Unraveling the complexity of socioeconomic and natural systems:

The case of the Lake Michigan nearshore.

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Introduction

Scientific dialogue over the interpretation and application of sustainable development has set the foundations for a new discipline of sustainability science. The main objectives of sustainability science are (i) to redefine the relationship between human beings and nature and; (ii) to formulate clear and applicable operational conditions for the harmonic coexistence and coevolution between biosphere ecosystems and anthropogenic systems (Baumgärtner & Quaas 2010; Kates et al. 2001; Palmer et al. 2005). The basic requirements of sustainability science are interdisciplinarity and the incorporation of the knowledge of natural sciences into the decision making process (Clark & Dickson 2003). Ultimately, the concept of sustainable development is redefined and calls social sciences and decision making to secure primarily ecological sustainability and secondary economic development (Bithas & Nikjamp 2006). On the other hand, researchers in the natural sciences are called to focus on the effects of anthropogenic activities on ecological processes in concrete terms to better inform decision policy makers (Cash et al. 2003).

The complexity characterizing the interaction between human and natural systems has led to the Coupled Human and Natural Systems approach (CHANS). CHANS approach studies how human actions affect biophysical systems, how biophysical forces affect human well-being, and how humans, in turn, respond to these forces (Guan et al. 2011; Kotchen & Young 2007; Liu et al. 2007; Mavrommati et al. 2014; Millennium Ecosystem Assessment 2005; Pickett et al. 2005; Stevenson 2011; Zvoleff & An 2013). CHANS approach rejects the traditional separation of natural and social sciences calling for 'synthesis' of sciences and development of advanced methodological tools. The challenge for the scientists is to move beyond the barriers of their discipline into approaches that recognize the impacts of anthropogenic activities on the planet and address the effects of human actions on natural systems (Ariza et al. 2012; Barnosky et al. 2012; Rockstrom et al. 2009). Human actions and well-being play a key role for analyzing and developing CHANS. The components of human well-being determine the planning and enforcement of environmental policies; human well-being regulates what and how much should be preserved.

Illustrating the components, pathways and hypothesized responses among the subsystems in a CHANS framework is the first step in order to build quantitative models. This is a complicated process that requires both extensive scientific and applied knowledge from various disciplines (Ostrom 2009). In this case, expert and stakeholder engagement is essential in order to identify the components of the CHANS framework and unfold future pathways.

We used the CHANS framework developed by Mavrommati et al. (2014) for the Lake St. Clair watershed in order to test its applicability to one more case study in the Laurentian Great Lakes system and refine it by hosting a one day workshop. We integrate stakeholders' knowledge to better understand their concerns in the Lake Michigan nearshore and increase social learning. We propose a conceptual framework for coupling the socioeconomic and natural system in the Lake Michigan nearshore. Our proposed framework provides a decision tool to scientists and decision makers interested in identifying the linkages among the systems' parameters and illustrating the effects of future pathways.

Methods

Case Study

Milwaukee, Wisconsin is a Great Lakes city where three major rivers join to form an estuary that discharges directly to Lake Michigan (Fig. 1). The Milwaukee River has the largest watershed of the three rivers and represents the most diverse land use, with mainly rural and agricultural land uses in the headwaters and dense urban use near the mouth. The Menomonee River drains a smaller watershed dominated by urban and residential land use in the southern reaches with about 36% of the watershed classified as agriculture and natural located mostly in the headwaters. The smallest watershed drains to the Kinnickinnic River, with nearly all urban and industrial land uses and over half of the watershed covered by impervious surfaces. At the confluence of the three rivers is the Milwaukee estuary, which was designated an Area of Concern (AOC) in 1987 under the Great Lakes Water Quality Agreement. The original boundaries of the AOC extended approximately 2-3 miles up the mouth of each river and also include the outer harbor and a portion of nearshore Lake Michigan. In 2008 there was an

