Journal of Environmental Management 181 (2016) 312–325

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

To manage inland fisheries is to manage at the social-ecological watershed scale

Vivian M. Nguyen [a,*], Abigail J. Lynch [b], Nathan Young [c], Ian G. Cowx [d], T. Douglas Beard Jr. [b], William W. Taylor [e], Steven J. Cooke [a]

[a] Fish Ecology and Conservation Physiology Laboratory, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada
[b] U.S. Geological Survey National Climate Change and Wildlife Science Center, 12201 Sunrise Valley Drive, MS-400, Reston, VA 20192, USA
[c] Department of Sociology and Anthropology, University of Ottawa, 120 University Private, Ottawa, ON K1N 6N5, Canada
[d] Hull University, International Fisheries Institute, Hull HU6 7RX, United Kingdom
[e] Center for Systems Integration and Sustainability, Michigan State University, 1405 South Harrison Road, Suite 115 Manly Miles Building, East Lansing, MI 48823, USA

A R T I C L E I N F O

Article history:
Received 21 March 2016
Received in revised form
14 June 2016
Accepted 23 June 2016

Keywords:
Watershed
Coupled social-ecological systems
Human behaviour
Inland fisheries
Integrated water resource management

A B S T R A C T

Approaches to managing inland fisheries vary between systems and regions but are often based on large-scale marine fisheries principles and thus limited and outdated. Rarely do they adopt holistic approaches that consider the complex interplay among humans, fish, and the environment. We argue that there is an urgent need for a shift in inland fisheries management towards holistic and transdisciplinary approaches that embrace the principles of social-ecological systems at the watershed scale. The interconnectedness of inland fisheries with their associated watershed (biotic, abiotic, and humans) make them extremely complex and challenging to manage and protect. For this reason, the watershed is a logical management unit. To assist management at this scale, we propose a framework that integrates disparate concepts and management paradigms to facilitate inland fisheries management and sustainability. We contend that inland fisheries need to be managed as social-ecological watershed system (SEWS). The framework supports watershed-scale and transboundary governance to manage inland fisheries, and trans-disciplinary projects and teams to ensure relevant and applicable monitoring and research. We discuss concepts of social-ecological feedback and interactions of multiple stressors and factors within/between the social-ecological systems. Moreover, we emphasize that management, monitoring, and research on inland fisheries at the watershed scale are needed to ensure long-term sustainable and resilient fisheries.

Contents

* Corresponding author.
E-mail addresses: Vivian.m.n@gmail.com (V.M. Nguyen), ajlynch@usgs.gov (A.J. Lynch), Nathan.Young@uottawa.ca (N. Young), i.g.cowx@hull.ac.uk (I.G. Cowx), dbeard@usgs.gov (T.D. Beard), taylorw@msu.edu (W.W. Taylor), steven_cooke@carleton.ca (S.J. Cooke).

http://dx.doi.org/10.1016/j.jenvman.2016.06.045
0301-4797/

1. Introduction

Inland fish and fisheries serve important nutritional, economic, cultural, and recreational roles in human society (reviewed in Lynch et al., 2016). Found in freshwater above mean tide levels, inland fish are a major source of protein, essential fats and oils, and micronutrients for hundreds of millions of people worldwide with potential to improve human health and combat malnutrition (Roos et al., 2007; Youn et al., 2014). More than 60 million people in developing countries rely on inland fisheries as a source of livelihood and as a ‘safety net’ for food security and income (Welcomme et al., 2010; FAO, 2014). In the lower Mekong basin alone, inland fisheries provide roughly 60% of the animal protein intake of inhabitants and economic benefits of about US$17 billion (Nam et al., 2016). Inland fisheries also provide cultural and recreational services that contribute to human health, social benefits, and well-being (Holmlund and Hammer, 1999; Lynch et al., 2016).

While fishing is often the largest anthropogenic influence on marine fisheries (e.g., Jackson et al., 2001; Mullon et al., 2005), inland fisheries are often impacted by other societal needs and uses of inland water resources, particularly competition for freshwater for agricultural production, municipal use consumption, waste disposal, and power generation (Cooke et al., 2014). Freshwater ecosystems and their intimate connection with their watersheds make them receptors of a number of stressors and threats – in other words, the “stream is a reflection of its valley” (Hynes, 1975). The vulnerability of freshwaters to numerous, often multiple, threats, including extraction, damming, habitat degradation, pollution, and nutrient enrichment (Malmqvist and Rundle, 2002; Dudgeon et al., 2006) increases pressures on the productivity and sustainability of the ecosystem services they deliver. This in turn puts inland fish and fisheries at risk of population declines, biodiversity loss, and extinction (e.g., Maitland, 1995; Duncan and Lockwood, 2001).

Inland fisheries do not often receive the same degree of attention relative to other sectors of freshwater and related watershed usage (e.g., hydropower, agriculture, and transportation; Cooke et al., 2013), perhaps because inland fisheries assessment data is so poor that it is often disregarded. Inland fisheries have generally been a low priority for researchers and regulators, putting the livelihoods and food security of many communities at risk (Beard et al., 2011; Cooke et al., 2016). However, there is increasing acknowledgement among scientists and managers that to manage inland fish and fisheries is to manage for the broader environment (Welcomme et al., 2010; Cooke et al., 2016). It is argued that we must consider the activities from the entire watershed because whatever happens in a watershed will directly and indirectly affect the quality and quantity of water, productivity of resident biota, including fishes, and ultimately people (Baron et al., 2002; Collares-Pereira and Cowx, 2004).

The challenge of conserving fish populations and communities, and maintaining fisheries production is enormous, especially when considering the numerous freshwater users and system stressors (e.g. Dudgeon et al., 2006; Vörösmarty et al., 2010). This paper proposes a framework that unites disparate concepts from the literature with the goal of reorienting how we, as inland fisheries researchers and managers, think about the complexity of inland fisheries, and by extension how they are researched and managed. To do this, we contend that inland fisheries needs to be evaluated and managed as a *social-ecological watershed system* to inform effective fisheries management and maintain watershed resilience.

2. Managing inland fisheries as a social-ecological watershed system (SEWS)

While inland fishes do not recognize socio-political jurisdictions, they do respect watershed boundaries. ‘Watershed’ (also commonly referred to as catchment or drainage basin) refers to the geographic boundary within which rainfall drains into a particular river, stream, or waterbody (Borre et al., 2001). Whatever happens within these watershed boundaries influences these water bodies; thus, the watershed is an appropriate management unit for inland fisheries as it encompasses the ecological barriers to the system, the terrestrial influences, and resource gradients, particularly for lotic systems (Hynes, 1975; Vannote et al., 1980; Ward, 1989). Watersheds are also complex social ecological systems (SES), which are systems that illustrate the interplay between humans and natural environments and the powerful reciprocal feedbacks between them (Berkes and Ross, 2013). Therefore, with the intimate connection of inland waters to their watershed, management of inland fisheries ought to be viewed as a SES at a watershed scale (Baron et al., 2002). We thus argue that inland waters and the services they provide are nested in social-ecological watershed systems (SEWS, Fig. 1); a holistic and transdisciplinary framework that integrates watershed and SES principles (see Ostrom, 2009). With that in mind, inland fisheries research and management ought to be approached at an SEWS scale. Doing so requires understanding the interactions among human and ecological components of watersheds, how both the watershed and its inhabitants respond to changes, what trade-offs exist between social and ecological needs (or decisions), and how to optimize those trade-offs.

