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Addressing knowledge gaps for transboundary environmental governance

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ABSTRACT

Knowledge is widely considered a key ingredient for the effective and sustainable governance of the environment. In transboundary settings – i.e., where political boundaries cross natural resource system boundaries – there are considerable barriers to knowledge production and use. Resulting knowledge gaps can be barriers to governance. This research examines three case studies in which international river basin organizations, tasked with facilitating cooperation in transboundary river basins, recognized and addressed knowledge gaps to support governance of shared waters. We synthesize across the three case studies to develop a typology of knowledge gaps and the strategies used to address those gaps. In identifying common types of knowledge gaps and the on-the-ground strategies used to fill them, this research provides an important framework for assessing and theorizing knowledge at the transboundary scale, as well as useful recommendations and examples for practitioners seeking to develop that knowledge.

1. Introduction

Knowledge is widely considered a key ingredient for the effective and sustainable governance of natural resources and ecosystems (Blackmore, 2007; Cash et al., 2003; van der Molen, 2018). Knowledge, in this context, includes awareness of the current state of the natural resource system and scientific understandings of the geophysical, environmental, and social processes that determine how that natural system functions and respond to stresses (Burton and Molden, 2005; Timmerman and Langaas, 2005). Such knowledge is useful for articulating the visions and normative goals that steer collective action (van der Molen, 2018). It can also help identify and evaluate policy options to achieve those visions and goals (Pfeiffer and Leentvaar, 2013; Sendzimir et al., 2008), and to help actors adapt to and respond to change (Raadgever et al., 2008; van der Molen, 2018).

While knowledge is a critical enabling factor for governance, knowledge of natural resource and ecosystems can be incomplete. Knowledge gaps are particularly prevalent in transboundary settings, including where political boundaries pass through a resource system such as water resources, wildlife and fisheries or where resource management has cross-border effects such as in the control and mitigation of pollution, flooding, or wildfire (see e.g., Brummel et al., 2012; Dieperink et al., 2016; Gollata and Newig, 2017; Koontz and Newig, 2014; Lim, 2015). The ubiquity of such knowledge gaps occurs because the production of knowledge in transboundary settings is typically highly decentralized, produced by a variety of entities from national and sub-national governments to NGOs, universities, and businesses. Sovereignty, and perceptions of sovereignty, in the transboundary

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context may also result in fragmentation (Alam et al., 2010; Karkkainen, 2005; Zeitoun et al., 2013). As knowledge production in transboundary settings tends to be dispersed, eclectic, and geographically specialized, gaps in knowledge are more likely to exist.

Knowledge gaps can be a barrier to transboundary governance. Knowledge gaps can inhibit agreement between decision makers both at the political level, where the policy agenda is deliberated and set, and at the operational level, where policies are finalized and implemented. Where knowledge gaps lead to a lack of common frames, there may be disagreement regarding the problems to be addressed and the need for solutions (Dewulf et al., 2005; Iida, 1993; Milman and Ray, 2011), inhibiting development of a policy agenda. Knowledge gaps can also add to mistrust or otherwise become politicized (Baycheva-Merger, 2019; Conca and Beevers, 2018), which in turn, may make it untenable for policy-makers to move to the operational stage of governance. Further, knowledge gaps may inhibit political support of domestic (national and sub-national) stakeholders who influence national decision-makers (Pfeiffer and Leentvaar, 2013; Sendzimir et al., 2008). Even where there is consensus as to the transboundary policy agenda and the situation is relatively removed from the political arena, decision-making may be stymied directly by a lack of clarity regarding the range of policy options available and the expected outcomes of each option (Fischhendler and Katz, 2013; Kettle and Dow, 2016; Nair and Howlett, 2017; Tribbia and Moser, 2008).

The implications of knowledge gaps for the governance of transboundary resources – both in terms of cooperative policy-agendas and policy formulation and implementation – compel the need to identify what knowledge gaps commonly occur in transboundary settings and to determine how those gaps can be filled. Our research makes strides in this arena by developing an empirically derived typology of knowledge gaps in transboundary governance and identifying examples of strategies used to fill those gaps. To do so, we examine three case studies in which International River Basin Organizations (IRBOs) – institutions established by countries sharing a transboundary river to formalize cooperation and facilitate coordinated governance – encountered and filled knowledge gaps in order to facilitate transboundary governance.

IRBOs are a useful point of entry for examining knowledge gaps in transboundary governance for several reasons. First, IRBOs serve as forums for dialogue, negotiation, and dispute resolution and, in this role, are deeply involved in knowledge production and exchange (Milman and Gerlak, 2020; Schmeier, 2014). In this context, IRBOs are similar to other bi- and multi-lateral organizations, including environmental cooperation commissions, health commissions, treaty secretariats, and hazards management institutions. Second, the IRBO is a well-established form of institution for transboundary governance, with currently over 81 IRBOs in existence, some of which have been functioning for more than 100 years (Schmeier et al., 2015). IRBOs thus serve as templates for establishment of other transboundary institutions. Lastly, the principal challenges associated with the governance of transboundary water – i.e., externalities, resource allocation, and concerns about the health of the resource itself – are common concerns of transboundary environmental governance.

Our research asks what knowledge gaps present operational challenges to transboundary governance and how are they addressed. The cases in our study were thus selected to reflect instances in which agreement existed on a transboundary policy agenda, yet knowledge gaps impeded policy formulation and implementation. By developing our typology based on cases in which politicking was more stable and less directly intrusive, we are able to highlight the role of underlying knowledge gaps that impede governance, and to examine cases in which closing those gaps was a priority of political actors. Our typology thus forms a starting point for differentiating knowledge gaps and addressing them in transboundary settings.

2. Knowledge gaps in transboundary settings

As many have noted (see e.g., Ackoff, 1989; Bernstein, 2009), knowledge sits on a foundation of data (discrete observations) and information (systematic, linked observations built from data). Key processes in the translation of data and information into knowledge include monitoring – which specifies how data and information are gathered, and modeling – which reflects a set of assumptions about causal mechanisms and dynamic interactions for the system in question. A knowledge gap occurs when there is a discrepancy between knowledge that is needed for governance or decision-making, and knowledge that exists. Knowledge gaps are related to but not synonymous with uncertainty. Scientific uncertainty generally refers to a bounded range over which expected values exist. Within natural resource systems, uncertainty is often aleatory, meaning outcomes are stochastic yet can be described with a probability and frequency distribution (Beven, 2016). While both scientific uncertainty and aleatory uncertainty can be barriers to transboundary governance, both can also be well characterized, and thus are not considered knowledge gaps for our purposes. Rather, knowledge gaps refer specifically to a lack of data, information, or underlying fundamentals that affect understandings.