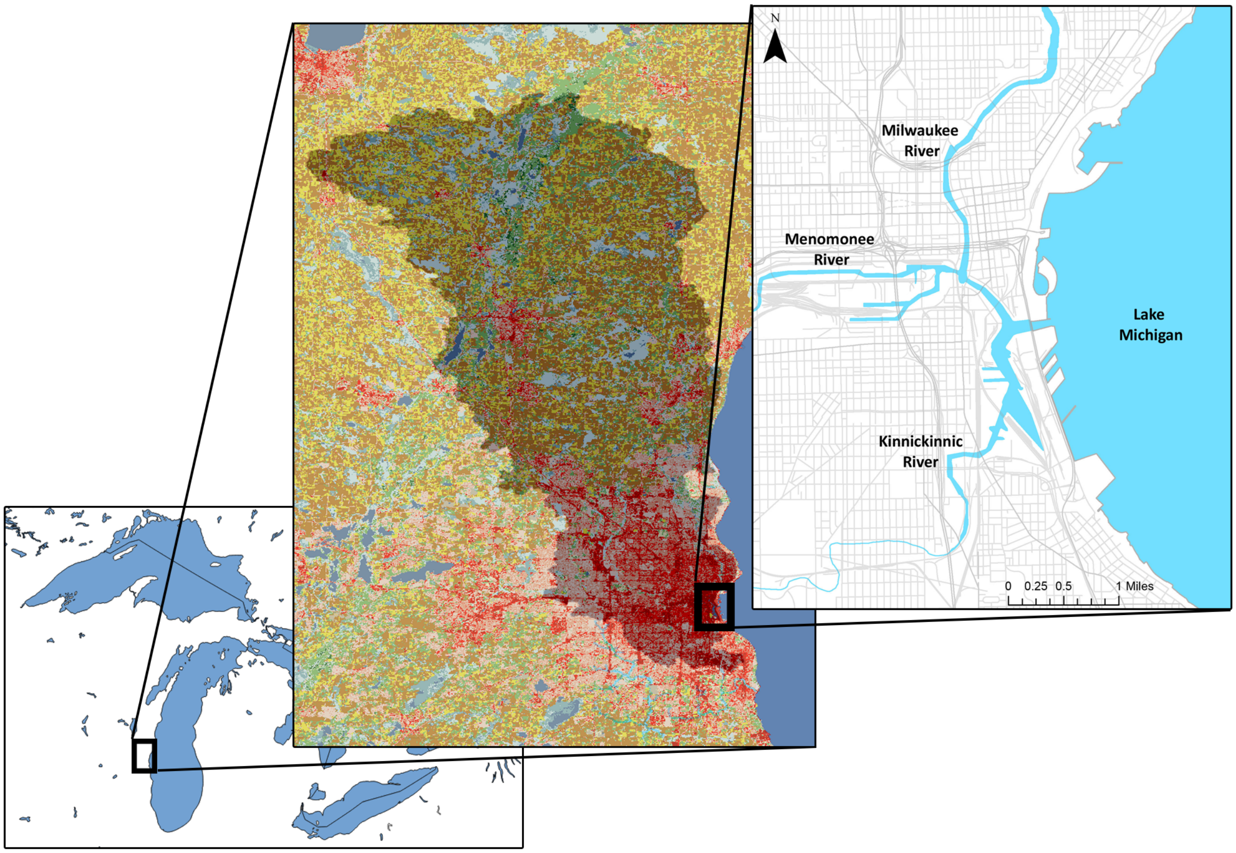

Fig. 1. Maps of the study area including: Great Lakes region (left), land use (inset center), and Milwaukee rivers (inset right). The Milwaukee, Menomonee and Kinnickinnic watersheds are darkened in the land use map, where urban areas are red and agricultural or natural areas are not. The three rivers join in an estuary that discharges directly to Lake Michigan from downtown Milwaukee, WI.

expansion to cover sites that contribute large contaminated sediment loads to the AOC. There are a number of Beneficial Use Impairments (BUIs) that limit public access and ecosystem services (ES) available from these waterways. Beach closings, recreational restrictions, and degradation of fish and wildlife populations with restrictions on consumption, are among the 11 BUIs assigned to the AOC. Several beaches located along the Milwaukee coastline are susceptible to pollution discharged from the rivers and estuary, and after heavy rains that cause sewage overflows, human sewage markers can be found 5 miles offshore in Lake Michigan (Newton et al. 2011).

Research Phases

Phase I: Testing and refining the framework by hosting a one-day stakeholder workshop

We organized a one-day workshop to elicit the expert knowledge of professionals working in the Lake Michigan nearshore. We followed the snow-ball sampling approach (Reed et al. 2009) to identify forty two individuals of various disciplines (i.e. ecology, urban planning, engineering, economics, law, policy) and organizations (i.e. public utilities, universities, county, state and federal agencies) and we invited them to discuss CHANS with reference to the specific case study. Twenty-six stakeholders responded (50% response rate) to our invitation and participated in the workshop. Invited stakeholders were not aware of the conceptual framework that we were using as a basis because we wanted to maintain their neutrality. The main objective of the workshop was to test and refine the parameters and linkages in the conceptual framework developed by Mavrommati et al. (2014) and identify future management options. The workshop goals were achieved by three exercises in which the stakeholders worked in five small groups. First, each group listed key parameters of concern in the socioeconomic and lake (i.e., natural) systems (Fig. 2). Second, as a team, they added arrows to show how the parameters affected each other (Fig. 2). Lastly, each group delineated future scenarios and management options. Most of our stakeholders, similar to (Mavrommati et al. 2014), were not familiar working with CHANS conceptual frameworks and found this process compelling, constructive, and challenging. Most workshop participants found the interaction with other participants stimulating and for some of them it was the first time that they had to think in terms of systems.

