Specifically, the study demonstrates the usefulness of two-mode network data and the application of a two-dimensional grid to characterize network governance attributes.

To gain insights into governance structures within organizations, network analysis has been extensively used in prior studies. For instance, researchers have explored how power is distributed among network members and the governance structure of inter-organizational networks. Notably, previous research has underscored the significance of establishing network ties between local watershed organizations and senior levels of government for achieving high-performing governance systems (Koontz, Heikkila, et al., 2019). Furthermore, other studies have examined the emergence of governance networks and the role of actors in influencing network structure and evolution.

Previous research has found that purposeful design and a combination of networks, bureaucratic hierarchies, and market needs are necessary for the emergence of effective watershed systems (Pahl-Wostl, 2009). This study supports these observations, highlighting the importance of coordination, purposeful design, and social factors in the OBWB's network governance for achieving improved governmental performance (Pahl-Wostl, 2019; Pahl-Wostl and Knieper, 2014). By analyzing network centralization and coordination, we gain new insights into macro-level institutional network traits and their impact on organizational performance and broader social-ecological interactions. This research can inform efforts like the OBWB's watershed-level initiatives to reduce lake pollution by incentivizing timely wastewater treatment technology implementation. Social network models offer a framework to understand how the structure of social and policy relationships affects policy outcomes (Lubell, Scholz, Berardo, & Robins, 2012).

Administrative theory proposes various models with different indicators to explain organizational fitness (March & Simon, 1993). The classic Gulik and Urwick (1937) organizational theory highlight the significance of shared goals, the satisfaction of individual needs, and competition as crucial factors (March & Simon, 1993). This theory emphasizes that the division of work and coordination are essential drivers of change, and process departments must coordinate to guarantee positive cooperation (March & Simon). According to this theory, organizations' network structures are expected to evolve over time, and as organizations grow larger, the marginal advantages from process organization become smaller,

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while the coordination costs become larger. Thus, the balance of net efficiency “shifts from process to purpose organization as the organization's size increases” (March & Simon, 1993, p. 48). Our study's results are consistent with the expectation from administrative theory where a well-functioning organization demonstrates centralized and coordinated characteristics. Understanding these foundational drivers of organizational fitness can inform the design and evolution of network structures, ultimately leading to improved organizational performance.

Whole-network social network analytics have provided new insights into action situation conditions, as highlighted by Ö Bodin et al. (2019b) and Scott & Greer (2019). For instance, research has shown that a mix of binding and bonding structures in the network can exhibit evidence of both cooperation and coordination problems, demonstrating the complexity of governance systems in which actors have partially aligned and partially clashing policy views and preferences (Berardo & Lubell, 2019). Additionally, two-mode social network research has been useful in identifying motifs and building blocks of the network and describing how the motifs change over time (Borgatti & Everett, 1997; Rosenthal et al., 1985).

Different action situation configurations, such as autonomous decision-making centers and coherence, have affected policy development (Vaas et al., 2017). For example, network analysts have used three structural motif configurations to describe components of a social system: network activity, degree dispersion, and network closure (Lubell, Robins, & Wang, 2011). Other governance researchers have explored testing metrics of network density and network cohesion and related them to the underlying level of collaboration (Ulibarri & Scott, 2017). We use the OBWB case study to illustrate a new proof-of-concept that uses two network model parameters to provide insights into policy network structure (meso-level) for network watershed organization.

Previous studies have further identified that watershed systems emerge with purposeful design and require a combination of networks, bureaucratic hierarchies, and market needs acting in concert (Pahl-Wostl, 2009). It appears that in the case of the OBWB network governance, and in particular, the features of coordination, purposeful design, and a combination of social factors are essential elements for “improved governmental performance” (Pahl-Wostl, 2019, p. 6-16, Pahl-Wostl and Knieper, 2014, p. 147). This study supports previous observations that social network model parameters affect policy outcomes, whereby,

a network conceptualization provides a framework to understand how the structure of social and policy relationships mediates the causal processes between macro-level institutions and microlevel behavior (Lubell, Scholz, Berardo, & Robins, 2012, p. 369).

Through analyzing network centralization and coordination, we are interested in better understanding several aspects of macro-level institutional network traits. And how new insights we may gain into organizational performance and broader social-ecological interactions. For example, the OBWB's watershed-level efforts to reduce lake pollution by incentivizing timely wastewater treatment technology implementation.

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In this context, our study indicates that ERG modelling of a network organization can provide valuable insights into a watershed network organization. However, it is important to note that the findings may not be generalizable to other organizations or contexts. While ERG modelling can shed light on the characteristics of network governance, it may not fully account for external factors that can influence governance structures, such as political and economic conditions. Nonetheless, our study highlights the potential of using whole-network social network analytics and ERG modelling to better understand the dynamics of network organizations in watershed management and other contexts.

The current study's findings are consistent with previous research that suggests network governance structures evolve over time in response to changing internal and external environments. The transition from a polycentric network to a more centralized and coordinated network observed in the OBWB is similar to the findings of other studies on the evolution of governance networks. Additionally, the study's observation of outliers in the network's attributes is consistent with previous research that highlights the role of external shocks or crises in disrupting governance structures.

However, the current study's application of a two-dimensional grid to characterize network governance attributes is a unique contribution to the field. This approach provides a more nuanced understanding of governance structures by distinguishing between different types of centralized and decentralized networks. By identifying four distinct governance configurations, the study provides a more comprehensive analysis of the OBWB's governance structure than previous studies.

Overall, this study contributes to our understanding of network governance and provides insights that may be useful to other organizations facing similar challenges in evolving their governance structures.

Study strengths and limitations

The study has several strengths that add value to the research. Firstly, the study covers a long period of 50 years, which provides a comprehensive view of the evolution of network governance within the OBWB. This feature adds to the credibility of the study as it shows the development of the organization over time.

Secondly, the use of two-mode network data and a two-dimensional grid to characterize network governance attributes is a novel and innovative approach. This approach can provide a useful framework for analyzing governance networks in other contexts, making the study a valuable resource for other researchers in the field.

Finally, the study provides valuable insights into the OBWB's network governance, which may be useful to other organizations facing similar challenges in evolving their governance structures.

Despite the strengths, the study also has some limitations that need to be considered. Firstly, the study is limited to the OBWB and may not be generalizable to other organizations or contexts. The findings may be context-specific and not applicable to other governance networks.

Secondly, the study relied on board meeting data, which may not capture the entire scope of the OBWB's governance activities. Other governance activities, such as informal communication and decision-making, may not have been captured in the data.

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Thirdly, the study did not consider external factors, such as political and economic conditions, which may have influenced the OBWB's governance network. The findings may not fully account for the impact of external factors on the organization's governance structure.

Finally, the study is retrospective, which means that it may be subject to hindsight bias. The authors may have unconsciously selected data and analyzed it in a way that confirms their preconceived notions about the OBWB's governance structure. Therefore, it is important to consider these limitations when interpreting the study's results.

Underlying mechanisms or processes that may explain the findings

There may be several possible explanations for the findings in this study. One possible explanation for the transition from a polycentric network to one that oscillates between centralized rent seeking and centralized coordination is that as the OBWB grew and complexity, it became more difficult to coordinate decision-making across a decentralized network. This may have led to a shift towards more centralized coordination to improve efficiency and effectiveness.

Another possible explanation for the shift towards centralized rent seeking in the 1970s is that the OBWB was facing increased pressure to secure funding and resources for its programs, and centralized rent seeking was seen to achieve these goals. However, this may have come at the expense of decentralized decision-making and the participation of provincial actors in the network.

The mixed attributes displayed by the network in the 1980s may be due to a combination of factors, including changes in the external environment and the OBWB's internal governance structures. The OBWB may have been responding to new challenges and opportunities in the water management sector, which required a mix of centralized coordination and rent seeking.

The shift towards a more centralized and coordinated network in the 1990s may be explained by a renewed focus on knowledge generation and policy implementation. The OBWB may have recognized the importance of centralized coordination to effectively implement new policies and programs, and to ensure that knowledge generated by the network was shared and utilized across the organization.

The outliers in 1992 and 2017 may be due to external events or changes in the OBWB's internal governance structures. For example, the fragmentation observed in 1992 may have been a result of changes in government policies or funding priorities that impacted the OBWB's ability to coordinate decision-making across the network. The highly centralized and coordinated network observed in 2017 may have been a response to new challenges or opportunities in the water management sector, such as changes in climate patterns or new regulatory requirements.

Overall, the findings of this study suggest that the evolution of the OBWB's network governance can be explained by a combination of factors, including changes in the external environment, the organization's core governance functions, and its internal governance structures.

Study implications

The findings of this study have several implications for future research and practice in the context of network governance. First, the study highlights the importance of examining the evolution of network

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governance structures over time, as they may change in response to internal and external factors. Therefore, future research could investigate the underlying mechanisms and drivers of these changes, including how changes in leadership, policy priorities, and external factors such as climate change or economic conditions, affect network governance structures.

Second, the study suggests that different network governance configurations may be appropriate for different stages of an organization's development. For example, a polycentric governance structure may be more effective during the formative years of an organization, while a more centralized and coordinated structure may be more appropriate when an organization is mature and has well-established governance functions. Therefore, future research could investigate how network governance structures vary across different types of organizations, and how they can be adapted to suit different organizational contexts.

Finally, the study's insights may be useful to practitioners who are involved in managing network governance structures. For example, the findings suggest that organizations should consider the balance between centralization and decentralization, and the coordination of actors within their networks. Practitioners may also benefit from using two-mode network data and the two-dimensional grid approach to characterize network governance attributes and monitor changes over time.

In conclusion, this study provides valuable insights into the evolution of network governance structures in the context of the OBWB. The findings have implications for future research on network governance, including investigations of underlying mechanisms and drivers of change, variations across organizational contexts, and applications of the two-mode network data and the two-dimensional grid approach. Furthermore, the findings may be useful to practitioners involved in managing network governance structures in a variety of organizational contexts.

