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Transportation Infrastructure and Ecosystem Resilience to Climate Change in the Great Lakes

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ABSTRACT

This paper provides a review of Great Lakes ecosystem and transportation infrastructure resilience to climate change, specifically climate change-induced water-level declines. We synthesize existing understanding of historic and projected water-level variability on the Great Lakes, and survey resilience research on the Great Lakes ecosystem using lake eutrophication as a case study and on transportation infrastructure for freight shipping. From the review knowledge, gaps in the literature are identified. By comparing the resilience of lake ecosystems with transportation infrastructure, we further propose an integrated framework that unifies resilience of both. The integrated framework is important to the design of coordinated mitigation strategies for enhancing the overall resilience in the Great Lakes region.

1. Introduction

The impacts of climate change on transportation infrastructure and ecosystems have garnered growing attention over the past decades. Owing to systemic changes in average and extreme weather events, climate change impacts the hydrologic cycle in the form of water-level change. While climate change-induced increases in ocean levels have received significant interest in academic, regulatory and the lay public spheres, the opposite problem of projected water-level decreases in the Laurentian Great Lakes through increased evaporative losses is not well understood. In fact, since the 1990s the Great Lakes have experienced large decreases in water levels, with Lakes Michigan-Huron reaching the lowest recorded level in 2013, more than one meter below the historic average (Figure 1). It remains to be explored whether and how the transportation infrastructure in the Great Lakes region should best react to the climate change-induced water-level declines. Further, there is almost a complete lack of understanding of how both physical limnological changes, as well as changes in the transportation infrastructure system in response to these impacts, will affect the lake ecosystem. This uncertainty is particularly unsettling as a population of over 50 million people from eight US states and the Canadian province of Ontario depend on the Great Lakes for water, transportation, commerce, ecosystem services, and recreation, with total GDP in excess of $4.9 trillion (Shlozberg et al., 2014). The same study estimated that the economic impact of projected low water levels may amount to $9.6 billion through 2030 and $18.8 billion through 2050.

Conceptually, negative impacts of water-level decline on the Great Lakes transportation infrastructure and lake ecosystem response are not difficult to foresee. Decreasing water depths at critical locations of waterborne shipping infrastructure such as channels and ports forces lake vessels to reduce cargo loads. For an average Great Lakes freighter, every 1.0 m decrease in water depth results in 14% reduction in vessel cargo loading (Shlozberg et al., 2014). The reduced vessel load increases unit shipping cost, causes shippers to shift to truck and rail transportation, and results in greater overall emissions and conges-

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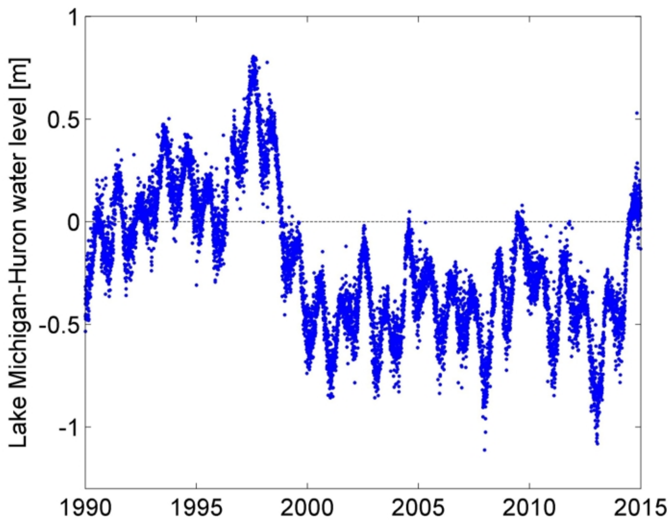
Figure 1: Lake Michigan-Huron water levels since 1990 (0 m is historic average).



Source: Great Lakes Environmental Research Laboratory (2017).

