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Sechindra Vallury
University of Georgia, sechindra.vallury@uga.edu

Brian C. Chaffin
University of Montana, brian.chaffin@umontana.edu

Samantha L. Hamlin
University of Nebraska-Lincoln, shamlin@unl.edu

Craig R. Allen
University of Nebraska-Lincoln, callen3@unl.edu

Communication in the science-policy interface: Evidence from a boundary organization in Nebraska, USA

Sechindra Vallury,[1] Brian C. Chaffin,[2] Samantha L. Hamlin,[3] and Craig R. Allen [3]

1 Odum School of Ecology, University of Georgia, 203 D.W. Brooks Dr., Athens 30602, GA, USA
2 W.A. Franke College of Forestry & Conservation, University of Montana, 32 Campus Dr., Missoula 59812, MT, USA
3 Center for Resilience in Agricultural Working Landscapes, University of Nebraska–Lincoln, 203 Keim Hall, Lincoln 68583, NE, USA

Corresponding author — S. Vallury, sechindra.vallury@uga.edu

Abstract

Boundary organizations have a crucial function in environmental governance by facilitating the processes through which scientists and decision-makers generate, exchange, evaluate, and utilize knowledge to identify societal problems, propose potential solutions, and make decisions on appropriate courses of action. This support for evidence-informed decision making is essential in addressing environmental challenges effectively. Despite the growing popularity of boundary organizations, there remains a significant

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challenge in designing information dissemination platforms to bridge the communication divide between scientific experts and non-experts. To address this gap, we used natural language processing tools to analyze the communication strategies of a specific boundary organization — the Nebraska Water Center — and examined how these strategies evolved over time to address relevant water policy issues in the state. We identified three prominent topics in the Center's periodicals between 1970 and 2018: policy and planning, water quality and quantity, and public engagement and workforce development. The prevalence of each topic changed over time, reflecting changes in both federal and state legislative priorities and subsequent responses from the scientific community. Our results also demonstrate how boundary organizations can design information exchange platforms that consider perspectives and needs of not only scientists and policymakers but also more diverse groups of actors. These findings are critical for developing strategies for bridging science and policy in environmental governance.

Keywords: Science-policy interface, Boundary organizations, Water governance, Topic modeling, Boundary object, Science-policy communication

1. Introduction

Addressing environmental challenges requires clear communication linking scientific knowledge and discovery with decision-making contexts of environmental governance (Jabbour and Flachsland, 2017; Clark et al., 2016b; Balvanera et al., 2020). Environmental issues are frequently complex and interconnected, and addressing them requires multiple actors, institutions, and political processes, often interacting across multiple levels of society. Organizations connecting scientific research and policy, referred to as science-policy interfaces (Wagner et al., 2023) or boundary spanning organizations (Bednarek et al., 2018) (herein "boundary organizations"), play a crucial role in connecting researchers with policymakers and facilitating relevant knowledge transfer and sharing scientific evidence to support public policy decisions (Balvanera et al., 2020; Van den Hove, 2007; Lee et al., 2014). Given the significance of scientific knowledge for complex and often contested environmental decision-making processes, there has been considerable interest by scholars to identify and investigate the processes through which these organizations facilitate effective

relationships between science, policy, and society (Posner and Cvitanovic, 2019; Cvitanovic et al., 2016; Marshall et al., 2017; Fazey et al., 2018; De Donà, 2021). Previous research on science-policy interfaces, boundary organizations, and boundary objects provides guidance to support identification of important elements of these processes, which often include multi-stakeholder forums where experts convene discrete groups, facilitate social learning, and ultimately create opportunities for collaboration, translation and knowledge transfer between groups (van Enst et al., 2016; Osmond et al., 2010; Cash, 2001; Kowarsch and Jabbour, 2017; Sarkki et al., 2020; Pereira et al., 2021; Clark et al., 2016a). In this research, we use the term "boundary organizations" to refer to organizations that actively work to facilitate the production of scientific knowledge and disseminate this knowledge to inform evidence-based decision-making in environmental management contexts (Cash et al., 2006). Examples of such organizations include non-governmental organizations, universities, and professional organizations such as community organizations or public agencies (Goodrich et al., 2020).

Boundary organizations commonly facilitate the production, dissemination, and exchange of knowledge across boundaries by employing a notion known as "boundary objects". We use the term "boundary objects" to refer to artifacts, concepts, or platforms that are utilized to facilitate communication and collaboration across different social worlds (Star and Griesemer, 1989; Star, 2010; Bowker and Star, 2000). They serve as linchpins in diverse collaborations, fostering dialogue across the science and policy domains (Star, 2010). An effective boundary organization must, therefore, create boundary objects that enable meaningful engagement between scientists and policy communities in a coordinated way and should have lines of accountability on both sides (Wyborn, 2015; Nunes et al., 2016; McGreavy et al., 2013). Despite the rise of boundary organizations as facilitators of communication at the science-policy interface, it is evident that there is a dearth of empirical evidence on the strategies employed by boundary organizations to establish effective communication platforms (or boundary objects) that bridge the science-policy interface.

The complexity and technical nature of scientific information can pose a challenge in communicating it to broader audiences (Scheufele, 2014). Additionally, one-way communication in the science-policy

interface, with scholars assuming what questions decision-makers would find relevant, can result in ineffective communication (Cash et al., 2003). Infrequent communication can also hinder the mobilization of knowledge for action, resulting in outdated or non-credible information being provided to decision-makers (Scheufele, 2014). A lack of trust between the scientific community and the public can also impede the effective communication of important scientific findings (Pielke, 2007). To overcome these challenges, boundary organizations need to develop communication strategies and platforms that solicit the diverse needs and concerns of different stakeholders, and offer frequent information that is relevant to those needs (Guston, 2001; Ding et al., 2011). This approach can foster more productive and collaborative relationships between the scientific community and the public. Despite the importance of effective science-policy communication in environmental governance, there is a paucity of empirical studies that investigate the communication mechanisms employed by boundary organizations (Akhtar-Schuster et al., 2016; Suni et al., 2016).