Key points and their overall significance

This study used two-mode network data and a two-dimensional grid to analyze 50 years of board meeting data from the Okanagan Basin Water Board (OBWB) to explore the evolution of its network governance. The study found that the OBWB's network governance had evolved over time, with its network attributes transitioning from a polycentric governance network to one that oscillated between centralized rent-seeking and centralized coordination. The study also revealed two outliers in the network's attributes in 2017 and 1992. The findings suggest that changes in the organization's core governance functions and the external environment have influenced the evolution of its network governance. The study demonstrates the usefulness of two-mode network data and the two-dimensional grid approach in characterizing network governance attributes. The insights from this study may be valuable to other organizations facing similar challenges in evolving their governance structures. Future research can further explore the mechanisms behind the observed transitions and outliers and investigate the effectiveness of different network governance configurations in achieving organizational goals.

Conclusion

The application of ERG modeling proved to be a valuable tool for analyzing longitudinal network data, particularly for understanding certain structural aspects of network governance and watershed organization performance. This new diagnostic framework provides several benefits for watershed organizations, including the ability to visualize changes over time, compare organizations, and analyze social-ecological relationships. Furthermore, future research analyzing a range of network attributes and their relationship with service performance will provide even more valuable insights and support for creating purpose-built watershed organizations. Ultimately, the application of social network models and metrics of coordination and centralization can help improve governance and ecological outcomes in shared water commons.

Watershed organizations, such as the OBWB benefit from this type of diagnosis for several reasons. First, there is an opportunity to visualize how several social network variables of interest change over time. Second, the chance to compare watershed organizations becomes possible using this new diagnostic framework applying metrics of coordination and centralization as one lens to explore an organization's relative position. Third, this framework supports further analysis of social-ecological relationships that are of interest. For example, the opportunity to measure the effects of social programs such as the SFA grant program on reducing anthropogenic eutrophication of water bodies is enabled through the application of this new framework.

To gain a better understanding of watershed governance, longitudinal ERG models will be useful in future research. This will provide important insights into the action situations of watershed organizations and enable the development of pragmatic recommendations for social entrepreneurs. Additionally, research will analyze an organization's network attributes and how they relate to service performance, particularly the success of a service in achieving ecological outcomes, such as preventing eutrophication and the introduction of invasive species. This analysis will help to identify areas for governance improvements and practical change management strategies. Moreover, the findings will be valuable for the creation of new purpose-built watershed organizations that address complex social-ecological watershed issues and trade-offs in shared water resources.

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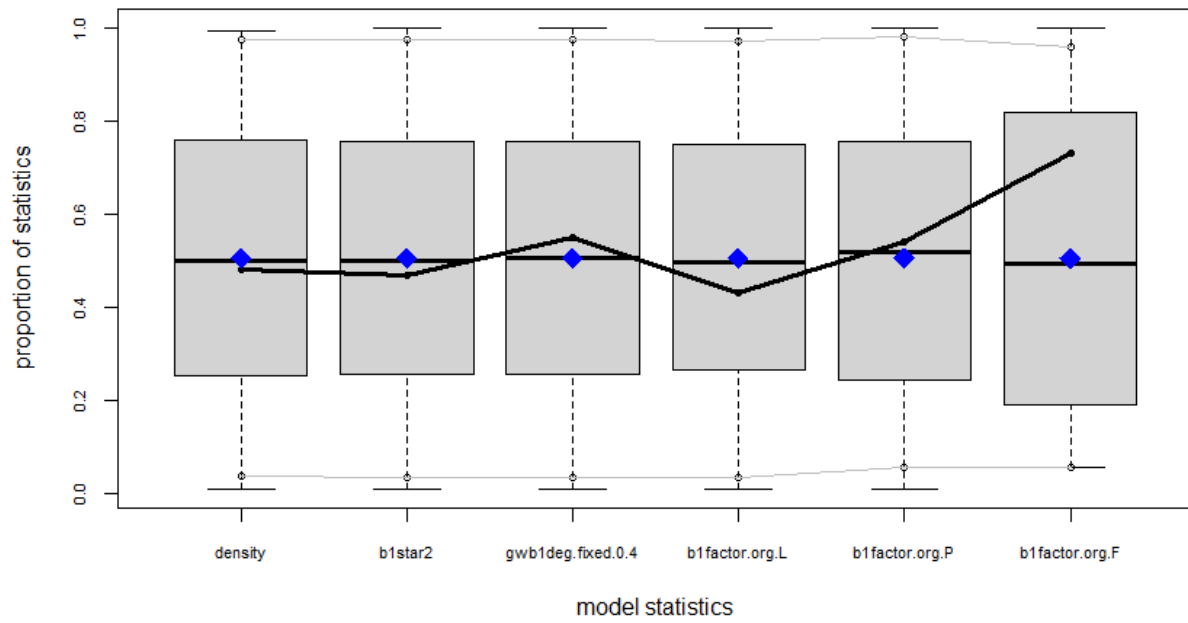
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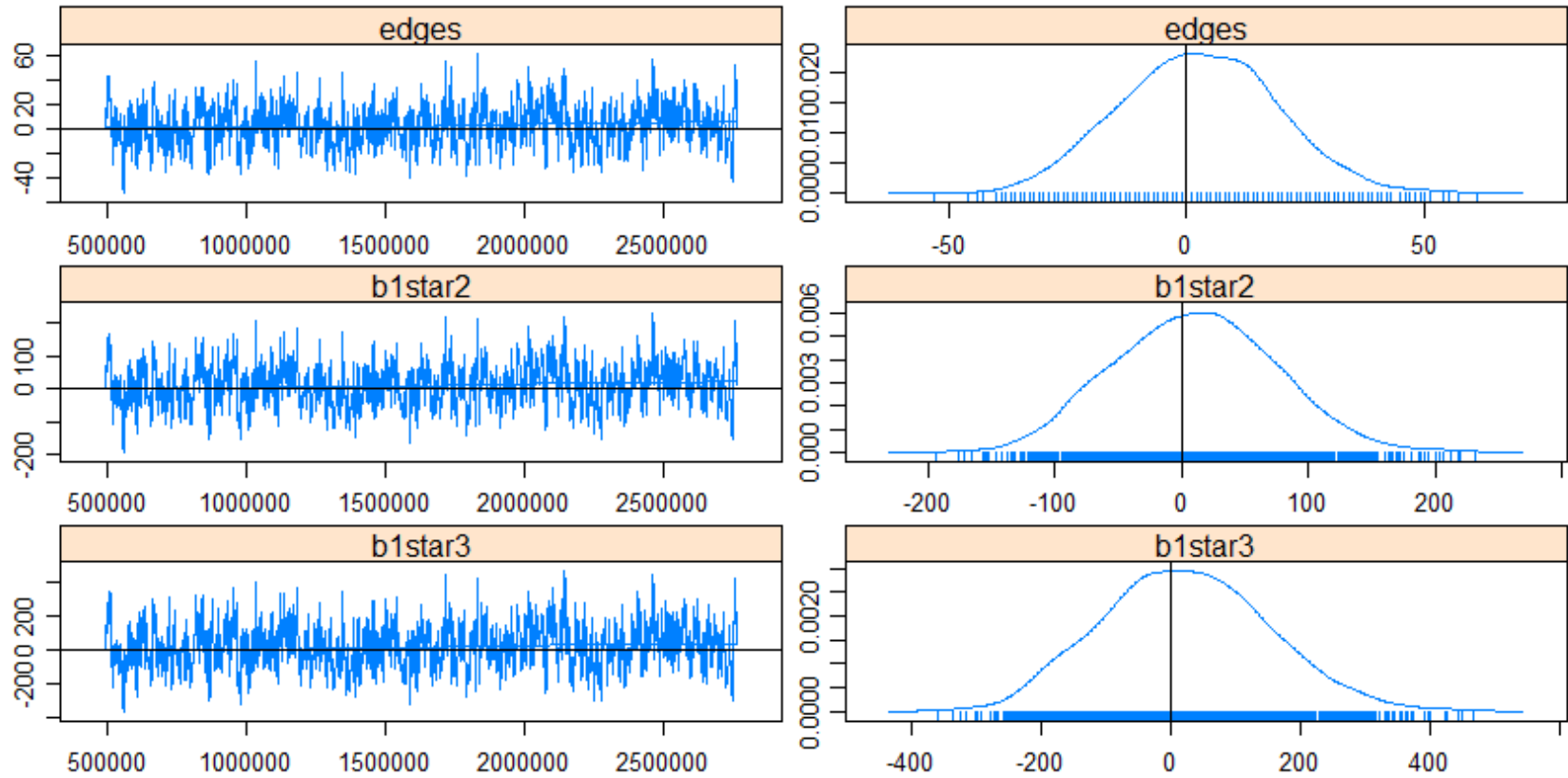
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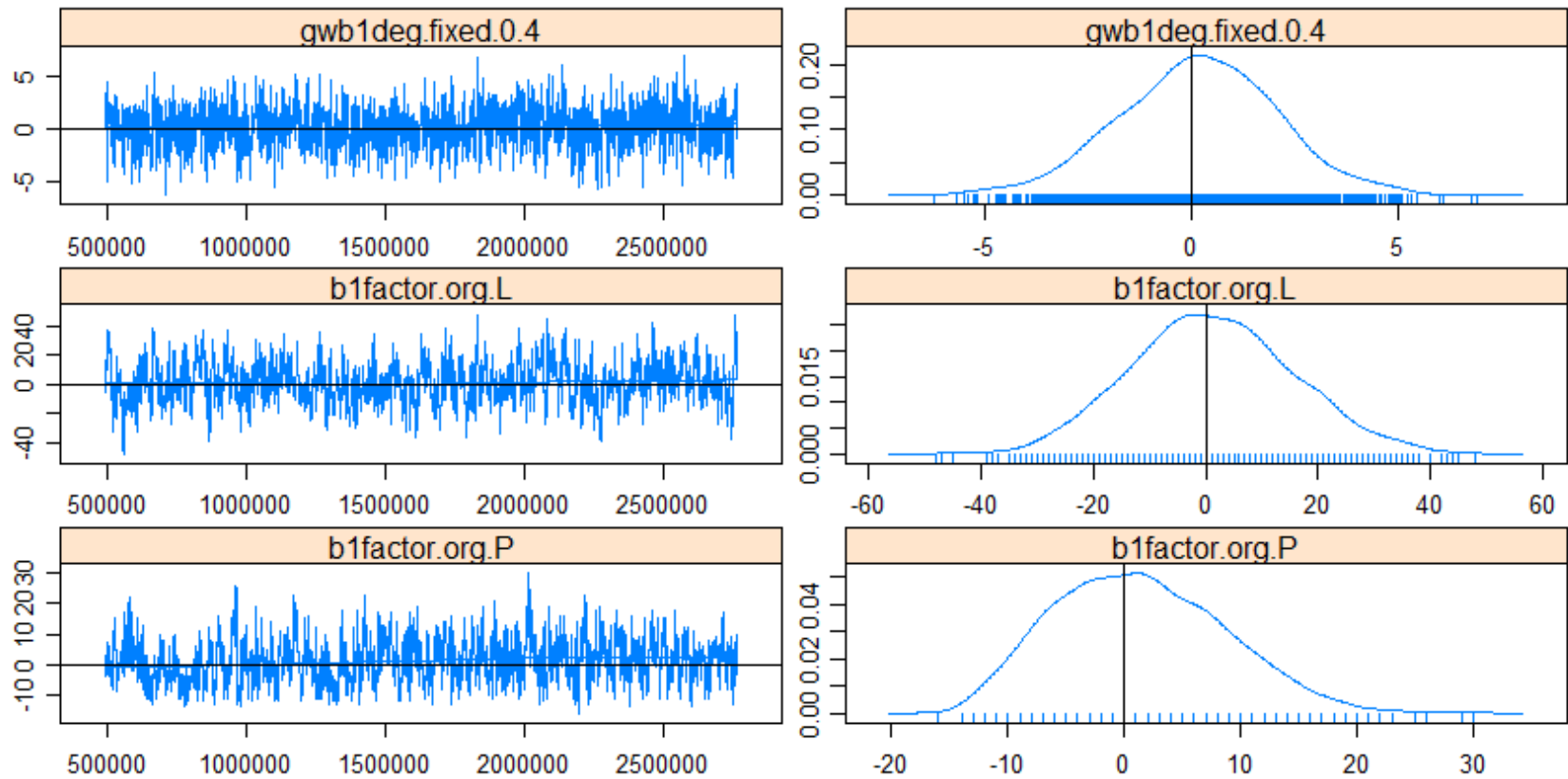
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Sample statistics