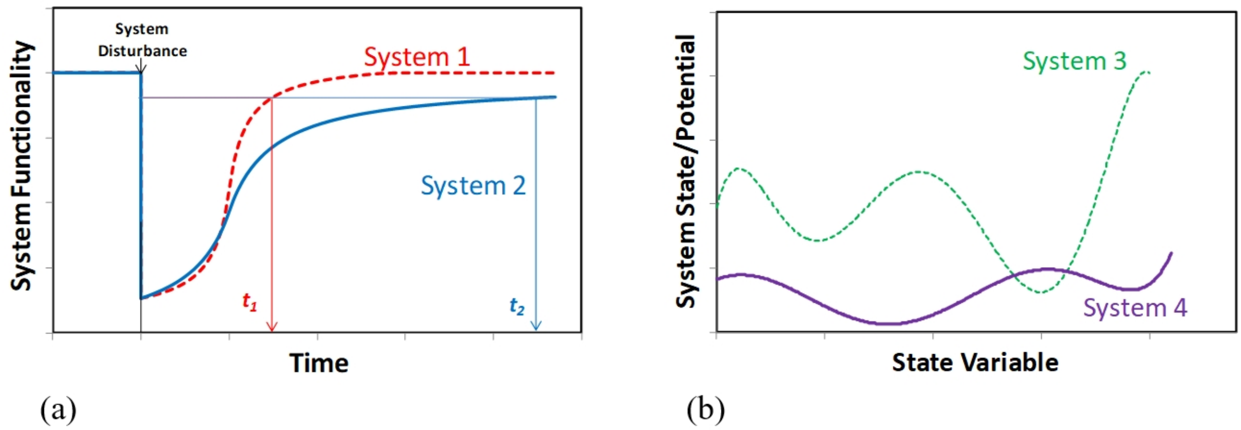
tion in the multimodal freight transportation system of the region. To mitigate the impacts of water-level decline on freight transportation, dredging activities are triggered at critical infrastructure locations to maintain navigational depths. These activities, however, will inevitably make the Great Lakes ecosystem vulnerable by exhuming contaminated sediments, disturbing benthic ecosystems, increasing turbidity, and exposing the ecosystem to unfavorable conditions throughout its food web (Trebitz et al., 2007). To make both the transportation infrastructure and ecosystem more resilient to climate change-induced water-level decline, a better understanding of both the transportation infrastructure and lake ecosystem responses, as well as the ability to design appropriate mitigation strategies, are necessary.

Resilience was first introduced by Holling (1973) in the field of ecology as a system property to persist without eventually moving to a different state of behavior when exposed to changes or shocks. Holling (1996) and Holling and Meffe (1996) further refined the concept of ecosystem resilience by understanding the dynamic nature of ecosystems and emphasizing the quality of the change in response to perturbations. This led to two different definitions of resilience (Gunderson 2000). The first defines resilience by the time required to return to an initial stable steady-state following a perturbation. Thus, a system that requires long time periods to recover (e.g., System 2 in Figure 2a) would be less resilient than one that recovers quickly (System 1 in Figure 2a). This way of viewing resilience is alternatively referred to as stability or "engineering resilience" in the language of Holling (1996). The second definition termed "ecological resilience" by Holling (1996) describes resilience as the magnitude of perturbation that can be absorbed by the system before it transitions to another stable state. Note that the ecological resilience definition includes multiple stable states (sometimes termed "basins of attraction") that can be transitioned to, whereas there is only one stable state in engineering resilience. One way to visualize the ecological resilience of a system is to describe the state of the system as a point along the potential function describing the stability domain of the system in response to perturbations (Scheffer et al., 1993). If the system state resides near the bottom of a local or global minimum, it would be at or near a stable steady-state with low precariousness (defined as the proximity to a transition state). This concept is shown in Figure 2b that depicts two system potential functions. For System 3, the steep "well" indicates a high resistance to change, but the system can shift into a new stable steady-state with relatively smaller perturbations (distance along the x axis). In contrast, System 4 is less resistant to change (i.e. a smaller "well" depth), but it can absorb a large disturbance before shifting to a new stable steady-state (i.e., it has greater system latitude) and thus has a greater ecological resilience.

