Canadian Science Publishing

REVIEW

Historical, contemporary, and future perspectives on a coupled social–ecological system in a changing world: Canada's historic Rideau Canal

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Abstract: Anthropogenic waterways and canal systems have been part of the cultural and natural landscape for thousands for years. As of the late 20th century, more than 63 000 km of canals exist worldwide as transport routes for navigation, many with barriers (e.g., locks, dams) that fragment the system and decrease connectivity. Fragmentation alone can have negative implications for freshwater biodiversity; by isolating populations and communities, other human-mediated disturbances associated with canals like poor water quality and invasive species can exacerbate these negative effects. As such, the capacity of these interconnected freshwater systems to support biodiversity is continuously degrading at a global level. One critical, highly complex issue that unites canals worldwide is the challenge of governing these systems in a holistic, unified way to both protect biodiversity and preserve historical elements. Managing historic canals involves multiple objectives across many agencies and stakeholders, often with different or conflicting objectives. Here, we use the Rideau Canal, a UNESCO World Heritage Site and National Historic Site of Canada, as a case study to demonstrate the importance of considering canals as social–ecological systems for effective and efficient governance. Historic canals are integrated systems of both humans (social) and the environment (ecological), linked by mutual feedbacks and coevolution, and must be managed as such to achieve conservation goals while maintaining commemorative integrity. We discuss the history of the Rideau Canal and its current governance, biodiversity in the waterway, different threats and issues (user conflicts, aquatic pollution, shoreline development, water management, species at risk, and invasive species), and conclude by outlining ways to address the challenges of managing it as a coupled social–ecological system. We present different research needs and opportunities that would enable better management, though above all, we propose a shift from the current governance structure — which at best can be considered "patchwork" — to a coordinated, multi-scalar and multi-stakeholder governance regime such that the Rideau Canal can be maintained for its historical integrity without compromising biodiversity conservation. Given that canals are now pervasive worldwide, this article is not only topical to the Rideau Canal, but also to other waterways in Canada and beyond.

Key words: social–ecological system, adaptive governance, resilience, biodiversity conservation, aquatic connectivity.

Résumé : Les voies navigables et les systèmes de canaux anthropiques font partie du paysage culturel et naturel depuis des milliers d'années. À la fin du 20e siècle, plus de 63 000 km de canaux existent dans le monde comme voies de transport pour la navigation, dont beaucoup comportent des barrières (par exemple, des écluses, des barrages) qui fragmentent le système et réduisent la connectivité. La fragmentation à elle seule peut avoir des répercussions négatives sur la biodiversité des eaux douces; en isolant les populations et les communautés, d'autres perturbations d'origine humaine associées aux canaux, comme la mauvaise qualité de l'eau et la présence d'espèces envahissantes, peuvent exacerber ces effets négatifs. Ainsi, la capacité de ces systèmes d'eau douce interconnectés à soutenir la biodiversité se dégrade continuellement à l'échelle mondiale. Un problème crucial et très complexe qui unit les canaux à travers le monde est le défi de gérer ces systèmes de manière holistique et unifiée afin de protéger la biodiversité et de préserver les éléments historiques. La gestion

Received 10 March 2021. Accepted 2 July 2021.

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*John Smol served as an Editor at the time of manuscript review and acceptance; peer review and editorial decisions regarding this manuscript were handled by Kathleen Rühland.

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des canaux historiques implique des objectifs multiples entre de nombreuses agences et parties prenantes, qui ont souvent des objectifs différents ou contradictoires. Les auteurs utilisent ici le canal Rideau, site du patrimoine mondial de l'UNESCO et site historique national du Canada, comme étude de cas pour démontrer l'importance de considérer les canaux comme des systèmes socioécologiques pour une gouvernance efficace et efficiente. Les canaux historiques sont des systèmes intégrés à la fois de l'humain (social) et de l'environnement (écologique), liés par des rétroactions mutuelles et une coévolution, et ils doivent être gérés comme tels pour atteindre les objectifs de conservation tout en maintenant leur intégrité commémorative. Les auteurs discutent de l'histoire du canal Rideau et de sa gouvernance actuelle, de la biodiversité de la voie navigable, des différentes menaces et préoccupations (conflits entre utilisateurs, pollution aquatique, aménagement des rives, gestion de l'eau, espèces en péril et espèces envahissantes), et ils concluent en décrivant des moyens de relever les défis de sa gestion en tant que système socioécologique couplé. Ils présentent différents besoins et possibilités de recherche qui permettraient une meilleure gestion, mais surtout, ils proposent de passer de la structure de gouvernance actuelle — qui, au mieux, peut être considérée comme une « mosaïque » — à un régime de gouvernance coordonné, multiscalaire, et multiacteurs, de sorte que le canal Rideau puisse être maintenu dans son intégrité historique sans compromettre la conservation de la biodiversité. Puisque les canaux sont désormais omniprésents dans le monde entier, cet article n'est pas seulement d'actualité pour le canal Rideau, mais aussi pour d'autres voies navigables au Canada et ailleurs dans le monde. [Traduit par la Rédaction]

Mots-clés : système socioécologique, gouvernance adaptative, résilience, conservation de la biodiversité, connectivité aquatique.

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Introduction

For thousands of years, humans have modified natural waterways (e.g., lakes, rivers) and created others where they did not exist. The first canals constructed were done so by Mesopotamians around 4000 BC, where waters from the Tigris–Euphrates river system were diverted for irrigation, drainage, household water supply, and navigation (Bjornlund and Bjornlund 2010; Geyer and Monchambert 2015). Canals were commonly built by various ancient empires across the globe, primarily for urban and agricultural water consumption and for transportation, extending from ancient times to British "canal mania" (Hadfield 1986; Lin et al. 2020). To this day, canals continue to be constructed to support human development in both rural and urban areas (Lin et al. 2020). Beyond these uses, canals also provide cultural, aesthetic, and economic values through historical heritage, cultural identity, and recreational opportunities (Walker et al. 2010; Hijdra et al. 2014; Guo et al. 2016). Though some canals still serve their original purpose, many historic canals have been either abandoned, partially buried or drained, or are now used and managed for other purposes. Managing historic canals today often includes objectives like conservation of heritage value and protecting ecosystem services and biodiversity, which are beyond their original development and economic functions and services (Arlinghaus et al. 2002; Walker et al. 2010; Guo et al. 2016). Many canals are now used in ways that were not envisioned when they were built and thus are not always optimally designed to fulfil their new roles.

The Rideau Canal in Ontario, Canada, exemplifies the social–ecological challenges facing many canals and waterways today. In the Rideau Canal, there is a legal requirement to maintain navigation and protect the commemorative integrity of the system, including historical infrastructure and associated landscapes, and contemporary issues related to biodiversity. The Rideau Canal is also faced with competing user interests, external development pressures, and complex governance. Waterways like the Rideau Canal are coupled social–ecological systems (Gunderson et al. 2017; Llausàs et al. 2020) — that is, complex adaptive systems where social and biophysical agents interact at multiple temporal and spatial scales (Ostrom 1990; McGinnis and Ostrom 2014). Recognizing that canals are coupled social–ecological systems is intuitive because the natural environment — and how humans use it — is inherently linked to the built environment, and because it acknowledges that these are difficult systems to govern, particularly in the face of change. Changes can come in many forms, though relevant to the Rideau Canal is the fact that human behaviour (e.g., increased development in watersheds, continued use of canals for recreation) and climate change (e.g., Perry et al. 2010) are major drivers that will shape the complex interactions in social–ecological systems in the coming years. The challenge lies within the need to strike a balance between conservation of heritage value and supporting the ecosystems within; for the Rideau Canal, protection of ecosystem services and biodiversity is more an inadvertent consequence of this waterway being protected for navigation over the past 100 years. It is not the current primary management focus, nor was conservation considered by engineers during canal construction in the 1830s.

The environmental status and capacity of canals and other artificial waterbodies depend on their history (e.g., original landscape, design/structure, purpose, and associated management) and ongoing management (Clifford and Heffernan 2018; Lin et al. 2020). Thus, we use the Rideau Canal as a case study and explore its history, current state, and future as a prime example of a coupled social–ecological system. This article is a narrative synthesis; its purpose is to detail ongoing social–ecological issues relevant to conservation and management of the system, and serve as a template for other canal managers worldwide. We describe the system and its interconnected components, consider challenges and opportunities for the future, and identify research needs. To conclude, we provide information to managers on ways to improve the Rideau Canal's resilience for its continued benefit to users and the environment. Although each canal system has its own unique set of conditions and history, many aspects of the Rideau Canal are analogous to other waterways globally, and thus the information detailed below is useful to managers not only in Canada but worldwide.

History of the Rideau Canal

Purpose and construction

The Rideau Canal was conceived and designed by the Ordinance Department of the British military and opened in 1832. Prior to the start of the railway era in the 1840s, waterways and canals were a key method of transportation in North America. The Rideau Canal is located in eastern Ontario and is a 202 km continuous route that connects the Ottawa River at Canada's capital city of Ottawa to Lake Ontario at the city of Kingston (Fig. 1). It was originally built to enable trade and military defence by the British in the face of military pressures from the United States (Fig. 2E; Tulloch 1981). By the late 1800s, the Rideau Canal began to transform into a recreational waterway (Acres 1994; Forrest et al. 2002). Today, in addition to its purpose as a recreational waterway, the Rideau Canal serves as a heritage tribute to Canada's early history.