Although these ideas are not necessarily new, globally, they appear to not be widely adopted in inland fisheries research and management. To date, there are many proposed frameworks, management approaches, and concepts that are potentially relevant for addressing the long-term sustainability of inland fisheries, such as ecosystem services approaches, ecosystem-based

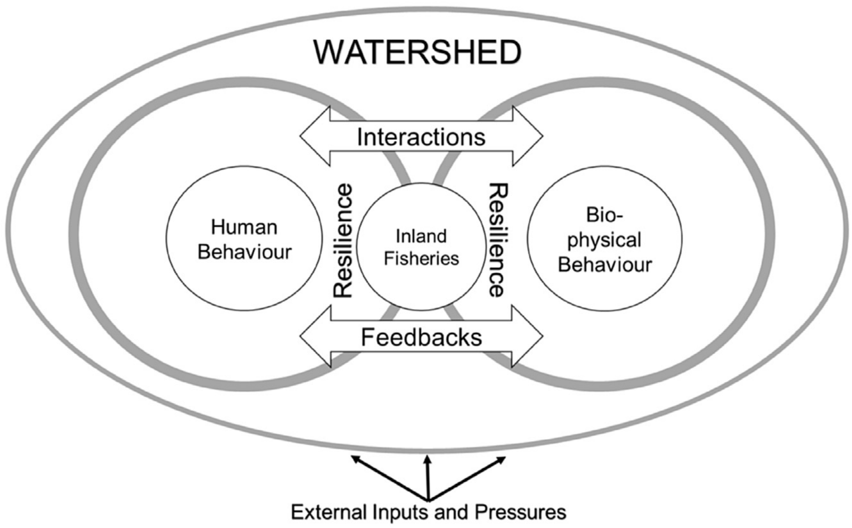

Fig. 1. Schematic diagram of the social-ecological watershed systems framework for inland fisheries management.

management, and integrated watershed approaches, but not all have been made explicit and synthesized for application to inland fisheries research and management (Table 1). Instead, inland fisheries tend to be ignored in the face of more high-profile activities of rivers such as dams and navigation.

One particular approach using the watershed as a water management unit is integrated water resources management (IWRM). The proposed SEWS framework borrows guiding principles and core ideas from the IWRM, which is a process that promotes the coordinated development and management of water, land and its related resources in order to maximize the resultant economic and social welfare in equitable manner without compromising the sustainability of vital ecosystems (Cardwell et al., 2006). The core principles of the IWRM approach that are parallel with the SEWS include a systems view, integration, partnerships and cooperation, participatory approaches, uncertainty, adaptation and reliance on scientific evidence (Simonovic, 2008). However, the IWRM and other similar approaches like ecosystem-based management, have been criticized for being too generic, open-ended, and political to be effective (McLain and Lee, 1996; Blomquist and Schlager, 2005; Allen and Gunderson, 2011). As such, the proposed SEWS framework uses similar ideas but targeted towards an explicit water resource, inland fisheries, to provide better delineation of inland fisheries issues and focused solutions.

We thus argue that integrating the best elements of these approaches (Table 1) under one umbrella (i.e. framework) can create a more comprehensive and effective framework specifically, and explicitly, for effective management of inland fisheries. To that end, this article attempts to address the complexity and challenges of inland fisheries research and management by synthesizing concepts and ideas from the literature that may help effectively guide research and management decisions towards achieving sustainability of inland fisheries. It is our intention to shift current research and management perspectives and practices towards a more holistic and integrative framework that can be implemented successfully.

3. The framework

We propose a coupled social-ecological system framework to assist in guiding and implementing inland fisheries management and research. The framework is by no means a 'one-size-fits-all' approach, but is sensitive to the diverse context of fisheries and their watersheds including, but not limited to, the diversity in socio-economic, political, cultural and governance of the regions. The framework puts emphasis on:

- Accounting for the *behavioural dimensions* of both social and ecological systems, which are often what drives and directs the outcome of a change or a disturbance to the systems. These behaviours include the *bio-physical behaviour* of inland fishes and waters, since these systems are never in equilibrium state but constantly moving and dynamic, as well as individual and collective *human behaviours*.
- Understanding the *feedbacks* between social and ecological components that are fundamental to maintaining system structure and function in the face of disturbance.
- Understanding the *interactions* of multiple factors (such as stressors) at multiple scales and levels with and between the social and ecological systems.
- Building social and ecological *resilience*.
- The overarching *external inputs* (or pressures) and outputs to the watershed system.

3.1. Behavioural dimensions

Often neglected in inland fisheries research and management is the theme of behaviour as a unifying concept that links and mediates social (e.g., governance, political, institutional) and ecological (e.g., climate, flooding, hydrological) changes, which may influence the outcomes of those changes (Fig 1). For example, human production and consumption activities drive demand for electricity, specifically green, renewable energy, which encourages the proliferation of dam construction. Dams in turn cause changes to the bio-physical behaviour of a river (e.g., hydrological and thermal regimes, sediment loadings), thus altering ecosystem functioning in the form of fish community shifts and food web changes. We therefore define behaviour in our framework as the dynamic response dimension of the SEWS, and propose that behaviours of the water, of fishes, and of humans are directly connected and must be conceptualized together to understand the interactions of stressors and feedbacks within both social and ecological systems. Different from the IWRM and other similar frameworks, the

Table 1
A snapshot synthesis of the definitions, features and potential avenue for implementation and application for the various frameworks and concepts relevant to inland fisheries research and management that make up the social-ecological watershed framework. Note that this table *is not a comprehensive synthesis* but a highlighted overview.