While knowledge gaps are broadly recognized as a barrier to transboundary governance (see e.g., Armitage et al., 2015; Rivera, 2015; Schmeier, 2014), the types of knowledge gaps that commonly exist and how they are addressed has received scant attention (Dimitrov, 2003). Little differentiation is made between types of knowledge gaps that, even though might expect differing forms of knowledge gaps to affect governance uniquely and require differing strategies to resolve. Where research and guidance on transboundary governance examines knowledge gaps, it primarily focuses on data, in part because data is often the subject of transboundary negotiations and is needed for assessing treaty compliance (see e.g., Chenoweth and Feitelson, 2001; Grossmann, 2006). Data sharing is a component of many international agreements over natural resources, including water (e.g., the 1992 UNECE Convention on the Protection and Use of Transboundary Watercourses and International Lakes), air quality (e.g., the Paris Agreement, the US – Canada Air Quality Agreement), and wildlife management (e.g., the Pacific Salmon Treaty, the US-Japan Migratory Bird Treaty, the Convention for the Conservation of Atlantic Tuna), among others.

Implicit in an emphasis on data is the presumption that data provides or can lead to sufficient knowledge for governance. However, the governance of transboundary resources may require greater knowledge than can be achieved through data and data sharing alone, for several reasons. There may be limits to what data exist, and thus, what can be shared. Monitoring networks may be incomplete or transboundary assessments may be missing (Karki et al., 2011). Existing data may be narrowly focused on physical or ecological components of the system, and insufficiently capture socio-economic processes (Timmerman and Langaas, 2005). Technical issues related to data formats and quality may impede the interoperability of cross-border data that is necessary to allow for the integrated analysis of cross-border datasets (Schuurman et al., 2008; Yang and Maxwell, 2011). Further, shared data does not necessarily lead to knowledge or common understandings (Timmerman et al., 2010). Application of separate conceptual models or analytic methods as well as differences in technical expertise mean that knowledge may not be congruent across the border (Chenoweth and Feitelson, 2001; Schuurman et al., 2008). Thus, there is a need to examine what types of knowledge gaps affect transboundary governance.

Little is known about the on-the-ground practices to address transboundary knowledge gaps by producing, sharing, using, and improving scientific knowledge (Armitage et al., 2015). Research on knowledge production in transboundary settings has primarily focused on either obstacles to knowledge production and exchange (see e.g., Fazey et al., 2014; Plengsaeng et al., 2014; Weichselgartner and Kasperson, 2010) or how social learning and co-production of knowledge can support transboundary relationships (see e.g., Pahl-Wostl et al., 2013). Not studied, yet also needed, are insights into potential on-the-ground strategies that can be used for filling knowledge gaps. Especially important is to identify which strategies can be used to address or prevent a given type of knowledge gaps. Clarity on types of knowledge gaps and strategies for addressing them is also important for future research that seeks to resolve debates regarding the role of knowledge gaps in international relations, decision-making and outcomes (Dimitrov, 2006). Thus our research offers important insights for both researchers and practitioners on both the nature of knowledge-related challenges and the efforts by IRBOs to help mitigate or address these gaps.

3. Methods and approach

To shed light on how knowledge gaps are perceived and addressed in transboundary settings, we examine three case studies of IRBOs recognizing and addressing knowledge gaps in international river basins. The IRBOs include the International Commission for the Protection of the Danube (ICPDR), the Mekong River Commission (MRC), and the (US-Canada) International Joint Commission (IJC). Collectively, these three IRBOs span three continents and encompass a broad geographic diversity including variation in environmental and water conditions, history, economics, cultural, and political features. Overall, the three IRBOs have similar advisory and facilitatory duties, though there is some variation across them. The ICPDR has significant coordination yet minor implementation responsibilities, as most implementation occurs at the country level. The MRC has oversight roles (in reviewing and monitoring projects) and some implementation responsibilities. The IJC has oversight responsibilities (in approving applications for projects, such as dams, that affect boundary waters) and serves as a neutral advisor, though has limited implementation responsibility. The ICPDR and MRC also have strategic planning responsibilities that the IJC does not share. These IRBOs are recognized as leaders in transboundary water governance and have been actively generating scientific knowledge (see e.g., Bleser and Nelson, 2011; Heikkila et al., 2013; Kittikhoun and Schmeier, 2021; Ma et al., 2008; Weller and Popovici, 2012). As such, they provide an ideal starting point for examining how IRBOs have dealt with the challenge of knowledge gaps.

For each IRBO, we examine a prominent example of how it addressed a knowledge gap. A summary of the cases selected, including the scope of each IRBO and the operational task the knowledge gaps affected, is listed in Fig. 1. Cases were selected with input from senior officials who work with each IRBO, including officials within the IRBOs and national country representatives, who participated in a series of workshops funded by the National Socio-Environmental Synthesis Center (SESYNC) between 2017 and 2019 to study the science-policy interface in transboundary water settings. The cases we examine were selected specifically to represent instances in which the member countries had an agreed-upon agenda for the IRBO. In this way, the cases represent best-case scenarios (as per Gerring, 2007) in which knowledge gaps were identified and processes established to collaboratively address these gaps. As such, these cases provide a useful starting point to expose the nature of those gaps and the actors and processes engaged, so as to inform a future research agenda.

Our dataset for assessing the knowledge gaps and how the IRBOs addressed them is based on information collected from publicly available reports and documents as well as interviews with key IRBO personnel, consultants, and national and sub-national government officials. Our analysis of each case follows the same format and structure. We begin with a brief background context and then describe the knowledge gaps faced. Next, we delineate the strategies adopted to address the knowledge gap in each case and describe the outcome of the effort.

4. Recognizing and addressing knowledge gaps

4.1. Case #1: ICPDR – development of a transboundary river basin management plan

4.1.1. Background

In 1994, eleven Danube riparian states[2] (hereafter, contracting parties) signed the Convention on Cooperation for the Protection and Sustainable use of the Danube River (hereafter, DRPC). Established as the Danube's IRBO, the ICPDR is tasked with facilitating data and information exchange, elaborating proposals and making recommendations to contracting parties to aid in fulfilling the objectives of the DRPC. When the European Union Water Framework Directive (WFD) was adopted in 2000, contracting parties, including both EU member states and non-EU member states, committed to coordinate WFD implementation through the ICPDR (ICPDR, n.d.-a). The WFD requires development of River Basin Management Plans (RBMP) that assess the status of surface and ground waters and lay out policies and programs that will ensure surface waters achieve good ecological and chemical status and ground waters achieve good chemical and quantitative status by 2015. Where a river is crossed by international boundaries, EU member states are directed to ensure cooperation by producing joint RBMPs (European Commission, 2016).