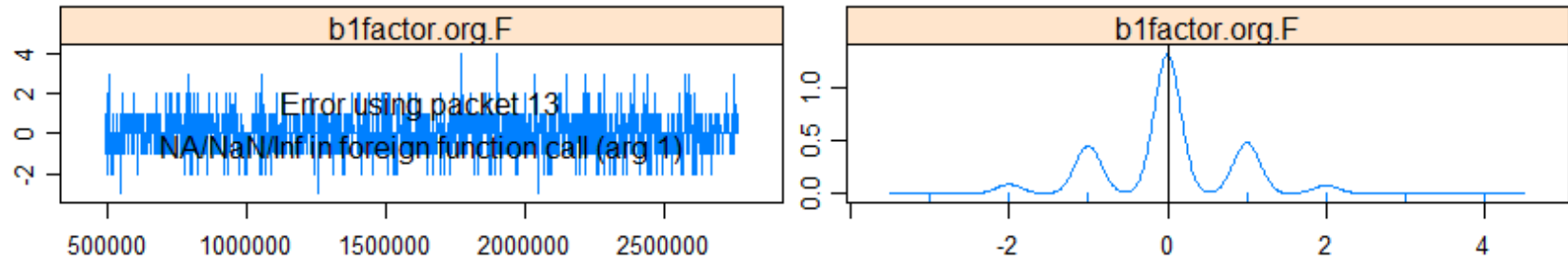
Sample statistics



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Appendix 2. (cont.) ERGM 1969 sample statistics

Sample statistics



Exploring changes in 50 years of social networks to improve our understanding of a watershed organization's performance

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Abstract

Social network building is an essential responsibility for any organization and is expected to become even more critical with climate change and technology advancements. Robust indicators reflecting the effects of network-building tactics aligned with strategic plans are needed to support watershed management. However, watershed managers need indicators to help assess network performance. In 1970, local governments created the network watershed organization, the Okanagan Basin Water Board (OBWB), to address issues such as invasive aquatic weed management and the eutrophication of valley bottom lakes. I examine the participation of 743 actors over 50 years of attending OBWB meetings and model several network measures. This exploratory analysis focuses on two indicators of interest, based on available network data, for analyzing aspects of social network-building. Specifically, I explore the likelihood of forming anti-centralization network motifs and provincial actors attending OBWB Board meetings. The changepoint analysis method is used to help understand where changes in network trends occur. In this study, I demonstrate the application of a multi-method approach to identify changes in network trends that indicate changes in several aspects of watershed governance. The results show that several changepoints in the network attributes align with internal and external factors and show potential for application as watershed governance indicators.

Keywords: water, governance, indicators, social capital, exponential random graph model, change point analysis, social network analysis

Acronyms

AME – Average Marginal Effect

CPA – Change Point Analysis

ERG – Exponential Random Graph

GWD – Geometrically Weighted Degree

MCMC – Markov Chain Monte Carlo

MCP – Milfoil (*M. spicatum*) Control Program

OBWB – Okanagan Basin Water Board

Introduction

Measuring various aspects of watershed governance is imperative. Despite many global performance indicators for water management, there remains a crucial gap in indicators to gauge water governance (Dunn & Bakker, 2011). This hinders watershed organizations from evaluating their performance and implementing effective change management strategies. Comprehending network transformations over time is essential for successful performance evaluation and change management. In this study, I aim to provide insight into how strategies to change organizational governance, and internal variables within the control of an organization's management team, align with changes in network governance outcomes.

An organization's network structure provides valuable insights into aspects of an organization's governance (Lubell, Jasny and Hastings 2017, Lubell 2013). Watershed organizations often focus on managing natural resources, improving water quality, and reducing the impacts of human activities on the environment. The following are some examples of governance outcomes that a watershed organization might aim to achieve:

- Adoption of best management practices (BMPs) to reduce the impact of agricultural and urban activities on water quality.
- Development and implementation of policies and regulations to manage water usage and prevent water pollution.
- Restoration of the degraded stream and river habitats to improve water quality and biodiversity.
- Engagement of stakeholders in decision-making processes to ensure that the community needs and concerns are addressed.
- Education and outreach programs to increase public awareness of water quality issues and promote conservation practices.
- Collaboration with local governments, businesses, and other organizations to address shared water resources and environmental challenges.
- Monitoring and reporting on water quality and ecosystem health to track progress and identify areas for improvement.
- Investment in infrastructure and technology to improve water management and reduce the risk of environmental degradation.

These are just a few examples of governance outcomes that a watershed organization might pursue. The specific goals and, subsequently, the network social capital objectives of a watershed organization will depend on the needs and priorities of the watershed and the actors involved.

It is posited that network social capital is crucial in understanding an organization's governance. Social capital encompasses a wide range of ideas, including socio-structural factors such as

trust, social integration, and the rule of law (Putnam, 1995), as well as the value of an individual's social relationships (Burt, 1992). It encompasses "the social structure that facilitates certain actions of actors within the structure...Making possible the achievement of certain ends that, in its absence, would not be possible" (Coleman, 1988, p. 98). Borgatti et al. (1998) have outlined four categories of networked social capital and the application of social network analysis to measure social capital. In this study, I adopt a narrow definition of social capital, focusing on the social network measures of a group of actors, specifically the attendance of actors at an OBWB Board meeting.

Studies have shown that social networks can influence performance in policy development (Levin et al., 2013; Pearse & Quinn, 1996; Vaas et al., 2017), program implementation (Heikkila, 2004; Imperial, 2005; Schneider et al., 2003; Seijger et al., 2018), disaster management (Bodin & Nohrstedt, 2016), and communications (Baggio & Hillis, 2018; McCubbins & Weller, 2020). Scholars have found network structures to influence social capital and associated positive outcomes, including watershed security (Dale & Sparkes, 2008).

Social networks and building social capital are essential activities that contribute to the performance of social-ecological systems, as they "link members and their resources, facilitate joining action and learning, and leverage from collective interactions to respond in new and innovative ways to issues" (Mandell & Keast, 2008, p. 716). Further research studies have shown that building social capital enables actors to accomplish things (Ancona, 1991), successfully deliver on project outcomes, and enhance organizational innovation (Cohen & Levinthal, 1990). Over time, these changing social network "maps" depict how people engage and relate to internal and external variables in shaping complex watershed governance outcomes.

Using social network analysis to study social-ecological systems is a growing area of research (Ö. Bodin & Norberg, 2005; Lubell, 2005). Various management research studies have applied network analysis to evaluate performance in different social contexts, for example, soccer teams (Clemente et al., 2020) and corporate supply chains (Seiler et al., 2020). Advanced methods in social network modelling provide new insights into how a watershed organization can establish strategic network objectives, implement network-building strategies, and assess network characteristics of importance.

Within social network research, there need to be more longitudinal studies on watershed governance (Binder et al., 2013). Most studies in this field are comparative snapshots in time and do not capture changes over time, such as programmatic changes, new water laws or the implementation of new technology. This study addresses this research gap by presenting findings from a case study of a Canadian watershed organization over 50 years of activity.

Longitudinal analysis of network panel data poses several challenges, including scaling, low statistical power, limited external validity, undefined variables, and unobserved heterogeneity

(Hill et al., 2019). However, recent advances in computational modelling algorithms (Robins et al., 2007; L. Wang et al., 2007) and standardization techniques (Duxbury, 2021) have overcome several of these challenges and enabled the use of new ERG modelling techniques to explore network attribute changes over time.

Changepoints (abrupt shifts) in social network data arise due to shifts in macro-level governance variables. To support an organization's strategic goals and deliver "truly collaborative partnerships suited to tackle the complexity of watershed issues" (Vollmer et al., 2023, p. 2), analyzing network changepoints is a method that provides insights into network performance over time. For example, in a longitudinal analysis of network data, periods of greater network decentralization or a higher likelihood of provincial government actor participation at Board meetings are network indicators of increased collaborative partnerships.