Colonel John By of the British Royal Engineers led the construction efforts (Fig. 2D). The first step involved extensive surveying

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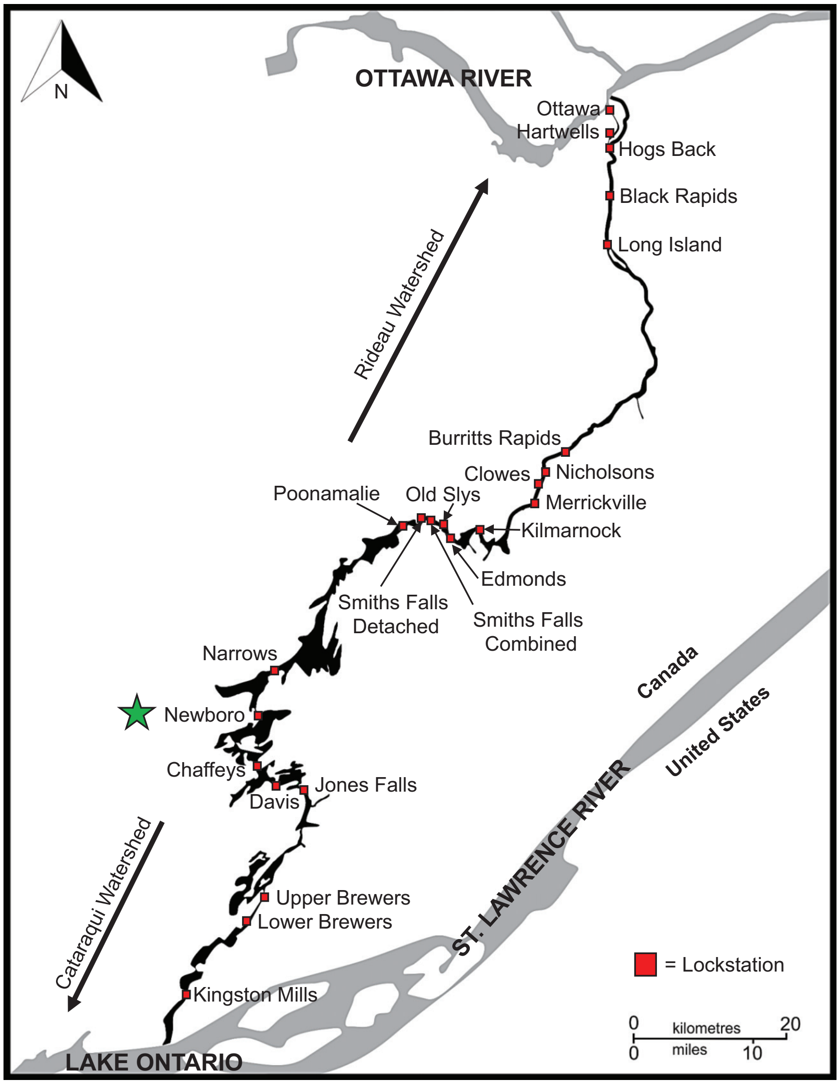
Fig. 1. Overview map of the Rideau Canal. The black channel represents the Rideau Canal, and the gray channels represent hydrologically connected waters (Lake Ontario and the St. Lawrence River in the south; the Ottawa River in the north). Red boxes indicate the 23 operating lockstations that interconnect the system. Newboro Lockstation, indicated by the green star, is the "isthmus", representing the highest elevation on the Rideau Canal and delineates the Rideau Watershed (flowing north) and the Cataraqui Watershed (flowing south). Lake Ontario and the St. Lawrence River act as a natural border between Canada and the United States. Base map source: Government of Canada 1:250 000 NTS maps — 31B (Ogdensburg), 31C (Kingston), and 31G (Ottawa). Locations of lockstations were plotted from the relevant 1:50 000 NTS maps (31B/13, 31C/8, 31C/9, 31C/16, 31G/4, and 31G/5).

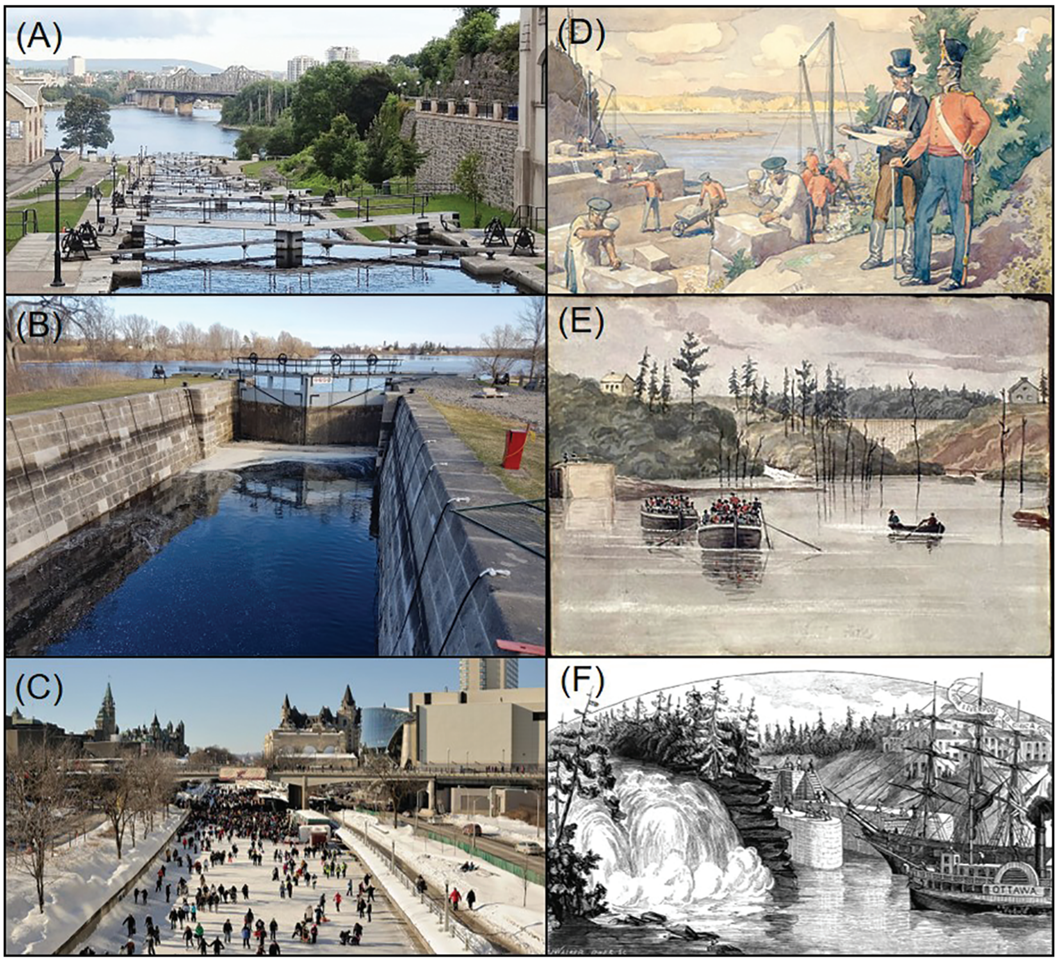


of the region, conducted on foot and by canoe, and began as early as 1783 to identify navigation impediments (Passfield 1983). The Rideau Canal was constructed largely by hand, with the use of small tools and stock animals to haul heavy materials. The completed Rideau Canal includes a series of rivers, lakes, and constructed channels connected by lockstations that form the continuous waterway. The route includes ~19 km of human-built canal cuts with 45 locks at 23 lockstations, many of which have adjacent water-control dams (Legget 1986). Many lockstations included mills (lumber, grist, and carding), which were later replaced by hydroelectric facilities (https://www.pc.gc.ca/en/lhn-nhs/on/rideau/histoire-history/histoire-decluse-lock-history). Even today, most lockstations are operated by hand and do not rely on automated systems to drain and fill locks for navigation. From Lake Ontario at Kingston, the Rideau Canal rises 50.6 m to the summit at Newboro Lockstation and then descends 83.8 m to the Ottawa River at Ottawa (Fig. 1). Although most of the canal system is shallow (several metres deep), there are deeper areas within some of the larger lakes (e.g., Big Rideau Lake, maximum depth 91 m). The system operates based on the use of European slackwater technology (see https://www.pc.gc.ca/en/docs/r/on/rideau/whl-lhm/chap3/chap3C), which exploits the existing natural lake and river reaches and relies comparatively little on constructed reaches (only 9% of total canal distance). Using the natural local environment and its waters to develop a canal system for human use only emphasizes the interconnectedness of the social and ecological components in the Rideau Canal. Extensive investments have been made to preserve heritage components of the system via restoration of masonry and wooden construction materials (Narduzzo and Naudts 1994; Parks Canada 2012). See Fig. 2 for present-day and historical images of the Rideau Canal.