4.1.2. Recognizing the knowledge gap

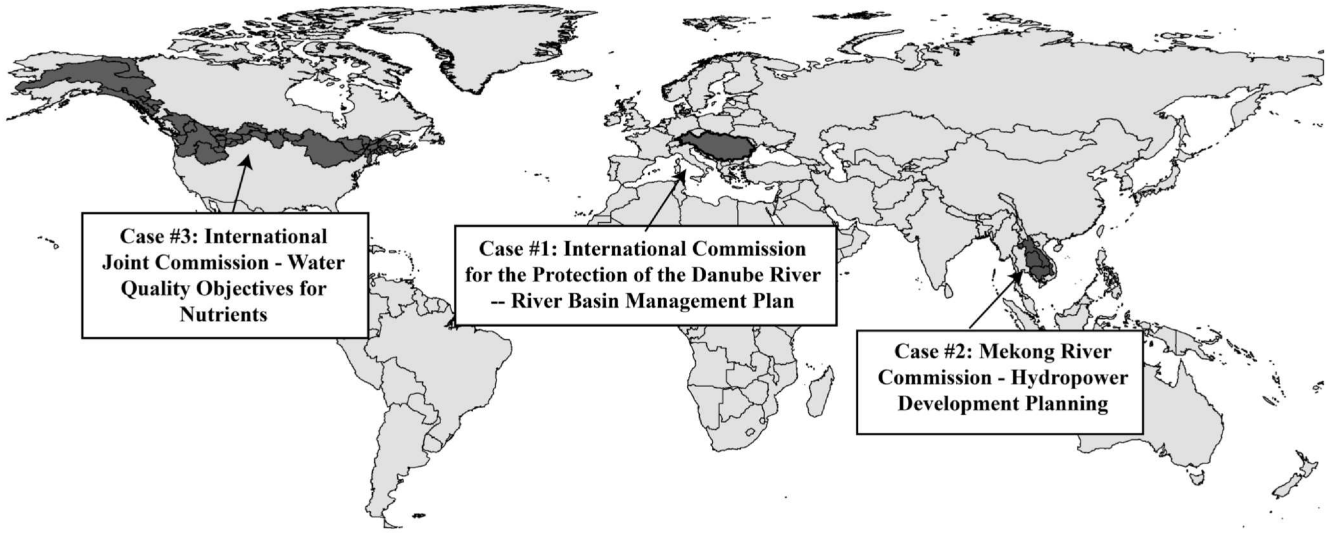
In responding to its newly assigned (2000) mandate to develop a RBMP, the ICPDR faced two challenges. The first challenge was that assessment of good status under the EU WFD required additional monitoring data that did not exist. Under the DRPC, each contracting country agreed to cooperate on monitoring and assessment of water resources (Kittinger, 1997). In 1996, contracting countries had launched the TransNational Monitoring Network (TNMN) a platform that would compile national monitoring data from 61 monitoring stations across the basin. (ICPDR, n.d.-b). However, the TNMN compiled information on a narrow set of parameters, in part due to capacity constraints that limited the ability of some contracting parties to carry out extensive monitoring programs (personal communication, ICPDR, June 26, 2018). For example, the TNMN did not include data on biota (fish, benthic invertebrates, aquatic flora) or hydromorphic quality, and had limited data on persistent organic and inorganic micropollutants in sediment and suspended solids. The second challenge the ICPDR faced was that, because the TNMN relied on multiple technicians and laboratories working independently to collect data, measurements were not easily comparable and existing datasets were difficult to harmonize (personal communication, Liska, June 12, 2018; (ICPDR, 2002). Consequently, even where data existed, the ICPDR encountered difficulties in using that data to assess ecological and chemical status as part of the requirements for RBMPs.

4.1.3. Addressing the knowledge gap

Assessment of the ecological and chemical status of the basin, as required under the EU WFD, was not possible due to incomplete monitoring and absent or incompatible data. To address these knowledge gaps, the ICPDR designed and launched the first Joint Danube Survey (JDS) in 2001. The objective of this multinational river monitoring expedition was to build a homogenous dataset on water quality across the basin. The JDS would help close knowledge gaps by improving the comparability of water quality data collected by contracting parties and by providing capacity-building for member countries on essential data- and monitoring-related tasks (ICPDR, 2002).

Through the ICPDR's Monitoring and Assessment Expert Group, representatives from each country worked together to identify survey

[2] Austria, Bulgaria, Croatia, the Czech Republic, Germany, Hungary, Moldova, Romania, Slovakia, Slovenia, and Ukraine.



Case #1: International Commission for the Protection of the Danube River (ICPDR) - Development of a River Basin Management Plan

IRBO:	The ICPDR was formed as part of the 'Convention on Cooperation for the Protection and Sustainable use of the Danube River Danube River Protection Convention' (1994 signed/1998 Ratified) with the mission of ensuring the sustainable and equitable use of waters and freshwater resources in the Danube River basin
Contracting Parties:	Austria, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Germany, Hungary, Moldova, Montenegro, Romania, Serbia, Slovakia, Slovenia, Ukraine, European Union
Operational Task in the Case Study:	The ICPDR sought to produce a River Basin Management Plan that would include an assessment of waters in the basin and a joint programme of measures to achieve good ecological and chemical status

Case #2: Mekong River Commission (MRC) – Hydropower Development Planning

IRBO:	The MRC was formed as part of the 'Agreement on Cooperation for Sustainable Development of the Mekong River Basin' (1995) with the mission of promoting and coordinating the sustainable development and management of water and related resources of the Mekong River, while reducing any potentially harmful effects on people, the economy, and the environment
Parties:	Member Countries: Cambodia, Laos, Thailand, Vietnam Dialog Partners: China, Myanmar
Operational Task in the Case Study:	The MRC sought to support comprehensive evaluation of hydropower development as part of prior notification and consultation processes and strategic planning in the basin.

Case #3: International Joint Commission (IJC) – Water Quality Objectives for Nutrients

IRBO:	The IJC was as part of the 'Boundary Waters Treaty' (1909) with the mission of aiding the United States of America (US) and Canada in protecting their shared water resources and to prevent and resolve disputes concerning those resources
Member Countries:	US, Canada
Operational Task in the Case Study:	The IJC, through its International Red River Board (IRRB) sought to determine what, if any, water quality objectives to set for nutrients in the Red River basin

Fig. 1. Location and Summary of Case Studies.

locations and select data collection and analysis methodologies. Representatives from each country, together with other ICPDR staff, then embarked on boats for the river expedition. Within each country, a national team of experts joined the ship and aided in the survey. Water quality samples were analyzed simultaneously by ICPDR JDS Reference Laboratories and contracting parties' national laboratories (ICPDR, 2002). This arrangement helped JDS National Teams learn about and gain experience with standardized methodologies utilized in the JDS, and made it possible to analyze compatibility across national and JDS Reference laboratories. After completion of the survey, monitoring data were uploaded to an online data repository and harmonized with existing TNMN data. Findings were reported in a comprehensive survey report and then used to make recommendations to the heads of national delegations at ICPDR meetings and to prepare River Basin Management Plans (personal communication, ICPDR, June 12, 2018).

To date, the ICPDR has conducted four such joint surveys – in 2001, 2007, 2013, and 2019. The first JDS sampled from 74 locations on the main river and 24 locations on major tributaries. Samples were analyzed for more than 140 biological and chemical parameters, aquatic flora and fauna, and bacteriological indicators (ICPDR, 2002). With each successive survey, the ICPDR has expanded the number of sampling locations and parameters measured. The ICPDR has also used the JDS to test new sampling and monitoring approaches.