Specifically, our study poses the following questions: *how can boundary organizations develop long-term boundary objects that incorporate the needs and perspectives of not only the scientific community and policymakers but also broader societal actors? How can such boundary objects disseminate information concerning critical policy milestones?* To address these questions, we investigate the communication practices of Nebraska Water Center (NWC), a boundary organization at the University of Nebraska-Lincoln that disseminates water governance information to a wider audience. In particular, we analyze the organization's Water Current newsletters, which serve as an example of a boundary object, over a 48-year period to identify the strategies employed by NWC to recognize relevant water policy issues in the state and establish their science-policy communication.

The NWC was created by the 1964 Water Resources Research Act (WRRA) in response to the nation's growing water problems. This legislation (and subsequent amendments) mandated each state, three territories, and Washington D.C. to create a water center that (1) conducts research to aid in the resolution of regional water problems, (2) disseminates and promotes practical applications of research findings, (3) trains scientists through their participation in research, and (4) provides competitive grants to researchers, practitioners, and other

organizations engaged in water resources research (Burton, 1986; Donohue et al., 2021). As a whole, these objectives directly translate into a mission to bridge the science-policy interface, which is why we consider the NWC a boundary organization. Central to NWC's mission are the Water Current newsletters (NWC, 2015). These quarterly newsletters, which started in 1969, chronicle key water challenges in the state, disseminate the center's research, and acquaint water resources planners, managers, developers, researchers, and educators about the problems facing water resources across the state-as well as potential solutions. The range of topics covered in these newsletters over time have included, but are not limited to, water efficiency in agriculture, wastewater management, water quality and quantity management, aquatic ecology, and human dimensions of water consumption.

Given the centrality of the newsletters to the NWC's mission to bridge the science-policy interface, we used natural language processing tools, specifically topic modeling, to analyze this textual data. Topic modeling is an unsupervised machine learning method often used to investigate a large collection of documents to discover unknown patterns or trends in the data (Silge and Robinson, 2017; Hirschberg and Manning, 2015). Using this approach, we identified the primary water policy issues and topics that were the focus of the newsletters from 1970 to 2018. We also examined the changes in the emphasis of these topics over time and the relevance of these periodicals in reflecting state and federal policy initiatives. Additionally, we analyzed the mechanisms used by the organization to identify relevant water policy issues in the state and how this process evolved over time. We contextualize the shift in NWC's communication strategies within the broader context of the literature on communication models in the science-policy interface. This literature offers valuable insights on how boundary organizations can integrate the input and needs of scientists, policymakers, and members of civil society in the development of long-term communication channels.

Our empirical study, the first of its kind in the field of environmental governance, provides insights into how boundary organizations can formulate long-term communication platforms (or boundary objects) that take into account the needs and viewpoints of not only the scientific community and policymakers but also broader societal actors. We

show that the design of effective communication platforms requires boundary organizations to carefully consider the intended audience for the scientific information. Our findings reveal that the NWC not only gathered input from well-informed stakeholders regarding pressing water-related concerns and noteworthy policy achievements in the state, but also made a conscious effort to understand the information requirements of a diverse audience, encompassing policymakers and the general public. The NWC then tailored the information to meet the specific requirements of each group. Such an approach is central to developing processes and strategies for bridging science and policy in sustainability science (Kates et al., 2001; Clark et al., 2016a).

2. Methods

2.1. Topic Modeling

To evaluate the trends in NWC's communication of science-policy information, we apply topic modeling to the quarterly Water Current newsletters from 1970 to 2018. Topic modeling, similar to clustering on quantitative data, is a method for unsupervised classification of a collection of documents to uncover natural groups of topics in the "corpus" or totality of textual data. The specific method of topic modeling we use is Latent Dirichlet allocation (LDA), a popular Bayesian method for fitting a topic model that has been effectively utilized in research on environmental governance (Lambert et al., 2021; Bell and Scott, 2020; Grubert and Siders, 2016). The advantage of LDA is that it mirrors the use of natural language, i.e., it treats documents as continuous, overlapping content rather than discrete groups (Blei et al., 2003).

A topic model represents the content of documents within a collection of documents based on the relative importance and co-occurrence of words and phrases within each document (Grubert and Siders, 2016). LDA is a mathematical model that is guided by two principles: (1) each document is a collection of topics and may contain word and phrase content from multiple topics in varying proportions. For example, in a 2-topic model, document A may contain 70 % topic 1 % and 30 % topic 2 while document B may contain 40 % topic 1 % and 60

% topic 2; and (2) each topic is a collection of words or n-grams.[1] The objective of LDA is to simultaneously estimate the probability distribution of the collection of words or n-grams associated with each topic and topics across documents. This allows us to identify the theme of each topic and the topical focus of a given document.

Our primary data consists of 260 quarterly newsletters published by UNL's Nebraska Water Center from 1970 to 2018. These data are published on UNL's Digital Commons website[2]. All newsletters followed a similar structure, beginning with metadata on volume and issue numbers, year, and location. This was followed by a director's note highlighting recent research, education, and achievements of local researchers and the institution at large. Next, the newsletters highlighted key federal and state policy changes, upcoming academic conferences and seminars, select research results, and list of important recent publications. All the newsletters are drafted in prose, allowing a systematic analysis of content analysis across documents and time.