Framework, concept and/or Paradigm	Definition and highlighted features	Implementation and application	Sources
Watershed approaches/c atchment scale management	• Fish and fisheries management can no longer be treated in isolation and an integrated approach to aquatic resource management is required • Integrating the conservation and management of the species or the fishery into a wider resource user scenario will yield greater environmental gains • Key contributions to species recovery should be aimed at the conservation/rehabilitation of its natural habitats and not at the species itself	i) Citizen and stakeholder involvement is important throughout planning and management processes; ii) geographic focus of management activities includes the river or lake and its entire watershed; and iii) mechanisms need to be in place to promote cooperation among different government jurisdictions, sector users and organizations in the watershed; iv) environmental impact assessments are required at all levels of planning; v) mechanisms need to be in place to resolve cross-sectoral conflicts	Collares-Pereira and Cowx, 2004; Borre et al., 2001
Feedback framework	• Social and ecological components cannot be understood in isolation because of feedbacks between them • Feedbacks are fundamental to maintain system structure and function in the face of disturbance	• Feedback structures need to be incorporated into assessment and management activities	Miller et al., 2012
Human behaviour, social movement, social network theories and frameworks	• Many theories and frameworks exist for explaining and predicting human behaviour related to the environment such as attitudinal and normative variables, values and beliefs models, motivational attributes, and other hierarchical models • Frameworks also exist for influencing pro-environmental behaviours such as demographic factors, external factors (e.g., institutional, social or cultural factors), and internal factors (e.g., motivation, knowledge, awareness, values, emotion, locus of control, responsibilities and priorities)	• Resource managers can work closely with stakeholder engagement specialists and environmental educators to modify human behaviour	Ajzen and Fishbein 1973; Dunlap and VanLiere 1978; Vlek and Steg 2007; Rokeach 1973, Schwartz 1994, Stern and Dietz 1994; Homer and Kahle 1988, Stern et al., 1999; Stern 2000; De Young 1993; Kollmuss and Agyeman, 2002; Crona and Bodin 2011, 2012
Social-Ecological Systems (SES) Framework or Coupled Human-Nature Systems (CHANS)	• Explicit recognition of the connections and feedbacks linking human and natural systems • SES provides theoretically grounded means of testing hypotheses about the dynamics and implications of social-ecological interactions	• Integrate interdisciplinary research that includes both qualitative and quantitative data for richer understanding of SESs in specific areas to identify optimal management strategies • Implementation and application will be context-dependent • Modelling and social network analysis help understand interactions and dynamics in an SES/CHANS (e.g., Crane, 2010; Gray et al., 2012)	Ostrom 2007, 2009; Liu et al., 2007; Carpenter et al., 2009; Collins et al., 2011; Binder et al., 2013 (review of frameworks); Berkes and Jolly 2001; Berkes et al., 2003; Bodin and Tengö, 2012; Naiman 2013; Leslie et al., 2015
Cross-scale and cross-scale interactions framework	• Scale is the spatial, temporal, quantitative, or analytical dimensions used to measure and study any phenomenon, and “levels” as the units of analysis that are located at different positions on a scale (Cash et al., 2003:2) • Cross-level interactions refer to interacting among levels within a scale • Cross- scale interactions are interactions across different scales (e.g. between spatial domains and jurisdictions)	• Governance structures and management activities need to occur at scales that are relevant to a given watershed • Implementing bridging organizations and using social networks to facilitate cooperation and cross-scale interactions/activities within the watershed governance (e.g., Rathwell and Peterson, 2012) • Refer to projects such as the European SCALE (Securing the Conservation of Biodiversity across Administrative Levels and Spatial, Temporal and Ecological Scales) project (greater focus on biodiversity) and REFORM (Restoring Rivers for Effective Catchment Management), http://www.reformrivers.eu/	Cash et al., 2003, Gibson et al., 2000; Milner-Gulland 2012; Soranno et al., 2014
Scale mismatches	• Scale mismatches occur when there are changes in the relationships between spatial, temporal, or functional scales at which the environment operates, and how society is organized, and the imbalance between the demands of people and other organisms for resources		Cumming 2006; Henle et al., 2010

(*continued on next page*)

Table 1 (*continued*)

Framework, concept and/or Paradigm	Definition and highlighted features	Implementation and application	Sources
Driver-Pressure-State-Impacts-Response (DPSIR) Framework	• DPSIR is a flexible framework that can be used to determine the impacts of human activities to the state of the environment and the identification of (appropriate) measures for ecological rehabilitation of rivers and other ecosystems • Socio-economic sectors that fulfil human needs (Driving Forces, D) exert Pressures (P) on the environment/biological agents, and consequently, the State (S) of the environment changes leading to Impacts (I) on the ecosystems, human health and society, which may initiate a Response (R) that feedback on Driving Forces, on State or on Impacts via various mitigation, adaptation, or curative actions	• Two features have contributed to wide use of DPSIR: i) it structures the indicators with reference to the political objectives related to the environmental problem addressed; and (ii) it focuses on supposed causal relationships in a clear way that appeals to policy actors (Smeets and Weterings, 1999) • Create indicators of environmental conditions to evaluate the DPSIR (e.g. describe the DPSIR categories) • Identify sector drivers (e.g. agriculture, industry, energy, transport) in the DPSIR framework (e.g., Karageorgis et al., 2005) • Necessary to understand the multidimensional scale of processes in relevant landscapes (for example see Ward, 1989 for lotic ecosystems) • Using cost-benefit analysis in decision making (see REFORM deliverables)	Organization of Economic Cooperation and Development (OECD, 1993); European Environmental Agency; Gari et al., 2015; REFORM
Trade-off concepts	• Trade-offs exist between human needs and biodiversity conservation goals, and between conservation and other economic, political and social agendas across multiple scales – win-win scenarios are almost impossible to realize • Trade-offs involve "hard choices", meaning that there are different options, each with their own suite of possible outcomes relevant to human well-being and the diversity, functioning, and services provided by ecosystem over space and time. Even the optimal option involves loss in some way	• Scenario building, modelling, projection of future trends (e.g., Butler et al., 2013) • Communicating trade-offs • Non-market valuation/ecosystem services valuation to inform opportunity costs of trade-offs (Costanza et al., 1997; Daily et al., 2000; De Groot et al., 2002, 2010; Brauman et al., 2007) • Use of Millenium Ecosystem Assessment	Rodriguez et al., 2006; Nelson et al., 2009; McShane et al., 2011
Multiple disciplinarity: muli-, cross-inter- and transdisciplinarity	• Multiple disciplinarity is a term that catches all forms of integration of multiple disciplines (including non-science disciplines) and perspectives into one activity • Transdisciplinarity research transcends formal disciplinary boundaries and explicitly acknowledges that many perspective (scientific and non-scientific) are relevant to solving complex problems while actively engaging with the users of research • Transdisciplinary is a specific form of interdisciplinarity that recognizes invaluable contribution from different scientific and non-scientific fields (e.g. cultural/social dimension), but also focuses on cooperation and communication between society and science	• Much of the implementation for multiple disciplinarity involves social dimensions such as patience and time investment. Building transdisciplinary teams are challenging and takes long-term investments. Need to gain consensus across all players and turning issue into researchable questions takes time and emotional energy • Need facilitators skilled in social process of running meetings with multiple perspectives, cultures and languages. • Transparency and openness; overcoming corruption and political override, and more	Naiman 1999; Steffen 2009; Öberg, 2009; Klein 2008 (review); Pohl 2005, 2008; Max-Neef 2005; Stokols 2006; Hadorn et al., 2006; Tappeiner et al., 2007; Roux et al., 2010
Adaptive co-management	• Cooperative learning-by-doing process that allows institutional arrangements and ecological knowledge to be tested and revised in a flexible, dynamic, ongoing, and self-organized manner	• Decentralizing the command-and-control fisheries management regimes • Giving control of fisheries to local users under the direction of informed personnel. • Management framework that allows flexibility and adaptation to new knowledge while collaborating with stakeholders operating on different levels (from local to global) through participatory processes, stakeholder consultations and engagement	Pinkerton, 2011; Olsson et al., 2004; Folke et al., 2002; Jentoft, 2003; Armitage et al., 2007
Social-Ecological Resilience management	• Resilience is the capacity to absorb shocks and still maintain function	• Two useful tools for resilience-building in SES are: i) structured	Holling 1973, 1987; 2001; Adger 2000, 2006; Peterson 2000; Folke 2006; Folke