Historical governance and management

From 1856 to 1936, various jurisdictions were responsible for the Rideau Canal as a commercial transportation corridor. In 1925, the Rideau Canal was recognized by the (Canadian) federal

Fig. 2. Historical and present-day images of the Rideau Canal. Images on the left (A–C) illustrate modern day usage of the Rideau Canal; images on the right (D–F) illustrate historical use. (A) The multi-flight lockstation in Canada's capital city, Ottawa, represents the northern terminus of the Rideau Canal and consists of 8 locks in flight. (B) Edmonds Lockstation, located in Smiths Falls, Ontario, and most other Rideau Canal lockstations are still manually operated. Note the hand crank in the far left and right corners, which lockmasters use to open and close gates and fill and empty the lock chamber. Additionally, this lockstation marks the location of the recently discovered invasive round goby (*Neogobius melanostomus*). (C) Each winter, the National Capital Commission transforms the canal into the Rideau Canal Skateway. Known as the "world's largest skating rink", the Skateway extends for 7.8 km through downtown Ottawa and can bring in over one million visitors in a single season. (D) Colonel John By of the British Royal Engineers (on far right) led construction of the Rideau Canal. Here, he watches over building efforts in 1826. (E) This 1838 painting by Philip John Bainbrigge displays military use of the Rideau Canal as a company of Royal Marines passes through Jones Falls on their way to Kingston. (F) Image of a steamboat docked at the wharf at Entrance Bay, just outside of the Ottawa Lockstation, sketched between 1850 and 1855. Image credits: (A) Swanee Payne, distributed under a CC BY-SA 3.0 license; (B) Photo taken by Kate Neigel; (C) Saffron Blaze via http://www.mackenzie.co, available from Wikimedia Commons; (D) Charles William Jefferys, Imperial Oil Collection series, Library and Archives Canada, accession number 1972-26-795, C-073703; (E) Philip John Bainbrigge fonds, Library and Archives Canada, accession number 1983-47-44, C-011835; (F) John Henry Walker, available from the McCord Museum under access number M930.50.7.868.



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government as a National Historic Site of Canada (Charron et al. 1982). The federal agency Transport Canada held primary responsibility for managing the Rideau Canal from 1936 to 1972 (Charron et al. 1982). In 1972, Parks Canada (which was then part of the Department of Indian and Northern Affairs) became the primary stewards of the Rideau Canal, after which there was a marked shift towards recreational use (Charron et al. 1982). Parks Canada promoted the unique engineering of the Rideau Canal and its connectivity between Ottawa and Kingston as a tourism and recreational boating destination (Charron et al. 1982). The Canadian (federal) and Ontarian (provincial) governments signed an agreement in 1975 outlining a plan for development and land use, and established jurisdictional responsibilities (Charron et al. 1982). The federal government was to manage navigation, water flows, recreation, historical and cultural heritage, while responsibilities pertaining to natural resource management were divided among municipal, provincial, and federal organizations (Fig. 3). Below, in the "Current governance and management" section, we describe the different governing bodies managing the Rideau Canal and their responsibilities.

Ecological implications of construction and operations

Prior to construction, the area surrounding the Rideau Canal was composed of mixed woodland and wetland (Karst and Smol 2000), with original inhabitants in the area including Anishinaabe, Omàmiwinini (Algonquin), Haudenosaunee (Iroquoian Confederacy), and Huron–Wendat peoples (Native Land 2020). The lakes and rivers in the region were used as important traveling

Fig. 3. Horrendogram of the Rideau Canal governance structure. A "horrendogram" is a visual tool used to map and describe complex relationships. Here, we present the many organizations governing the biotic and abiotic elements of the Rideau Canal. The Rideau Canal is governed by six different "governing bodies": (1) the Parks Canada Agency (a federal Canadian organization), (2) other federal departments (Transport Canada (TC), Environment and Climate Change Canada (ECCC), the Canadian Council of Ministers of the Environment (CCME), Fisheries and Oceans Canada (DFO), the Impact Assessment Agency of Canada, and the Canadian Food Inspection Agency (CFIA)), (3) provincial groups (the Ministry of Environment, Conservation, and Parks (MOECP), the Ontario Ministry of Natural Resources and Forestry (MNR), Public Health Units, the Ministry of Heritage, Sport, Tourism, and Culture Industries (MHSTCI), the Ministry of Agriculture, Food, and Rural Affairs (OMAFRA), and the Ontario Provincial Police (OPP)), (4) Conservation Authorities (the Rideau Valley Conservation Authority (RVCA) and the Cataraqui Region Conservation Authority (CC)), (5) municipalities (including the Municipal Engineers Association (MEA), and often working with provincial groups like OMAFRA, MOECP, the Ministry of Municipal Affairs and Housing (MMAH), and the Ministry of Health and Long-Term Care (MOHLTC)), and (6) First Nations. The different organization(s) that manage the same element under each governing body is written in white font inside of the ring. This horrendogram is meant to visually describe the six governing bodies and associated organizations regulating different elements of the system, whether legally mandated to or not. Each circular ring represents a biotic or abiotic element of the Rideau Canal. Elements have been color-coded to clarify themes: blue indicates Management of Waters (Water Management, Hydroelectricity, Navigation, Riverbed Administration), red indicates Wildlife Management (Fish Habitat & Sanctuaries, Aquatic Vegetation Management, Species at Risk, Invasive Species), yellow indicates Outreach (Engagement & Consultation, Tourism & Recreation, Environmental Education), purple indicates Fisheries (Recreational Fisheries, Commercial Fisheries), teal indicates Law Enforcement & Safety, gray indicates Reserve Lands, and green indicates Impact Assessments (Environmental Assessment, Land Use Planning). Dotted lines do not indicate that governing body manages that element; it is to simply make clear the continued path of the elements' ring. See Supplementary Table S1[1] for a detailed list of each figure element, governing bodies, organizations, legislation and documents, and the actions and (or) purpose of each governing organization. *The CCME is an intergovernmental organization in Canada with members from the federal, provincial, and territorial governments. **OMAFRA is a provincial group; however, municipalities work with OMAFRA for permitting.

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and trading routes by Indigenous peoples, and construction of the Rideau Canal had a significant impact on their unique relationship with the land by disrupting these routes. The initial expansion of European colonization in the 1780s was accompanied by ecosystem alteration, including the construction of small dams and mill ponds (Karst and Smol 2000). Construction of the Rideau Canal incurred profound changes to the local environment. System-wide flooding is clearly delineated in sedimentary records via changes in sediment physical characteristics (Sonnenburg et al. 2009), as well as changes in aquatic organism and pollen assemblages (Karst and Smol 2000; Forrest et al. 2002). Prior to construction of the Rideau Canal, the "Rideau Route" existed across three watersheds: Rideau River, Gananoque River, and Cataraqui River. The latter two — the Gananoque and Cataraqui — were heavily altered, transforming a delta-like wetland into a constructed river, and forming a new connection between the upper (Rideau) and lower (Cataraqui) watershed (see Watson 2019). Additionally, the construction of dams and mills further fragmented the Rideau and Cataraqui rivers, creating barriers to passage and increasing the possibility of blade strike for migratory species (e.g., American eel (*Anguilla rostrata*), which have not been observed in the Rideau Canal since 2000; D.A. Algera, K. Neigel, K. Kosziwka, A. Abrams, D. Glassman, J. Bennett, S. Cooke, and N. Lapointe, unpublished data). Several lakes were created (e.g., Colonel By Lake) or greatly expanded (e.g., Bobs Lake, Opinicon Lake) during construction. The magnitude of ecological change appears to have differed across lakes, with biological indicators in deeper lakes, like Big Rideau Lake, suggesting less change compared to shallower lakes, like Lower Rideau Lake (Forrest et al. 2002). Indicators of terrestrial change suggest strong local human impacts: pine (presumably white pine, *Pinus strobus*) pollen diminished in the system during the construction period, while ragweed (*Ambrosia*), an indicator of open land, greatly increased (Karst and Smol 2000). Post-construction sedimentary records suggest gradual increases in nutrients, corresponding with increased housing development in the region during the early 20th century (Forrest et al. 2002), while terrestrial indicators suggest increased growth of secondary forest (Karst and Smol 2000).

Canal systems worldwide are widely recognized as conduits for invasive species (Kim and Mandrak 2016; Lin et al. 2020), and the Rideau Canal is no exception (see "Invasive species" section under "Threats and issues"). Key invasive species include Eurasian watermilfoil (*Myriophyllum spicatum*), which was first observed in the Great Lakes in the 1960s and has spread rapidly through connected waterways (Borrowman et al. 2014). Zebra mussels (*Dreissena polymorpha*) have also expanded rapidly, colonizing most of the Rideau Canal by 2015 (Martel and Madill 2018). More recently, the round goby (*Neogobius melanostomus*) was discovered to have colonized portions of the Rideau Canal, having first been observed in the system in 2019, and are now dispersing rapidly (Fig. 2B; J.N. Bergman, personal observations; McIntosh Perry Consulting Engineers Ltd. 2019). Connecting the watersheds facilitated new corridors and habitats, which results not only in new invasions, but also encourages biotic homogenization (i.e., the replacement of local biotas with non-indigenous species, resulting in increased genetic, taxonomic, and (or) functional similarities over time across regions; McKinney and Lockwood 1999; Olden and Rooney 2006). Biotic homogenization is not unique to the Rideau Canal (Rahel 2007); this ecological concept impacts canal systems worldwide including but not limited to the Nicaragua Canal (Nicaragua; Härer et al. 2017), the Chicago Sanitary and Shipping Canal (United States; Kolar and Lodge 2000), the Suez Canal (Egypt; Galil 2000), and the Rhine–Main–Danube Canal (Europe; Leuven et al. 2009). Herein lies the ecological paradox of artificial waterways; they provide a novel connection between previously separated ecoregions or watersheds, therefore offering new (and potentially more suitable) habitat for native species, yet they also facilitate the introduction of non-native species and exotic pathogens (Leuven et al. 2009; Rahel 2013; Lin et al. 2020). In the Rideau Canal, the level of ecological and landscape connectedness is unknown and understudied, making successful conservation actions difficult to develop and apply.