Prior to analysis, we employed a series of standard pre-processing techniques on the data, including tokenization, stemming, and stop word removal (Silge and Robinson, 2017). Through tokenization, we separated each line of text in the original document into tokens (e.g., words, numbers, symbols, and punctuation) and filtered out non-essential tokens. We then stemmed the words to analyze only the root of the tokens (e.g., review, reviewing, and reviewed would become review). Finally, we filtered out "stop words," which refer to extremely common words that do not convey any context and of little value to analysis (e.g., "the," "a"). This is done in order to reduce the noise in our data and improve the accuracy of our analysis. Furthermore, we excluded terms such as "newsletters," "Nebraska," "DigitalCommons," and "University of Nebraska" as additional stop words in order to account for words that occur commonly on the front page of every newsletter.

1 An n-gram is a consecutive sequence of words of length *n*. For example, a bigram refers to a pair of two consecutive words, such as water rights or stream control; trigram refers to a consecutive sequence of three words, such as nonpoint source pollution. In our study, we used unigrams, bigrams, and trigrams.

2 https://digitalcommons.unl.edu/water_currentnews/

We trained the LDA model by examining n-grams present in more than four documents, but no more than 72 % of the documents in the corpus. The rationale behind these limits, which were determined by running a series of models with different limits, is to exclude words that are either extremely common or too infrequent and, therefore, not useful for an analysis. Examples of commonly occurring words include generic words (e.g., "of," "and") and context-specific words (e.g., "water," "university"). The number of topics in a LDA model is prespecified by the researcher, but there is no single approach to select the optimum number of topics to analyze. We used two approaches: (1) the "elbow" heuristic, which finds the optimal number through k-means clustering (Kosinski et al., 2016); and (2) a multi-model fit index that is implemented in R through the *ldatuning* package (Nikita and Nikita, 2016). However, both these approaches were inconclusive in our study (Appendix 1). Therefore, we used an iterative approach, adjusting the number of topics until the groups of words and n-grams reflected logical and distinct topics (Feuerriegel et al., 2016). We found that fitting three topics generated groups that were qualitatively explicable and empirically validated by regional water policy issues and initiatives.

2.2. Identification of key policies

After using topic modeling to analyze the content of newsletters, our objective was to investigate whether and how the content of these newsletters reflected significant policies at the federal and state levels. To achieve this, we took a two-step approach. First, we identified major water policies that were critical for water governance in Nebraska and influenced significant shifts in policy decisions between 1970 and 2018. Second, we conducted an in-depth review of the analysis content, with a specific focus on the years preceding and succeeding the identified policy milestones. It is important to clarify that our aim was not to establish a causal relationship between policy milestones and changes in newsletter content. Instead, we sought to gain insights into how the newsletters potentially reflected notable shifts in policy at both the federal and state levels.

To identify the policy milestones, we conducted a thorough review of relevant literature (Aiken, 1987, 1998) and consulted online

sources.[3,4] From this research, we identified six significant policy milestones. At the federal level, this included the Clean Water Act of 1970. At the state level, the policy milestones encompassed the creation of Nebraska's Natural Resource Districts in 1972, the passage of the Nebraska Groundwater Management Act in 1975, the Nebraska Legislative Bill 1106 of 1984, and the NE Chemigation Act in 1986 (Aiken, 1987). Additionally, the Platte River Cooperative Agreement of 1997 was another key policy milestone at the state level (Aiken, 1998).

For our analysis, we focused on studying the broader, high-level outcomes of these policies to better explain potential changes in the content of the newsletters over the 48-year period. Using this two-step approach, we successfully identified the high-level policy changes that were pertinent to water governance dialogues within the state. Additionally, we examined the correlation between these high-level policy changes and the corresponding changes in newsletter content over time.

3. Results

3.1. Topical emphasis of newsletters

Fig. 1 shows the top eight words and phrases that are associated with each of the three estimated topics. The Y-axis in this figure refers to the terms for each topic that appears most frequently. The X-axis refers to a statistical measure, β, which is the per-topic-per-word probability of each phrase. A higher value of β reflects stronger association of a phrase with a given topic.

Elements of the first topic are primarily terms for water resources planning and policy developments. Focus on water policy is evident through bigrams and trigrams like "federal legislature", "river basin management", and "advisory panel", which were common terms in several of the newsletters. Common unigrams like "extension", "procedures", and "natural resource district management" indicate that the newsletters frequently published information on regional water planning.