Table 1 (*continued*)

Framework, concept and/or Paradigm	Definition and highlighted features	Implementation and application	Sources
	• Capacity for renewal, re-organization and development • In a resilient SES, disturbance has the potential to create opportunity for doing new things, for innovation and development; while in vulnerable systems even small disturbances may cause dramatic social and ecological consequences	scenarios and ii) active adaptive management • Facilitation of a social context with flexible and open institutions and multi-level governance systems that allow for learning and increase adaptive capacity without foreclosing future development options • Involvement of SES stakeholders for a participatory approach (Walker et al., 2002) • Expand opportunities for great social-ecological response diversity (Bottom et al., 2009) • Management institutions and incentives must support sufficient diversification of human activities, including diverse fishing portfolios and economic opportunities for communities to respond to changing conditions (Bottom et al., 2009)	et al., 2002; Walker et al., 2002, 2004; Gallopin 2006; Elmqvist et al., 2003 (review); Bottom et al., 2009

behavioural dimension is novel to the SEWS framework, especially with the emphasis on the social nature of inland fisheries management.

3.2. Biophysical behaviour: dynamics of inland waters and fishes

We often do not think about water as having a behavioural component, but in our schema it does. For instance, fluvial systems move unidirectionally with significant potential energy, and the behaviour of the river is determined by its biophysical and hydrogeomorphical features, such as the landscape of their watershed (biophysical behaviour, Fig. 1). Fluvial systems supply trophic energy and transport organic matter (Vannote et al., 1980), they cycle nutrients (Newbold et al., 1982), expand and contract laterally to create floodplains (Junk et al., 2013), and have hydrological regimes (Statzner and Higler, 1985), which are the fundamentals of ecosystem structures and functioning. Similarly, lakes and reservoirs have dynamic processes throughout different seasons such as changes in stratification, lake turnovers, and biogeochemical cycling of essential micronutrients, which all drive productivity (Wetzel, 2001). The behaviour or response of these waterbodies to stressors, disturbances or changes depend on variables such as the energy source (i.e., organic matter or leaf litter deposited), scale and size (e.g., water volume), landscape (e.g., elevation and bed morphology), climate (e.g., temperate or tropical), sediment delivery and loading, hydrological regimes, and other biophysical and chemical variables relevant to the water body. The interactions of these variables ultimately mediate how the ecological system responds to changes. It is therefore important to consider the dynamic processes of these aquatic systems within the framework of inland fisheries management, and how they are continuously changing in response to multiple stressors.

The behaviour of fish is also essential to consider in inland fisheries management (biophysical behaviour, Fig 1.). Fish are dynamic in their physiological responses, as well as their reproductive, foraging, migratory, and movement behaviours. These various behaviours mediate the ultimate outcome of stressors or change. For example, dams block fish migration and access to essential habitats required to complete all aspects of their life history. Dam construction can result in loss of large spawning areas for fishes by blocking upstream passages or altering the spawning environments in both lower and upper reaches of around dam barriers (Haxton and Findlay, 2008). However, sometimes fish find alternatives. Lake sturgeon, a migratory fish in North America, for example, has been found to spawn below water control structures if suitable habitat exists (Lahaye et al., 1992; Thiem et al., 2013). Ultimately, these individual-altered fish behaviours may have drastic impacts at the population level and subsequently influence socio-ecological outcomes of inland fisheries. For example, sturgeon now spawn below the Iron Gates dam in the Danube instead of further upstream and fishers have changed their methods to exploit the aggregation of fish in the area.

3.3. Human behaviour

Human behaviours are arguably the most complex of the entire watershed (human behaviour, Fig. 1). They can be influenced by socio-demographics, values, norms, beliefs, emotions, experiences, situational variables, perceptions/worldviews, and a multitude of other cognitive and psychometric variables (e.g., Dunlap and VanLiere, 1978; Stern et al., 1999, 2000; Slimak and Dietz, 2006). Human behaviour differs from fish and watershed behaviour by being both reactive and proactive, whereas ecological behaviour is purely reactive (Smithers and Smit, 1997; Davidson, 2010).

A number of theoretical models and frameworks have been developed to understand environmental behaviours (e.g., adoption-diffusion theory, value-belief norm theory, motivational factors) and research on this question is abundant in psychology, sociology and other human behavioural sciences (Table 1). Several strategies for changing behaviours have been proposed, such as providing technical alternatives, regulatory rules, financial incentives (e.g., payment for watershed services; Lin and Nakamura, 2012), information, social examples, and/or organizational change (e.g. Geller et al., 1982; Geller, 1995, 2002; Gardner and Stern, 2002; Steg and Vlek, 2009). Furthermore, socio-demographics, such as gender differences may also play a role in influencing behaviour and attitude towards the environment (e.g., Bord and O'Connor, 1997). In turn, understanding socio-demographic roles can shed light on the social practices and interactions of humans and the environment in the SEWS. For example, in Tonle Sap Great Lake region in Cambodia, fisheries management is dominated by males, and influenced by power in patron-driven transactions among male fishing lot owners and their stakeholders, military officers, local politicians and villagers. Decisions on access rights to fisheries are thus strongly dominated by these male-male interactions rather than a holistic representation between people's actual practices, which include the women who are predominantly involved in preparation and processing of fish, non-fish trade, handicrafts and household work (Resurreccion, 2006). Gender and their associated roles play an important part in understanding the social nature and interactions in the SEWS. The SEWS framework makes explicit the need to understand human behaviour to understand the drivers, potential interactions, and outcomes of change. As such, borrowing tools, approaches, and concepts from the social sciences can help fisheries managers and researchers to understand and navigate the social complexities of inland fisheries governance (Ban et al., 2013).

