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Making Lake Erie Smart by Driving Innovations in Technology and Networking

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Tomorrow's smart lakes and oceans will be able to, among other things, predict changes in the water environment and produce information critical to proper management and planning. Smart Lake Erie – a proof of concept – will integrate data from distributed sensors using resilient networks to feed adaptive, predictive analytics that define and perhaps even perform necessary management actions. This paper presents the Smart Lake Erie pilot as a series of steps that include convening innovation competitions, engaging stakeholders, securing the core observation system, and designing then building a sustainable early warning system for harmful algal blooms. The pilot's data platform will show what is needed to serve new data contributors, service providers, stakeholders and consumers of the data and information service paradigm. Lessons learned from the early implementation of the pilot will be applicable to the overall Great Lakes region, other regional associations within the U.S. Integrated Ocean Observing System (IOOS), and the Global Ocean Observing System (GOOS).

Keywords: smart technologies, smart lakes, smart cities, HABs early warning system, Great Lakes water management, innovative observation technology

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INTRODUCTION

The Great Lakes, which provide drinking water, recreation, and natural environmental capital to 48 million people, are stressed by population growth, climate change, and invasive species (Great Lakes Commission, n.d.) (National Science and Technology Council, 2017). Lake Erie in particular has received much recent attention because of public health risks from harmful algal blooms (HABs) and is therefore an excellent testbed for innovative management approaches.

The Great Lakes Observing System (GLOS) is a bi-national (United States and Canada) node of the U.S. Integrated Ocean Observing System (IOOS) focused on the freshwater Laurentian Great Lakes. In partnership with NOAA Great Lakes Environmental Research Laboratory (GLERL), Cleveland Water Alliance, LimnoTech, and Ohio Sea Grant, GLOS is piloting the first "*Smart Great Lake*."

The goal of the Smart Lake Erie pilot is to deploy a new suite of technologies supporting intelligent water management and decision-making, thereby demonstrating the viability of the *Smart Great Lakes* concept. The pilot brings together a broad coalition of partners (federal, academic, nonprofit, and for-profit organizations) to implement a system that leverages diverse data into usable tools informing effective decision-making. Smart Lake Erie aims to reduce public health risks, increase access to the water, and mitigate the economic impacts caused by HABs. Through sustained co-development with partners, this system will transition to an operational funding model and scale to address an evolving set of water challenges.

This paper presents the Smart Lake Erie pilot with a focus on communications (data and information) and user engagement. It does not outline a strategy to improve the observing system itself.

WHAT IS "SMART?"

For the past decade, smart technologies have transformed the way society and the world interacts as smart phones and inexpensive, distributed sensors have become ubiquitous, allowing us to collect far more data than we can currently use. Visionaries identified the opportunity to better connect the urban landscape with people and organizations to form "smart cities," addressing issues around transportation, waste management, and housing. GLOS and its partners look to extend this vision to address unique challenges in natural resource management, specifically related to the Great Lakes and starting with Lake Erie.

Components of a smart city typically include distributed sensing, resilient networking, integration of diverse data, adaptive and predictive analysis, and automated control and interoperability. These components, often colloquially referred to as "smart technologies," transform diverse, high-volume, high-velocity data into value in the form of actionable information and sometimes even direct action (Kumar and Prakash, 2013). Examples of actionable information include notification- based alerts given some data threshold exceeded for a particular measurement and results of automated analysis delivered to end users or that feed other systems (i.e., command and control) from a variety of input data streams/sources.

In GLOS' case, the foundation of such a smart system is already laid. An existing monitoring network measuring real-time water quality data (chlorophyll, turbidity, blue-green algae, etc.) from a fleet of buoys, sondes, and other sensors in western Lake Erie feeds web-based data portal and station pages for easy access. Smart technologies can be applied in the water resource and coastal management context to extend this foundation in a variety of ways. For example, imagine:

- An army of sensors collects real-time, *in situ* data in the open waters of Lake Erie.
- Data is communicated through an underwater modem to servers which are part of a distributed regional network.
- Data on the servers is pushed to a cloud data assembly center.
- At the center, real-time analytics integrate the *in situ* data with remote sensing products from satellite or drone surveillance, predictive models, and other data sources.
- The analytics create actionable information for a range of stakeholders, from drinking utility operators and beach managers to soil and water conservation districts, state officials, and the general public.
- Users also communicate with the system, informing it of observed phenomena.
- "Smart" sensors trigger alerts or even direct autonomous decisions. Examples of autonomous decision making include triggering events in a Command and Control system based on field measurements that exceed some predefined tolerance or threshold.