Previous research has shown that social networks and building social capital play a crucial role in the performance of a social-ecological system, as they allow for members and their resources to be linked and for collective action and learning to take place (Barnes et al., 2016; O. Bodin et al., 2011; Hileman & Lubell, 2018; Lubell, 2015; Lubell & Fulton, 2008). Recent research has shown that building social capital is critical in various performance outcomes, such as innovation (Levy & Lubell, 2018), collaboration (Ö. Bodin, 2017), learning (Pahl-Wostl, 2002), and knowledge transfer (Gupta, 2016). This is an emerging field of study. Modelling various aspects of an organization's network and identifying when the likelihood of forming network attributes changes can help decision-makers adjust their network-building tactics to better align with their strategic goals and improve network performance.

Furthermore, by analyzing internal and external context (macro level) variables, I aim to understand better why the network may change during different periods of an organization's history. To support this analysis, the organizational structure model (Figure 1.) depicts the importance of network structures as a focus of analysis.

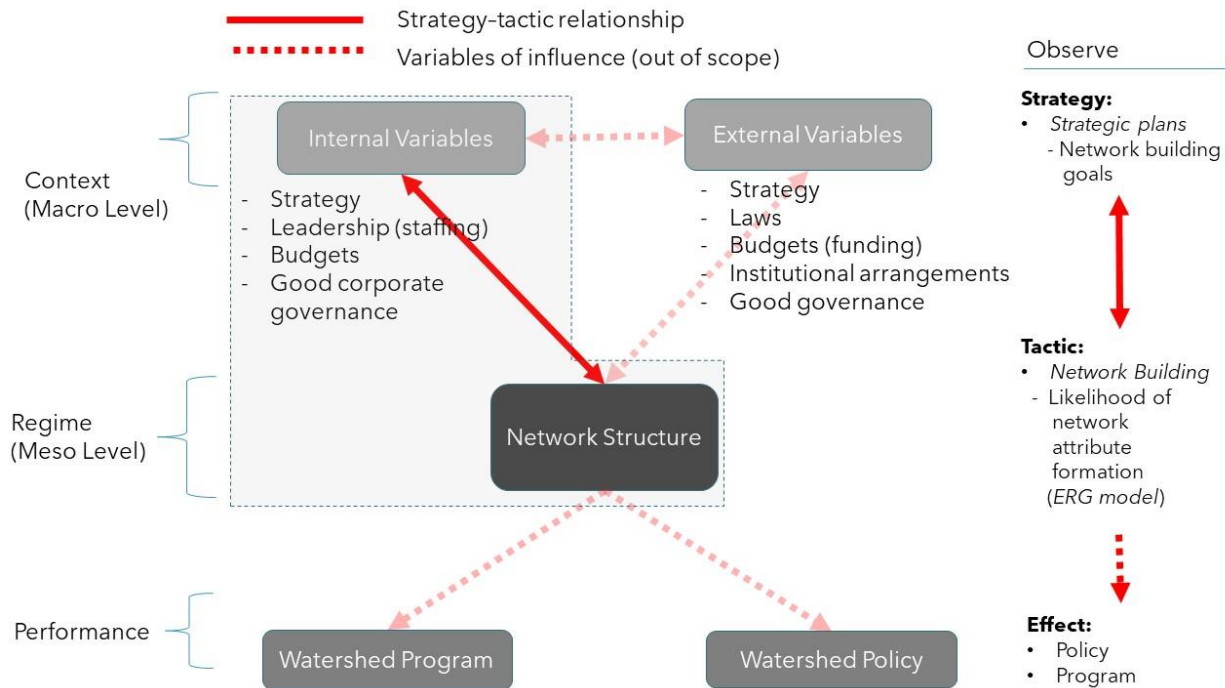


Figure 1. Tactical network formation: a model of a watershed organization's internal strategic goal setting and network performance.

This paper addresses the following research question: how can longitudinal trends in network characteristics, as identified through Exponential Random Graph Model (ERGM) analysis, inform our understanding of governance performance measures? To answer this question, a longitudinal social network analysis approach is employed to examine the network characteristics of a Canadian watershed organization responsible for various social-ecological programs. The changepoint analysis is used to uncover specific periods where policies or interventions may have impacted the organization's network structure and performance. By combining these methods, I shed some light on the dynamics of network characteristics in organizations and offer several new valuable insights that can inform future change management strategies. The importance of this study is particularly relevant in watershed management, where networks of actors play a crucial role in shaping decision-making processes.

In this study, I aim to develop effective governance indicators for (watershed) organizations. It is hypothesized that these indicators can measure improvements to watershed network governance outcomes, precisely network-building effects, and enhance decision-making processes within watershed organizations in support of positive change management strategies—for example, improving multi-level government collaboration and coordination.

I aim to investigate how internal and external factors influence social network attributes and how a watershed organization can impact these variables to improve governance outcomes. Specifically, I will focus on anti-centralization motifs and provincial government participation at Board meetings. To achieve this, I will use a standardized panel data model and Exponential Random Graph Model (ERG) data to study how network motifs change over time. By identifying change points in the data, we can gain new insights into measuring network performance and identifying the internal and external factors that affect it. By analyzing these indicators, we can gain insights into change management strategies that intentionally alter an organization's social network and, in turn, lead to positive outcomes for watershed governance. Understanding the relationship between contextual variables and social network attributes is crucial in developing effective change management strategies that improve governance outcomes.

Figure 1 presents a comprehensive conceptual model that displays the relationship between meso- and macro-level variables and organizational performance to help answer this research question. The model considers program resourcing, budgeting, and policy development factors and builds upon previous governance models (Lubell, 2015; Pahl-Wostl, 2015). This model emphasizes the reciprocal influence between macro-level context, comprising both internal and external variables, and the attributes of network structure. The network, in turn, affects the organization's performance.

I applied an exploratory approach to this data analysis and focused on discovering patterns and relationships in the data without preconceived notions about the results. This type of analysis is often used to understand the data better, identify interesting trends or patterns, and develop questions for further investigation.

In the subsequent sections of this paper, I describe the four methods used to analyze contextual and social network data. I then present my research findings and discuss the relevance and contribution to watershed governance. I present results on the network's likelihood of forming anti-centralization and provincial attendance motifs, providing valuable insights into the organization's social capital. Overall, this study contributes to our understanding of how the structure of a watershed organization's network can impact its governance and delivery of social-ecological programs.

This research interests the water resources community in Canada and abroad because it provides a replicable method to measure network metrics and apply them to an organization's management framework. Building on a Canadian watershed case study, I describe a new network model depicted as a measurable tactical tool at the disposal of managers and decision-makers in this manuscript. By explicitly developing strategic network goals and measuring network attributes, watershed managers can better understand a network's influence on organizational performance. Matching social network tactics to strategic goals support transparent, measurable, and high-performing management outcomes.

Methods

I used a combination of methods to study the social network of a watershed organization, the Okanagan Basin Water Board (OBWB). This includes collecting and analyzing data on the policy participants and meetings of the OBWB. I consider each annual data frame of OBWB public meetings as an action situation (McGinnis, 2011). Each sampling unit consisted of one year of meeting corpora data.

Using multiple methods, I triangulated several data sources to generate model network characteristics and compare these characteristics over time. I present the findings from four different types of analysis: text analysis, two-mode social network analysis, ERG modelling using AME standardization, and changepoint analysis. This multi-method approach offers valuable perspectives on understanding the network characteristics and how they change over time within a watershed organization, such as the OBWB.

Case study research design

The OBWB is a unique example of a network (Provan & Kenis, 2008) watershed organization in British Columbia. Applying the proposed social model (Figure 1.) helps define and analyze dependent and independent variables discussed in more detail in the following sections. Using network theory, I examine the structure of the OBWB as a two-mode network consisting of 743 policy participants and 50 years of meetings (1868 -2017).

The Okanagan Basin Water Board (OBWB) is a vital network organization that plays a central role in addressing water-related concerns and conflicts in the Okanagan region of Canada. This exploratory study uses social network analysis to examine the effectiveness of the OBWB in delivering programs such as the Milfoil Control Program (MCP). The Okanagan basin is a particularly relevant case study for this social research as it has been identified as a national watershed of interest due to its high number of species at risk. The OBWB has a wealth of meeting notes dating back to 1968 that are readily available online. Additionally, the relatively small size of the OBWB makes it an ideal "living laboratory" for studying water governance and further exploring network indicators.

The OBWB was officially formed in 1970 through a supplementary letters patent granted by the British Columbia provincial government to the three regional districts (the original network) and is an "inter-regional local governance entity serving the Okanagan regional districts by addressing their shared water interests and concerns" (OBWB, 2016, p. 1). At a constitutional level, the OBWB organization is within an international multilevel governance system (Melnychuk, Jatel, & Warwick Sears, 2016). The OBWB has no "command authority" (Koontz, 2019, p. 124); it provides a valuable role as a network organization within the watershed. The OBWB has public board meetings that occur six to ten times annually and are open to the public and guests.

Text analysis

Text analysis was used to generate the contextual data needed to address the exploratory nature of this study. The study subjects participated in OBWB meetings as Board members, staff, or guests. I included the organization affiliation and government level (local, provincial, federal, and First Nation) meta-data of all participants in the network. NVivo software (Bazeley & Jackson, 2013) supported meeting minute corpora's theme and text analysis, including word frequency analysis, to show critical concepts discussed at the OBWB meetings.

Social Network Analysis & Modelling

Network analysis is a powerful tool for investigating relationships between entities. In the context of two-mode data, where actors (e.g., individuals) attend meetings, and the meetings have a shared purpose, I used this approach to create a bi-partite network. This network represented actors and meetings using nodes and indicated the attendance of actors at meetings through edges. To better understand the relationships within this two-mode network, I calculated various network measures, including network density and size. I utilized the UCINET version 6.665 software developed by Borgatti, Everett and Freeman (2002) to facilitate this. These network measures provide insights into the network's structure through visual representation (see Table 2). Next, I modelled the observed bi-partite network data using the ERGM method.