The fourth JDS differed from prior ones in that each country used its own national experts to conduct sampling and monitoring within its own national boundaries. Prior to the survey, ICPDR conducted training workshops to ensure all nations have adequate capacity to carry out monitoring and ensure that comparable methods were used (personal communication, ICPDR, June 12, 2018; June 26, 2018). The ICPDR also dedicated staff to liaise with contracting parties and provide additional training as needed (personal communication, ICPDR, June 26, 2018). For quality assurance, all samples for testing chemical parameters that are particularly difficult and/or expensive to measure were sent to designated laboratories in western Europe (personal communication, ICPDR, June 26, 2018). The ICPDR developed this new strategy to allow for broader participation and equal involvement of all Contracting Parties, to increase individual nations' capacity for and ownership of monitoring within their nation, and to improve the national-level capacity of contracting parties (personal communication, ICPDR, June 12, 2018; June 26, 2018).

4.1.4. Outcome

Data and information collected during the JDS were used by the ICPDR in developing the 2009 Danube River Basin Management Plan and its 2015 the update, as well as the 2015 the Danube River Basin Flood Risk Management Plan. Results from the JDS were also used to devise the first list of priority substances specific to the Danube River Basin (personal communication, ICPDR, June 26, 2018). The priority substance list helps Danube nations streamline their water management and water quality monitoring efforts.

4.2. Case #2: MRC – hydropower development planning

4.2.1. Background

In 1995, Cambodia, Laos, Thailand, and Vietnam signed the 1995 Mekong Agreement with the aim "to cooperate in all fields of sustainable development, utilization, management and conservation of the water and related resources of the Mekong River Basin" (MRC, n.d.). To implement this agreement, the countries formed the MRC, whose mandate is to coordinate and promote the sustainable development and management of all water and related resources of the Mekong. In this role, the MRC engages in data acquisition, exchange, and monitoring; analysis, modeling, and assessment; basin development planning; forecasting, and emergency preparedness; and implementation of Procedures for water utilization.[3] One of these Procedures includes a notification and consultation process through which member countries discuss about proposed water development projects. As part of the process of consultation, countries conduct a technical assessment, with the support of independent experts, of the potential transboundary impact of the project on ecosystems and livelihoods, and countries recommend agreed-upon measures to address those issues (MRC, 2003).

4.2.2. Recognizing the knowledge gap

Though substantial data collection and information exchange already occurs in the Mekong (Kittikhoun and Staubli, 2018), the MRC and member countries determined they did not have sufficient knowledge base to support comprehensive evaluation of hydropower development in the region. This lack of knowledge became apparent on multiple occasions, including during formulation of a Basin Development Strategy, the Strategic Environmental Assessment Process, and several consultations for proposed hydropower developments. Specifically, the MRC identified a paucity of both whole-of-river and long-term information. Such information is necessary in order to integrate information from specific projects and locations into analyses of impacts at a broader scale; evaluate potential transboundary impacts; and enable comparisons and temporal trend evaluation throughout the Mekong mainstream (MRC, 2013). The ability to perform such evaluations and make such interpretations was deemed important in order to better understand the hydrological and environmental dynamics in the basin and their potential economic and social implications, especially in the context of basin planning and potential cumulative impacts. Of particular concern was the need to develop knowledge in order to evaluate the impacts of hydropower development, including run-of-river operations, on flows, socio-economic conditions, bio-diversity, capture fisheries, and nutrient and sediment transport.

4.2.3. Addressing the knowledge gap

To address this knowledge gap, the MRC conducted a study that aimed to develop improved environmental and socio-economic baseline information for hydropower planning (MRC, 2013). The MRC created a research team consisting of in-house staff from the MRC Secretariat, six international experts (with expertise in hydropower operation, macroeconomics, socio-economic, fisheries science, sediment transport, and aquatic ecology, respectively), and one national consultant from each MRC member country. The objective of this study was twofold: to determine what information was needed to assess hydropower development, and to develop a framework for ensuring that such information would be available in the future (personal communication, MRC, March 26, 2019).

The study team conducted an extensive review of the literature and evaluated the experiences of the MRC members and other countries. Based on this review, the study team devised a framework that delineated the information needed for hydropower assessment and planning. This framework then guided the study team in conducting a status and gap analysis, which identified missing and available information on the basin. This analysis, which was quite extensive, included reviewing existing monitoring and information management systems of the MRC and member countries, sources of information external to the basin, and information from ongoing or planned studies. The review examined data and information on hydrology, sediments, geomorphology, water quality, aquatic ecology, fisheries, and socio-economics. The review also included an assessment of methods, tools, and capacities for collecting, managing, and processing information. One output from the analysis was a comprehensive list of currently held information, including for each topic a description of the parameters for which data were collected, the spatial and temporal scope of that information, the analyses that had been conducted using that information, and how and where that information had been stored and used (MRC, 2013).

Once the status and gap analysis was completed, the study team proposed actions to address the knowledge gaps and developed a set of recommendations, known as the Guiding Framework, for comprehensive information collection and monitoring (MRC, 2014). Through a series of national and regional consultations, these recommendations were refined into priorities for immediate action and longer-term considerations. Priority needs included improving socio-economic baseline information; updating the hydropower project database; finalizing and establishing standardized fish sampling methods and applying them at locations important to hydropower information needs; improving the bio-monitoring database; enhancing sediment monitoring methods, location, and timing; and enhancing the parameters, location and timing of water quality monitoring so as to enable integrated analysis of environmental data (MRC, 2013, 2014). The study team also developed a set of detailed recommendations for collection of future information, including best practices for monitoring and data collection, information on sampling locations and parameters to be collected, and potential analytic methods (MRC, 2013, 2014).

4.2.4. Outcome

The Guiding Framework has significantly informed a pilot Joint Environmental Monitoring program for mainstem dams (MRC, 2018) as well as for development of a basin-wide indicator framework, which member countries will use for tracking basin conditions and reporting as part of the MRC's quinquennial State of the Basin Report as well the update of the Basin Development Strategy (personal communication, MRC, March 26, 2019).

[3] See MRC (2017) for more information on the five procedures.

4.3. Case #3: IJC – water quality targets for nutrients in the Red river

4.3.1. Background

The 1909 Boundary Waters Treaty between the US and Canada formalizes the commitment not to negatively impact the other country and creates the IJC as an entity tasked to prevent and resolve disputes and pursue the common good of both countries. In 1969, the US and Canada authorized the IJC to "establish continuous supervision over the quality of the waters crossing the boundary in the Red River and to recommend amendments or additions to the objectives when considered warranted by the International Joint Commission" (IJC, n.d.). In 1998, as part of its International Watershed Initiative (IJC, 2005), the IJC reorganized its boards to create the International Red River Board (IRRB), which was directed to monitor trends and exceedances of water quality objectives, to document discharge of pollution and pollution control measures, to establish a spill contingency plan, to identify potential future water quality issues, and to recommend appropriate strategies to maintain ecosystem health (IJC, n.d.).