The Rideau Canal today

Tourism and use patterns

The primary use patterns and associated management of the Rideau Canal changed over time from defense and development to recreational activities and heritage preservation (Parks Canada 2017*a*), similar to many historic canals around the world (Lin et al. 2020). Beyond today's management of navigation and water levels along the entire corridor, the Rideau Canal is used for

[1]Supplementary data are available with the article at https://doi.org/10.1139/er-2021-0026.

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recreation by local residents and tourists. Parks Canada estimates that more than one million people visit the lockstations annually, while another 1.4 million people visit Ottawa in the winter to recreate on the Rideau Canal Skateway (which is promoted as the largest outdoor skating rink in the world; Fig. 2C) each winter (Parks Canada 2005). Common activities on the Rideau Canal include both nonmotorized (e.g., canoe, kayak, stand-up paddleboard, windsurfing, sailboats) and motorized vessel use (e.g., fishing boats, water ski and wakeboard boats, seadoos), and land-based activities along the shores like hiking (e.g., Rideau Trail and Cataraqui Trail), picnicking, camping, swimming, fishing, and wildlife viewing (Donohoe 2012). There are several resorts and fishing camps along the Rideau Canal, as well as housing developments. Not only does the history and culture of the Rideau Canal attract visitors, but the natural landscape and environmental features do as well. This contributes to the social–ecological nature of a system whose marketing successes rely not only on local partnerships, but also on sustaining a healthy freshwater ecosystem (Donohoe 2012).

In 2005, an economic analysis revealed that the Rideau Canal itself contributes more than $24 million to Canada's national GDP and sustains over 600 full-time jobs (Parks Canada 2005).

One method of quantifying and monitoring canal use is through the number of boats locked on a daily and annual basis. In 2019, there were 61 145 total vessel passages through locks; in 2020, only 44 141 vessel passages occurred likely as a result of COVID-19 restrictions that decreased tourism (see http://www.rideau-info.com/canal/statistics.html). Nevertheless, lockages alone do not provide a full picture of use or boating pressures facing the Rideau Canal given that many reaches can be accessed by boat ramps (i.e., lockages not required). Ottawa's population in 2021 is estimated at 1.4 million people and is expected to continue growing (World Population Review 2021), which will presumably lead to increases in use and urban development pressures in the watershed. Investigating demographic changes will be important to target the right people with policies and programs. While tourism activities may be economically profitable, and in some ways socially desirable, they can have negative or positive environmental impacts depending on how they are organized. There is a need to better understand the various use patterns, tourism priorities, and stakeholder perspectives on these patterns and priorities to balance social and ecological needs in the system. Surveying the public and conducting interviews could help better understand the diversity of interests and values among stakeholders like community groups, businesses, and environmental organizations.

Current governance and management

Water resource management is recognized globally as challenging, especially when governance regimes are not cooperative or collaborative, and most notably in the context of urban waterways that have ecological importance and are also sources of human welfare (Naustdalslid 2015; Chikozho and Mapedza 2017; Cooper et al. 2017; Muneepeerakul and Anderies 2017; Schweizer 2017; Kattel et al. 2021). Managers of the Rideau Canal (and other Ontario waterways) are tasked with water management, navigation, and the maintenance of aging infrastructure, with development and construction on a mix of private and public properties. They must additionally consider energy generation (hydropower), fisheries, water quality, and tourism and economic activities while ensuring the protection of cultural, historical, and environmental heritage. Governance of the Rideau Canal is complex because it encompasses not only the actions of different levels of government, but also other actors like community groups, nongovernmental organizations, and businesses (Lemos and Agrawal 2006) (Fig. 3). Parks Canada has ownership and jurisdiction over all in-water (i.e., the bed of the Rideau Canal including its lakes and rivers) and shoreline works built in, on, or over the system (Parks Canada 2017*b*), while adjacent lands and the watersheds are privately owned or under other jurisdictions like municipalities or the provincial government. The Rideau Canal spans 13 municipalities and counties, and two watersheds (the Cataraqui River watershed and the Rideau River watershed), with their respective Conservation Authorities (the Cataraqui Conservation Authority (CC) and the Rideau Valley Conservation Authority (RVCA)), and is regulated by a variety of legislative acts, regulations, and policies from multiple provincial and federal authorities. As such, the governance structure of the Rideau Canal can be described as "patchwork", as it is complex and at times unclear, characterized by overlapping jurisdictions and coupled with many stakeholders that may have competing interests (Van Tatenhove 2013). We outline the various governing bodies, associated management organizations, relevant legislation, and tasks of each governing body in Fig. 3 and in the online Supplementary material, Table S1[1]. Similar governance circumstances (i.e., jurisdictional fragmentation and multi-layered governance) can be found in other historic canals, such as the Grand Canal in China (Wang 2012).

Governance of the waterway also includes several First Nations. Parks Canada engages with the Algonquins of Ontario, the Haudenoshaune (Mohawks of Bay of Quinte, and the Mohawk Council of Akwesasne), Alderville First Nation, and the Williams Treaties First Nations Signatories, whose territories intersects with the Rideau Canal. Parks Canada has stated its commitment to growing their relationship with Indigenous communities and recognition of the significant pressures that communities may have due to limited resources and external pressures. Engagement and consultation activities undertaken by Parks Canada with these First Nation groups includes management planning, advisory committees, project input, and operational interactions (see https://www.pc.gc.ca/en/agence-agency/aa-ia; Fig. 3).

As the primary stewards of the waterway, Parks Canada also engages with stakeholders at different levels ranging from full and occasional engagement to "one-way" information-sharing. The Rideau Canal National Historic Site Management Plan produced by Parks Canada in 2005 was due to be updated in 2015; it is currently being reviewed in a multi-year process which includes nonmandated engagements with key stakeholders and mandated (i.e., required by law) consultations with the public and Indigenous rights-holders. The new plan aims to establish a vision for the waterway with clear, measurable targets that would facilitate progress-tracking and keep the agency accountable. Parks Canada operates under the Parks Canada Agency Act and Historic Canals Regulations whereby their main management focus is to maintain the commemorative integrity of the Rideau Canal and manage visitor use and tourism — this focus aligns with some stakeholders, while others have different priorities. For example, the town of Smiths Falls embraces tourism and there are partnerships with "Le Boat", a cruising company that arrived in the town in 2018. Because of fragmented and multi-layered governance, the Rideau Canal is difficult to manage in a unified way, with consequences for both environmental governance and ecological health (Bakker and Cook 2011). We describe this situation, which can undermine natural resource management of the Rideau Canal, as a social–ecological mismatch between (1) the connected ecosystem and watershed boundaries and (2) the fragmented social–political structure that governs the system (Sayles 2018).

Research on the various perspectives and interests of stakeholders involved in management is necessary to better understand this complex social–ecological system and improve governance and management (see examples of historic canal management in the Netherlands (Hijdra et al. 2014) and Spain (Llausàs et al. 2020)). Considering stakeholders' passion and enthusiasm for the Rideau Canal, and their involvement in community science (see section that follows: "Case study — lake associations"), research on how to best engage the plurality of actors involved and mobilize their knowledge about the system in decision-making and policy processes is crucial. Research findings indicate that stakeholders want more opportunities to participate in governance and inform environmental policy (Mistry 2020). Upcoming research should help identify opportunities to improve governance through social–ecological alignment that allows for holistic management of the system.

Case study — lake associations

Volunteer residents and cottage owners around the Rideau Canal unite through their love of the water to create lake associations. These local groups play various roles as stewards in communities along the waterway by educating residents through newsletters and conferences, participating in community science, monitoring the state of their lakes, contributing to recreational programming, and promoting environmental awareness (Rees 2014). Lake associations also foster relationships among lake residents, users, and partners. They work with each other as well as other community groups, scientists, regional groups (e.g., Federation of Ontario Cottagers' Associations), and governmental entities like municipalities, Parks Canada, and Conservation Authorities. While lake associations are well placed to support and participate in ecological research, more could be known

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about their role in communities and collaborative governance initiatives.

Biodiversity in the Rideau Canal

Despite comprising only <1% of the water on Earth, freshwater ecosystems host remarkable biodiversity. A global inventory revealed that freshwater ecosystems hold approximately 10% of Earth's described species, including one-third of all vertebrates (Balian et al. 2007; Strayer and Dudgeon 2010). The Rideau Canal is a biodiverse freshwater system, and has been described as having one of the most diverse fish assemblages (107 documented fish species; Coad 2011) in Canada (Poulin 2001; Parks Canada 2005). Although local fish communities in most regions are characterized by warm-water species (e.g., pumpkinseed (*Lepomis gibbosus*), bluegill (*Lepomis macrochirus*), largemouth bass (*Micropterus salmoides*); Walker et al. 2010), the canal system is also home to cool-water (e.g., smallmouth bass (*Micropterus dolomieu*), northern pike (*Esox lucius*)) and cold-water (e.g., lake trout (*Salvelinus namaycush*)) species (thermal guild assignment as per Gertzen et al. (2017)). The Rideau Canal also supports one of the few wild urban muskellunge (*Esox masquinongy*) fisheries in North America (Gillis et al. 2010), as well as species at risk across several taxa (e.g., bridle shiner (*Notropis bifrenatus*) (special concern); eastern milksnake (*Lampropeltis triangulum*) (special concern), least bittern (*Ixobrychus exilis*) (threatened); COSEWIC 2020; see "Species at risk" section). Similarly, high biodiversity has been noted in other canal systems (Lin et al. 2020). For example, Dorotovičová (2013) found canals in Slovakia to be macrophyte biodiversity hotspots, and Smith et al. (2004) discovered that the Panama Canal, which connected isolated freshwater communities in Pacific and Caribbean watersheds, resulted in a local increase in freshwater fish species richness with no species extinctions.