Phase II: Creating a conceptual framework based on stakeholders input

We used the stakeholder input from participants as a basis for developing the conceptual framework by compiling the parameters and arrows from the five groups into one diagram. We aimed at using this framework to formulate a simulation model based on system dynamics methodology to represent the structure and dynamic behavior among some of the parameters indicated in the conceptual framework.

Results

The proposed framework for understanding the complex interactions between socioeconomic and lake systems has similar structure to Lake St. Clair (LSC) framework (Fig. 2). Four interconnected sub-systems compose the socioeconomic system: human activities, stressors from socioeconomic activities, human well-being and environmental policies (Fig. 2). Two subsystems outline the structure of the lake system and its interdependence with the socioeconomic one: water quality indicators and the ecosystem condition responses. Given that the concept of ES is widely used the last few years to communicate to the public and policy maker the indirect and direct ways that ecosystems contribute to human well-being, we linked the two systems by using the notion of ES. For example, the lake system directly affects the socioeconomic system by supplying ES that are inputs to specific human activities (e.g., commercial water use) and indirectly affects human well-being (e.g., recreational ES that contribute to happiness).

We applied the LSC framework in Milwaukee area rivers and Lake Michigan nearshore. Similar to LSC framework, we identified four main pathways that describe: (i) how human activities affect the ecological condition and ES provided by the lake and; (ii) how ES contribute to human well-being. With this method, we validated the applicability of LSC framework to other case studies in the Great Lakes Region. Human activities may impact more than one ecosystem service and, in some cases, different than the one they hinge on. For example, residential and nonresidential water use and discharge depend on and affect the ES of freshwater, waste prossessing and nutrient cycling, but it also affects the ES of primary production, recreation and food. Detailed description of the pathways is given by Mavrommati et al. (2014).

Identifying Key Parameters of the Natural and Socioeconomic Systems

The first exercise involved listing key parameters of the natural system (see Table 1), the ES (see Table 1 and Table 2), and the parameters of the socioeconomic system (see Table 2). Instead of listing all the parameters identified at the workshop, we categorized them into groups. We included ES in both systems since they can be seen as inputs to socioeconomic system (e.g., beach use as an recreational ecosystem service that contribute to regional income and human well-being) as well as responses to natural system condition (e.g., high quantities of fecal becteria and total coliform that result in reducing the beach usage due to beach closures) .

Connecting the Systems

To understand the couplings between the natural system and socioeconomic systems, we asked stakeholders to connect the systems with arrows. Arrows were drawn within each of the systems and between the main systems. We followed an approach based on systems' thinking in order to make stakeholders think holistically, identify the relation of their expertise to the others, and build a qualitative CHANS model. Figure 2 has blue and red arrows. Blue arrows indicate direct (cause and effect) relationships and red arrows indirect relationships. Cause and effect relationships constitute the basis for bulding causal loop diagrams.The numbers on arrows indicate the groups and shows their similarities and differences. The differences among the groups are attributed mainly to what extent participants addressed indirect relationships (red arrows).

Natural System

A major challenge during the workshop was the distinction between water quality indicators and ecosystem condition responses. This distinction is essential for modelers aiming at representing interactions among parameters quantitatively. One group had a double arrow between water quality and ecosystem condition responses. This relationship is indirect through policy making. For example, the Clean Water Act defines specific water quality standards that human activities comply with and reduces the amount of pollutants in discharged wastewater.

Socioeconomic System

All the roundtables had a double arrow between environmental policy and institutions and human well-being reflecting their interdependencies. Even though each group indicated parameters belonging to the same themes in the subsystems, they had different considerations on how these parameters interact and connect. Most of the tables suggest the couplings between the natural and socioeconomic system through ES.