Compared to the field of ecology, resilience as a transportation infrastructure property is a relatively recent development, and has mainly been used in the context of disaster management. An important characteristic of transportation infrastructure resilience is that human actions—both before and after disasters—are considered and play a key role. A recent review of transportation infrastructure performance defined resilience to account for possible interventions that can aid in returning system performance to pre-disaster levels (Faturechi and Miller-Hooks, 2014a). Interventions are determined based on the potential benefits of both pre-disaster mitigation actions at increasing the system's ability to cope with disaster impact, and post-disaster adaptive actions that aim to restore system functionality. In describing transportation infrastructure performance, resilience is closely related to several related metrics such as reliability (Chen et al., 2002), vulnerability (Kermanshah and Derrible, 2016), robustness (Scott et al., 2006), and flexibility (Morlok and Chang, 2004). However, a resilient transportation infrastructure system does not mean it is also reliable, robust, and flexible, or vice versa (Chen and Miller-Hooks, 2012). This distinction is mainly attributed to post-disaster recovery actions not being considered in the non - resilience metrics. While the field is still evolving, research in transportation infrastructure resilience to date has looked into multiple types of transportation infrastructure, including freight transportation (Nair et al., 2010; Chen and Miller-Hooks, 2012; Miller-Hooks et al., 2012; Baroud et al., 2014), roads (Faturechi and Miller-Hooks, 2014b), and airfields (Faturechi et al., 2014).

The objective of this paper is to provide a review of lake ecosystem and transportation infrastructure resilience to climate change in the context of Great Lakes. Specifically, as the potential for climate change to cause water-level declines in the Great Lakes is better understood, it is of critical importance to understand the implications for the lake ecosystem, the consequences on the Great Lake shipping and freight transportation infrastructure system, and how actions should be taken to enhance the resilience of both systems. Our efforts include first synthesizing existing knowledge of historic and projected water-level variability on the Great Lakes (section 2), and then reviewing previous research on both Great Lakes ecosystem re-

Figure 2: Representation of (a) engineering resilience and (b) ecological resistance.



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silience (using lake eutrophication as a case study) and transportation infrastructure resilience, to identify knowledge gaps (section 3). Although comprehensive studies on the ecosystem and transportation infrastructure resilience of the Great Lakes do not exist, we expect that established theories, previous experience, and empirical findings from other regions can provide helpful insight into the Great Lakes region. Also, by comparing the resilience of lake ecosystems with transportation infrastructure (typically viewed as unrelated topics), we seek an integrated framework that unifies resilience of both (section 4). This is particularly important for designing coordinated mitigation strategies for enhancing the overall resilience in the Great Lakes region that takes into account both environmental disturbances as well as socio-economic impacts on infrastructure systems and the public.

2. Climate change impact on the Laurentian Great Lakes.

2.1. The Laurentian Great Lakes system.

The Laurentian Great Lakes are the largest lake system on earth, representing one fifth of the world's surface freshwater (USEPA, 2014). The system consists of five lakes (Superior, Huron, Michigan, Erie and Ontario), as well as the Lake St. Clair connection between the upper Great Lakes (Superior, Huron and Michigan) and the lower Great Lakes. The system is connected to the Atlantic Ocean by the St. Lawrence Seaway, and other connections exist within the system to facilitate ship transport.

The system has a surface area to volume ratio ranging from 7-53 (Table 1). This ratio is much larger than the average of 0.27 for the world's oceans, making the system susceptible to surface exchange processes such as evapotranspiration and air deposition. Besides, the widely differing lake volumes and watersheds result in large differences in hydraulic residence times (HRTs, defined as the time necessary to replace the lake water volume from all inflows and outflows). These range from <3 years for Lake Erie to >170 years for Lake Superior (Table 1), and these differences have important implications for system perturbations and ecosystem resilience. A well-documented example of the impacts of anthropogenic change and system perturbation is the eutrophication of Lake Erie. Given its relatively short HRT, increasing phosphorus input (the limiting nutrient for phytoplankton growth) to the lake resulted in large increases in algal growth and eutrophication. The key management response was to reduce phosphorus input from point sources. This resulted in relatively rapid decreases in phosphorus concentrations and algal growth, as well as improvements in other ecological indicators of eutrophication (Ludsin et al., 2001). In contrast, had a similar situation occurred in Lake Superior, even complete cessation of phosphorus loading would not affect the phosphorus concentration in Lake Superior for decades to centuries due to its very long HRT.

2.2. Climate change impacts on the Great Lakes

Atmospheric CO_2 has recently surpassed 400 ppm, 45% more than pre-industrial revolution levels, and is expected to increase an additional 45% to 300% by 2100 (IPCC, 2014). Increases in atmospheric CO_2 and other greenhouse gasses will reinforce recently observed trends in global temperature, ice melt, sea-level rise, and climatic changes (Meehl et al., 2007). The Great Lakes region has experienced increases of annual air temperature by 0.25°C per decade (Hayhoe et al., 2010) and lake temperatures of 0.1°C per decade (McCormick and Fahnenstiel, 1999). Increasing air and water temperatures result in increased evapotranspiration over the region (Wilcox et al., 2007; Hayhoe et al., 2010). On the other hand, the frequency of extreme precipitation events in the Great Lakes region has also increased significantly over the 20^{th} century (Kunkel et al., 1999). The competition between precipitation and evaporation is the major driver of changes in Great Lakes water levels (Gronewold and Stow, 2014), and both are expected to increase in a warmer climate (Huntington, 2006).