In 2001, the Canadian Museum of Nature partnered with government agencies, educational institutions, and community groups to conduct a three-year multidisciplinary study, the Rideau River Biodiversity Project, to evaluate biodiversity in the Rideau River (Poulin 2001). Although the project solely examined the Rideau River (the northern 100 km portion of the Rideau Canal), researchers identified close to 600 species, including the discovery of several species previously unknown to inhabit the Rideau Canal (e.g., freshwater drum (*Aplodinotus grunniens*); Phelps et al. 2000). Their results illustrate a high diversity across taxonomic groups: 314 phytoplankton species, 59 aquatic plant species, nine mussel species, 128 invertebrate species, 35 fish species, 19 amphibian and reptile species, and 20 waterfowl species. It should, however, be noted that several of the species identified in the Rideau River Biodiversity Project are considered invasive (see "Invasive species" section). This project is an example of a successful collaborative initiative that could guide future efforts in the Rideau Canal, as it brought together various social actors to attend to ecological components of the system.

Threats and issues

User conflicts

Conflict can be common in social–ecological systems like historic canals, and often arises because of the various interests and users (Wang 2012; Lin et al. 2020; Llausàs et al. 2020). Conflicts are magnified with increasing numbers of users, and when users become more specialized and polarized in their specific outdoor pursuits (Jones 1996). In some reaches of the Rideau Canal, conflict arises in periods of high use during which the activities of some groups impede the activities or enjoyment of others (Gramann and Burdge 1981; see "Case study — bass fishing tournaments"). These issues can be magnified when some users are also landowners (e.g., cottagers), who may feel that their property rights outweigh the access rights of occasional users (e.g., day visitors). Conflict can also occur within groups. For example, research has shown that recreational anglers are a heterogeneous group and that there is often more conflict within that sector than between it and other sectors (Arlinghaus 2005). Differences in environmental values and individual behaviours among recreational fishers can lead to conflict (Arlinghaus 2005). Such conflicts can be mitigated by increasing opportunities for shared understanding via communication, mediated by government or independent parties (Graefe and Thapa 2004; Bruckmeier 2005). Further research on the environmental values and governance expectations of stakeholders could help inform the design of communication mechanisms and help determine common values and objectives among users.

Case study — bass fishing tournaments

Big Rideau is the largest lake within the Rideau Canal and is among the most heavily fished water bodies in eastern Ontario (OMNRF 2020). The OMNRF, a provincial government agency, sets fishing regulations and manages fisheries (excluding species at risk) for the Rideau Canal. Bass fishing tournaments occur regularly throughout the open fishing season and sometimes multiple events take place on the same day. Tournaments tend to start and finish within close proximity to publicly accessible boat launches on the Rideau Canal. Shared space and resources associated with bass fishing tournaments (e.g., congestion at boat launches, large-scale fish displacement, noise, speed of bass boats), as well as the conspicuous nature of these events, fuels intergroup conflict that persists today (Kerr and Kamke 2003). Conflict has existed for decades (Schramm et al. 1991); however, there remains a need to better understand polarizing opinions. Research is required to examine user perspectives of bass populations and management in Big Rideau Lake. This information would be beneficial to strengthening consensus among user groups and thus diffuse intergroup conflict (Nguyen et al. 2016).

Aquatic pollution

Managing pollution, specifically from nonpoint sources, in freshwater systems is a "wicked problem" (Rittel and Webber 1973) that threatens water quality and security, ecosystem health and biodiversity, and consequently effects human livelihoods and wellbeing ranging from local to global scales (Patterson et al. 2013). Poor water quality in canals is a consistent theme worldwide and has been documented in New York canal systems (includes 12 major canals; Daniels 2001) and the Everglades canal system in the United States (Wan and Li 2018), the Mak Khaeng canal in Thailand (Wongaree 2019), the Cai Sao canal in Vietnam (Lan and Long 2011), the Taladanda Canal in India (Prusty and Biswal 2020), and the Kennet and Avon Canal in England (Neal et al. 2006), to name a few. In the Rideau Canal, water quality is largely impacted by chemical pollutants (Hamilton et al. 2011) and falls under the jurisdiction of municipal, provincial, and federal levels of government (Fig. 3; Charron et al. 1982). Chemical pollution is most often the result of anthropogenic factors like wastewater inflow and surface runoff from agricultural and urban land, as well as older infrastructure and leaky septic systems (Forrest et al. 2002; Mistry et al. 2021). Water quality in the Rideau Canal varies spatially and is closely monitored by municipalities, public health units, lake associations, citizen science groups, Conservation Authorities, the Ontario Ministry of the Environment, Conservation, and Parks (MOECP), and Parks Canada, all who use a combination of biological and chemical indicators to monitor water quality and ensure the safety of its users (Fig. 3 and Supplementary Table S1[1]; see Acknowledgements section for list of contributors). The example of water quality showcases the many overlapping jurisdictions that make social–ecological alignment a challenge in the Rideau Canal system. The Rideau Canal's two Conservation Authorities, the RVCA and CC, use the community composition of benthic invertebrates as biological indicators of water quality, following the Ontario Benthos Biomonitoring Network protocol, which identifies certain

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groups of benthic invertebrates as being pollutant-tolerant or pollutant-sensitive (Jones et al. 2006). Phosphorus concentrations are another key indicator of water quality, where high levels of phosphorus are indicative of poor water quality (Schindler 1974, 2006). Its presence in excess quantities causes the system to become eutrophic, leading to algal blooms (i.e., noticeable accruals of algae; Reynolds and Walsby 1975). Harmful algal blooms are often formed by cyanobacteria algae, which are potentially harmful to users as some strains can produce toxic substances (Anderson et al. 2002; see "Case study — cyanobacteria blooms"). The use of recreational waterways relies on both indicators of water quality and the user's perception of water quality (Steinwender et al. 2008; Artell et al. 2013). Users form perceptions of water quality based on physical characteristics like water clarity, smell, and general aesthetic of the waterfront which can be impacted by high nutrient levels and harmful algal blooms (Steinwender et al. 2008). In fact, residents and cottagers in the Cataraqui region (the lower portion of the Rideau Canal) have formed a group to better understand possible sources of nutrients and stakeholder perceptions of water quality (Mistry et al. 2021), and community science programs have been used to track the abundance of filamentous green algae. Maintaining good water quality in the Rideau Canal is a win–win situation that encourages tourism and economic activity in the region, while simultaneously supporting the health of the ecosystem (Smith et al. 2006). Further research on how to incorporate the results of community efforts in environmental management could help support a more collaborative form of governance.

Case study — cyanobacteria blooms

Cyanobacteria (also known as blue-green algae) are found naturally in all lakes and rivers (Backer et al. 2015). When conditions are favourable for these algae, they can form nuisance or harmful algal blooms (Nwankwegu et al. 2019). Cyanobacteria blooms are of particular concern as some strains produce cyanotoxins that can be harmful, or even fatal, to humans and other animals. Within the Rideau Canal, cyanobacteria blooms can occur throughout most of the system if conditions are favourable, though blooms are most common in the southern sector of the waterway where historical wetlands were flooded to create lakes during canal construction (Karst and Smol 2000) and phosphorus concentrations are consistently high (>35 μg/L). Research is required to determine what historical water quality conditions were in these sections of the Rideau Canal to set realistic targets for water quality and to determine whether management actions, like increasing water flow, can reduce cyanobacteria blooms. Setting reasonable expectations and actions may help ease social–ecological tensions brought on by blooms that hinder human activities like swimming. Given that the lakes within the Rideau Canal are also experiencing climatic warming (i.e., "longer summers"), the threat of more frequent and intense algal blooms has been heightened (Smol 2019). Collectively, the various organizations independently managing water quality in different portions of the system will need to work together to address and reduce point and non-point sources of pollutants (Fig. 3; see Supplementary Table S1[1] for list of managers).