3 https://water.unl.edu/article/agricultural-irrigation/regulations-policies

4 https://dnr.nebraska.gov/legal

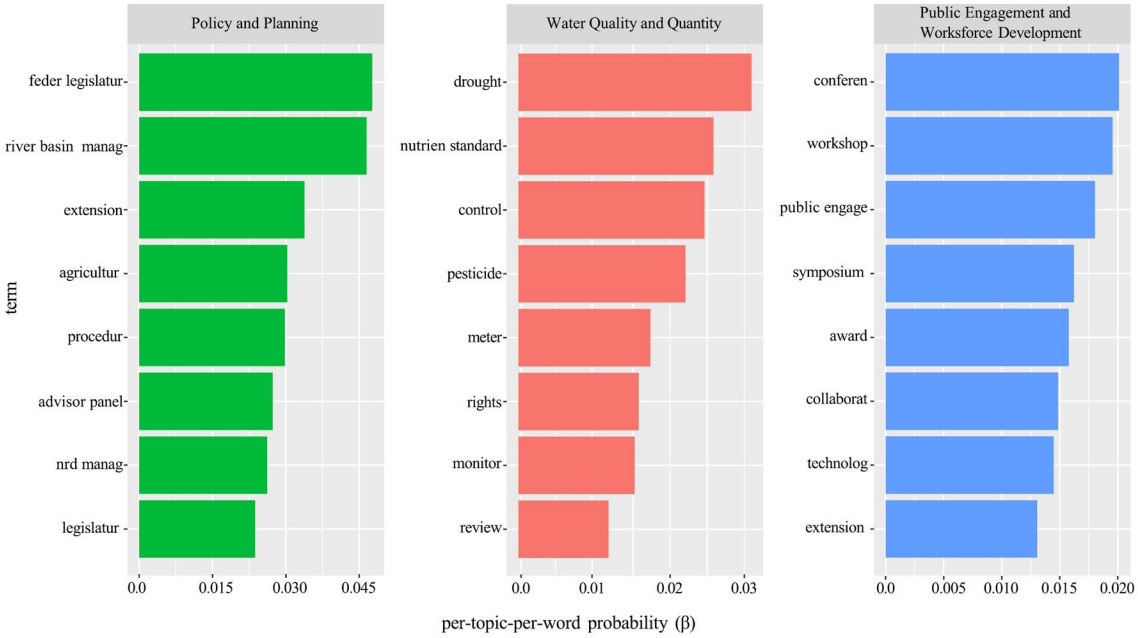

Fig. 1. Topic model of stemmed text from Water Current newsletters, 1970–2018.

The second topic includes words and phrases associated with water quality and quantity. For example, terms like "pesticide" and "nutrient standard" refer to contaminant concentrations that affect water quality and rules and standards that were established in accordance with the Clean Water Act. Another common theme was on water rights transfer, water withdrawals, and instream flow provisions during droughts. Additionally, the newsletters also focused on the use of official monitoring and review systems for sustainable management of groundwater resources. The term "control" also appeared in association with soil erosion and sedimentation control during harvest.

The terms in the third topic have lower β scores than the first and second topics and possibly a greater diversity in words and phrases. Nonetheless, the third topic includes terms that are associated with public engagement and workforce development. Common unigrams and bigrams like "conference", "public engagement", and "symposium" refer to workshops and conferences that the Nebraska Water Center hosts to bridge the communication divide between scientists, policymakers, practitioners, and other representatives of civil society. Furthermore, words like "award" and "collaborate" often surfaced in the

context of research funding for students, developing courses, and research collaborations with grassroots organizations, federal agencies, extension units, and other universities. The newsletters often discussed the future implications of such collaborations and funding opportunities and how this would impact the management of their water resources.

3.2. Topical emphases over time

We also estimated the probability distribution of topics over time for 1970–2018 to decipher if a trend in topic emphasis exists over time across the dataset of newsletter text (Fig. 1). Emphasis of the first topic— policy and planning protocols—peaks early in the publication period, beginning a period of decline in 1980, and leveling out as the least emphasized topic identified from roughly 1995–2018. Temporal patterns for the second topic—protocols for water quality and quantity— showed that it was relatively less discussed during the initial years compared to Topic 1 and showed increasing comparative frequency over time, beginning around 1985. Like Topic 2, the third topic—relating to community engagement and workforce development—showed greater frequency over time starting in the early 1980 s. In the next section, we discuss how changes in the topical emphases in the newsletters may be indicative of significant policy shifts at both the state and federal levels during the relevant time periods. We delve into the broad, high-level outcomes of these policies and explore how these policy developments may have influenced the content and focus of the newsletters over the years.

4. Discussion

4.1. Reflection of state and federal policies

Assessing changes in topic emphasis over time indicates (**Fig. 2**) that the temporal prominence of topics at specific points in the publication of newsletters aligned with key water policy and other related policy milestones at the state and federal levels. Emphasis of the first topic – policy and planning protocols – peaks early in the publication period.

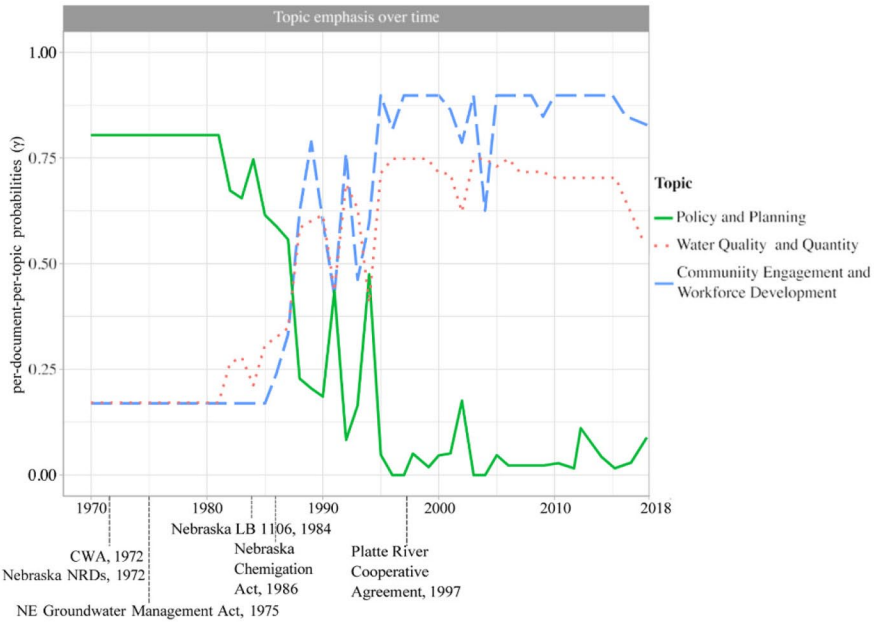

Fig. 2. Topical emphasis by year. Newsletters are published quarterly, but newsletters for some quarters were not available.