2.3. Water levels in the Great Lakes

Changes in Great Lakes' water levels reflect changes in lake volume. Because the Great Lakes are so vast, small changes

Table 1: Physical limnological characteristics of the Great Lakes.

Lake	Volume (km^3)	Surface area (km^2)	Average Depth (m)	Area/Volume ratio	Hydraulic residence time (yrs)	Surface elevation (m)
Superior	12,230	82,100	149	7	173	183
Huron	4920	57,750	85	12	62	176
Michigan	3540	59,570	59	17	21	176
Erie	480	25,670	19	53	2.7	174
Ontario	1640	19,010	86	12	6	75

Source: NOAA Great Lakes Environmental Research Laboratory (2016).

in water level represent large changes in volume. The large volume of the Great Lakes also leads to large HRTs compared to other lake systems, and thus to significant inertia when responding to variations in climate (Hayhoe et al., 2010), with the largest fluctuations occurring on decadal time scales. Because surface waters comprise roughly one-third of the basin, the Great Lakes' water budget is well defined via a balance of precipitation (including overland precipitation and terrestrial runoff) and overlake evaporation (Gronewold et al., 2013). Ground water inputs and consumptive losses are considered negligible (Great Lakes Commission, 2003). Water levels of individual lakes are primarily balanced by precipitation, outflows and inflows to and from neighboring lakes, and evaporation (Great Lakes Commission 2003; Wilcox et al., 2007).

An extensive network of observation stations has recorded historic water-level fluctuations on the Great Lakes since the 1900's. Figure 3 shows the observed and projected water levels for individual Great Lakes. Although lake levels exhibit variability on a range of time scales, mean lake levels over the 20^{th} century are fairly consistent. On annual time scales, the Great Lakes experience seasonal water-level declines of approximately 0.5 m during the fall and early winter due to increased evaporation that results from passage of cool, dry air over warmer lake waters (Wilcox et al., 2007). During the late winter and spring, snow melt and precipitation replenishes seasonal losses. Decadal variations in precipitation are responsible for the largest fluctuations in lake level (Gronewold and Stow, 2014). For example, the 1997-1998 El Niño event caused significant decreases in overlake precipitation (Changnon et al., 2000), increases in lake temperature and overlake evaporation, and a resulting 0.5 m decrease in lake level (Gronewold and Stow, 2014). Figure 3 demonstrates that decadal variations in lake level, due to decadal climate oscillations, can reach up to 1.0 m above and below the long-term mean (i.e., 2.0 m variability). The natural variability of the Great Lakes' water levels suggests that the system possesses some inherent resilience to small water-level perturbations caused by climate change. However, having experienced a relatively consistent mean lake level over the 20^{th} century, the Great lakes may experience significant impacts over the 21^{st} century if climate change leads to persistent trends in mean lake levels, particularly during periods where long-term trends reinforce decadal declines.