Shoreline development

In historic canals close to human settlements, and that provide rich recreational opportunities, there is a social–ecological tension among shoreline development, preservation of commemorative integrity, and conservation of local biodiversity and ecological systems (e.g., the case of Grand Canal, China; Wang 2012). This is particularly the case in the Rideau Canal where Parks Canada has a suite of regulatory tools for guiding in-water and shoreline works; many factors are weighed when making decisions such as respecting the designation of the Rideau Canal as a National Historic Site, protecting heritage landscapes, minimizing environmental impacts, facilitating the permitting process, and providing clear coordinated guidelines, among others. These tools are meant to work in conjunction with land-use planning guidelines and permits from Conservation Authorities and municipalities that guide riparian and upland development. In rural areas, most development is from waterfront landowners that are usually seasonal users (e.g., cottagers). Typical waterfront development includes docks, boathouses, erosion controls, and aquatic vegetation management. Most development along shorelines in urban areas is historical, but there are several redevelopment projects and other changes in waterfront infrastructure that can have negative social–ecological impacts. Issues with shoreline development range from the aesthetic value and interest in maintaining historic character, through to concerns about freshwater biodiversity and ecosystem health. Parks Canada works closely with landowners and other development proponents to identify development practices that are most consistent with their regulatory framework and guiding principles (e.g., using natural materials, minimizing use of concrete and other hardened structures). Other agencies (especially Conservation Authorities) and organizations (e.g., Love Your Lakes Program co-led by Watersheds Canada and the Canadian Wildlife Federation) engage with landowners and other partners in their collective goal to protect and enhance shoreline habitats. Watersheds Canada also uses homeowners that make efforts to naturalize their shorelines as champions of stewardship to encourage others to follow suit. In this manner, they are addressing the social values that intersect with ecological health. Further research is required to better understand how alteration of shoreline habitats affects water quality and other ecosystems services and how to use this knowledge to address conflicting social and ecological values of aquatic vegetation (e.g., approaching shoreline property owners who view weeds as undesirable to inform them on this vegetation's ecological purposes; see "Case study — aquatic vegetation management").

Case study — aquatic vegetation management

Macrophytes provide refuge to many species of invertebrates and fishes, and offer a wide array of ecosystem services (Jeppesen et al. 2012; O'Hare et al. 2018). The Rideau Canal and its associated lakes, wetlands, and tributaries host a wide variety of macrophytes, including both native and invasive species. Despite the ecological importance of vegetation, large dense beds of macrophytes, particularly canopy-forming native and, in the case of the Rideau Canal, invasive species like *Myriophyllum spicatum*, can be a nuisance to human activities such as boating, swimming, and angling. Macrophytes are subsequently managed by a variety of methods (Madsen 2000). On the Rideau Canal, Parks Canada directly removes macrophyte biomass by mechanical harvest when and where it impedes navigation, and indirectly by issuing permits allowing property owners to remove macrophytes over a 10 m × 30 m area adjacent to their shoreline (Parks Canada 2017*c*). Macrophytes may only be removed with a permit, following guidelines set out by Parks Canada (2017*c*) and in accordance with the Historic Canals Regulations (Minister of Justice 2017), as well as the Canadian Fisheries Act (1985). It is important that landowners and users of the waterway comprehend the positive role that macrophytes play in aquatic ecosystems so that they do not simply view them as weeds to be removed. It is critical we determine how shoreline alteration may be impacting water quality and local fauna, and provide outreach and educational programs for locals and stakeholders to share this knowledge and its social–ecological implications.

Water management

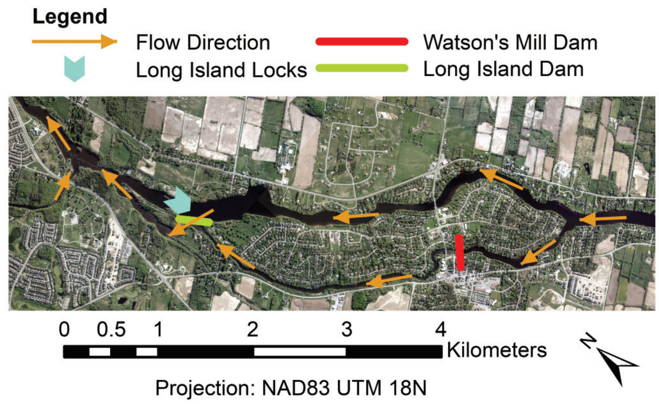
Managing water levels and flows to fulfil the requirements of multiple objectives is a challenge for canals and regulated rivers. Parks Canada manages and monitors water level and flow operations throughout the Rideau Canal to mitigate flooding, meet navigation requirements, fulfil fish and wildlife habitat objectives set out by provincial and federal regulations, and make various recreational activities possible (Parks Canada 2020*a*). They work closely with Conservation Authorities and the OMNRF (Parks Canada 2020*a*) to balance these interconnected social and ecological needs. There are numerous regulated and unregulated channels and reservoirs that feed into the Rideau Canal, making water management challenging (e.g., the Tay River regulated by Bobs Lake Dam and Kemptville Creek regulated by Oxford Mills Dam; unregulated inflows including but not limited to the Jock River, Cranberry Creek, and Mosquito Creek).

Parks Canada water managers specify dam operations daily based on monitored water levels and river flow (both in the Rideau Canal and its tributaries), temperature and precipitation, and future weather forecasts (Parks Canada 2020*a*). To aid in operations, water level measurements were recorded manually by lock masters; however, in the last five years automated gauges, including 28 real-time water level, four real-time discharge, seven rain, five temperature, and four snow gauges, were set in place with manual measurements ongoing at four lock stations and three snow depth areas. In addition, there are Water Survey of Canada water level and flow gauges located near Ottawa and in various tributaries, maintained by federal agency Environment and Climate Change Canada (Water Survey of Canada 2020).

Weir and gate elevations are set at dams, and water allowances are regulated by working with hydroelectric proponents at the Rideau Falls, Merrickville, Jones Falls, Brewer's Mills, Washburn, and Kingston Mills generating stations (Ontario Power Generation Inc 2020; Portage Power 2020). Drawdown (the lowering of water levels throughout the system) is completed each fall to create volume for precipitation and snow-melt run-off (spring freshet) and to mitigate flooding with minimal impact to fish spawning. Although efforts are made to minimally effect fish spawning in the spring, it is unclear how drawdown procedures impact overwintering. For example, in portions of the Rideau River, which is generally 5 m deep, with max depths of 10 m (Navionics 2020), water levels are dropped by ∼3 m in the late fall prior to winter, potentially reducing available overwintering habitat for species by a significant amount. In addition to "rule curves" (see http://www.rideau-info.com/canal/water-rulecurves.html), water management in the northern and central sector is supported by an extensive 1D hydrologic and hydraulic model created by the RVCA, extending from Upper Rideau Lake to the City of Ottawa (Ahmed 2010).

Water level and flow operations are determined on a system-wide basis, as operation of hydraulic structures can affect the upstream, downstream, and adjacent water levels, flows, and velocities in the Rideau Canal (Parks Canada 2020*b*). Currently, water level management attends to both social (e.g., navigation, historic flour grinding demonstrations, Ottawa's winter Skateway — Fig. 2C) and environmental (e.g., climate) pressures in the system. It should be noted however that Parks Canada has legal mandates to prioritize public safety, navigation requirements, and federally listed species at risk. Parks Canada must also comply with the federal Fisheries Act (regulated by Fisheries and Oceans Canada), which includes protecting fish and fish habitat, although Parks Canada itself is not a delegated authority under the act (V. Minelga, personal communication; see Fig. 3 and Supplementary Table S1[1]). To examine region- or site-specific research questions around freshwater connectivity from an ecological context, there is a need for hydraulic modelling at specific reaches to better understand the role of structures (locks and dams) on native and invasive fish movement and functional habitat, shoreline erosion and deposition, and flood levels and velocities. This ecological information coupled with information on human activities and values could provide useful scenarios to substantiate past and current water management strategies and understand the sustainability of the current and future ecosystem under climate change. Water management involves complex decision making, often with conflicting priorities; as such, combined social and ecological research (e.g., investigating fish interactions in and around lockstations) could support conservation actions and further inform the meeting of legislative requirements of Parks Canada.

Fig. 4. Complex flow split and confluence around Long Island, through the town of Manotick, Ontario, Canada. The flow arrows plotted resulted from velocities surveyed with an aDcp, and dam and lock locations are plotted from locations surveyed using RTK GPS. Orthoimagery provided by the City of Ottawa (2015).



Case study — understanding current water level management of separately controlled channels

Managing water levels in the Rideau Canal is extensive and difficult, particularly given that most structures are operated manually. In the town of Manotick, Ontario there is a complex flow split around an island creating two separately operated channels with dams at different downstream locations, orientations, and elevations (Fig. 4). The eastern channel is the primary navigation channel with a flight of locks, while the western channel is steeper and often has swift water conditions. Though a 1D hydraulic model exists for this reach, 1D models can have poor performance at flow splits and confluences due to the 2D (or 3D) velocities (Ghostine et al. 2012, 2013). In addition, calibration of roughness can be challenging without known calibration flow, velocity, and water level data in each channel prior to modelling (Knight et al. 2018). Due to the complexity of flow and dam operations in this region (i.e., Long Island), future multi-dimensional hydraulic modelling would be helpful for water managers to optimize water level and velocities through the reach, particularly under freshet conditions.

Species at risk

We are living amid a planetary wave of anthropogenically driven biodiversity loss: the sixth mass extinction (Ceballos et al. 2017). In respect to freshwater ecosystems, like those within the Rideau Canal, habitat destruction and connectivity loss (fragmentation) is a leading and persistent cause of the catastrophic declines in freshwater biodiversity (WWF 2018). Currently, the anthropogenic barriers (i.e., locks, dams) throughout the Rideau Canal appear to offer some level of connectivity to wildlife. Reports by anglers, boaters, and lockmasters of fishes and turtles in locks is common; however, to what extent animals are able to successfully move between reaches (i.e., the waterbodies separated by a lockstation) to potentially more suitable habitat is unknown. Interestingly, some canal systems can act as refuges for endangered species. For instance, Sousa et al. (2019) found that irrigation canals in Morocco supported a significantly higher

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density and condition of the critically endangered freshwater mussel *Pseudunio marocanus* compared to a natural river. The Rideau Canal, too, offers stable habitat to many at-risk species.