4.3.2. Recognizing the knowledge gap

Prior to the formation of the IRRB, the US and Canada had agreed upon water-quality objectives for dissolved oxygen, total dissolved solids, chloride, sulphate, and fecal coliform bacteria, and had set alert levels for pesticides metals and toxic substances in the Red River Basin (IJC, 2016). However, the basin was grappling with other, newly emerging water-quality concerns. The frequency and severity of algal blooms were increasing in Lake Winnipeg and to a lesser extent in the river, and state and local governments and environmental organizations suspected nutrient loading was the cause. In 2003, in response to eutrophication in Lake Winnipeg, the Canadian province of Manitoba requested the IRRB set nutrient objectives for nitrogen and phosphorus pollution at the international border. This request was repeated by the Red River Basin Commission (RBBC), a coalition of local governments, watershed boards, counties, First Nations, and provincial, state, and federal representatives (Harris et al., 2001).

In response to requests from Manitoba, the RRBC, and others, in 2008, the IRRB included in its five-year work plan the goal of establishing water quality objectives for phosphorus and nitrogen (IJC, 2008). Several knowledge gaps had to be filled in order to develop this strategy. The IRRB had to determine first whether nutrient loading contributes to algal blooms in the river, as that relationship would justify setting water-quality objectives. A concern was that the relationship between nutrients and algal growth would be difficult to detect because heavy sediment loading in the river reduces available light and impedes algal growth. Next, the IRRB needed to identify what levels of nutrient loading would and would not lead to substantial algal growth. Answering these questions required developing an understanding of existing nutrient loading and flows as well as the biological relationship between nutrients and algal growth.

4.3.3. Addressing the knowledge gap

Addressing these knowledge gaps, which were rooted in uncertainty about causal mechanisms, was a multi-step process. First, the IRRB assembled experts from across the basin to guide the initial development of a nutrient target. The IRRB then contracted a consultant to review potential methods to be used for developing water quality targets (Plevan and Blackburn, 2013). Based on the report's recommendation, the IRRB decided to develop a stressor-response model that uses statistical analyses to examine the relationships among nutrients, biological responses, and other variables. Concurrently, the IRRB sought to identify and quantify the sources of nutrient loading and pathways of nutrient transport. This information was needed both for the stressor-response model and for future management decisions (T. Miller et al., 2016).

To develop understandings of nutrient flows in the basin, researchers from both the US and Canada worked together to apply the USGS SPARROW model for nutrients (Jenkinson and Benoy, 2015). These efforts led to the identification of additional knowledge gaps. It became clear that the lack of seamless and scalable hydrographic data across the border was a barrier to applying the SPARROW model. Most data and information about the watershed are produced independently by federal, provincial, state and local agencies in both countries. In collecting, interpreting and storing data, each agency developed its own methods and procedures. Consequently, existing drainage and hydrographic data were developed based on different standards and interpretive rationales. The resulting incompatibilities in hydrologic accounting units, metrics and scales prevented development of a transboundary model. To address this, the IJC formed a task force to develop a harmonized dataset (Major et al., 2018). Success of that effort, along with recognition of the value of harmonized data, led the IJC to support similar harmonization efforts across other watersheds along the border.

During the process of developing the stressor-response model, further data needs were identified. Specifically, data were needed on algal growth and water chemistry along specific river reaches. An interagency sampling approach was quickly designed and the Minnesota Pollution Control Agency, Manitoba Sustainable Development, Environment and Climate Change Canada, North Dakota Department of Health and the Buffalo-Red River Watershed Management District collaborated to collect the necessary information on algae and water chemistry (T. Miller et al., 2016). The consultant then integrated this information and developed the stressor-response model. Results identified a relationship between the gradient of nutrient loading and algal growth. Modeling also showed that turbidity in the river repressed the relationship between nutrients and the growth of some algal communities (periphyton), but not others (phytoplankton).

4.3.4. Outcome

Knowledge gained from the IJC investigations has helped to guide management decisions. Results from the stressor-response model were compared with studies downstream in Manitoba and elsewhere, and used to inform a set of proposed water quality targets for nutrients. Results from the SPARROW modeling served to inform a proposal for apportionment of target nutrient load reductions between the US and Canada. In 2020, the IJC recommended the governments of the US and Canada adopt the proposed water quality objectives (IJC, 2020).

5. Synthesis of knowledge gaps and strategies to address knowledge gaps

The three case studies reveal a variety of knowledge gaps that may exist in transboundary settings. In each case, although national governments were committed to monitoring and sharing data, there remained key knowledge gaps that served as a barrier to transboundary governance. In the ICPDR case, member countries lacked information for assessing chemical and ecological status at the basin-level. Thus ICPDR member countries that are part of the EU were unable to produce the requisite plan needed to comply with EU laws. In the MRC case, new knowledge was needed to support discussions between its member countries on notification and consultation over the impacts of hydropower as part of implementation of the MRC's Procedures related to hydropower development. In the IJC case, member countries did not know if they had sufficient cause to set water quality objectives for nutrients, nor what those objectives should be. Knowledge was also needed to aid countries in developing a nutrient management strategy. In all these case studies, the knowledge gap served as a barrier to governance in the basin. To better inform our understandings of knowledge gaps, we synthesize across the three case studies to develop a typology of knowledge gaps and to examine the strategies used by the IRBOs to address each type of gap. In doing so, we provide a framework for assessing and theorizing knowledge gaps at the transboundary scale that can help inform future research and the design of cooperative

Fig. 2. Typology of Knowledge Gaps in Transboundary River Basins, with Examples from the Case Studies.

Strategy	Examples from the Case Studies
Inventory and Review * Provides clear understanding of what knowledge is available and what knowledge is needed. Supports prioritization of acquisition of new knowledge. * Requires ability to access and compile existing information. Updating needed to maintain an accurate inventory.	•**MRC: Knowledge base for evaluating the economic, social and environmental risks of hydropower development.** The MRC Secretariat and a team of consultants conducted a review to identify the information needed, and, with the assistance of member countries, compiled existing data sets in the basin to evaluate the status of data available. •**IJC: Approaches to setting nutrient targets.** The IRRB hired a consultant to review potential methods for setting water quality objectives.
Primary Data Collection * Directly fills information gaps and ensures compatibility of specifically collected data. * Requires resources for data collection; does not ensure future data collection will be harmonized.	•**ICPDR: Data to assess chemical and ecological status.** As part of the ICPDR Expert Group, representatives from contracting parties designed a longitudinal survey. Experts from member countries implemented the survey, collecting and analyzing data. Double samples were collected and compared results across differing laboratories for quality assurance. •**IJC: Data on the presences of nutrients, turbidity, and algal growth.** A consultant, IRRB, and sub-national governmental agencies collaboratively designed and implemented data collection.
Harmonization * Remedies incompatibility in existing data and information. * Requires consensus building across national and sub-national institutions as to conceptual definitions, metrics, benchmarks and standards.	•**IJC: Drainage and hydrographic data.** Representatives from governmental agencies in each country worked together as part of an IJC Task Force to identify inconsistencies in existing data and to develop shared definitions and methodologies. They then transformed existing data into a compatible format.
Guiding Frameworks for Collecting and Analyzing Data and Information * Provides a template that facilitates consistent and compatible collection and analysis of information by member countries. * Requires willingness and capacity of member to follow the framework.	•**ICPDR: Data to assess chemical and ecological status.** The ICPDR Secretariat provided a protocol, training, and technical assistance to aid member countries. •**MRC**: **Data to assess the economic, social and environmental effects of hydropower development.** The MRC Secretariat and a team of consultants provided detailed recommendations for countries to follow when collecting, analyzing, and managing data and information. Member countries reviewed and commented on the framework and jointly prioritized which data gaps to fill. •**IJC**: **Data related to drainage and hydrography.** Representatives from governmental agencies agreed to apply methodologies developed during harmonization of drainage and hydrographic data to future data collection.
Scientific Investigations * Provides new understandings of biophysical processes. * Requires substantial expertise to design and implement studies.	•**IJC: Controls moderating algal growth.** Consultants and government experts, with oversight of the IRRB, developed the SPARROW model to delineate flows of nutrients throughout the watershed and a stressor-response model to determine the relationship between nutrient loading, turbidity, and algal growth.