Topic 1 may have surfaced earlier in the publication period because of key water policy milestones at the federal and state levels in the period between 1970 and 1986. For example, the U.S. Congress enacted the Clean Water Act in 1972, which is the primary federal law aimed at regulating water pollution. In the same year, Nebraska established the system of Natural Resource Districts (NRDs). The state's 23 NRDs, organized around river basin boundaries, are locally elected governing boards with taxing powers and authority over the governance of a wide range of natural resources that are vital to Nebraska's economy. Following this, the state enacted the Groundwater Management Act in 1975 (Nebraska Legislature LB 577) that gave primary authority for regulating groundwater resources to the NRDs.

Following that, in 1983, President Reagan's budget proposal included $75 million for water development along the Missouri River. This resulted in a series of construction and reclamation projects by the U.S. Bureau of Reclamation, Office of Water Research and Technology, and several state agencies. Last, 1984 saw the introduction of a major piece of water legislation by then governor Bob Kerry: LB

1106. This bill would achieve several policy milestones, including creating the Nebraska Water Management Fund for water development projects and requiring Natural Resource Districts to prepare and implement groundwater management plans. Consequently, there was an increased focus on issues related to water conservation, groundwater management, and irrigation infrastructure construction and rehabilitation. The newsletters published from 1970 to 1985 reflect key water policy milestones such as the ones mentioned here and explain the relatively higher focus on topic 1 in the earlier publication period. Communication during this period focused on how different agencies were collaborating in addressing water challenges in the state, how these efforts were facilitated by state and federal legislatures, and the role of extension farm management specialists in coordinating irrigation projects.

Topic 2 and topic 3 diverge in frequency around the mid-1980s, with topic 3 — community engagement and workforce development — appearing more frequently in newsletters (Fig. 2). This trend coincides with a marked shift in the rhetoric of the state's environmental policy focus post 1985. This shift was motivated by a study conducted by the Nebraska Department of Environmental Control in 1985. The study reported 136 groundwater contamination locations in Nebraska, which found contaminants from synthetic organics, pesticides, gasoline storage tanks, other hydrocarbons, nitrates, and other contaminants. It was found that crop producers used an estimated 90 % of the pesticides in the state, as 91 % of all corn acres are treated with pesticides in Nebraska. Following this study, the Nebraska Chemigation Act (LB 284) was passed in 1986, aiming to protect Nebraska's groundwater and surface waters from contamination by fertilizers or pesticides. To accomplish this goal, the Nebraska Department of Environment Energy crafted and implemented rules and regulations to enforce this new law and guidelines for irrigators to use in practice.

The upsurge in the prominence of topic 2 can also be attributed to the delayed implementation of the Clean Water Act. Following its enactment in 1972, the U.S. Environmental Protection Agency required a significant amount of time to establish water quality standards for different chemical pollutants (Van Putten and Jackson, 1985). Subsequently, states were granted additional time to implement

enforcement measures for those standards, leading to a time lag. By the mid-1980 s, states such as Nebraska had begun taking proactive measures to comply with the Clean Water Act through a variety of regulatory pathways. This may account for the heightened focus on topic 2 in the newsletters after 1985. Increased concerns about potential limitations on future water supplies and endangered species in the Platte River Basin, including the South Platte River in Colorado and the North Platte River in Wyoming, could be another reason for the higher probability of topic 2 post 1985. In 1997, a cooperative agreement was signed by the three states after several years of negotiations that began in 1986. The agreement was aimed at protecting the flow of water in both the North and South Platte Rivers, as well as achieving target flows in the Central Platte River Basin to safeguard endangered species.

Based on the policy milestones and changing concerns of water resource managers and agricultural users towards groundwater contamination, we anticipated observing a change in the communication focus of the boundary organization. This shift is reflected by the increasing significance of topic 3 in Fig. 2, particularly after 1985. The NWC shifted the focus of the newsletters toward educating Nebraskans about water quantity and, especially, water quality. In the spring issue of 1988, the director's note expressed the center's objective to improve communication among research disciplines and disseminate the latest research findings to the public and state agency staff. During this period, a significant portion of the research was centered on contaminants and pioneering technologies for regulating pesticide use in agriculture. The newsletters also published information about initiatives, projects, and best practices to monitor water quality and pesticide application. The need for making such information accessible was reinforced in 2000 at the 29th annual Nebraska Water Conference, where participants voted on environmental issues of high priority. The top three issues were: (1) prevention and control of nonpoint pollution sources; (2) unified systems to govern surface and groundwater systems; and (3) state funding for water research. The newsletters continue to publish information on ongoing research projects and best practices for contaminant mitigation, pesticide application, and managing water quantity.

4.2. Communication strategies for boundary organizations

The involvement of a diverse range of actors in the science-policy interface is crucial, as it allows for interactions and co-production of knowledge between scholars and other stakeholders, which can lead to more informed, effective, and socially legitimate environmental policy decisions (Van den Hove, 2007; Pallett and Chilvers, 2015). Therefore, boundary organizations must solicit public input on environmental issues, understanding their values and priorities, and ensuring that scientific research and policy decisions align with societal needs (Guston, 2001; Leshner, 2003). By doing so, they can foster trust and create a more informed and engaged citizenry capable of making informed decisions on complex environmental issues (Ding et al., 2011). The growing awareness of the importance of the science-policy interface has led to increased investments in boundary organizations to develop various forms of communication or information exchange platforms between universities, policymakers, and the public. Through these channels, knowledge and evidence can effectively inform political decision-making processes (Lentsch and Weingart, 2009).

To gain a deeper understanding of how boundary organizations can develop communication channels that involve a wider range of societal actors, we examine the body of work on communication phases (or models) in science-policy interfaces. Sokolovska et al. (2019) outline three primary phases to describe communication channels in the science-policy interface. The first is the “linear phase”, which was prevalent in the 1960–1970 s and involved a unidirectional flow of scientific information from universities to inform policy-making in political contexts. The second, the “interactive phase”, emerged in the 1970 s to late 1990 s, where communication between science and policy became more two-way, with scientific knowledge traveling between science and political decision-makers. The third strategy, the “embedded phase”, began in the 2000 s and involved the explicit incorporation of citizens’ inputs within the science-policy interface. We find that this scholarly discourse on communication channels in science-policy interfaces is useful in describing the strategies employed by the NWC to structure their newsletters.