As much as humans can be the driver for altering the ecosystem, humans are also capable of conservation behaviours and environmental stewardship, including efforts to restore fish habitat (e.g., Cui-ui sucker of Truckee River, Nevada; Rood et al., 2003), and to create passageways for migratory fish at blockades (e.g. Schilt, 2007). Humans are also capable of cooperation and collective action towards a common goal. Elinor Ostrom uncovered that humans have the capacity to self-organize and solve common problems rather than relying on formal government processes and infrastructure. Ostrom observed that communities relied on combination of informal norms, trust and small set of formal rules that the users themselves developed, monitored and enforced (e.g., Ostrom, 1990, 1998; Anderies and Janssen 2012). Building on the human capacity to self-organize, is an evolving concept of 'heartware' that includes community-based shared values and sense of identity and belonging as part of watershed approaches, which suggest that management planning and governance may not rely on scientific and technological knowledge alone, but must integrate the diverse non-tangible values that humanity has with nature and their relationships with each other (e.g., Mohamad et al., 2015). Management planning must place importance on the human dimension, and recognize historical, cultural, anthropological and religious implications. Empirically, these concepts have been explored using social network perspectives and analyses to understand social interactions and leadership in relation to natural resources governance (e.g., Crona and Bodin, 2011, 2012; Bodin and Crona, 2009). Thus, the SEWS recognizes the importance of social capital, social networks, empowerment, identity and the human dimension to support sustainable fisheries.

In North America and parts of Europe, considerable efforts have been devoted to protecting and restoring coldwater temperate streams that support(ed) salmonid populations. Much of this activity is driven by the public's desire to see recovery of the species, often with support from government stewardship coordinators (Litke and Day, 1998). Environmental non-governmental organizations such as Trout Unlimited and the Atlantic Salmon Federation in Canada and the United States and Atlantic Salmon Trust and The Wild Trout Trust in the United Kingdom work with their volunteers and landowners to achieve real conservation gains (e.g., see Duff, 1993). Efforts include instream works such as placement of structures that reduce erosion and enhance physical habitats as well as planting trees in riparian zones and installing fences that keep livestock out of streams (e.g., Kauffman et al., 1997; Roni and Beechie, 2012). In some cases, these citizen groups also maintain small hatcheries used for supplementation and also engage in routine monitoring and assessment in parallel citizen science projects. Such activities are also used to engage youth as part of educational programming (e.g., salmonids raised in classrooms), which helps to connect them with nature and to understand watershed processes (Blair, 2007). The most effective stewardship activities tend to focus on higher order streams or subwatersheds (Roni and Beechie, 2012), but when conducted in a coordinated manner, entire watersheds can benefit given that water flows downstream, and fish migrate upstream (France, 2005).

3.4. Feedbacks

Fisheries are, by definition, coupled social and ecological systems (or CHANS, coupled human and nature systems; Lynch and Liu, 2014). Human and societal activities create changes to the dynamics of inland fisheries, through activities that directly impact fisheries (e.g., overharvesting, damming, water extractions) as well as activities that indirectly influence aquatic habitat and fish through land-use activities (e.g., deforestation, agriculture) resulting in changes to the aquatic system and resources. Many fish populations have collapsed due to overexploitation and habitat degradation, and in turn, many people have incurred economic, social and cultural losses such as village displacement, increased malnourishment or resource competition from decreased fisheries productivity (Lynch and Liu, 2014).

Inland fisheries research and management can benefit from a SEWS approach, because it provides a framework to understand the interplay and feedback between social and ecological systems. *Feedback* refers to a chain of cause-and-effect. It occurs when outputs of a system or variable is looped back to become an input, which may amplify or diminish the magnitude of the effect of that variable (Miller et al., 2012). One well-known example is "fishing down the food web" (Regier and Loftus 1972, Pauly et al. 1998). The fishing selectivity by humans on larger individuals and species means the elimination of these larger fish. Evidence from inland waters supports this general model, where the fish assemblages may experience intense selection on size and age at maturity (Welcomme, 2001). This, in turn, may lead to natural selection of smaller, faster maturing fish, and may create the necessity of larger harvests to maintain profits in the face of dwindling fish stocks of the more valuable species – a socio-ecological feedback. Generally, research on feedbacks focuses on either the effects of humans on the environment or the effect of conservation practices on humans (Miller et al., 2012). The SEWS framework benefits research and management of inland fisheries by ensuring feedback effects on *both* social-ecological systems are considered through approaches adopted such as those in the ECOPATH literature (e.g. Downing et al., 2014) – synthesis work from researchers using the ECOPATH approach, which provides a mass-balanced snapshot of the ecosystem by exploring four parameters: biomass, production/biomass ratio (or total mortality), consumption/biomass ratio, and ecotrophic efficiency for each functional groups in the model. Key results can help identify data gaps, and common goals between parties that were previously hidden or obscure (ecopath.org).

3.5. Interactions

Actions or variables that change the dynamics of inland fisheries, such as drivers, pressures (DPSIR framework Eurostat, 1999), stressors, threats, "pulses and presses" as per Collins et al. (2011), often interact to yield a range of social and ecological outcomes. Social outcomes due to changes to the dynamics of the SEWS can include village displacement from dam constructions, malnourishment, or resource competition from decreased fisheries productivity; while ecological outcomes may include species extinction or displacement that can lead to food web collapses, and changes in ecological functioning of the aquatic system due to disturbances such as migration barrier, poor water quality, or overharvesting. The interactions of these interventions or variables have varying effects that can be additive, synergetic, or antagonistic, leading to sometimes predictable, and other times, unpredictable socio-ecological outcomes (Folt et al., 1999; Schweiger et al., 2010). The SEWS framework benefits inland fisheries management and research by integrating multiple interactions of relevant variables at the watershed scale, as well as considering the two-way feedbacks that can occur between social and ecological systems.

3.6. Interactions and scales

The traditional focus on studying single stressors (or pressures) may yield misleading conclusions and often ineffective, misguided, or failed conservation efforts (Tockner et al., 2010). Misunderstanding the complexity of a system and its interactions can also lead to ‘surprising,’ or unpredictable, outcomes (Liu et al., 2007; Folke, 2006). For example, smelt were initially introduced to Wisconsin lakes as a prey species for game fish such as walleye, but smelt in some lakes became significant predators on juvenile walleye leading to loss of walleye populations in some of these lakes (Liu et al., 2007). Understanding the effects of interacting variables when making management decisions is imperative; but this is challenging when these interacting effects are not predicted by evidence from single-stressor or single-variable focused based studies.

Further complicating matters, the interactions of stressors can occur at various scales (e.g., spatial, temporal, jurisdictional; Gibson et al., 2000; Cash et al., 2003). A watershed functions at multiple spatial and temporal scales with respect to material flow and balance, dynamic climate conditions (present and future), varied patterns of resource use, hierarchical structure of social and cultural organizations and ownership (Wilson, 1998; Umetsu et al., 2007). The concept of nesting is highly relevant to inland fisheries, as many of the processes and dynamics that influence these fisheries extend across multiple spatial and temporal layers and levels. For example, a localized waterbody maybe nested in its watershed, which in turn is nested in larger external driving forces (e.g., globalization, climate change) that comprise both slower and faster processes (Imhof et al., 1996). Some influences are local (e.g., point source pollution) while others operate globally (e.g., economic drivers), complicating efforts to address such pressures. Indeed, some inland waters, such as large rivers, cross multiple jurisdictional and international boundaries, which can represent a major governance challenge for addressing multiple stressors and managing for sustainability in a coordinated manner. In the proposed framework, we emphasize the importance of interactions (synergistic or antagonistic) that occur at multiple levels and scales, which affect both social and ecological systems.