2.4. Lake-level projection

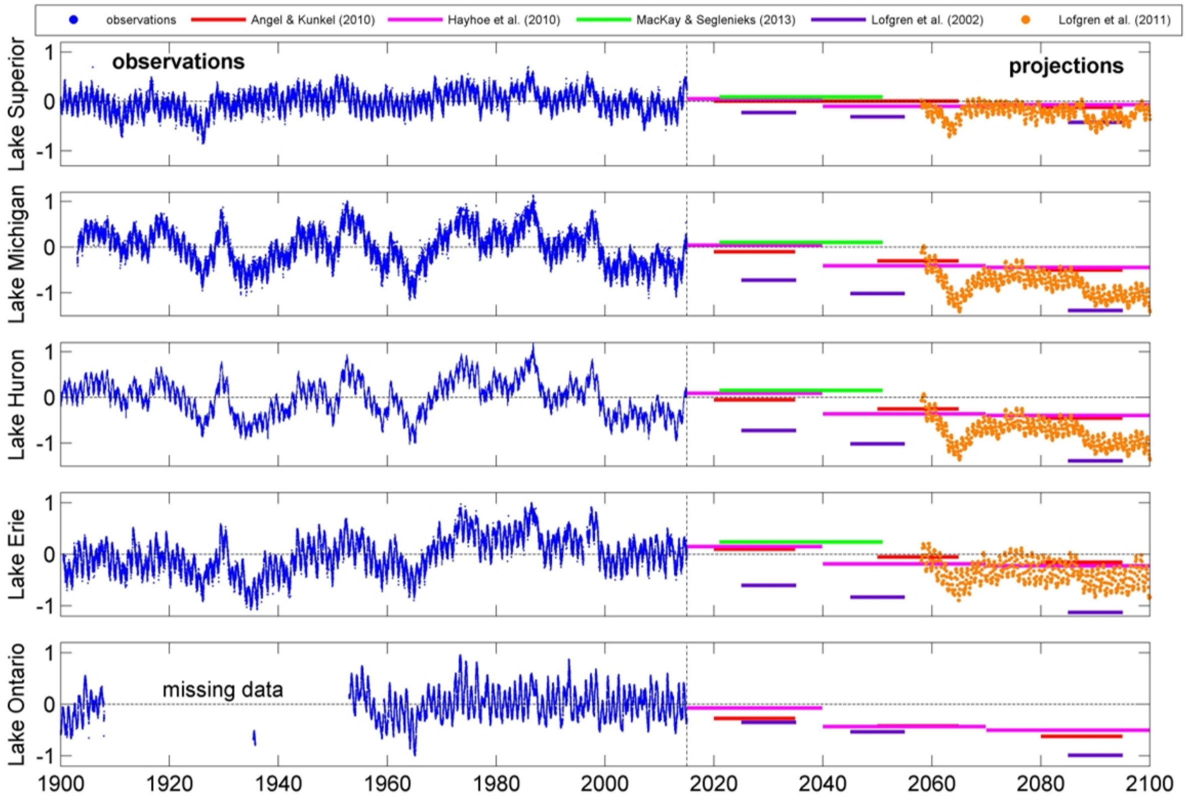
Numerous studies have produced multi-decadal water-level projections for the Great Lakes due to climate change (Hayhoe et al., 2010; Lofgren et al., 2011; MacKay and Seglenieks, 2013). As shown in Figure 3, most simulations predict mean lake level decreases of approximately 0.5-1.0+ m by 2100. Most of these projections originate from applying hydrologic models of the Great Lakes with temperature, precipitation, and evaporation inputs from global climate models (GCMs) under high-emission scenarios. For example, Hayhoe et al. (2010) estimate 46 cm of water-level decline by the end of the century using high-emission scenarios of downscaled GCMs coupled with the Large Basin Runoff Model (LBRM) (Croley and He, 2005). Interestingly, the projected 0.5-1.0 m drop represents only one quarter to one-half of the 2.0 m variability in the observed water level. Thus, even without a long-term trend of water-level decline, the decadal variations can still challenge the resilience of both the water ecosystem and the transportation infrastructure system.

3. State of the science for the Great Lakes ecosystem and transportation infrastructure resilience.

3.1. Resilience of lake ecosystems.

The concept of resilience has been applied frequently in the realm of shallow lake management focused on lake eutrophication, which has been recognized to result primarily from disturbances in the ecosystem that cause increased nutrient loading. This leads to a predictable response of the lake phytoplankton to increased nutrient levels and the transition to a new undesirable state with increased turbidity, increased nuisance/harmful algal blooms, shifts in fishing stocks and decreased dissolved oxygen due to increased heterotrophic consumption of organic matter. Many of these processes can be self-reinforcing depending on the system. An understanding of the lake system food web can suggest strategies to create positive feedback and reduce the harmful ecological effects of lake eutrophication. However,

Figure 3: Observed and projected water levels (m) on the Great Lakes.



Source: Authors.

sustainable strategies to manage eutrophication almost universally require the sustained reduction of nutrient inputs.

Lake eutrophication is seen most dramatically in more recent developments in Lake Erie. Expectations were that phosphorus levels would decrease significantly with concomitant decreases in phytoplankton following point source nutrient reduction in the lake. Although this indeed happened, phosphorus reduction was not the sole cause of the positive water quality improvements. More recent discoveries regarding nutrient cycling within the lake further dramatize the complexity in understanding system inter-dependencies, and demonstrate the need to correctly describe the system response to management actions for both infrastructure and resource users.