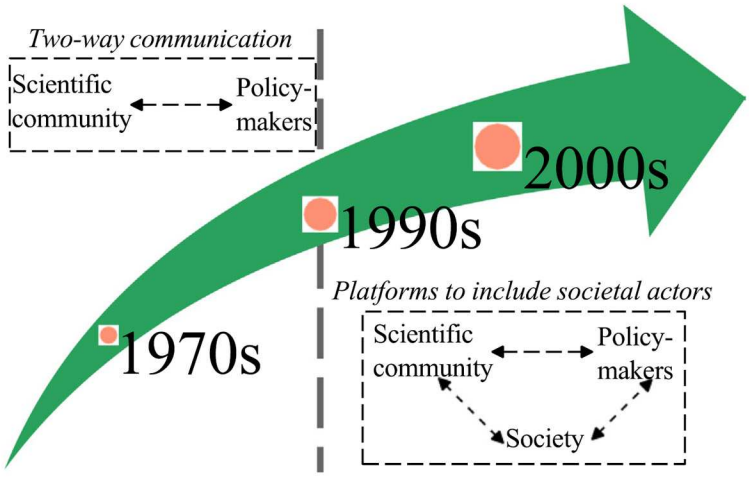

Fig. 3. Communication phases of the Nebraska Water Center's Water Current newsletters.

Upon reviewing the newsletters from the 1970s to the early 1990s, we observed that the quarterly newsletters during this period predominantly focused on key policy accomplishments at the federal and state levels, as well as research achievements by faculty at the University of Nebraska on water challenges in the state. Based on our analysis of the newsletters' content, we found no evidence indicating that the NWC solicited feedback from its readership regarding topics or issues that were important to them[5] (**Fig. 3**). We arrived at this conclusion based on the fact that during the observed time period, the NWC's newsletters predominantly featured content on (1) summarizing important state and federal agency reports, (2) highlighting key legislative updates and milestones, (3) presenting research findings from faculty members, (4) promoting NWC seminars that often featured research officers from state and federal agencies as keynote speakers, and (5) providing key insights from the annual Nebraska Water Conference and Platte River Basin Symposiums.

In addition, the newsletters also frequently summarized the outcomes of meetings between federal and state agencies such as the U.S. Geological Survey, Soil Conservation Service, Missouri River Basin

5 We must note that our inference is based solely on the analysis of the newsletters' content, and we did not use other primary data sources (e.g., interviews) to validate this deduction.

Commission, Environmental Protection Agency, Nebraska Department of Water Resources, State Office of Planning and Programming, Natural Resources Commission, Game & Parks Commission, and the Department of Environmental Control. The newsletters also provided overviews of major research conducted by University of Nebraska faculty in ten study areas, including groundwater, water quality, conservation and water use efficiency, environmental quality, planning-management technology, flood control, energy-water relationships, transbasin diversion, and sedimentation-stabilization. The limited scope of the NWC director's annual remarks in the newsletters, which largely emphasized center milestones and policy developments, further supports the postulation of a hierarchical approach in determining the newsletter's content.

After analyzing the newsletters from the mid-1990s onwards, we observed that the NWC adopted a more collaborative approach to content selection and actively sought input from a wide range of actors, including policymakers, scientists, and representatives of civil society. It is possible that the shift in communication strategy was influenced by administrative changes (e.g., changes in NWC's leadership), societal factors (e.g., evolving perceptions and values of its readership), and environmental factors (e.g., droughts of 2004–2005). In 2004, the Nebraska Department of Natural Resources updated the state's groundwater rules and regulations to include plans to manage hydrologically connected groundwater and surface water areas (Bleed and Babbitt, 2015). The involvement of a wide range of stakeholders in the development of these plans may have highlighted the importance of effective communication and collaboration in managing water resources in the state. As a result, the Nebraska Water Center may have recognized the need to modify their communication strategy to engage with a broader range of stakeholders and ensure that their knowledge and expertise were effectively co-produced, shared, and utilized for water governance. This change in strategy is consistent with the NWC's commitment to actively educate Nebraskans about water challenges (Fig. 3). To achieve this, they introduced a new section called "Water News Briefs", which focused on community engagement and workforce development. We believe that this shift in the NWC's communication strategy corresponds with the phases of communication identified in the broader

discourse on the science-policy interface (Sokolovska et al., 2019; Kowarsch, 2016; Edenhofer and Kowarsch, 2015).

The objective of the "Water News Briefs" was to tailor expert knowledge in a way that addresses the challenges faced by the societal actors with whom NWC and newsletters are communicating. This section published brief and concise information on conferences, awards, grants, pilot programs for farmers and residents, training opportunities for students, and best practices. There was also an increased attention to best practices for what individual farmers, residents, and other societal actors may or may not do in order to mitigate a variety of water quantity and quality challenges. The trend in Fig. 2 shows that the newsletters maintained an increased focus on community engagement and workforce development from late 1990 s to 2018. We posit that this shift in content may be correlated with the NWC's renewed mission in 1990 s to act as a convener of information on scientific research, best practices, projects, and initiatives that focus on the environmental issues identified by societal actors at the Nebraska Water Conference.