Fig. 3. Strategies for Addressing Knowledge Gaps, with Examples from the Case Studies.

international institutions.

5.1. Typology of knowledge gaps

Knowledge gaps across the case studies encompass a wide variety of topics, ranging from basic hydrography to hydromorphology, ecology, and socio-economics. While some of the gaps are related to a lack of data, many of the knowledge gaps are more complex and cannot be solved by data collection alone. Grouping the knowledge gaps based their characteristics leads to a typology that includes five categories of gaps described below. Fig. 2 includes examples from the case studies of each of these categories of knowledge gaps.

The ***unidentified gap*** category encompasses the situation when the knowledge needed for addressing transboundary issues or the knowledge available is unknown. Unidentified knowledge gaps may exist due to the complexity of a topic or because a topic is new or emergent within the watershed. For example, in the MRC case study, the impacts of hydropower development are multi-dimensional and interacting. The MRC needed to identify the types and amounts of data that might be useful for evaluating hydropower development so that it could both determine what data gaps exist and work on overcoming technical, capacity-related, and political challenges to filling those gaps. Whereas in the IJC case study, the IRRB was just beginning the process of addressing nutrient pollution and there were not set procedures for setting water-quality objectives.

The ***missing information*** category includes gaps in knowledge that arise because the information or data needed for management does not exist. The all three case studies, information was missing because it had not been collected and analyzed. For example, the ICPDR lacked sufficient data on biota, geomorphic conditions, and organic pollution to assess the chemical and ecological status of many parts of the basin. In both the ICPDR and the MRC case studies, missing information includes not only knowledge regarding a single point in time, but also knowledge of temporal trends.

The ***incompatibility*** category includes knowledge gaps that exist due to differences in definitions and data collection methods that impede compilation and analysis of existing information. In some of the case studies, even where information existed, there were limits to its usefulness. For example, in the IJC case study, differences in definitions of drainage and hydrographic networks were a barrier to use of existing information for in transboundary analyses of nutrient flows.

The ***quality control*** category includes knowledge gaps that arise from uncertainties and/or concerns about the quality of information. This type of gap can occur due to variation in the validity and precision of data collected by differing agencies. For example, in the ICPDR case, knowledge gaps arose because countries used different protocols for monitoring. Further, there were questions about whether data collected under national-level monitoring programs were of comparable accuracy.

Lastly, the ***lack of science understandings*** category encompasses knowledge gaps that occur because understandings of biophysical processes are lacking. For example, in the IJC case, the relationship between nutrient loading and algal growth in the river was unknown, as it was possible that turbidity in the water blocked the light needed for algal growth. In many transboundary basins, biophysical processes, as well as social and economic processes are poorly understood.

As demonstrated by the case studies, knowledge gaps frequently do not occur in isolation. Addressing one knowledge gap often requires concurrently a tackling of other knowledge gaps that arise. For example, as seen in the IJC example, missing information about nutrient loading and algal growth impeded understanding the relationship between the two. This lack of understanding contributed to questions regarding how to set water quality objectives for nutrients. While individually, many of the aforementioned categories of knowledge gaps (including the lack of knowledge, incompatibilities, and quality assurance) have been recognized as challenges to transboundary management (Rougé et al., 2018; Timmerman et al., 2010), the connections between knowledge gaps merits greater attention. As illustrated by the IJC case study, the compounding effects of multiple concurrent gaps can add substantially to the time, effort, and cost required to develop the knowledge ultimately needed to take action.

5.2. Strategies to address knowledge gaps

In each of the case studies presented, the IRBOs were able to address the knowledge gaps experienced, yet the overall approach to solving the knowledge problem was tailored to their individual situations. The ICPDR focused on primary collection of new data while developing capacities for quality assurance across member countries. In contrast, the MRC began with a stock taking exercise and provided guidance for future data collection. Finally, the IJC sought to use existing data to develop new scientific understandings, and in the process, discovered a need to address data inconsistencies and to collect new primary data. These differences notwithstanding, as illustrated in Fig. 3, there are similarities in the strategies adopted for addressing each type of knowledge gap.

Inventories and reviews were used by the IRBOs to fill ***unidentified knowledge gaps***. These strategies included compilation of existing information from within and from outside the basin, and using that information to assess knowledge needs for the basin. For example, in the MRC case study, inventories and reviews were used both to determine the ideal set of information use in analyzing the impacts of hydropower development as well as to identify gaps in existing information and how to best fill those gaps. Inventories and reviews provide the IRBOs with a systematic method for identifying knowledge gaps. They also serve to synthesize information and can provide a valuable tool transferrable outside the basin. The MRC's review of information needs for assessing the social, economic, and environmental impacts of can be used in any river basin in which hydropower development is occurring.

Where the problem was ***missing information***, and the IRBOs had a solid understanding of the knowledge gap, the IRBOs engaged in ***primary data collection.*** All three case studies involved IRBOs addressing missing information by collecting additional data and expanding monitoring. The need to fill knowledge gaps in each of these case studies is indicative of the fact that basin-wide datasets are a persistent gap and that knowledge needs in transboundary contexts are not static. These three case studies highlight the need for treaties to include provisions for adapting monitoring and data collection and developing new knowledge as new circumstances arise.

The IRBOs used a strategy of ***harmonization*** to address knowledge gaps arising due to ***incompatibilities*** in existing data and information. For example, through the IJC, agencies within the US and Canada worked together to reconcile differences in definitions and methods used to delineate drainage and hydrographic data. Once those differences were resolved, existing data were transformed to match the agreed upon definitions and formats, making it possible to jointly use existing data in transboundary analyses. An added benefit of harmonization is that it reduces problems of incompatibly in future data collection.