Beginning in the 1990's, water quality in Lake Erie started to deteriorate as a result of increasing non-point source nutrient loading to the point where hazardous algal blooms are common and water column anoxia is routinely observed. This more complex situation requires a more comprehensive strategy encompassing agriculture and residential areas to reduce nutrient loading to the system. Thus, viewing the situation solely from an engineering resilience framework may miss the possibility of multiple stable ecosystem states, a situation that is only describable by ecological resilience.

Although lake eutrophication is thought to be well understood and a classic example of ecological resilience, our experience with Lake Erie shows that unknown or ignored complexities can result in reversion to poor system behavior. Thus, we should be careful in attacking the problem of climate change given the level of unknowns. However, an ecological resilience framework can help understand potential risks should system disturbances shift the system into a new basin of attraction. From our current state-of-the-science, it is not known when decadal cycles may reinforce (or counter-balance) climate-induced lake-level changes. This uncertainty points to the need for a stochastic framework for assessing lake system resilience, a feature well within the capacity of the ecological resilience framework (Nolting and Abbott, 2016).

3.2. Resilience of freight transportation infrastructure.

To our knowledge, studies dedicated to Great Lakes freight transportation infrastructure resilience do not exist. Nonetheless, helpful insights may still be drawn from resilience research of freight transportation infrastructure of other regions. Ta et al. (2009) was among the first to define resilience specific to freight transportation systems as the ability of a system to absorb the consequence of disruptions to reduce the impacts on freight mobility. The intricate relationships between infrastructure, transportation users, and managing organizations were highlighted. Later, Ta et al. (2010) examined specifically the role of a state department of transportation in resilience planning for freight transportation systems. A set of low-cost actions were suggested and proven to improve system resilience in the state of Washington. Miller-Hooks et al. (2009) proposed a conceptual framework and developed a simulation–assignment tool to assess the impact of potential security measures on mobility and demand in an intermodal freight system. The tool was applied to the Washington DC-New York City freight corridor. Baroud et al. (2014) developed two stochastic resilience-based importance measures, based respectively on network service loss and resilience worth, to quantify the ability of an inland waterway network to recover from disruptions in the Mississippi River Navigation System. Pant et al. (2014) introduced three stochastic resilience measures and applied them to assess the resilience of Port of Catoosa in Oklahoma.

We devote close attention to the series of studies conducted by Miller-Hooks and coauthors, as they represent one of the systematic lines of research to date on freight transportation infrastructure resilience. Among them, a network resilience indicator was defined in Chen and Miller-Hooks (2012) as the expected fraction of post-disaster demand that can be satisfied for a given amount of recovery budget. A stochastic mixed-integer program was formulated to obtain the optimal course of recovery actions and applied to the Western US rail-based intermodal container network. The authors concluded that post-disaster activities can greatly improve system resilience and thus should not be neglected. This work was extended in Miller-Hooks et al. (2012) by simultaneously determining the optimal set of pre-disaster preparedness and post-disaster recovery actions using a two-stage stochastic integer program. The most important finding of this refined consideration is that, while resilience improvement can be achieved from taking either preparedness or recovery actions alone, the greatest extent of resilience improvement is attained when preparedness and recovery actions are jointly performed. Zhang and Miller-Hooks (2015) further relaxed the assumption that all actions be taken simultaneously and immediately, which did not account for the limitations of resources available at a given time point. Finally, although originally intended at the system level, resilience was also applied to individual components like ports and terminals in an intermodal freight transportation system (Nair et al., 2010).