One example demonstrating the importance of the interplay from multiple pressures involves recent economic developments in the Mekong region, which have brought with it considerable environmental change, with more to come (Dugan et al., 2010; Grumbine and Xu, 2011; Ziv et al., 2012). The river has already been highly modified by activities such as damming for hydropower and irrigation, disconnection of the floodplains for agriculture (especially rice) and growing industrialization and urbanization. There is now a growing body of evidence that these changes have impacted the fish and the harvest of aquatic food products from the system, although the system appears, to date, to remain largely resilient in terms of harvest, delivering in excess of 2.3 million tonnes of fish from the Lower Mekong Basin alone, worth an estimated US$ 17 billion (Nam et al., 2016). Unfortunately, the fisheries are in transition with many highly valuable long-distance migrating fish species disappearing and being replaced by lower value, smaller species. Many species are now endangered and production being maintained by considerable stock enhancement activities or being replaced by aquaculture (Cowx, 2015). The fundamental problem is that fisheries have been treated in isolation from other economic sectors, and not considered fully in basin development planning (Dugan et al., 2010; Brummett et al., 2013). As a result, local communities are not receiving many benefits from these water resource projects, but have been obliged to bear the costs, especially in the loss of fish (and other species) that they depend on for livelihoods and food security.

3.7. Scale mismatches

Mismatches in scale between management and ecological processes have often led to failure of management practices and conservation regimes, resulting in inefficiencies and the loss of ecosystem function and services (see framework by Cumming, 2006). Scale mismatches occur when there is a disjuncture between the scales and speeds at which the natural system operates, and those of human society, including the demands of people for resources (Cumming, 2006). For example, in Brazil government policies in the Amazon watershed are driving dam building to exploit the great untapped potential for hydroelectricity generation. However, the spatial and functional mismatch between the dam management operations and ecological processes put the connectivity of the Amazon watershed at risk, and can impact large migratory fish such as Amazonian catfishes and the fisheries that rely on them (Finer and Jenkins, 2012; Silvano et al., 2005). Additionally, social impacts to the fishers and villages immediate to the dam sites are seen through flooding, as well as changes in fisheries access, productivity and crop yield. Ignorance of scale may also lead to inappropriate allocation of limited resources, for example, when one country focuses conservation resources on a rare species within their boundaries that may be abundant and widespread at the scale of their continental distribution. For example, warmouth (*Lepomis gulosus*) is fish that is considered Endangered in Canada because of a restricted range and small population (see Crossman et al., 1996; COSEWIC, 2015) while in the United States it is widely distributed. The Canadian population is at the northern edge of the species range. There is still limited understanding of scale mismatches, but consequences include mismanagement of parts of the ecosystem, resulting in decline or degradation of both social and ecological systems. This can be magnified if different government institutions have different values.

3.8. Resilience

Social-ecological resilience (Fig. 1) is an important concept that highlights how social-ecological systems adapt to changes (Berkes et al., 2003). Holling (1973) first introduced the notion of resilience as the amount of disturbance a system can absorb without changing state. Ecological resilience of a system determines the capability and rate that the ecosystem can recover, regenerate, and re-organize following disturbance (Folke et al., 2004). Social resilience refers to the ability of humans (individuals and groups) to adapt to environmental change and withstand external shocks to their social infrastructure, such as environmental variability, climate change or social, economic, and political disruption (Adger, 2000).

The resilience of ecosystem services has been linked to the diversity of species within functional groups (i.e. sets of organisms that support similar ecosystem processes; Walker et al., 1999, Carpenter et al., 2009). For example, the diverse life histories of Pacific salmon species (e.g., subpopulations) are a population-level example of response diversity and confer resilience to salmon ecosystems as conditions vary (Bottom et al., 2009). Over the years, however, salmon ecosystems have become less resilient because of damming of rivers, change oceanic conditions and general heavy degradation of river systems. Populations have crashed and some gone extinct. Rapid climatic and economic changes have created novel environments and greater uncertainties for the future. These challenges and uncertainties call for strengthening of salmon, and other threatened species, ecosystems' resilience and acknowledging that ecosystems continually adapt to disturbances at varying scales and cannot be controlled to maintain optimal productivity (Bottom et al., 2009). However, targeting an iconic species that has similar habitat needs to other sympatric threatened species can provide a mechanism for multi-species conservation initiatives (i.e., umbrella species concept; Collares-Pereira and Cowx, 2004).

Reestablishing resilient keystone species populations (such as salmon) benefits social-ecological resilience by providing adequate water quantity and quality, functional wetlands and floodplains, habitat connectivity, productive fisheries, and other ecosystem services that are linked to the health of these iconic/keystone species. A resilient system has a buffer that protects the system from erroneous or outdated management decisions, thus (hopefully) allowing managers to learn from their mistakes and/or adapt to changing conditions (Walker et al., 2004). Building resilience should increase the capacity of both social and ecological systems to cope with surprises and provide buffer to persist in the face of shocks and disturbances (Folke et al., 2002; Liu et al., 2007).

3.9. External inputs

Many factors affecting the watershed also occur outside of their boundaries (external factors, Fig 1). These overarching external inputs/pressures such as biogeophysical, political and economic conditions often operate at large scales with slower processes, and are often uncontrollable and ambiguous (Walker et al., 2002). These pressures may have direct influence on the SEWS by interacting with existing pressures or influencing factors that are acting within the SES. For example, aquatic invasive species can be introduced into the system from ship ballast as an external input and pressure. The zebra mussel introduced in the Great Lakes cost the North American economy over $100 million, and caused a significant disturbance in the food web of the aquatic ecosystem (Strayer, 2009). Additionally, global climate can influence the system by increasing water temperatures, shifting hydrological regimes, decreasing dissolved oxygen levels, and/or increasing toxicity of pollutants. Alterations to inland fisheries from global climate change include the exacerbation of eutrophication and stratification in lentic systems, changes to fish physiology and life histories as they are directly linked to temperature, and range shifts of aquatic communities (Ficke et al., 2007). Therefore, overarching external inputs to the SEWS are not to be neglected and can interact with activities within the watershed, which may further compound impacts from activities within the watershed.

3.10. Application of the framework

The framework is proposed to frame the disparate concepts and ideas that are important to inland fisheries management onto one common ground and propose a pathway for the application of these concepts (Fig 2). One major criticism of holistic frameworks, such as the IWFM, is the fact that it attempts to encompass multiple aspects of water management and becomes too complex and challenging to apply to current situations (e.g., Cohen and Davidson, 2011). Similarly, the SEWS attempts to capture multiple stressors, scales and behaviours, and may be challenging to implement; but we hope that the following section will assist in navigating these complexities and challenges. In the next section, we discuss how the proposed framework can be applied to various challenges for the governance and research of inland fisheries.