The importance of including broader societal actors in the relevant science-policy dialogues is highlighted in existing literature (Cash et al., 2003). Excluding them can result in a limited representation of environmental problems, perspectives, and policies in the newsletters. Furthermore, it raises concerns about the legitimacy of shared information, irrespective of its credibility or relevance. This can lead to a disconnect between the organization and its readership, ultimately resulting in ineffective knowledge dissemination (Scheufele, 2014). Therefore, for a boundary organization to effectively broker knowledge, it needs an audience that seeks policy advice (Gluckman et al., 2021). Unsolicited or unrequested information is likely to have limited impact on decision-making and can diminish interest in the communicated information over time (Schäfer et al., 2018). Boundary organizations, such as the NWC, have a critical role in identifying issues that require policy advice and presenting evidence to the policy community on topics of concern to the society.

The effectiveness of boundary organizations depends on how various publics perceive the information shared on the science-policy interface (Cash et al., 2003; Pielke, 2007). While disseminating information based on science is an important part of the policy-making

process, there is also a critical need for putting out relevant information that the public needs in order to address issues that they are concerned about. *Is this information relevant for the broader audience that the organization aims to engage? Is there a demand for this scientific information? Where does this information fit in the broader policy-making processes?* A boundary organization must be able to discern the answers to these questions by engaging a wide range of actors (e.g., scientists, science communicators, decision-makers, non-experts) in order to set the agenda for their communication, develop trust with their audience, and be effective in their roles as knowledge brokers (Gluckman et al., 2021; Van den Hove, 2007).

4.3. Methodological reflection

Scientific communication and dissemination platforms often generate significant "paper trails" (Bell and Olivier, 2022). We present an example of how natural language processing (NLP) tools can be used to analyze and extract information from such documents. While our analysis is descriptive in nature, it is a scalable approach to measure how scientific communication processes in sustainability science function over time. The obvious appeal of NLP tools is that they automate the process of characterizing the contents of documents. This feature makes the technique more promising for scaling up research to compare large textual datasets across time. Traditional qualitative coding methods are significantly more laborious and challenging to replicate and/or scale up in a similar fashion, particularly between different researchers. In contrast, replicating the analysis done using NLP tools is a matter of implementing a common algorithm to conduct longitudinal analyses of multiple science-policy dissemination platforms.

There are, however, limitations when using NLP tools in empirical sustainability science research. Topic modeling is an unsupervised type of analysis, which means that defining and labeling the topics can introduce subjective bias because the researcher does not know a priori what words and phrases will cluster together. Therefore, a key point to consider for researchers while using the Latent Dirichlet allocation model is to assess the validity of selected topics. One way to overcome this bias is for authors to freely define their topics and then deliberate on the validity of their definitions and topic selections (similar to

intercoder reliability in manual textual coding) (Riddell, 2014. Nonetheless, NLP tools offer a means by which larger comparisons and longer analyses can be done relatively easily to advance our understanding of the trends, causal pathways, and outcomes of scientific communication in sustainability science (Yan, 2014; Dorgo et al., 2018).

5. Conclusion

The literature on boundary organizations in environmental governance argues that communication between the scientific community with policymakers and the public must be an integral part of robust governance processes (McGreavy et al., 2013; Megdal et al., 2017; Shrivastava et al., 2020). However, a closer look at the literature reveals that, beyond this general assertion, there is a lack of evidence-based assessment on how boundary organizations can develop long-term communication platforms (or boundary objects) that incorporate the needs and perspectives of not only the scientific community and policymakers but also broader societal actors. We use the Nebraska Water Center's Water Current newsletters as an example of a boundary object that disseminates water governance information to a broader audience and bridges the science-policy interface.

Our analysis shows how natural language processing tools can be used to analyze and link patterns in the content of these communications to the broader patterns of environmental policy at the state and federal levels. While topic modeling is not a new method, its application to communication in boundary spanning and sustainability science is novel. Similar applications of topic modeling or other natural language processing tools to publicly available textual datasets have the potential to uncover hidden themes, patterns, and changes in the design of boundary objects and the functioning of boundary organizations over time. This analytical approach can offer valuable insights into the evolution and dynamics of boundary organizations, aiding in their continuous improvement and effectiveness in bridging the science-policy interface. As the newsletters we analyzed in this study are published by a research university, it is reasonable to assume that their content might be influenced by the university's broader goals and objectives. Nevertheless, we observe differences in the newsletters'

content over time that appear to coincide with policy conditions, such as groundwater contamination, in the state. Elucidating these trends in communication from a boundary organization like the Nebraska Water Center provides a yardstick for other similar organizations seeking to maintain relevance and effectively engage stakeholders over several decades of research and collaborative efforts.

We draw on the broader scientific discourse on communication models to better understand the role of boundary organizations in bridging the science-policy interface. Starting from science and policy as two discrete groups with limited interaction, models of scientific communication evolved to engaging broader societal actors (Winckelmann, 1965; Sokolovska et al., 2019). Despite this evolution, scientific communication by boundary organizations in sustainability science is impeded by lack of deliberation on who is the intended audience and poor communication skills within the scientific community (Besley and Tanner, 2011; Gluckman et al., 2021).

The Nebraska Water Center created relevant information in the Water Current newsletters by engaging closely with researchers, professionals, farmers, local managers, and decision-makers through regular meetings, workshops, surveys at the Nebraska Water Conference, and other forms of communication. This method of soliciting input not only informed stakeholders about urgent water-related issues and significant policy achievements but also provided an opportunity for the Nebraska Water Center to gain valuable insights into the information requirements of a diverse audience, including policymakers and the broader public, and tailor the newsletters' content accordingly. This is an important takeaway for boundary organizations similar to the Nebraska Water Center. We may posit that the Water Current newsletters are well-regarded and remain a relevant means of science-policy communication for the Nebraska Water Center's readership based on their lengthy history of publication, sustained number of downloads, and ongoing funding.