The fundamental components of a Smart Lake include:

- Mesh network of connected technologies that leverage cloud computing, edge processing, data tunneling and data sharing from sensors, samples, models, and remote sensing.
- Adaptive and predictive management of processes, analytics, processing, visualization, and presentation.
- A framework of infrastructure, technology, software and data processing providers, partners and vendors.
- An active and engaged user community receiving and contributing information, feedback, and data.

These components are not new; with smart technologies already highly prevalent at GLOS and many of the other IOOS Regional Associations that integrate data from diverse sensors, models and remote sensing platforms. GLOS is demonstrating the potential of smart technologies by developing an Lake Erie Early Warning System as described in this paper.

Smart Great Lakes Conceptual Design

The *Smart Great Lakes* will connect people, policy, and technology. In the example of the Lake Erie early warning system (EWS), people connect with monitoring technology through warnings. Data from the EWS will be available to inform policy decisions that can direct technology advancements that can improve the system. The *Smart Great Lakes* design, as first conceived at GLOS, includes all the components that make a lake "smart." Synergy is created as each node informs the others and makes the system smarter, improving the way people learn about and respond to lake events, informing critical policy, and directing future science and technology innovation.

(1) *People:* It will take a broad coalition of stakeholders (water-dependent industry, local governments, recreational users, regional NGOs, IT sector) working together to leverage financing, technology innovations, and the latest science in order to implement *Smart Great Lakes*. GLOS and its partners provide the foundational mechanisms necessary for these stakeholders to work collaboratively toward collecting data, translating it into actionable information, and cultivating a knowledgeable and smart approach to management and policy in the Great Lakes.

(2) *Technology:* GLOS provides an IOOS certified data management infrastructure that can transform and deliver data and information to users. This flexible and scalable platform enables open data, analytics, and other technology solutions required to support the data-to-information life cycle. This technology is a valuable resource and point of leverage for *Smart Great Lakes* stakeholders who require agile solutions to information needs.

(3) *Policy*: *Smart Great Lakes* enables broader access to data and more nimble analytical application which can inform management and policy decisions on various levels from daily operations of a water treatment plant to the longer-term investment decisions of a federal agency. For example, understanding real-time water quality conditions will better inform beach closing decisions of a local beach manager. Another policy example could be a provincial or state government requiring all data collection agencies to make their data publicly available through a smart ecosystem. The coalition of *Smart Great Lakes* stakeholders will need to advocate together for increased investment in improved monitoring, open data, and technology innovations to support "smart" Great Lakes management and policy.

BUILDING A SMART GREAT LAKES

Smart Lake Erie Pilot

The first step toward the *Smart Great Lakes* is implementation on a smaller scale. GLOS is therefore starting with a pilot implementation for Lake Erie. This builds on earlier efforts with a variety of stakeholders for a proof-of-concept phase that is limited to a specific use case and targeted end-users. A broader Smart Great Lakes initiative would target a much more diverse set of use cases across a large community.

Why Lake Erie?

Lake Erie and its communities have been plagued for many years by HABs caused primarily by filamentous cyanobacterium *Microcystis* blooms. Occurring annually from mid-July through September, HABs pose a serious threat to regional public health, ecosystem integrity, amenity access, and economic growth (Environment, and Climate Change Canada [ECCC], and U. S. Environmental Protection Agency [US EPA], 2015).

This threat leapt to the national stage during the 2014 Toledo Water Crisis, an incident where HAB toxin infiltrated the drinking water system, depriving over 400,000 residents of access to public water for 3 days (Wines, 2014). Fundamental gaps in knowledge continue to limit efforts to develop and implement effective strategies to address this persistent crisis.