ERGM is a statistical method for analyzing network data, including bi-partite network data. It has been widely used in recent years to study a variety of social, economic, and biological networks (Box-Steffensmeier et al., 2018; M. S. Handcock, Hunter, Butts, Goudreau, et al., 2020; Lusher et al., 2013; Morris et al., 2008; Scott, 2016; P. Wang et al., 2013). Some key findings from recent ERGM studies include:

- The role of network ties in shaping individual behaviour and outcomes, such as health, education, and employment.
- The influence of network structure on the diffusion of information and the spread of diseases and innovations.
- The impact of network centralization, homophily, and heterogeneity on group-level outcomes, such as collaboration and cooperation.
- The role of network dynamics in shaping network structure over time, including the formation and dissolution of ties and the emergence of subgroups and communities.
- The impact of network interventions, such as adding or removing ties, on network structure and outcomes.
- The relationship between network structure and the allocation of resources, such as the distribution of wealth and political power.

These ERGM research findings have important implications for public health, political science, sociology, and economics. By improving our understanding of the mechanisms underlying

network structure and dynamics, ERGMs have the potential to inform policies and interventions aimed at improving social, economic, ecological, and health outcomes.

The Statnet software ERG model package, R-4.11 (M. Handcock et al., 2018; M. S. Handcock et al., 2019; Hunter et al., 2008), was used to analyze the panel data with a comprehensive suite of tools suitable for analyzing model fit, statistics and diagnostics.

To determine the appropriate ERG model for this analysis, I employed a two-step process. First, I conducted a literature review to identify potential motifs that provide useful insights into a governance network. Second, I compared various ERG models by combining the identified motifs and using Akaike's Information Criterion (AIC) values to assess the model's fit (refer to Appendix 2). A lower AIC score indicates a better match between the modelled and observed network data (refer to Appendix 3). Based on this evaluation, I selected the ERG model with the variables of interest while maintaining a low AIC score and applied it to the rest of the observed network data from 1968 to 2017. The selected ERG model includes variables including the likelihood of forming new edges, the degree of the GWB1, and the presence of both local and provincial actors (as seen in Equation 1). These variables were used to calculate the Maximum Likelihood Estimate (MLE) for the OBWB empirical data. Each coefficient in the ERG model represents a likelihood estimate based on the chosen variables and the formation of new edges.

$$\text{ERGM}_{(\text{exd})} = \text{edge} + \text{gwb1degree} + \text{b1factor} (\text{local} \mid \text{provincial})$$

Equation 1. Selected ERG model coefficients applied to this OBWB social network analysis.

The relationship between network structure and social capital mobilization in ecosystem protection has been previously explored in the literature (Dale & Sparkes, 2008; Klenk et al., 1995). The use of ERG models in previous studies is summarized in Appendix 1. It is important to note that the involvement of stakeholders and the development of social capital are crucial factors in the success of watershed management (Lubell, 2005; Lubell et al., 2016; Mullen & Allison, 1999). In this study, the two network motifs of interest are described in Table 1.

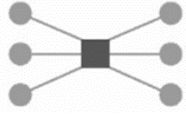

Description	Motif	ERG Model reference
Anti-centralization motif.		GWB1Degree
Likelihood of forming new provincial actor ties.		B1Factor

Table 1. Summary of network motifs examined in this study.

The study applied a statistical method known as geometrically weighted degree (GWD) to measure the distribution of connections among actors in a network (A Levy, 2016). A negative coefficient of GWD suggests a centralization tendency, while a positive coefficient indicates a more dispersed network. This method aimed to understand better OBWB's network structure and how it may have influenced its governance performance over time. GWD statistics have been referred to as "anti-centralization" network measures (Lubell & Robbins, 2022), and I applied the same logic to this study. The application of the anti-centralization motif in social network analysis is supported by previous research (Lubell & Robbins, 2022; Ren et al., 2023).

This study also employed a categorical nodal attribute, B1Factor, as a second motif of interest. B1Factor statistics were commonly used to identify the number of occurrences of a node with a specific attribute (i.e., provincial actor) in an edge (M. S. Handcock, Hunter, Butts, Krivitsky, et al., 2020). This attribute was incorporated into the Exponential Random Graph Model (ERG model) as a predictor variable, as described in Equation 1. The ERG model was used to estimate the likelihood of a new edge formation, given the predictor variables selected, including the B1Factor attribute.

Standardizing panel data

Standardization of Exponential Random Graph Model (ERG) panel data is essential for comparing network characteristics over time or between organizational cases (Duxbury, 2021). In this study, I built upon previous research that has developed ERGMs (Robins et al., 2007) and a topological framework for analyzing longitudinal social networks (Uddin et al., 2015) as methodological foundations. However, due to the dynamic nature of network characteristics, direct comparisons of panel data modelled using ERG are problematic as network size and density variations are present in the observed data. To address this issue, the Average Marginal

Effect (AME) for each ERG model Markov Chain Monte Carlo output was calculated (Duxbury, 2021). This standardization procedure enables the comparison of ERG panel data and allows for a more accurate understanding of the dynamics of network characteristics in organizations over time.

Changepoint Analysis (CPA)

A changepoint analysis is a statistical method that allows researchers to identify and analyze significant changes in trends over time in longitudinal social network panel data. It helps to determine the specific points in time where the trend in the data changes direction or changes significantly. In the context of social network analysis, changepoint analysis can be used to identify shifts in the formation of network structures or motifs or changes in the participation of actors in the network over time. The results of the changepoint analysis provide valuable insights into the evolution of social networks and can help to explain the underlying causes of the observed changes in network patterns. By identifying changepoints in longitudinal social network data, researchers can gain a deeper understanding of the dynamics and evolution of social networks and how they are influenced by external factors such as policy changes, resource availability, or shifts in societal attitudes and norms, and vice-versa.

A CPA was conducted using the standardized ERGM data derived from observed network panel data. The CPA method is a powerful technique for detecting shifts in network characteristics over time. CPA can be analyzed using various indicators of change. Specifically, this approach identifies changes in the mean and variance of standardized network panel data and can indicate significant variation in an organization's network.

To implement the CPA, the changepoint R software package (Killick & Eckley, 2014) was utilized. The mean-variance method was applied to analyze the AME-corrected ERG model Markov Chain Monte Carlo data. This approach allows for the identification of multiple changepoints and integrates information from multiple observed variables. This method has been used to analyze dynamic system shifts in previous research (Shi et al., 2022).

Several changepoints in the longitudinal network data provide evidence of changes in the modelled network data. For example, a drop in the likelihood of anti-centralization motifs could indicate a shift in internal structural changes, such as changes in the mandate, staffing and budget. Moreover, observed periods with a lower likelihood of provincial actor participation could indicate that several external factors influenced the OBWB organization's network.

Results

The results of the study on social network-building efforts of the Okanagan Basin Water Board (OBWB) in addressing issues related to watershed management are presented in this section. The study examined the participation of 743 actors over 50 years of attending OBWB meetings and modelled several network measures. The exploratory analysis focused on two indicators of

interest: the likelihood of forming anti-centralization network motifs and provincial actors attending OBWB Board meetings. This analysis aimed to identify network trend changes that could serve as robust indicators of watershed governance. The results show several changepoints in network attributes that align with internal and external factors and demonstrate the potential for application as watershed governance indicators.

Text analysis

The analysis of the OBWB meeting minutes provided essential data on several macro-level contextual datasets and gave insight into variables of interest and our network CPA. In 1977, the British Columbia government's B.C. Aquatic Weed Committee managed the Okanagan Weed Eradication Program, which the government fully funded (Figure 2) and was later known as the Milfoil (*M. Spicatum*) Control Program (MCP). Today, MCP is one of three primary service areas of the OBWB.

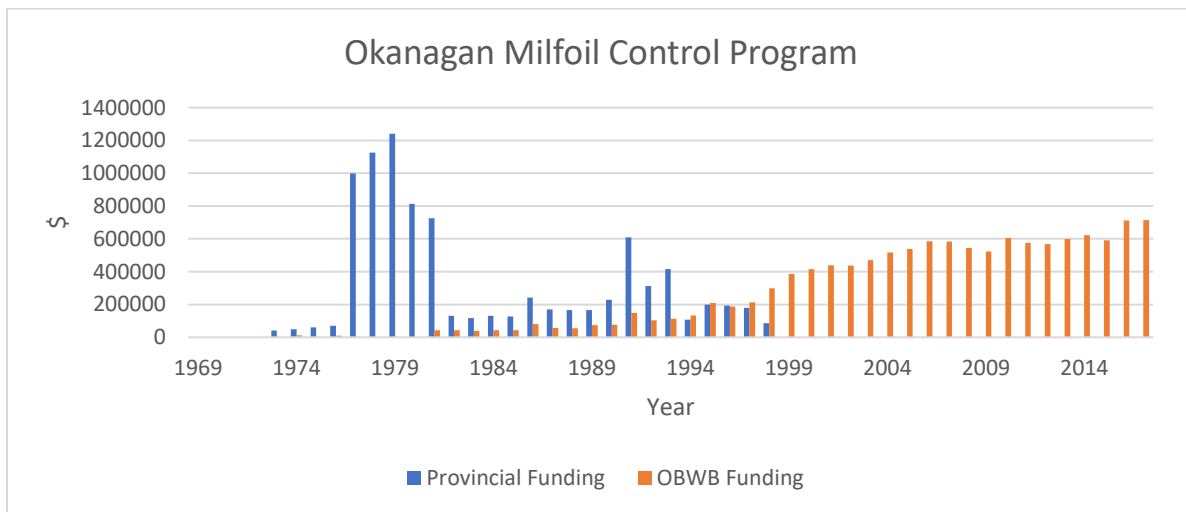


Figure 2. OBWB funding history of the Okanagan aquatic Milfoil Control Program.