Canada has national legislation to protect species at risk and provide for their recovery (the federal Species at Risk Act), which generally applies to lands under federal government jurisdiction. If a species leaves federal land and enters provincial land, then species protection would fall under provincial species at risk legislation (i.e., Ontario's Endangered Species Act). Sixty species at risk are currently listed as being historically and (or) currently present in the Rideau Canal (many freshwater-dependent terrestrial species), across a range of taxa (protected information provided by Parks Canada). More importantly, several species at risk in the Rideau Canal are migratory (e.g., American eel (*Anguilla rostrata*), snapping turtle (*Chelydra serpentina*)); as the level of ecological and landscape connectedness is currently unknown in the Rideau Canal, it is difficult to develop and apply conservation actions to support their populations. Although management by Parks Canada of the Rideau Canal is not primarily focused on wildlife conservation, continued operation of the system has indeed allowed biodiversity to persist. Reviewing the many different species-specific recovery strategies and conservation actions for species at risk in the Rideau Canal is outside the scope of this article; however, Parks Canada is currently drafting a Multi-Species Action Plan for the canal to update current conservation actions and develop new ones that will be available online (V. Minelga, Parks Canada, personal communication).

Case study — turtles

Turtles are among the most threatened vertebrates worldwide (Lovich et al. 2018). The Rideau Canal is home to several at-risk turtle species, including the northern map turtle (*Graptemys geographica*), Blanding's turtle (*Emydoidea blandingii*), eastern musk turtle (*Sternotherus odoratus*), midland painted turtle (*Chrysemys picta*), snapping turtle (*Chelydra serpentina*), and spotted turtle (*Clemmys guttata*). It is unclear whether locks act as barriers to movement or migration of turtle species for feeding, reproduction, or overwintering. Although genetic assessments of turtles in the Trent-Severn Waterway (an Ontarian waterway similar to the Rideau Canal) revealed little evidence of connectivity loss (Bennett et al. 2010), the Rideau Canal is an older waterway for which no connectivity assessments have been conducted. The Rideau Canal's social–ecological nature entails several recreational and economic activities like boat-induced injuries, small-scale commercial fishing, and anthropogenic noise from watercraft and lock infrastructure that may be negatively impacting turtle populations; thus, it is important we determine ways to promote population connectivity and persistence. In addition to investigating how lock infrastructure and operations may be impacting turtle connectivity, collaborations can be fostered with local community groups to protect key habitat features (e.g., basking and nesting sites) and share information about turtle conservation.

Invasive species

In 2006, Dudgeon et al. (2006) identified "invasion by exotic species" as a leading cause of population declines and range reductions of freshwater organisms globally; since then, researchers have confirmed that the threat of invasive species has evolved and escalated (Reid et al. 2019; Tickner et al. 2020). Invasive species pose one of the greatest threats to the biotic integrity of freshwater ecosystems, with potentially adverse socioeconomic effects (Reid et al. 2019). The ecological impacts of invasive species range from behavioural shifts of native species, to restructuring of ood webs, to species extinctions (Gallardo et al. 2016), all of which negatively impact resource users. Additionally, the economic costs of managing invasive species are significant — estimated at $1.4 trillion in damages worldwide (Pimentel et al. 2001). With the continued construction of canals and regional and global trade intensifying connectivity, the potential for aquatic invasive species to expand their range and distributions has only increased (Panov et al. 2009).

The Rideau Canal hosts numerous invasive species across fish, invertebrate, and plant taxa. For example, the common carp (*Cyprinus carpio*), one of the world's most widespread and "worst" invasive fish species (Lowe et al. 2004), can be found throughout the system, and has caused economic, ecological, and social impacts on several continents (e.g., Australia and North America; Stuart et al. 2006; Kulhanek et al. 2011). The invasive aquatic plant Eurasian watermilfoil (*Myriophyllum spicatum*) has also proliferated throughout much of the system and can be a major hindrance to boat traffic in deeper regions of the waterway (e.g., navigation channel; Poulin 2001). Perhaps the most infamous invasive species found in the Rideau Canal is the zebra mussel (*Dreissena polymorpha*), which has incurred negative impacts both ecologically and economically (Martel and Madill 2018). The Welland Canal, a shipping channel that connects Lake Ontario and Lake Erie, has similarly facilitated biological invasions of sea lamprey (*Petromyzon marinus*) from Lake Ontario to the upper Great Lakes as well as other non-native species (Sullivan et al. 2003; Siefkes 2017). Anthropogenic waterways and canals with barriers (e.g., navigation locks, dams) can act as "invasion highways" and efficiently transport biological invaders (Leuven et al. 2009). Boaters visiting from other water systems can also facilitate invasive species transmission (e.g., zebra mussels can attach to the hulls or motors of boats and be transported to new waters; Timar 2008). If the variety of invasion routes and movement patterns of invasive species could be evaluated, the same barriers that may be enabling passage could instead be used to restrict movement and act as a complete barrier, minimizing population movement and (or) expansion. Research and modelling on connectivity, and how and when locks and dams can act as barriers or facilitate movement, would be required to help prevent the spread of invasive species and enhance native species movement. This research could help adjust lock and dam operations, and guide the development of effective education programs.

Case study — preparing for a potential future Asian carp invasion in the Rideau Canal

As a hydrological connection between Lake Ontario and the Ottawa River, the Rideau Canal faces potential biological invasions from both the Laurentian Great Lakes and the St. Lawrence River (Fig. 1). One group of invasive species of serious concern are Asian carps, including grass (*Ctenopharyngodon idella*), bighead (*Hypothalmichthys nobilis*), silver (*Hypothalmichthys molitrix*), and black (*Mylopharyngodon piceus*) carps, which have received extensive attention from both Canadian and American authorities throughout the Great Lakes basin because of their ability to negatively impact and modify native ecosystems and associated socioeconomic activities (Cudmore et al. 2012, 2017). Although the Rideau Canal's lockstations may hinder movement to some extent, Asian carps have been documented to successfully pass upstream through dams and lock chambers (Lubejko et al. 2017; Zielinski et al. 2018; Fritts et al. 2021). The Rideau Canal has not yet been identified as a system suitable for establishment (Mandrak et al. 2020; Heer et al. 2019, 2021), although there is indeed suitable habitat (e.g., wetlands, eutrophic lakes) present through the system. If Asian carps do enter the waterway via the Kingston Mills locks (Fig. 1), they could negatively influence the local ecosystem through competition, consumption of plankton and macrophytes, and alter turbidity and dissolved oxygen (Cudmore et al. 2012, 2017). To determine the capability of Asian carps invading the Rideau Canal, expert elicitation and system-specific mechanistic invasion models are needed, as currently there is a lack of empirical data for the system (Chenery et al. 2020). Conceptualizing

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the Rideau Canal as a social–ecological system could also help build resilience and adaptive capacity in the system (Folke et al. 2003). As a still-functioning historic heritage canal, any changes to infrastructure or operation scheme to reduce the risk of biological invasion must consider the mandates for other management objectives (e.g., maintaining aesthetic sceneries, conserving historic structures, protecting threatened species, providing recreational and economic functions). Future research that incorporates different social and ecological objectives, and examines the trade-offs among objectives, will be needed.

The future

As anthropogenic pressures in the Rideau Canal corridor continue to increase, we can expect more social–ecological disturbances (e.g., potential social conflicts, loss of habitat and biodiversity, toxic algal blooms, water management with aging infrastructure). These pressures may also be exacerbated by global trends like climate change and the sixth mass extinction, which increase uncertainty about natural phenomena and environmental variations like water levels, erosion, and invasive species (Woodward et al. 2010; Nichols et al. 2011; Ceballos et al. 2017). Other potential climate impacts could include warming waters, extreme weather events, and habitat transformation (Woodward et al. 2010; Nichols et al. 2011). As revealed by the case studies presented here, individual and collective human practices (e.g., bass tournaments, shoreline development, macrophyte removal) can reduce system resilience to these stressors. There are, however, opportunities for research and restoration actions, community science, and government coordination to increase resilience and promote positive environmental change in the Rideau Canal. Additionally, population growth and changing demographics along the Rideau Canal corridor could influence the diversity of interests and environmental values of stakeholders. For example, the generational gap between year-round residents, many of whom are retirees, and seasonal residents, often younger generations, could lead to tensions that should be investigated prior to additional conflict occurring. Finding a balance between preserving the natural environment and heritage character of the Rideau Canal with the recreation and leisure opportunities of various user groups is a challenging task for a fragmented governance regime.