3.11. Governance and management of inland fisheries as a SEWS

The hierarchical and nested nature of watershed boundaries (from a single lake or mountain stream to a watershed as large as the Amazon Watershed) can lead to challenges in defining which watershed boundary to use for the purpose of governance and management (Blomquist and Schlager, 2005; Cohen and Davidson, 2011). Furthermore, watershed boundaries often do not align with jurisdictional or electoral boundaries (municipal, provincial/state, or national boundaries) making management at a watershed level politically complicated. Who is accountable for the management of the watershed when multiple jurisdictions are involved (Wester and Warner, 2002; Blomquist and Schlager, 2005)? Misalignment between watersheds and 'policy-sheds,' a geographic area over which a governmental entity has legislative authority (Cohen and Davidson, 2011), can lead to gaps and overlaps in watershed scale legislation. This mismatch can result in policy implementation that is fragmented and uncoordinated, to the detriment of efforts to manage the watershed. This issue is particularly prominent in transboundary rivers like the Mekong or share lakes like Victoria in East Africa.

3.12. Watershed-scale and transboundary organizations

To address this challenge, the proposed framework encourages management to adopt watershed-level practices and decision-making, which consider all stakeholders within a watershed as well as cross-sectoral collaborations. The Mekong River Commission (MRC), founded in 1995 after the 'Agreement on the

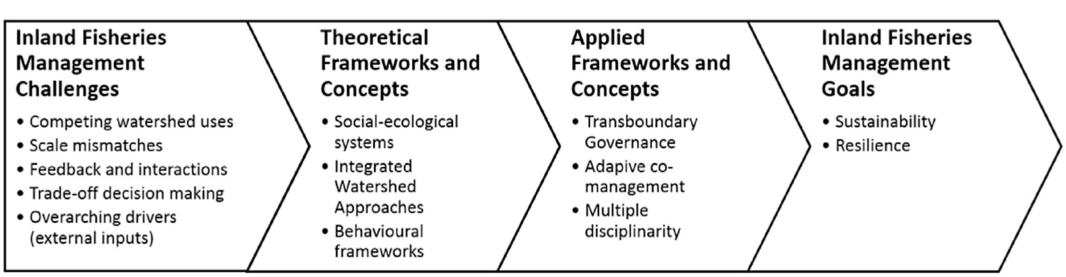

Fig. 2. A conceptual diagram illustrating where examples of the disparate concepts and framework (Table 1) fit within the proposed SEWS framework. The illustration shows a step-wise process and application of the proposed SEWS framework through: a) identification of inland fisheries management challenge, b) recognizing the various existing and relevant theoretical frameworks and concepts, c) moving forward the theory into practice by using the various existing and relevant applied frameworks and concepts, and finally d) the framework attempts to forward these disparate concepts and theories to achieve inland fisheries management goals. The conceptual diagram is not comprehensive and only present key examples for simplification.

Cooperation of the Sustainable Development of the Mekong River Basin', provides an example of a transboundary and watershed organization established to coordinate water resources planning and development across Southeast Asia's lower Mekong River Basin (Jacobs, 2002). Four member nations: Cambodia, Laos, Thailand and Vietnam, are members of the MRC where they tackle a number of challenges such as widespread poverty within the Basin, and the proliferation of emerging issues of dam constructions, which increases demands on water and environmental resources. The agreement among nations is a "milestone in international water resources management treaties due to its emphasis on joint development, ecological protection, and a dynamic process of water allocation" (Radosevich and Olson, 1999, 1). Post-2001, the MRC made key changes, shifting from project focus to programme focus. This allowed the MRC to focus on inter-disciplinary and trans-disciplinary research and management actions designed to be adaptable to the Mekong basin's dynamic environmental and social conditions, and increase resilience amongst the rural poor within the basin. Governments can also develop laws and regulations that encourage the creation of watershed committees (e.g., Brazil, 1994 Water Law created over 100 watershed committees; Abers, 2007). Here, the importance of human dimensions, social capital and networks, 'heartware', and capitalizing on the capacity for humans to cooperate and self-organize will facilitate the implementation of watershed-scale and transboundary governance. The SEWS framework would further enhance this by drawing together the wider socio economic and political agendas and addressing cross-sectoral conflicts, as well as drawing different skill sets together to address complex issues.

3.13. Knowledge systems and adaptive co-management

Problems with transboundary and watershed scale governance are compounded by incomplete knowledge and uncertainties. Given the complexity of the human and natural systems involved in inland fisheries, knowledge is likely to always be incomplete. Adaptive co-management strategies can help mitigate this challenge. Incorporating stakeholder knowledge, whether expert, local or traditional knowledge, into inland fisheries governance is considered to add flexibility to an SES because it represents multiple perspectives and promotes adaptability in decision-making (e.g., Gray et al., 2012). Relatedly, adaptive co-management is a cooperative learning-by-doing process that allows institutional arrangements and ecological knowledge to be tested and revised in a flexible, dynamic, ongoing and self-organized manner (Folke et al., 2002; Olsson et al., 2004). Inland fisheries management should have the capacity to be flexible and adaptive to use of existing indigenous and new knowledge, and should incorporate the learning process and input of stakeholders (Jentoft et al., 1998; Pinkerton, 2011). The success of adaptive co-management depends on the collaboration and cooperation among stakeholders operating on different levels (from local to even international levels), increased partnerships, participatory approaches and decentralizing the command-and-control fisheries management regime that we have historically relied on (Armitage et al., 2007).

The concept of adaptive co-management is well embraced in the Pacific northwest of North America where indigenous peoples and their tribal governments work collaboratively with state/provincial, federal and other partners (e.g., angling groups, hydropower utilities) to co-manage watersheds used by Pacific salmon. One such example is the Seton Watershed of British Columbia, a sub-watershed of the Fraser River Basin. The St'at'imc peoples have taken an active role though their Government Services unit where they engage in co-management of fisheries resources in the Seton Watershed in partnership with BC Hydro, a utility with significant hydropower infrastructure in the system, as well as provincial and federal governments. Through collaborative technical committees, the partners have used an adaptive co-management approach to address issues such as the need for improved fish passage at the Seton Dam. Field studies conducted by St'at'imc fisheries technicians, environmental consultants and academics have been used to test different configurations of flows intended to attract fish to the fishway entrance (Burnett et al., 2014). Each year the diverse members of the technical committee reflect on the findings from the previous year and then modify/refine as needed and devise ongoing monitoring activities. These small changes based on incremental learning represent important mechanisms by which policy and management actions are shaped in this region (Turner and Berkes, 2006). This specific example falls within a broader process (which is admittedly complicated by ongoing land claim negotiations among other legacy issues; see Pinkerton, 1999) where indigenous peoples take active roles in the co-management of shared resources of the Pacific Northwest (e.g., Pinkerton, 1994; Ebbin, 2002).