While we took an agnostic approach to examine the long-term communication patterns of a boundary organization, our analysis does not examine whether (and how) these changes impacted the organization's effectiveness at the science-policy interface. To gain a comprehensive understanding, future research needs to examine how these shifts in communication practices influenced the boundary organization's

role and standing in water governance discourses and stakeholder engagement within the state. Future research must also evaluate how the dissemination of water governance information through boundary objects, such as the Water Current newsletters, has influenced policy-making and environmental governance in the state. Additionally, investigating how the public responded to the altered knowledge communication methods and how these changes shaped discourses in decision-making forums would be valuable. More specifically, it is pertinent to investigate the legitimacy and social robustness of the scientific information published by boundary organizations (Cash et al., 2003; Gibbons, 1999). Understanding the degree to which this information is accepted among diverse stakeholders and its relevance to societal challenges can contribute to enhancing the effectiveness of boundary objects in evidence-based decision-making. Examining the relationship between authority, trust, and legitimacy of scientific information can also yield valuable insights on how to design effective communication practices for boundary organizations operating at the science-policy interface. By presenting these areas of research for future empirical investigations, we hope to foster robust, evidence-based conversations on how to optimally design boundary objects that effectively inform decision-making in environmental governance.

Boundary organizations hold the potential to enhance the efficiency of scientific evidence by utilizing boundary objects that actively engage a broader range of stakeholders. These objects enable the organization to solicit input on matters of concern, understand their values and priorities, and ensure that scientific research and policy decisions align with the needs of society. Recognizing the need and demand for information is essential for being an effective knowledge broker in the science-policy interface, and accelerating the translation of scientific knowledge into practice in environmental governance. This is possible only by creating opportunities and pathways, such as stakeholder consultations, workshops, and other collaborative platforms, for a more informed dialogue on environmental challenges rather than a unidirectional science-policy communication (Zurek et al., 2018); this dialogue can continue to be informed by the myriad digital datasets that sustainability scientists can utilize to ask ever-expanding questions at the science-policy interface.

Competing Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability The article includes a link to the website from which the data were downloaded.

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Appendix A. Supplementary data associated with this article (2 figures) can be found following the References.

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Optimal Number of Clusters

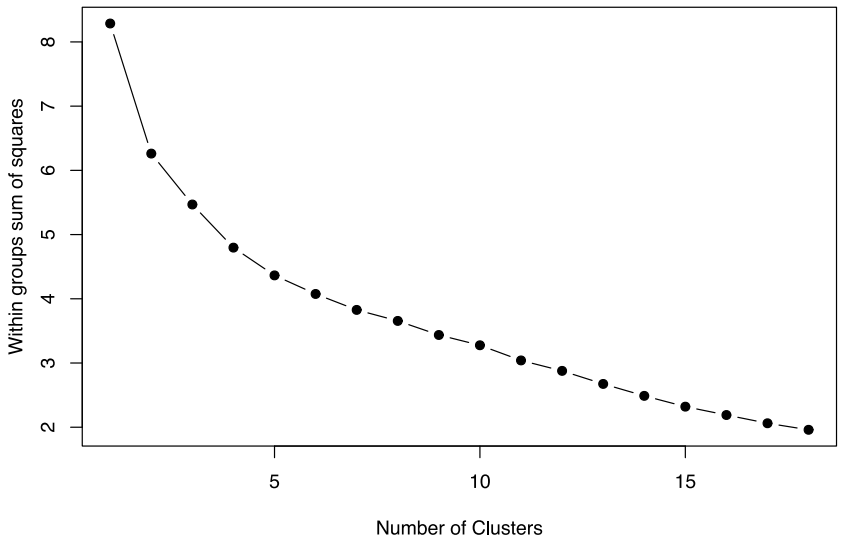

Figure 1: We used elbow analysis to determine the optimal number of topics to include in the LDA model. However, the analysis did not yield a clear elbow, and therefore, informed judgement was necessary to select appropriate hyperparameters.

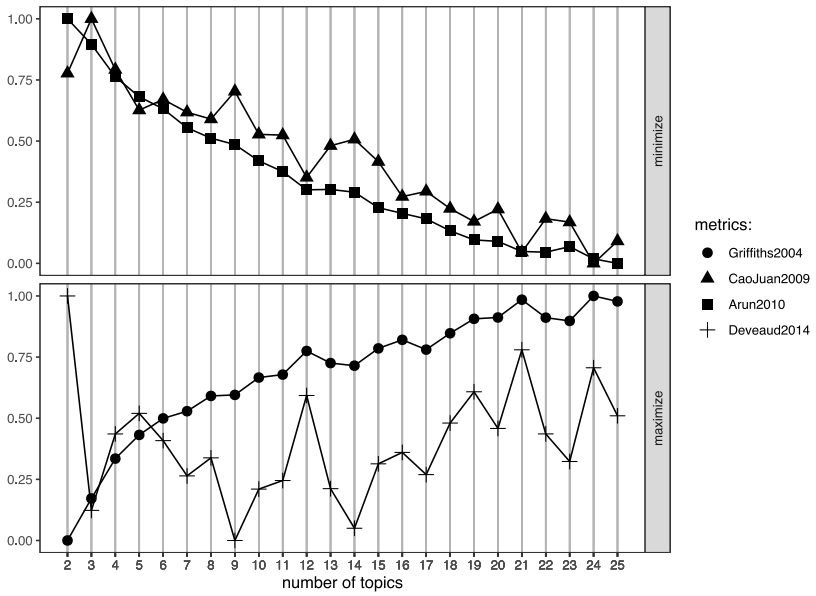

Figure 2: We employed the *ldatuning* package in R that utilizes four different algorithms to detect the optimal number of topics. While the determination of the best number of topics is typically based on the point at which the functions level out, no clear indication of this was observed in the results.