Where new data and information was to be collected and/or analyzed separately by differing countries, the IRBOS adopted the strategy of providing ***guiding frameworks***. This strategy addressed knowledge gaps arising from both ***incompatibilities*** and ***quality control***. For example, in the case studies associated with both the ICPDR and the MRC, the IRBOs provided frameworks to support national and sub-national level agencies in collecting and analyzing information. The ***harmonization*** and ***guiding framework*** strategies adopted by the IRBOs are particularly notable, as in transboundary settings, data and information collection and analysis is frequently conducted by separately by agencies on each side of the border.

Lastly, ***scientific investigations*** were used to address knowledge gaps arising due to a lack of science understandings. For example, in the

IJC case study, an investigation was undertaken to develop knowledge of the sources and transport of nutrients within the basin. That knowledge, combined with additional information, was then used in an investigation that provided knowledge regarding the relationship between nutrient loading, turbidity, and algal growth. While scientific investigations can be instrumental in filling knowledge gaps, IRBOs face challenges in design and implementation of such studies (Milman and Gerlak, 2020).

6. Discussion

6.1. Knowledge gaps in transboundary settings

Within each case, the IRBO contended with multiple knowledge gaps of varying forms. While missing information was indeed a knowledge gap in all three cases, rarely was data (or a lack of it) the sole barrier to achieving the IRBO's objective. Knowledge gaps related to incompatibilities and quality control were equally of concern – highlighting the common problem that knowledge components developed separately often cannot be adequately combined. Unidentified knowledge gaps were also an operational challenge – and in the case studies, included knowledge gaps related to what information was needed, what information exists, as well how to analyze and evaluate that information. These findings suggest and further the argument that data sharing provisions may not suffice for providing the knowledge needed for transboundary governance (Schmeier, 2014). Coordination in methodologies and approaches to knowledge production, as well as mechanisms that foment production of knowledge when gaps are identified, may also be necessary.

In comparing across the case studies, knowledge gaps caused by a lack of scientific understanding appeared only in the IJC case. In the ICPDR and MRC cases, the IRBOs sought to evaluate the state of the basin for planning purposes, whereas the IJC was seeking to determine the need for water quality standards – a task that requires more complex knowledge. A criterion for case selection was agreement over the transboundary policy agenda so we expect case selection is the reason this type of knowledge gap was only present one of the three case studies. It is likely that a lack of scientific understanding becomes a barrier to consensus over governance priorities and objectives, and must be resolved before arriving at the operational-level. The fact that this knowledge gap existed in the IJC case is a testament to the positive relations between the US and Canada over transboundary water governance as well as the IJC's well-defined and accepted role as a nonpartial advisor to the two governments (Macfarlane and Clamen, 2020).

While multiple knowledge gaps were identified in each case, in none were *all* knowledge gaps filled. It was neither feasible nor necessary for the IRBOs to have complete knowledge in order to achieve their objectives. In the ICPDR case, data collection and analysis were limited by sampling feasibility, testing capacity, and cost, among other factors, and the ICPDR adaptively prioritized which gaps were filled in each successive survey so as to answer the most urgent questions about the status of the basin. The MRC needed the missing knowledge for planning and analysis of the impacts of hydropower development. Given constraints to data collection and analysis, the MRC used developed a guiding framework to prioritize what data and information to collect. The IJC also faced time and resource constraints in collecting data to build the stressor-response model. These findings highlight the stresses associated with lack of sufficient funding and the adaptations and shortcuts IRBOs must take in addressing knowledge gaps to support transboundary governance (Henkel et al., 2014; Schmeier, 2018).

6.2. Addressing knowledge gaps in transboundary settings

As seen in Fig. 4, which maps the knowledge gaps in the case studies onto the strategies used to address them, the IRBOs adopted similar strategies for resolving each type of knowledge gap. These strategies are not unique to transboundary contexts (see e.g., Jansen, 2006; Larsen and Nilsson, 2017; Sorrell, 2007), yet identification of their use in filling transboundary knowledge gaps provides a conceptual starting point for theorizing and for conducting applied research into the resolution of knowledge gaps in such contexts. A useful next step would be to examine the factors that influence deployment and effectiveness of each type of strategy in the context of the fragmenting effects of sovereignty and heterogeneous institutional structures.

Developing and implementing an agreed upon strategy for filling knowledge gaps are not without complication (Milman and Gerlak, 2020). Even when there is agreement at the political level as to the policy agenda, there can be distributional issues associated with filling knowledge gaps. For example, when harmonizing data or detailing guiding frameworks for knowledge production, some if not all RBO member-states will need to divert from past practices. The question of who should bear the costs of changing and which country's capacities and levels of expertise should form the norm are socio-political rather than technical. Similarly, in terms of reviews, data collection, and scientific studies, details related to methods as well as human and financial resources needed to fill the knowledge gap, must be resolved (Larsen and Nilsson, 2017).

Even where knowledge gaps are a barrier at the operational level, the process of filling knowledge gaps may elevate to the political level and affect deliberations over the policy agenda (Fischhendler and Katz, 2013; Struthers, 2019). In the case studies, knowledge gaps remained an operational-level concern and the IRBOs were able to successfully fill the gaps. Yet it is well recognized that a variety of factors, including disagreement over the accuracy and acceptability of data, political will, perceptions of the gains from sharing, cultural values, trust, and national security considerations can impede knowledge formation and sharing in transboundary settings (Chenoweth and Feitelson, 2001; Plengsaeng et al., 2014; Weichselgartner and Kasperson, 2010). These potential barriers raise unanswered questions about the circumstances in which knowledge gaps may escalate from operational to political barriers, as well how to implement each strategy effectively in contexts with differing degrees of potential contention.

In each of the case studies, the IRBO took steps to preclude potential concerns of member countries. For example, in the ICPDR case, to support member-country buy-in and capacity building, the ICPDR included equal representation from all countries in designing and implementing the river expedition. In the MRC case, the prioritization of information in its Guiding Framework was determined through discussion across member countries, including consideration of each country's capacities to collect data and priorities for information. In the IJC case, fully bi-national work groups led the process of filling knowledge gaps. These approaches resemble science co-production (see e.g., Lemos and Morehouse, 2005; Miller and Wyborn, 2018), which may help to build legitimacy and credibility (van der Hel and Biermann, 2017; van Enst et al., 2016). Studies of implementation of co-production, however, demonstrate mixed results (Jagannathan et al., 2020). Research is needed to determine the contributors to successful co-production in transboundary settings, and in particular, whether and how it can be used to reduce the potential for knowledge gaps to be elevated from the operational to the political level.