Scenarios for the Future

The last exercise at the workshop was to think about changes that are likely to occur by 2050. The scenarios stakeholders identified fell into six main categories:

1. Land-use and population changes
2. Climate change impacts to the lake (temperature and rainfall)
3. Limiting funding sources for research and monitoring
4. Invasive species
5. Wastewater infrastructure and unpredicted threats (aging and technological changes)
6. Emerging contaminants

A common theme among the roundtables was that the increased precipitation resulting in increased runoff will impact the ecology (change in fish communities, water quality, and habitat) and that local communities will need to adapt with green infrastructure and other best management practices to the increased rainfall in order to prevent increased combined sewage overflows and storm-water discharge. Aging water infrastructure was also mentioned as a concern for the future.

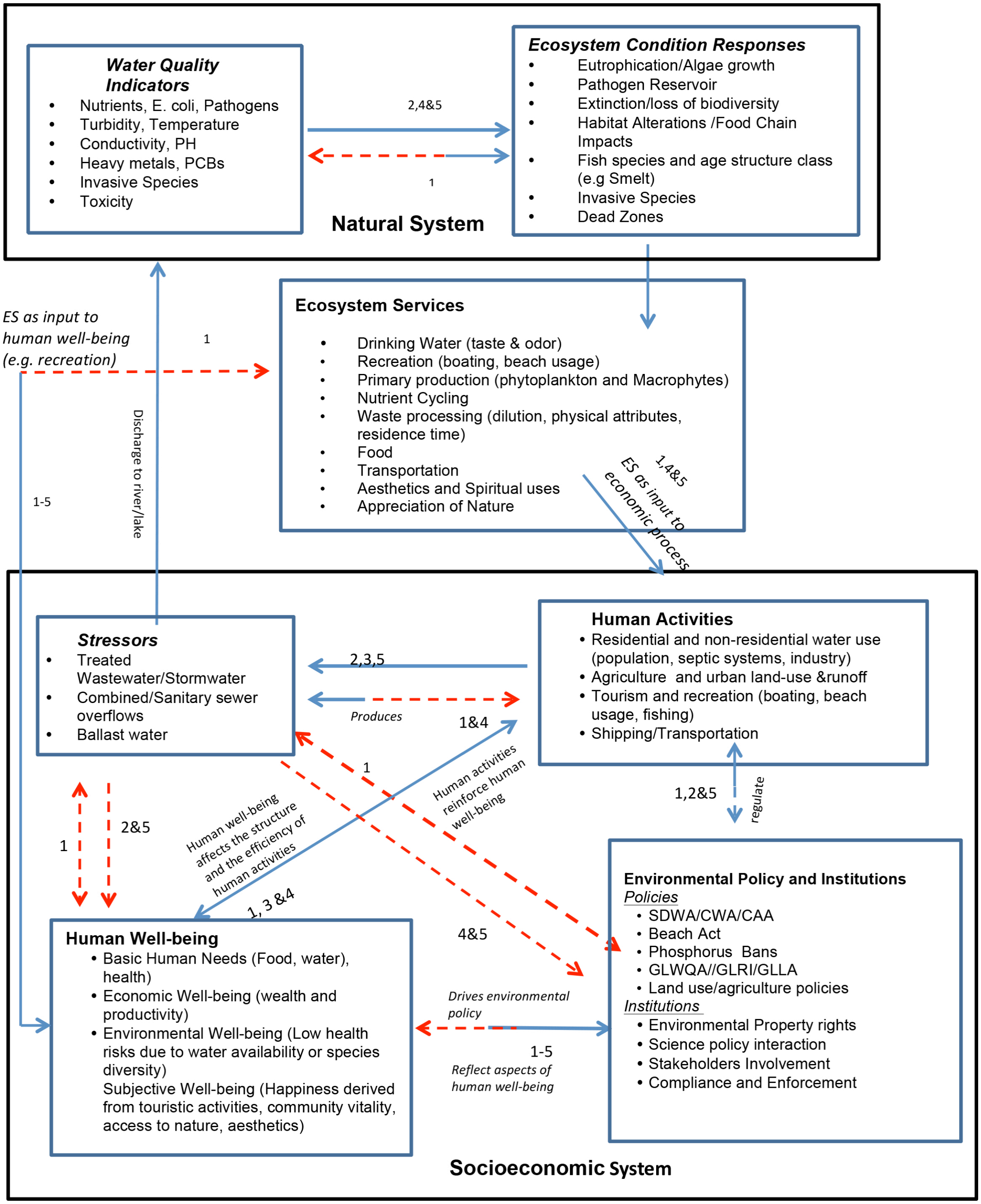

Fig. 2. A CHANS framework for the Milwaukee area rivers and Lake Michigan nearshore. Blue arrows indicate direct (cause and effect) relationships and red arrows indirect relationships. Numbers indicate the workshop groups that identified the specific arrows. Abbreviations: SDWA = Safe Drinking Water Act; CWA = Clean Water Act; CAA = Clean Air Act; GLWQA = Great Lakes Water Quality Act; GLRI = Great Lakes Restoration Initiative; GLLA = Great Lakes Legacy Act.