The Movement – Smart Lake Erie Community Partnerships and Collaboration

The Smart Lake Erie initiative is led by a network of organizations including state/federal agencies, residents, municipal governments, industry partners, nonprofit actors, and policy makers. Since the 2014 Toledo water crisis, LimnoTech worked together with GLOS to deliver near-real water quality data to the water utilities. This activity formed the core observing system for the EWS. Tangentially, from 2016 to 2017, CWA and DigitalC (a civic tech nonprofit) spearheaded a series of innovation competitions to inspire solutions to the challenge HABs in Lake Erie. Many innovation teams responded to these competitions with prototype smart technologies for monitoring like micro buoys or underwater modems to transmit data.

The Great Lakes Observing System, CWA, LimnoTech, Ohio Sea Grant, and NOAA-GLERL are now working to advance the Smart Lake Erie pilot by operationalizing the current Lake Erie monitoring efforts as a sustainable HABs EWS. The NOAA IOOS Ocean Technology Transition (OTT) program is supporting this effort over 3 years with $2 million in funding. Once completed, the core observation system in Lake Erie will be major component of the HABs EWS and Smart Lake Erie. This effort also unifies operation and maintenance procedures across water plant operators and develops a dynamic information delivery system built upon the GLOS data platform, both providing the basis of scaling the smart lake concept to the entire Great Lakes. Described below is a 3-step process for operationalizing the HABs EWS.

Step 1 – Engage Stakeholders

Implementing the Smart Lake Erie pilot began with a broad assessment of stakeholders to understand what data and information needs were necessary for a HABs EWS. CWA conducted over 75 interviews with existing and potential stakeholders during the winter and spring of 2018. CWA had three different programmatic scopes in these initial fact-finding interviews:

- Identifying critical stakeholder contacts.
- Identifying potential sustainable funding mechanisms.
- Identifying technology adoption, technology review, and acceleration of needed technology as part of an ecosystem through the voice of private industry.

Drinking water utilities are the primary stakeholder in Lake Erie water management. With 17 treatment plants subject to seasonal HAB risk, water treatment managers are on the front line in protecting communities. All drinking water utilities interviewed by CWA expressed interest in being part of a combined warning (and forecast) system for HABs, microcystins, and hypoxia, along with other data parameters (dissolved oxygen, temperature and turbidity).

Step 2 – Secure Core Observing System for Drinking Water

The core observing system includes sensors installed both at drinking water utilities and at stations put in place by researchers. The system for drinking water utilities started in 2015 with support from the Ohio Environmental Protection Agency. LimnoTech assisted these utilities in building the observing system, which includes phycocyanin and chlorophyll data transmitted sub-hourly into the GLOS data management system. This information supports real-time decision-making about treatment processes, dramatically reducing the risk of another Toledo water crisis.

Gaps in coverage exist as not all utilities yet participate in the core observing system and are still miles away from the nearest buoy-based station. Many of these gaps are also associated with areas of high recreational traffic. The OTT project will help to fill

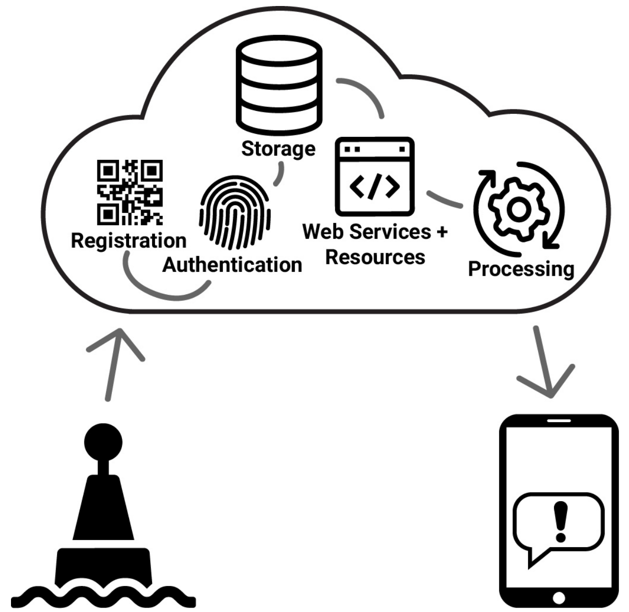

FIGURE 1 | Early Warning System (EWS).

observing gaps that are critical to meeting the objectives of the Smart Lake Erie's HABs EWS.