The challenge of managing the Rideau Canal as a coupled social–ecological system

The Rideau Canal is best conceptualized as a coupled social–ecological system — humans and their activities influence system properties (e.g., invasive species, algal blooms, loss of biodiversity, etc.) — while the physical and ecological properties of the waterway provide a rich environment for human actors to engage with (e.g., for recreation, income, food), thus shaping behaviour and institutions. Using a transdisciplinary social–ecological approach (Angelstam et al. 2013), whereby experts from multiple disciplines (e.g., biology, engineering, social science) work together to understand and manage freshwater systems as a whole, or certain specific aspects like pollution or invasive species could be adopted to canals and waterways worldwide. For example, biological invasions (Ferreira-Rodríguez et al. 2019) are inherently and often explicitly social–ecological in nature, both directly and indirectly linked to human activities, and must be managed as such; developing strategies to manage either the humans or the animals, instead of both simultaneously as one unit, is illogical. In the Rideau Canal, managing invasive species will require knowledge on how and when organisms move (i.e., the ecological aspect) and how operations of infrastructure and the infrastructure itself influences movements (the social aspect); effective management actions will then need to be developed by canal managers, biologists, and hydraulic engineers. Canals are fundamentally anthropogenic ecosystems and accordingly should be managed as the complex social–ecological systems they are. With more than 60 000 km of canals with anthropogenic barriers worldwide (Revenga et al. 2000), and their implications in biodiversity reductions having a global reach, it is critical that managers shift from single disciplinary management to evidence-based, transdisciplinary governance.

A multitude of linkages and feedback loops exist in the Rideau Canal among specific resource systems and units (e.g., fish and turtle populations, habitat, water composition, macrophyte expansion), actors and governance systems (e.g., locals, decision-makers, community groups), and technologies (e.g., locks and dams, built canal sections) (McGinnis and Ostrom 2014). As a highly managed system, the Rideau Canal presents interesting and rare opportunities to influence management and address several social–ecological challenges; for instance, Parks Canada could manage barriers to promote or restrict movements of native or invasive species, respectively, or manipulate water levels to satisfy recreational activities and navigation while still offering critical habitats to fish and turtles for spawning and nesting, respectively. Social–ecological factors external to the Rideau Canal can also influence the system like the Ottawa River and the Laurentian Great Lakes, public attitudes towards climate change, and international recommendations for environmental policy. Such connectivity and complexity underline the need for reliable transdisciplinary environmental and social sciences (Perz 2019) about the state of the Rideau Canal's interdependent natural conditions and social dynamics. Transdisciplinary research can involve strategic collaboration among researchers from many disciplines, as well as stakeholders, members of the public, and Indigenous groups, so that various forms of knowledge can be considered to tackle the complex challenges of the Rideau Canal (Perz 2019). Here, we have included a team of authors with expertise across several disciplines, as well as several early-career researchers, to increase the diversity of perspectives represented and produce a meaningful, transdisciplinary review of the Rideau Canal as a social–ecological system.

As we noted previously, water systems are uniquely difficult to govern because of their geographic variability, large numbers of stakeholders, and the involvement of multiple levels of government with different jurisdictional authority, frequently leading to a social–ecological mismatch (Fig. 3; Sayles 2018). Successful governance of the Rideau Canal system in a time of social–ecological change will require governance innovations. Some of these innovations are "easy wins" that can be undertaken quickly with broad support — for instance, findings from interviews with Rideau Canal stakeholders indicated a strong desire for increased participation in decision-making and co-governance (Mistry 2020). This would require an extension and expansion of current stakeholder engagement and consultation practices, but models exist in other parts of Canada (e.g., Fraser River salmon fisheries in British Columbia) that could be adopted. Other innovations may, however, be more difficult to implement. For example, stakeholders have shown interest in the creation of a single regulatory board that could coordinate leadership at the various local, regional, Indigenous, provincial, and federal governing levels to consider cross-jurisdictional questions like engagement practices, development proposals, zoning issues, fishing regulations, and others (Mistry 2020). This holistic type of management is seen as more desirable than the current reality of fragmented authority in which proposals must be tabled to multiple authorities, and feedback or approvals from one authority (for instance, a municipality) may conflict with those offered by others. While the establishment and operation of such a coordinating body would be difficult for the Rideau Canal, examples do exist (e.g., the National Capital Commission in the Cities of Ottawa and Gatineau). Future research about collaborative governance opportunities, and specifically participatory processes, could also help support social–ecological resilience in the Rideau Canal while considering environmental justice (Moran et al. 2019).

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Needs and opportunities

The most immediate opportunity is to work towards building resilience in the Rideau Canal and formally acknowledging and managing it as a social–ecological system. Doing so means thinking about resilience in terms of adaptive co-governance (Berkes 2017), social systems, and the ecology of the system, as well as the ways in which those domains interact. Revisiting relationships among governmental and nongovernmental actors is essential to facilitate the development of adaptive and collaborative capacity. The history of the Rideau Canal, its contemporary complexities, and the threats and issues presented in this article can guide future research about the various bidirectional interactions between social and ecological components in the system. Additionally, if management of the system could be conducted successfully and cooperatively across the different governing bodies, it could serve as a model for other waterways within Canada and beyond.

There are opportunities to engage in philosophical discussions about modified ecosystems composed of historical built infrastructure within natural reaches, and how our conceptualizations of the "natural" and the "human-made" shape worldviews, behaviours, and social–ecological linkages (e.g., natural versus artificial water bodies; Clifford and Heffernan 2018). Considering which values (e.g., social, environmental) society wants to collectively sustain in the future will be necessary so that we can use appropriate strategies to protect those values. This rethinking of our conceptualizations of, and relationships with, the environment can help us shift from fragmentation and misalignment towards inclusion, coordination, and ecosystem health. Such processes must engage stake- and rights-holders, especially Indigenous peoples who have stewarded this land since time immemorial, in meaningful and sustained ways. There is an opportunity for greater collaboration with Indigenous nations whose traditional territory includes the Rideau Canal to inform transdisciplinary research.

There are also opportunities to address specific social–ecological issues through use of creative management and policy options. Opportunities exist for thinking about aquatic plant management beyond simply navigation and incorporating more ecological knowledge into plant management (both at the individual shoreline scale and harvesting scale) to enhance habitat for fish and threatened species. There is also much opportunity for continued work on improving water quality throughout the system by reducing nutrient loading into the waterway, especially in the middle (Rideau Lakes region) and southern (Cataraqui watershed) portions where lakes are prevalent and there are engaged stakeholders willing to change their behaviour. Located in the central region of the Rideau Canal, Newboro Lockstation represents the highest point of elevation (i.e., the "isthmus"; Fig. 1), and as such, ecosystems downstream in both the northern and southern directions would also benefit from reduced nutrients and associated harmful algal blooms. Many sections of the waterway have undergone transition from agricultural landscapes to urbanization, resulting in increased runoff and alterations to water chemistry and flows. As land-use change is expected to continue, it is essential we consider how these impacts can be mitigated. Determining the level of connectivity at both individual locks and across the Rideau Canal is vital to support native species migrations, and there is opportunity to use connectivity evidence to minimize invasive species dispersal as well. Finally, there are opportunities to mobilize existing efforts and programs (e.g., Love Your Lake program, lake associations, bass fishing tournaments) as starting points to collectively work toward common objectives.

Conclusion

Historic canals occur worldwide, and a common feature is that their history both constrains and defines current uses. This is exemplified in the Rideau Canal, a National Historic Site of Canada and UNESCO World Heritage Site. Here, the federal management agency and primary steward, Parks Canada, focuses on preserving the systems commemorative integrity while simultaneously creating contemporary recreational opportunities and considering certain aspects of ecosystem integrity. This creates an inherent tension, but also yields fascinating governance challenges, particularly when one considers that environmental change and other drivers of change can be synergistic and (or) dynamic. Though it is difficult to plan for the future when we do not precisely know what it holds, there is an opportunity for Parks Canada, stakeholders, and other jurisdictional management organizations to develop actionable plans to protect and restore biodiversity throughout the waterway. Engaging visitors and residents in community science efforts could serve as a stepping stone for social–ecological change while building meaningful relationships. Most importantly, the current governance structure must shift from "patchwork" governance that is punctuated by periods of consultation towards consistent, coordinated multi-scalar and multi-stakeholder governance. Parks Canada and the Ontario provincial government move on long and slow cycles (the 2010 consultation is still ongoing with a plan yet to be seen), whereas municipal governments and Conservation Authorities move at a faster pace. This mismatch does not always generate conflict, especially if it can be coordinated with appropriate communication. Further research on how we could envision this coordination would clarify confusion about the current governance regime and help identify a common goal to which actors can align their agendas. The social–cultural features of the Rideau Canal create a rich foundation for re-envisioning waterways of the future — waterways that respect and celebrate the past while simultaneously recognizing that the world is changing and our systems must benefit future users and the environment.

Acknowledgements

Funding for this work was provided by an NSERC Strategic Project Grant focused on the Rideau Canal Waterway. We thank the many different people who provided input regarding governing actions of different organizations and agencies on the Rideau Canal, including Peter McKenna, Malcolm Morris, and Karl Grenke of the Smiths Falls municipality; Christine Woods of the Township of South Frontenac; Joffre Côté of the Ontario Ministry of Natural Resources and Forestry; Jennifer Lamoureux of the Rideau Valley Conservation Authority; Holly Evans of the Cataraqui Conservation; and Colin Hoag, Anna Ciorap, and Susan Miller of the Parks Canada Agency. We also thank the heritage researcher and author Ken Watson for offering guidance and wisdom as a user of the Rideau Canal and for providing permissions to use his maps of the Rideau Canal as a template for Fig. 1. We appreciate the thoughtful input of two referees and the associate editor (Sapna Sharma).

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