Lastly, it is important to recognize that transboundary governance is multi-faceted. Each of the three cases reflects only one of the many instances in which each of the IRBO identified and addressed knowledge gaps. Countries involved in transboundary governance face multiple concurrent policy-issues and concerns (Conconi and Perroni, 2002; McGinnis, 1986). IRBOs contend with multiple water issues including managing flows, addressing pollution, protecting ecosystems, infrastructure development and navigation, among other topics (Do and Dinar, 2014; Dombrowsky, 2010). Countries in each basin interact in other venues over these are related issues such as air pollution, transportation, and invasive species (Gerlak and Mukhtarov, 2016). Filling knowledge gaps in one arena may support another. For example, the

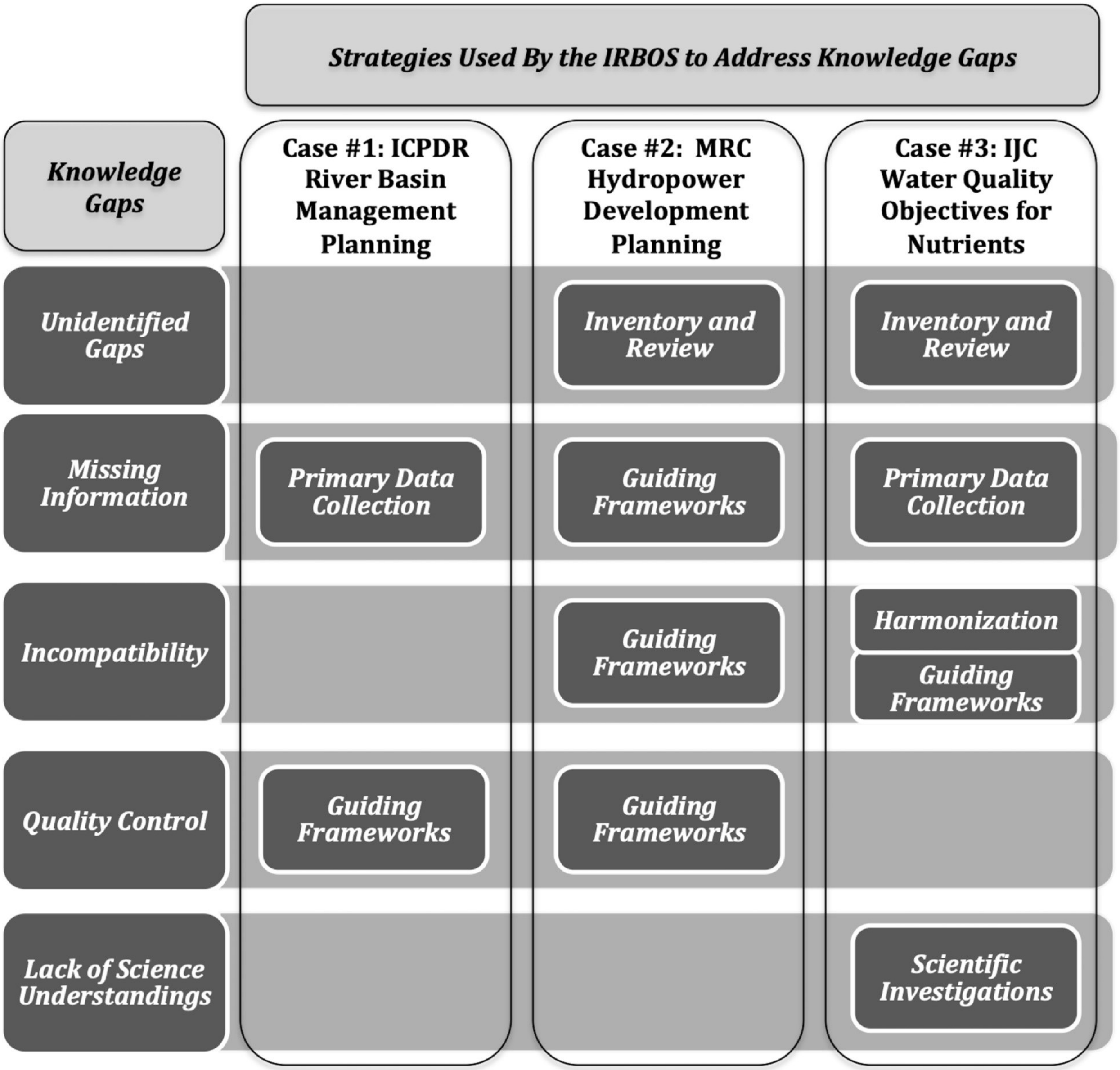


Fig. 4. Diversity of Knowledge Gaps Identified and Strategies to Address Knowledge Gaps across the Case Studies.

IJC applied the methods developed for filling knowledge gaps in the Red River basin to other basins along the US-Canada border. Yet filling knowledge gaps may also have implications for, or be affected by both knowledge gaps and political processes in other arenas. Thus the role of linkages within transboundary settings merits further investigation.

7. Conclusions and next steps

This research highlights the varying types of knowledge gaps that may exist and offering insights into some of the strategies adopted to address these gaps. Yet, we would be remiss if we did not acknowledge the limitations of our work. In examining case studies in which knowledge gaps were largely filled, our research does not answer the question of the necessary conditions for knowledge gaps to be filled. Further, the three IRBOs we examined receive strong support by their member countries and have strong institutional structures and capacities. While our framework can help less-institutionalized IRBOs identify the types of knowledge gaps that may exist and identify strategies for filling those gaps, there is a need to identify factors that facilitate and potential constraints in applying such strategies where transboundary cooperative mechanisms are not as well developed. In addition to country capacity and the political nature of the knowledge gap being addressed, the duties and implementation powers of the IRBO may affect the ways in which knowledge functions, a topic beyond the scope of our analysis. Lastly, the three cases in our research relate to transboundary water, and, while water shares many properties with other transboundary resources, our research does not seek to determine whether the forms of knowledge gaps that exist and strategies for filling them vary by transboundary management concern or type of resource (e.g., air, wildlife, etc.).

Given the extent to which global environmental change is stressing natural resource systems around the world, and the importance of knowledge for adaptive management, it is critical that we develop better understandings of the nature of knowledge gaps and the processes that countries and international organizations can use to address them. There is a need to more comprehensively identify existing knowledge gaps, the scope of possible strategies to address them, and the most effective strategies under different institutional and biophysical settings. Better understandings are also needed as to what catalyzes knowledge production in transboundary settings and the determinants of whether and how knowledge is used. Greater attention to the science-policy interface in transboundary settings, with an emphasis on what motivates and yields useful, usable, and used knowledge, and how institutional design might shape those outcomes, will facilitate better management of shared natural resources.

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CRediT authorship contribution statement

Anita Milman: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Andrea K. Gerlak:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Tamee Albrecht:** Investigation, Formal analysis, Writing - review & editing. **Mark Colosimo:** Formal analysis. **Ken Conca:** Formal analysis, Writing - review & editing. **Anoulak Kittikhoun:** Formal analysis, Writing - review & editing. **Péter Kovács:** Formal analysis, Writing - review & editing. **Richard Moy:** Formal analysis. **Susanne Schmeier:** Formal analysis, Writing - review & editing. **Kelsey Wentling:** Investigation. **William Werick:** Formal analysis. **Ivan Zavadsky:** Formal analysis, Writing - review & editing. **Jim Ziegler:** Formal analysis, Writing - review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Some of the co-authors are employees or have previously worked with the international river basin organizations that are examined in this study.

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