The OBWB signed an agreement to provide administrative support for the MCP program in 1977. By 1978, the provincial government had spent \$1.8 million on the program. In 1981, operational control of the program was transferred to the OBWB with a cost-sharing agreement. However, in 1989, the provincial government announced the termination of funding for the program, citing their "Fiscal Restraint Program" as the reason. Despite protests from local governments, the program was ultimately transferred to the OBWB with support from local governments, and it is still managed by the OBWB today. The participation of BC government actors at the OBWB Board meetings varied over the 50 years of analysis, as shown in Figure 3.

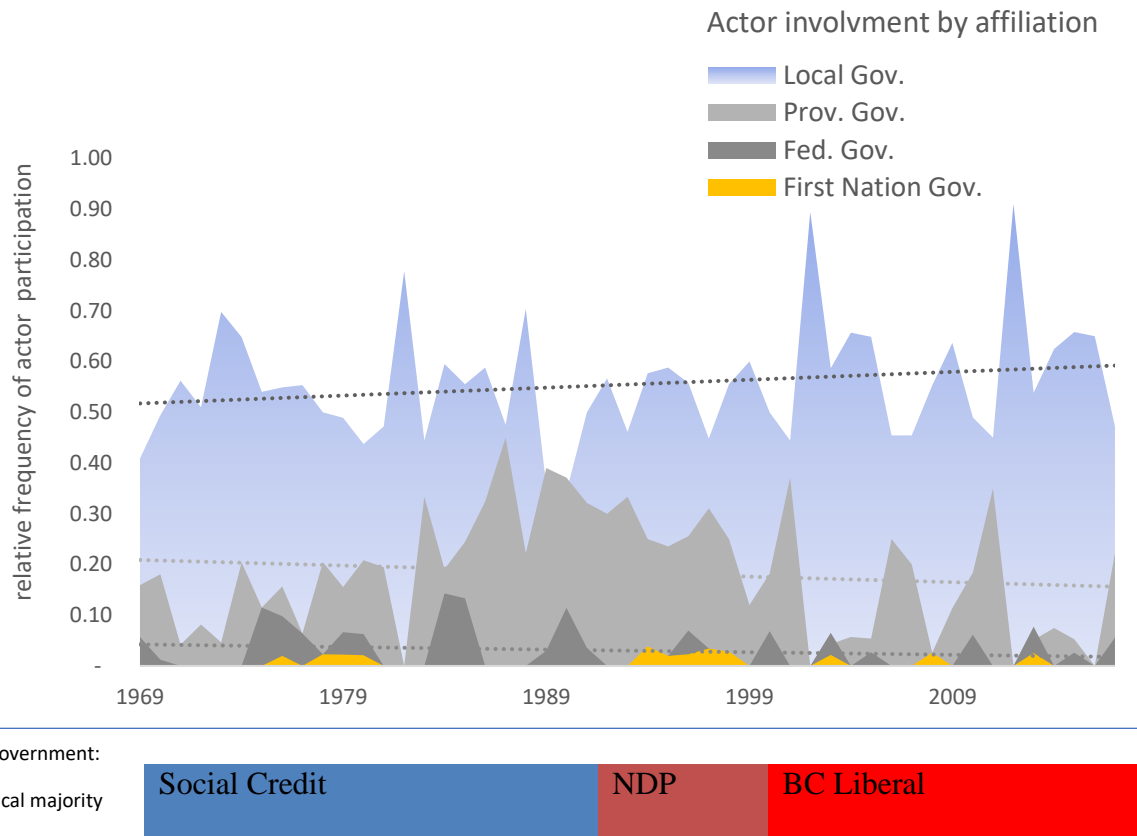
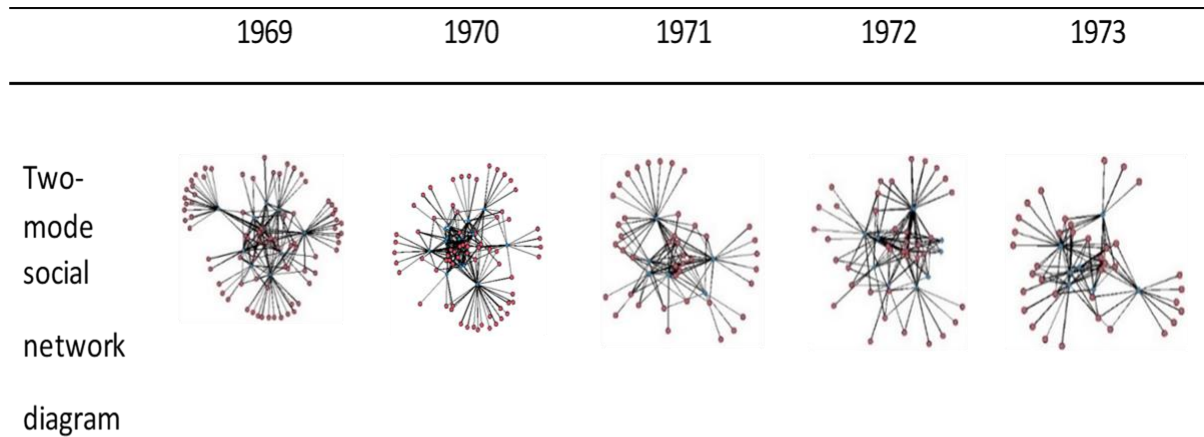


Figure 3. Relative frequency of different government actor participation at OBWB Board meetings over time (1969 – 2017).

Social Network Analysis

Social network analysis provides insight into the often-hidden network structures that shape the delivery of government programs related to freshwater resources. By examining observed social network data, in this research, I expand our understanding of how actors within a network influence watershed governance outcomes. As an illustrative example, Table 2 shows the social network analysis results from five years of OBWB network data between 1969 to 1973.



	Whole-network Data				
Density	0.04	0.07	0.09	0.12	0.10
Dyad count	711	966	252	390	259
Edge count	177	236	106	144	98
Network size	88	83	48	49	44

Table 2. shows the panel data variation in network density, size, and edge counts. These variations in input network data reinforce the need for standardization.

This observed network data is necessary to develop statistical models, as reported in the next section.

Exponential Random Graph (ERG) Model Results

In this section, I report on the ERG model results. Figure 4 illustrates 50 years of standardized ERG model outputs (annualized). These different structural motifs are expressed as coefficients representing "the change in the log odds of tie formation" (M. Lubell & Robbins, 2021, p. 17). The modelled data were standardized using the AME method using a recently developed package in R software (Duxbury, 2021).

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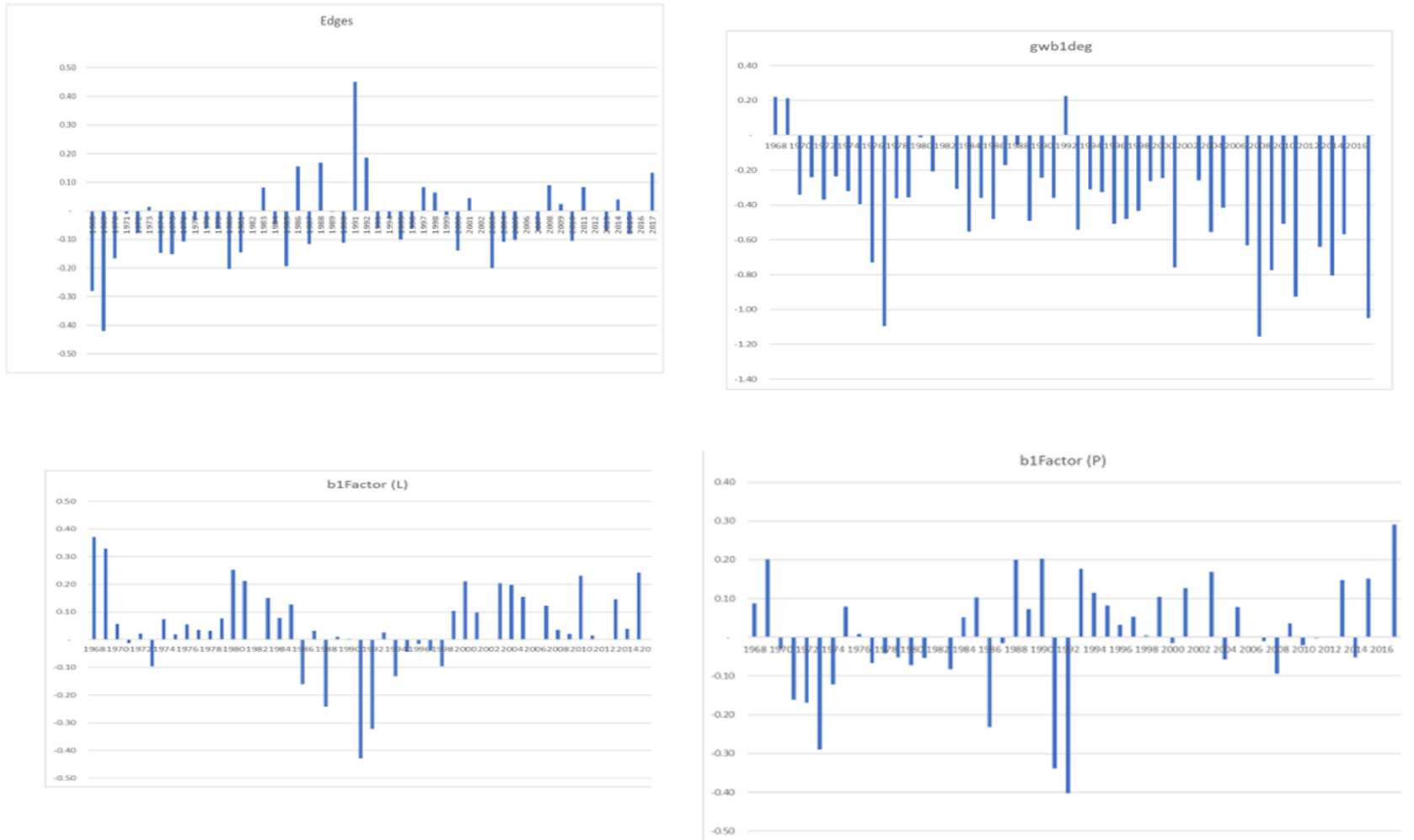


Figure 4. Summary of standardized ERG model MCMC coefficients (1968 - 2017) for four likelihood MCMC results: edges, anti-centralization (gwb1degree), local government actor tie formation, and provincial government actor tie formation.