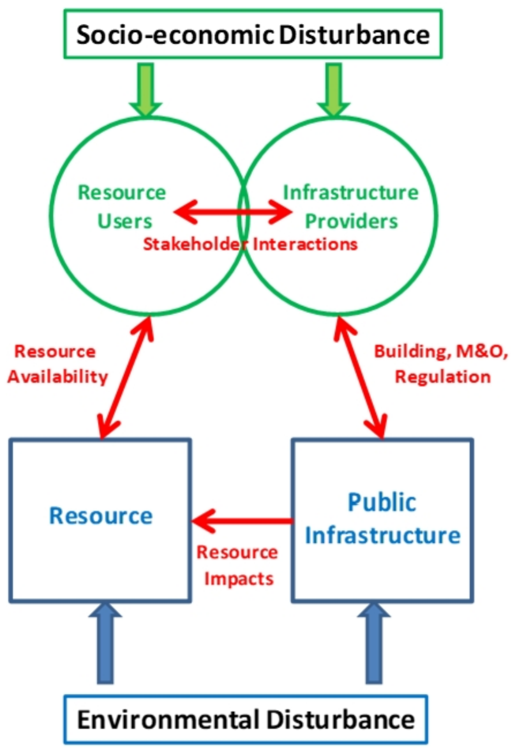
Despite the many efforts to quantify and improve freight transportation system resilience, we identify two important gaps in the literature. The first gap relates to the nature of the disruption events considered. Among all the aforementioned studies, disruption events are implicitly treated as single-event disasters. System disturbances resulting from climate change have not received as much attention. A fundamental difference of resilience with respect to climate change versus disasters is that climate change has the potential to continuously affect transportation infrastructure. Because of this persistent nature, it is neither sufficient nor possible to associate transportation infrastructure resilience to climate change with only a single or a limited set of discrete disruption events. Rather, considering resilience in a much longer time horizon (e.g., the life cycle of infrastructure) is warranted. In the context of the Great Lakes, climate change is expected to continuously drive water-level decline with fluctuations. Thus, any transportation infrastructure management response such as waterway dredging will need to account for these dynamics over decadal time scales.

The second gap is on characterizing freight transportation system response. Resilience of freight transportation infrastructure is ultimately reflected by infrastructure user performance in terms of shipping time, cost, and environmental emissions. In considering the resilience of freight transportation infrastructure to disasters, existing studies implicitly assume that a planner can manage system-wide traffic in a centralized fashion. This can be viewed as mimicking the role of the government in directing traffic during a short period of post-disaster recovery. However, for the continuous impact of climate change, the ability for a central agency to optimize network flows is very limited. Instead, a freight transportation system is expected to function under the equilibrium principle: each shipment chooses its transportation mode and route to minimize its generalized cost, which is the sum of shipping cost and monetized shipping time. At equilibrium, no shipment can change its mode-route choice to reduce the generalized cost. Specifically for the Great Lakes, with climate change-induced water-level decline, lake freighters will reduce vessel carrying capacity and charge higher rates. Shippers will shift partly to truck and rail, which aggravates highway and rail congestion. For some commodities such as grain, ores or bulk materials that would be too expensive to be transported by non-water modes, the demand will simply be foregone. Ultimately, the state of the freight transportation system will shift from one equilibrium to another, with redistributed commodity flows and greater system-wide shipping cost, time, and emissions. There is a dearth of models in the literature that can characterize freight transportation equilibrium sensitive to climate change. We are only aware of two studies investigating how climate change affects inland waterway in Europe, although they have limited applicability to the Great Lakes as they either only focus on the waterborne mode (Jonkeren et al., 2007) or do not account for traffic congestion effects (Jonkeren et al., 2011).

4. Future research directions.

Although we understand conceptually the role resilience plays in the Great Lakes ecosystem based on the example of lake eutrophication, we do not as yet have a firm grasp of how climate change will impact the system. This is due in part to a lack of understanding of how the lake ecosystem will respond to the likely reduction in lake levels in Michigan-Huron and the lower lakes as the result of climate change. Similarly, while considerable advances in understanding how transportation infrastructure can be made resilient to discrete disasters has been gained, it is still largely unknown how freight transportation infrastructure in the Great Lakes region should react to water-level declines to maintain and enhance its resilience. As climate change-induced water-level decline affects both the lake ecosystem and the freight transportation infrastructure system, it is clearly important to take an interdisciplinary, system-of-systems approach that can describe the resilience of both systems. From an even broader perspective, the resilience issue will become magnified when viewed holistically in combination with the societal demands on the lake system as a resource not only for waterborne freight transportation and water supply, but also to meet the needs for commercial and sport fishing,

Figure 4: Interactions between public infrastructure, resources, resource users and infrastructure providers.



Source: Modified from Anderies et al. (2004).

recreation, industry and agriculture. Thus, we argue that a starting point for understanding the system response must include understanding how societal responses will be made in response to the projected lake-level decreases.