The self-organization process of adaptive co-management development (such as the example described above) has the potential to make inland fisheries and their social-ecological watershed systems more resilient and robust to change (Ebbin, 2009). More resilient systems allow managers to learn and to actively adapt to ecosystem management policies and reduces the risk of entering in unsustainable and undesirable development trajectories (Olsson et al., 2004). Our framework proposes the use of adaptive co-management as a mechanism to apply the theoretical concepts that are prominent in the literature and enhance success of achieving management goals (Fig. 2) by embracing a flexible management system driven by stakeholder contributions such as that in the abovementioned Seton Watershed case study.

3.14. Researching inland fisheries as a SEWS

Research and understanding of the SEWS frameworks' elements are required to make informed decision for inland fisheries management. At a watershed scale, a fundamental question arises: how do we consider the large number of variables that have influence on inland fisheries without falling into the traps of either being too narrow in scope and risking missing the big picture, or, alternatively, being too broad and therefore losing scientific depth and precision (Romero and Agrawal, 2011; Bodin and Tengö, 2012). Often, the lack of common methods among research disciplines can delay progress on quantitative studies of social-ecological interactions and interdependencies – a problem that is compounded by the complexity and dynamism of inland fisheries (Bodin and Tengö, 2012). In Lake Victoria, for example, the isolation of fisheries management from the parallel work of limnologists and ecologists on the Lake led to misleading results from fisheries models. While efforts and resources were inefficiently used to manage heavy fishing pressures, in reality, by looking at a more holistic integrated ecosystems approach using phenomenological analysis of key processes and a comprehensive set of indicators (spanning physical, biological, and human development), it was found that eutrophication was the most import driver of the productivity of the fishery, rather than fishing pressure (Kolding et al., 2008). Thus by employing holistic approaches, fisheries management, in the Lake Victoria case, could be more effective by tackling the more serious threat, eutrophication (noting that state changes are occurring in the system; Soranno et al., 2014). Balancing the scope of the research and management agenda will prove to be a challenge when applying the framework, but by looking to transdisciplinary approaches, researchers and managers can find a common ground and pull on various resources to understand the complexity of managing inland fisheries.

3.15. Multiple disciplinarity projects and teams

The management of complex adaptive systems may benefit from the combination of different knowledge systems (e.g., traditional, indigenous, expert; McLain and Lee, 1996; Berkes and Jolly, 2001). Transdisciplinarity is a specific form of interdisciplinarity that, while recognizing invaluable contribution of different disciplines, also emphasizes the need for cooperation and communication among the various parts of society with these academic disciplines to meet some of the complex challenges we face today (Tappeiner et al., 2007). The advantage of a transdisciplinary project or team is the ability to focus on the issue and solutions from different angles. Members leave their disciplinary roles to focus on issues rather than deriving solutions based on disciplinary constraints. Often this can be achieved through identifying common goals and objectives as a platform.

Management goals across fisheries and non-fisheries sectors (e.g. water quality) can be overlapping, conflicting, or mutually dependent. However, sector-specific management goals are usually expressed in broad terms that reflect the interests of a specific group of stakeholders (e.g. "increase fisheries harvest" or "improve water quality") rather than being co-dependent, interdisciplinary goals and objectives. This problem is further magnified by the fact that the same word(s) can mean different things among sectors. Ideally, management objectives should be mutually dependent, so that the achievement of one objective can reinforce the opportunity for success of achieving another objective with a common integrative agenda. In such cases, resource professionals promote synergy across sectors. As an example, the original Great Lakes Water Quality Agreement (GLWQA) signed by the USA and Canada in 1972 focused on controlling water pollution (e.g., inputs of nutrients and contaminants). However, natural reproduction of lake trout (*Salvelinus namaycush*) in the Great Lakes, a fisheries sector management objective (Eshenroder et al., 1995), was hypothesized to be impaired by organic pollutants (Mac et al., 1985), demonstrating how achieving one water quality objective might simultaneously achieve another fisheries management objective. As the interactions and understanding of water impairment and biotic integrity developed, the International Joint Commission amended the GLWQA in 1978 to add co-dependent objectives as the restoration of waterways included measures of biological integrity. Understanding these interrelationships proved to be useful in developing ecosystem based management objectives in the latest GLWQA amendment in 2012, explicitly recognizing the impact of contaminants on fish and fisheries production as water quality issues. The SEWS framework proposes the implementation of multiple disciplinarity approaches (whether it'd be multi-, cross-, inter- or transdisciplinary depending on the context) as the common ground to apply the theoretical concepts (e.g., SES framework, integrated watershed approach; Fig. 2) as demonstrated by the benefits achieved from the common cross-sectoral goal of the GLWQA.

4. Conclusions

Our article argues for a shift in inland fisheries research and management toward a holistic and transdisciplinary approach, as proposed by the SEWS framework (Table 1; Fig. 2), i.e. moving away from the more traditional ecosystem based approaches. Inland fisheries are inherently complex social-ecological systems that are nested within a watershed (Fig. 1). By taking a SEWS approach to inland fisheries research and management, we pay special attention to the interactions and feedback of multiple stressors within the system, and consider the various relevant environmental and social scales. Scale mismatches and single-stressor studies have often led to failed or inefficient management and conservation regimes of natural resources and ecosystem services. Lack of understanding of the complexity of inland fisheries has also led to surprising and unpredictable outcomes. For long-term sustainable and resilient inland fisheries, researchers and managers need to understand the complex behaviours of the inland fisheries system, because they mediate how vulnerable the system is to changes, the system's ability to adapt to these changes, and its resilience to these changes.

To that end, our proposed framework supports watershed-scale and transboundary governance to manage inland fisheries as an SEWS, and transdisciplinary projects and teams to ensure relevant and applicable research. Knowledge from scientists and non-scientists should be captured and implemented using an adaptive co-management system that allows fisheries managers to be flexible and learn-by-doing along with the advice and support of the stakeholders and the public. The SEWS framework is an approach for researchers and managers to employ to enhance understanding of the complexity of inland fisheries and their surrounding social-ecological systems and watersheds, to improve decision making, trade-offs, and maintenance of the resilient inland fisheries that directly or indirectly support billions of people worldwide.

Acknowledgements

Thank you to members of the Fish Ecology and Conservation Physiology Laboratory, Amanda Guthrie at MSU, and the "In Fish" group for support and feedback. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Nguyen is supported by the Natural Sciences and Engineering Council of Canada. Cooke is supported by the Canada Research Chairs Program, the Too Big To Ignore Network of the Social Sciences and Humanities Research Council of Canada (388029) and the Discovery Grant Program of the Natural Sciences and Engineering Research Council of Canada (315774).

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