The modelled network panel data revealed variations in network characteristics between years. As previously discussed, each model parameter in ERG models represents potential influences on network structure (Lubell et al., 2011) and the likelihood of forming a given network characteristic. Like regression models, it is necessary to compare watershed organization network panel data, or any future analysis between case studies, using the same ERG model coefficients.

Changepoint analysis (CPA)

I analyzed standardized ERGM panel data to determine the likelihood of forming anti-centralization. Using mean-variance changepoint analysis, I identified significant shifts in the OBWB network data over 50 years. The analysis revealed two periods identifying OBWB Board meetings with actor networks with different anti-centralization likelihoods, demonstrating significantly different means and variances (Figure 5). From 1968 to 2004, the mean was -0.3, and the variance was 0.07; from 2005 to 2017, the mean was -0.8, and the variance was 0.005.

These changepoints indicate times when network motif formation was significantly different. These changepoint observations suggest a shift in the OBWB network, from a polycentric structure in 1968-2004 towards a comparatively more centralized and coordinated structure in 2005-2017.

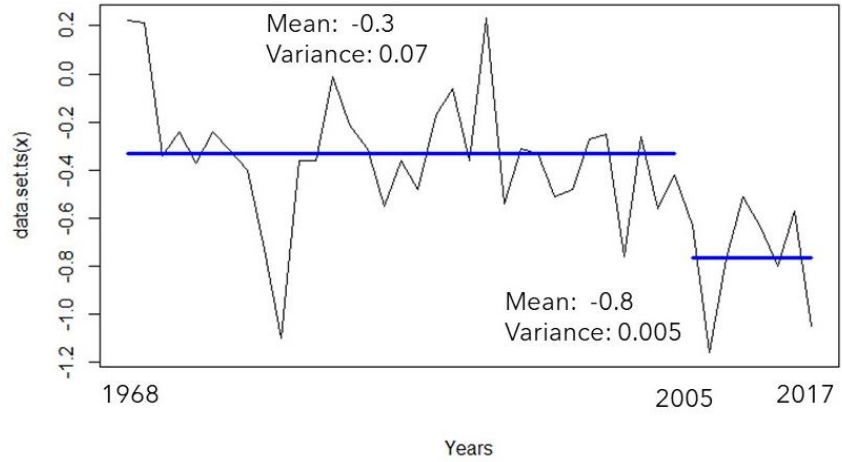
Moreover, the changepoint analysis identifies three distinct periods of network likelihood to form provincial government relationships. From 1968 to 1987, the first period observed in the OBWB network had a mean of -0.3 and a variance of 0.02. This suggests that the likelihood of forming these relationships was relatively low and consistent in this period.

In the second period, from 1988 to 1991, the OBWB network had a mean of -0.4 and a variance of 0.0009. The decrease in the mean and the decrease in variance suggest that the likelihood of forming these relationships became even lower and more consistent in this period compared to the first period.

The third period, from 1992 to 2017, had a mean of 0.07 and a variance of 0.009. The increase in the mean and the relatively higher variance suggests that the likelihood of forming these relationships increased and became less consistent in this period. These results indicate that the likelihood of forming provincial government relationships increased during this period.

Likelihood of :

Anti-centralization



Provincial actor attendance

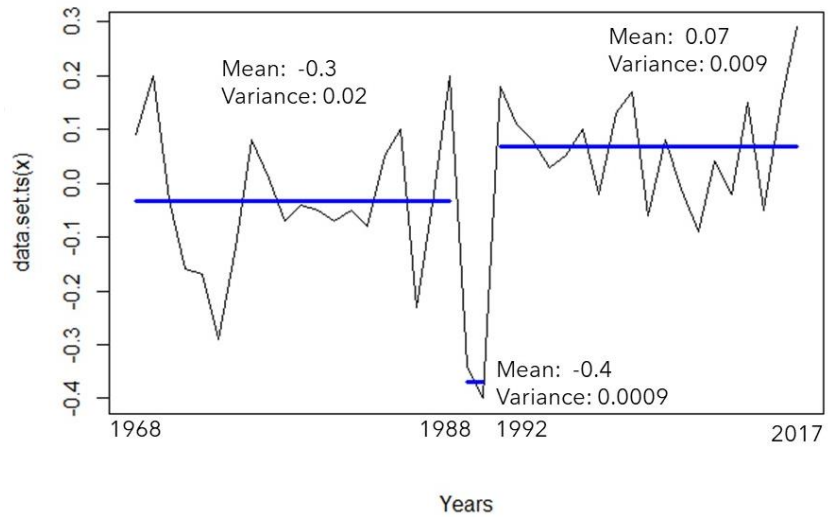


Figure 5. Images of Changepoint analysis (mean-variance method) for the OBWB standardized network attributes (1968 - 2017) of two modelled network indicators, the likelihood of forming anti-centralization motifs and provincial actor attendance at OBWB meetings.

Discussion

This exploratory study investigated longitudinal trends in network characteristics alongside internal and external contextual factors to enhance our understanding of governance performance measures. The analysis employed a new model that describes the connection between the recently developed tactical network model (Figure 1) and organizational performance. Through social network analysis, I evaluated the prevalence of network configurations (motifs) relevant to internal and external variables changes.

The success of watershed programs relies on several crucial factors, including accountability, legitimacy, fit and scale recognition, adaptability, learning, and bridging knowledge and implementation, according to a synthesis of watershed governance characteristics (R. C. de Loe et al., 2009). The authors of the same study also emphasize the importance of “clarifying roles and ensuring adequate capacity for effective participation” (R. C. de Loe et al., 2009, p. 31) as crucial initial steps in water governance processes. In the following sections, I examine various internal and external variables that have impacted the OBWB’s social network analysis of watershed governance over the past 50 years.

Motifs are social structures built from the bottom up through combinations of simpler components defined as terms of the local configuration of ties or "motifs" (Lusher et al., 2013). This exploratory study of changes in network motifs provides a step toward understanding one aspect of the complex social-ecological watershed governance system. By improving our understanding of social network characteristics and how they change over time, we can better understand the often-opaque actor networks (Jatel, 2013) that influence organizational performance.

Internal variables

The panel-data changepoint analysis highlights two key internal variables. The first variable relates to the Board's developing a new vision and mandate in 2005-06. It emphasizes its leadership role in addressing critical water management issues such as community resilience to climate change and communication. This vision was reflected in reinstating monthly Water Stewardship Council meetings in 2006. These changes signalled a clear departure from the previous approach and marked a significant turning point in the organization's evolution.

The second variable of interest is the OBWB organization's leadership and management between 2005 and 2007. This change involved hiring new leadership staff in 2006 and 2007, which marked a significant shift in management strategy.

These two internal variables highlight the importance of strategic decision-making and vision-setting in shaping an organization's governance outcomes. The changes implemented between 2005 and 2007 have had a profound and lasting effect on the organization's priorities, focus, and performance. The Okanagan case study highlights the value of combining strategic goal setting with network analysis to match social network attributes with organizational goals.

External impacts on network dynamics

In my analysis, two external variables stand out. First, programs like the MCP were downloaded during the early 1990s (see Figure 2). According to political scientists, Canadian municipalities are considered "creatures of the provinces," and neoliberal policies support the notion that "less government is better government" (Young, 2007; Vengroff & Whelan, 2001). Over the past five decades, a trend has been observed of senior levels of government downloading governance responsibilities to local governments, including the management of infrastructure, which local governments now own more than 60% of (Ryser et al., 2019; Markey et al., 2021). The effects of senior government downloading on watershed organizations may impact the building of social capital between actors at various levels of government. This reduction in financial support and actor interaction from the British Columbia provincial government impeded the interface between knowledge generation, policy implementation, and innovation for both the government and local decision-makers.

Second, several changes to the provincial water-related laws occurred during the study window that influenced watershed organizations' social networks and in turn, watershed governance outcomes. The British Columbia government implemented a watershed security strategy that aligns with the newly enacted Water Sustainability Act (2016). This Act recognizes the importance of "Communicating [water-related] knowledge in an accessible way" to improve watershed governance efforts and decision-making (Watershed Security Strategy and Fund - Discussion Paper, 2022). The effects of a decade of provincial dialogue leading up to the implementation of the new Water Sustainability Act in 2016 profoundly affected how watershed governance was managed by the senior government, including the consideration of indigenous water rights.

Exploring the observed network results

It is posited that macro-level changes, not random events, caused these shifts in network motifs. This study's new tactical network-building model provides a framework for analyzing the relationships between network attributes, context, and performance.

Likelihood of anti-centralization as an indicator of watershed governance

One indicator of watershed governance polycentricity is the network motif for anti-centralization. I aimed to investigate the changes in anti-centralization motifs over time. By applying CPA, it was discovered that the board underwent two periods of anti-centralization. From 1968-2005, there was an increased likelihood of demonstrating anti-centralization characteristics when compared to the lower levels from 2006-2017. I postulate that the change in anti-centralization network characteristics aligns with the OBWB's re-organizational effects and changes in critical senior staff members – moving from a polycentric to a more centralized network structure.

Likelihood of provincial actor participation as an indicator of watershed governance

The OBWB was observed to have three periods of varying likelihood of forming new ties with provincial government actors. This indicator reflects the degree of coordination between watershed and provincial organizations due to changes in funding to watershed programs, such as the MCP, and general provincial decentralization of water services. This network analysis study's results suggest a corresponding decrease in provincial actor participation from 1988 to 1992. After this four-year window, the likelihood of provincial government participation rebounded to similar pre-1988 levels.

One likely hypothesis is that as the province divested from several watershed initiatives, such as the MCP, and implemented a decentralized model, the likelihood of participation by provincial actors in the organization's board meetings decreased. Subsequently, the province coordinated community consultation to implement the water sustainability act involving significant outreach efforts by the province before the new Act's implementation in 2016. This may have been one cause of the observed increased likelihood of provincial participation at OBWB board meetings in the latter years.