To this end, we propose adopting a modified framework based on social-ecological system robustness analysis by Anderies et al. (2004). They make the argument that understanding institutional interactions is necessary to define the robustness of the system. Our modified framework highlights the institutional interactions between resource users and infrastructure providers, and the role that socio-economic disturbances play in the resilience of any generic resource-infrastructure-user nexus such as the Great Lakes ecosystem and transportation infrastructure system (Figure 4). At the bottom of the figure are resources (i.e., the Great Lakes) and public infrastructure (e.g., waterways, highways, railways, recreation, and water supply systems) which encompasses both physical and social dimensions through maintenance, operations, and regulation. When subject to external environmental disturbances, the system resilience is embodied in the extent to which resources remain available to users, while the impacts of these disturbances on public infrastructure functionality is explicitly included. Resilience of the entire system is reflected by its ability to accommodate resource users, public infrastructure utility and function, and also be sensitive to external socio-economic disturbances.

Viewing the above framework within the context of the Great Lakes, we suggest a few directions for future research to understand the Great Lakes system resilience under climate change. Primary among these is a better quantitative understanding of future water-level projections in each lake (i.e., predicting external environmental disturbance). In general, we argue that a holistic approach is necessary to understand the system as a whole, while lake-by-lake responses must be on a sufficiently localized scale to better predict critical responses with reduced uncertainty. For example, existing evidence suggests that decadal cycles in lake water levels may reinforce or offset predicted changes in lake levels due to climate change. Given the current precariousness of the St. Clair river/Lake St. Clair/Detroit river channel to further decreases in water level, this system will likely be a focus point for further study. In addition, large predicted decreases in lake levels in Lake Huron coupled with relatively smaller predicted decreases in Lake Erie within the realm of some model predictions may suggest massive dredging operations to maintain connection between lakes Huron and Erie (recall the difference in lake elevation is only 2 m, Table 1). While such steps may be mandated by governmental regulation, there are significant ecological and social impacts of such measures. Stakeholder interactions (such as voting) may result in changes to regulation requiring such measures, or run into opposition from environmental regulations requiring ecosystem restoration. Conversely, the economic impacts of cutting off the upper Great Lakes to oceanic vessels may result in socio-economic disturbances to resource users, resulting in a greatly changed resource demand.

The second research direction is to better understand the Great Lakes ecological resilience to climate change. Once the future physical limnological impacts of climate change have been quantified with uncertainty, these data should be used to understand how changes in lake bathymetry, hydrologic cycle, as well as the chemical, biological and physical state will impact individual lake ecosystem resilience. These impacts are myriad, with but a few examples including the impacts of warmer lake temperatures on the pelagic food web, hydrologic cycle changes in watershed-lake cycling, changes in nutrient loading, impacts of lake acidification due to increased atmospheric CO_2, changes in susceptibility to invasive species, and increased / decreased atmospheric transport of pollutants to the lakes. Further, within the context of Great Lakes transportation system resilience, we argue strongly that a detailed study of the ecological impacts on the benthic environment will become necessary where lake-level changes are of sufficient magnitude to necessitate port and waterway navigational dredging. Given the clear differences in resilience between the lakes, we speculate that Lake Superior will have a greater resistance to system change and thus we may focus more on lakes that have less resilience like lakes Michigan-Huron and Erie.

The third direction is on improving freight transportation infrastructure resilience. In this effort, the first step is to model lake bathymetry in response to predicted lake-level changes in order to quantify areas where shipping may be significantly impacted. The modeling needs to be performed in the entire Great Lakes shipping grid. As opposed to the existing resilience work for discrete disasters, we recommend a different approach for assessing freight transportation infrastructure resilience, which will be based on system equilibrium performance and over a long time horizon. Given the inherent uncertainty about water-level projections, scenario analysis will be desired to identify optimal actions to enhance freight transportation infrastructure resilience under different projected water levels.

Lastly, from the system-of-systems perspective, whatever resilience-enhancing action taken will need to account for the consequences on the ecosystem and the transportation infrastructure system as a whole. This necessitates the development of performance metrics that combine the resilience of the two systems, and a better understanding of how socio-economic changes will impact the state of the combined regulatory, infrastructure, and resource utilization system. Such metrics should allow for optimal allocation of financial resources while maximizing the joint ecosystem-transportation resilience, and also for tradeoff analysis when priority is desired to certain part of the overall resilience.

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