Table 1: Key Parameters of the Natural System as defined by Wisconsin workshop participants.

Natural System		
Water Quality Indicators	**Ecosystem Condition Responses**	**Ecosystem Services impacted by the Natural System**
Nutrients, *E. coli*, Pathogens	Eutrophication/Algae growth	Drinking Water (taste & odor)
Turbidity, Temperature	Extinction/Loss of biodiversity	Recreation (boating, beach usage)
Conductivity, pH	Habitat Alterations	Primary Production (phytoplankton and macrophytes)
Heavy metals, PCBs	Fish species and age structure class (e.g Smelt)/ Food Chain Impacts	Nutrient Cycling
Invasive Species	Invasive Species	Waste Processing (dilution, physical attributes, residence time)
Toxicity	Dead Zones	Food
		Transportation
		Aesthetics and Spiritual uses
		Appreciation of Nature

Table 2: Components of the socioeconomic system in Milwaukee area rivers and Lake Michigan nearshore as defined by Wisconsin workshop participants.

Socioeconomic System				
Human Activities	**Stressors**	**Human Well-being**	**Environmental Policy and Institutions**	**Ecosystem Services as inputs to human activities and HWB**
Pathway 1: Residential and nonresidential water use	Treated Wastewater/ Stormwater	Basic Human Needs	Safe Drinking Water Act/ Clean Water Act/ Clean Air Act	Drinking water (taste & odor)
Pathway 2: Agriculture and urban land use & runoff	Combined and Sanitary sewer overflows	Economic well-being	Beach Act	Recreation (boating, beach usage)
Pathway 3: Tourism & recreation	Ballast Water	Environmental well-being	Phosphorus Bans	Primary production (phytoplankton and macrophytes)
Pathway 4: Shipping/ Transportation		Subjective well-being	Great Lakes Water Quality Act/Great Lakes Restoration Act/Great Lakes Legacy	Nutrient Cycling
			Land use/agriculture policies	Waste processing (dilution, physical attributes, residence time)
			Environmental property rights	Food
			Science policy interaction	Transportation
			Stakeholders Involvement	Aesthetics and Spiritual uses
			Compliance and Enforcement	Appreciation of Nature

Discussion

Using the CHANS framework

Understanding and modeling CHANS is a complicated and time consuming process. This process can benefit from participatory modeling for two main reasons. First, engaging stakeholders can unravel essential mental knowledge for identifying the components of CHANS and their interactions. Second, it seems that stakeholder interactions help them to think constructively about the linkages among human and natural systems and communicate the importance of their expertise and interests. Therefore, we suggest that participatory modeling may serve an important role not only for feeding simulation models but also as a tool for promoting stakeholder engagement that can resolve conflicts, and for increasing public awareness with respect to the dependencies between ecosystem services, human well-being, and policy making.

CHANS framework integrates science and policy responses and can promote the communication between scientists and decision makers. There is a growing demand for science that delineates the feedbacks between ES, human well-being, and policy intervention (Carpenter et al. 2009). Researchers can use the proposed framework to explore quantitatively the identified pathways and relationships given their expertise and identify what kind of collaborations they need to pursue in order to make their finidings policy relevant. For example a scientist who studies the combined impacts of human infrastructure and environmental processes on fecal or pathogen contamination of freshwater resources, has multiple stakeholders to consider when prioritizing and disseminating applied results. The primary concern is human health, but costly or excessive management strategies are also a concern to the public and to decision makers. Similarly, scientists who study emerging contaminants or climate change have a diverse collection of stakeholder audiences for their work, and there may be competing interests in management solutions. In this way, decision makers can use quantitative and qualitative model outputs to make informed decisions.

The proposed framework shares many similarities to LSC framework. Like the LSC framework, we identified four main pathways where human activities affect ES and, in turn, how ES affect human activities and well-being. In addition, stakeholders included publicly funded institutions as responders to ES disturbances. This suggestion complies with the growing literature on the role of institutions and governance schemes on managing ES (Carpenter et al. 2009; Ostrom 2009). Delineating these connections are the first steps in building quantative models for assessing management strategies and this workshop lays the ground work for future work examining the benefits and consequences of human actions on the Great lakes nearshore.

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