The findings of this study have three important implications for the field of water governance. First, it expands our knowledge of potential water governance indicators for implementation by management (Dunn & Bakker, 2011). Second, this study builds on previous attempts to use ERGM qualities of social networks to understand critical dependent variables (Lubell & Robbins, 2021). This research adds to the existing work on networked social capital (Borgatti et al., 1998), providing watershed managers with new tools for strategic planning and decision-making. The results from this study provide further insight into how network characteristics change and suggest possible internal and external factors that may influence these changes. Finally, the 50-year analysis of network characteristics sheds light on measuring changes in network social capital through time.

The results of this study demonstrate the significance of social networks in governance systems and their impact on opportunities and productivity. The study supports previous findings in the field (Berardo & Lubell, 2016a; de Loe, 2017; Koontz et al., 2015; Lubell et al., 2002; Pahl-Wostl & Kneiper, 2014; Sayles & Baggio, 2017) and emphasizes the importance of using network analysis as a tool for understanding the relationships between macro-level attributes and governance processes and outcomes. These findings offer new insights into using modelled network indicators to understand the structural changes in a watershed organization's network over time, the effects of macro-level contextual factors, and their potential impact on governance performance (and outcomes).

In summary, this study's modelled data suggest that the two social network indicators explored, the likelihood of anti-centralization and provincial government actor participation motifs, are *valuable indicators of a watershed governance social network performance*. Moreover, the

social network analysis and CPA methods show promise for use as strategic planning and goal-setting methods to support watershed organization leadership and management teams. Overall, this study provides new insights into the impact of the interplay between an organization's internal tactical actions and the resulting influence on social network motifs (a new indicator for watershed governance) and, consequently, on watershed governance outcomes.

Limitations of the approach

The relationship between network attributes and organizational performance is complex and bidirectional, influenced by internal and external factors. Developing governance analytics for a watershed organization is challenging, in part because of the complex nature of the social-ecological system and changes in the organization's strategic priorities (Berardo & Lubell, 2016a; de Loe, 2017; Koontz et al., 2015; Lubell et al., 2002; Pahl-Wostl & Kneiper, 2014; Sayles & Baggio, 2017). Applying a narrative approach to identify potential influence variables on select social network motifs provides a valuable starting point for developing a rigorous causal analysis. Causal analysis requires several factors, including lag effects between strategic action and network performance, multi-directional effects between network attributes and internal and external variables, and availability of high-quality longitudinal data.

Historically, the analysis of modelled network data was hindered because the data involved large datasets, modelling was computationally intense, and software applications needed to be developed. Applying advanced computational techniques, such as ERG models, allows for identifying network attribute motifs that can serve as indicators of organizational performance. However, it is crucial to note that there is no ideal network configuration and that network attributes should align with the organization's goals and objectives within a given context. The complexity of the system dynamics inherent to watershed organizations and the limitations of data may constrain the analysis of internal and external variables. Nevertheless, this study lays the foundation for future research on the causal relationship between strategic governance decisions, network outcomes, and organizational performance.

While options for modelling network attributes reduce comparability between studies, choosing appropriate model coefficients can be an involved process with limited data available. New, computationally intense social network models, such as ERG models, are emerging as a valuable framework for diagnosing governance systems. However, other analysis methods, such as temporal ERGMs (tERGM), although useful for many social network analyses, may not be suitable for evaluating specific panel datasets, like those examined in this study, due to significant actor turnover in each period.

Areas of future research

Several future research areas would enhance and contribute to this study's findings. One crucial next research step would be to apply the same ERG model to multiple watershed organizations to compare different watershed organizations with these OBWB findings.

Additionally, future research focusing on quantifying and attributing specific contextual variables (internal and external) to social network performance would be helpful. For example, research studies to better understand variables that have the most significant impact on network performance success and under what conditions would provide valuable contributions to this study area.

This study's results suggest that combining strategic goal setting with network analysis can enhance the value of applied multi-method network analysis and provide valuable insights into the relationships between context (internal and external variables), network attributes, and organizational performance. Future analysis that applies an *a priori* strategic goal for network attributes and then analyzes the data *a posteriori* would further our understanding of variables of influence on network performance.

Furthermore, a causal model analysis of (1) contextual variables' influence on network attributes and (2) network indicator performance on governance outcomes would provide insights into how different network performance metrics contribute to organizational performance and help align organizational strategies with appropriate network-building tactics. Ultimately, a better understanding the relationships influencing watershed governance performance will enhance change management strategies and improve decision-making support tools for watershed managers.

Concluding remarks

The study applied social network ERG modelling and changepoint analysis to investigate the Okanagan Basin Water Board (OBWB) development over 50 years. The findings reveal a shift in the OBWB network from a more decentralized network, characterized often as polycentric, to a more centralized and coordinated network characterization. These changes in network indicators correspond to an observed change in the organization's governance tactics. Moreover, provincial government (external) tactics to decentralize watershed governance align with an observed reduced likelihood of provincial government actor participation at OBWB Board meetings for several years. However, this phenomenon of reduced provincial government actor participation rebounded to similar levels as observed in the earlier network data. This rebound may be partly associated with provincial planning and implementing a new water act in 2016.

The results also highlight the potential of modelled network indicators as valuable measures of watershed governance. These findings provide important insights into the dynamics of social

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networks and their role in shaping the governance of complex systems such as watershed organizations.

This paper contributes to a growing field of social network analysis developing new and innovative approaches for analyzing and understanding the dynamics of social networks. The findings have important implications for improving our understanding of the factors that influence the governance of watershed organizations and for identifying new strategies for improving governance outcomes. In conclusion, in this study, I highlight the importance of understanding the dynamics of internal and external contextual tactics and analyzing changes in new social network indicators and, consequently, their impact on governance outcomes.

Disclosure statement

The author reports there is no competing interest to declare.

Data availability statement

Data is available on request from the author. The corresponding author's data supporting this study's findings are available upon reasonable request.

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Appendix 1. Summary ERG model examples that apply various parameters applied to environmental governance research.

Date	Authors	Study Title	Model variable	ERG term
2018	Hileman and Lubell	The network structure of multilevel resource governance in Central America	<ul style="list-style-type: none"> • Shared partners • Anti-preferential attachment • Within-level homophily • Level activity: local • Reported ties on a website? • Local, regional, and multilevel • Network centralization 	<ul style="list-style-type: none"> • gwesp • gwdegree • nodematch • nodefactor
2018	Levy and Lubell	Innovation, cooperation, and the structure of three regional sustainable agriculture networks in California	<ul style="list-style-type: none"> • Edge probability • Anti-centralization • Triangles • Survey respondent nominations • Professional role (vs. Grower) OUTREACH • Geography (vs. known different zip codes) 	<ul style="list-style-type: none"> • Edges • GWDegree • GWESP.fixed.0.7 • Nodecov.Survey_respondent • Nodecov.Outreach • Nodecov.Both • Nodecov.knownZip • Nodecov.possibleZip
2019	Pittman and Armitage	Network governance of land-sea social-ecological systems in the Lesser Antilles	<ul style="list-style-type: none"> • Density • Popularity • Triadic closure (collaborators of collaborators) 	<ul style="list-style-type: none"> • Density • Activity Spread (ASA) • Generalized transitivity (ATA)
2021	Lubell and Robbins	Adapting to sea-level rise: Centralization or decentralization in polycentric governance systems?	<ul style="list-style-type: none"> • Edges • Anti-centralization • Coordination/learning via open structures • Cooperation via closed structures • A shared audience of forums • Cross-scale networks • Regional actors to local forums • Geographic homophily 	<ul style="list-style-type: none"> • Edges • Gwb1deg.fixed.0.4 • Gwb2deg.fixed.0.4 • Gwb1nsp.fixed.0.1 • Gwb2nsp.fixed.0.1 • B1factor.regionalActor • B2factor_regionalVenue • B2starmix.2.regionalVenue • B2starmix.3.regionalVenue • Mix. Scale.Local.Regional • Mix. Scale.Regional.Local

Appendix 2. Summary of exploratory-survey results of ERG model development using different available parameters for two-mode network panel data – variable testing (Monte Carlo MLE Results). Review of model fit using 1969 panel data.

ERG MODEL	AIC	BIC
Edges	800	804.6
Edges + b2star(2)	739	748.1
Edges + gwbldegree	799.2	808.4
Edges + b1factor(L)	757.4	766.5
Edges + B1factor (P)	800	804.6
Edges + B1factor (F)	796.3	805.4
Edges + b2star(3)	799.6	808.8
Edges + b2star(2) + b1factor (L)	756.3	770
Edges + b2star(2) + b1factor (P)	801.3	815
Edges + b2star(2) + b1factor (F)	795.8	809.5
Edges + b2star(2) + b1factor (L) + b1factor (P)	749.2	767.2
Edges + b2star(2) + b1factor (L) + b1factor (P) + b1factor (F)	751.5	774.3
Edges + b2star(2) + gwbldegree	799.5	808.6
Edges + b2star(2) + gwbldegree + b1factor (L)	758	771.7
Edges + b2star(2) + gwbldegree + b1factor (P)	801.5	815.2
Edges + b2star(2) + gwbldegree + b1factor (F)	796.8	810.5
Edges + b2star(2) + b2star(3)	721.6	735.3
Edges + b2star(2) + b2star(3) + gwbldegree	678.3	696.5
Edges + b2star(2) + b2star(3) + gwbldegree + B1factor(L)	662.8	685.6
Edges + b2star(2) + b2star(3) + gwbldegree + B1factor(P)	681.3	704.1
Edges + b2star(2) + b2star(3) + gwbldegree + B1factor(F)	675.5	698.3
Edges + b2star(2) + b2star(3) + gwbldegree + B1factor(L) + B1Factor(P)	656.2	683.6
Edges + b2star(2) + b2star(3) + gwbldegree + B1factor(L) + B1Factor(P) + B1Factor(F)	656.9	688.9

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Appendix 3. Analysis of several ERG models illustrates how model variables affect AIC model fit scores for the 1969 example period. These models are referenced against simple Edge models. Lower AIC models (larger blue bars) reflect better model-appropriate parameterization.