Step 3 – Design and Implement an Early Warning System (EWS)

An EWS as depicted in **Figure 1** runs on the cloud-based, GLOS data management platform and utilizes the data from *in situ* sensors. The goals of the EWS are to reduce human error, increase automation of metadata and data capture and increase the throughput of the raw data to meaningful information pipeline. Examples of this include the potential automatic registration of metadata for new devices and sensors deployed in the field. Requiring automatic posting of raw or edge processed data directly to the GLOS Cloud infrastructure for either additional post-processing, consumption by end users or services is another example of improving the efficacy of the entire smart ecosystem. Data telemetry can leverage Wi-Fi, Bluetooth, Cellular or Radio based communications networks. End users can consume processed information or raw data for additional processing or analytics through a variety of means, including web services, mobile and web applications or other data tunneling services. Finally, a critical component of the EWS is notification-based alerts, messaging and triggers that assist the rapid dissemination of critical information that leads to intelligent, relevant and contextual decision making.

What does the Smart Lake Erie pilot, and more specifically the HABs EWS, look like to the end-user? Based on initial input from stakeholders, the following list of features and capabilities are desirable in a HABs EWS:

- An infrastructure that supports multiple data types and streams into a single environment for consumption through a variety of different technical mediums.
- Users can access an environment to customize alert thresholds and data dashboards for access to multiple dataset types.
- Administrators can control access, grant permissions and unlock features for additional users or organizations.
- Secure authentication for data, applications and services.
- Users can visualization information, data and analytics across a range of end points, including multiple form factors, web/data/map services and third party end points.

The current goal is to have a prototype developed and tested by the fall of 2019. The prototype will integrate into the larger GLOS data platform, serving as a model for future *Smart Great Lakes* applications. GLOS will implement a user-feedback process to improve the software.

LESSONS LEARNED TO DATE FROM THE SMART LAKE ERIE PILOT

Although the pilot is still in process, there are several lessons already available for engagement of stakeholders and promoting buy-in for a smart lakes concept.

User Preferences – Geared Toward Easy Access

Over the course of the first year of this project we have learned, and it is reinforced by existing GLOS tools such as the buoy information access product (glbuoys.glos.us), that people prefer:

- Easy access to information-based content on mobile devices.
- Real-time data or shorter-term forecasts.
- Alerts via SMS or email that reduce the need to visit a website or portal.

In 2019–2020, GLOS will expand the existing infrastructure to include the suite of data inputs (e.g., real-time water quality data, grab sample data, model forecast outputs, and interpreted satellite imagery) needed for a HABs EWS. Data inputs will eventually increase to mean additional sensors from devices deployed over a large geographic area and fleets of devices on a per organization basis. The architectural design of the EWS will then inform the development and enhancement of the GLOS data management platform to be more responsive to the user data and information needs.

Leave Room for Innovation

The interoperability of the smart lake design will allow for the easy incorporation of new detection devices, analytic tools, and networking methods into an existing system architecture. As the hub for Lake Erie's water innovation cluster, CWA will work with GLOS and its partners to identify and accelerate technologies with relevance to Smart Lake Erie as they are developed. These innovations could focus on addressing incorporating new modes of sensing (e.g., satellite spectrometry for water quality), user-created data (e.g., observation reporting – users reports on his/her observations in the field), or cutting-edge modes of networking and telemetry (e.g., underwater data transmission) as well as monitoring emerging contaminants (e.g., pharmaceuticals).

As new technologies emerge, the flexibility of the GLOS data platform will allow targeted initiatives like Smart Lake Erie to serve as a testbed for piloting and optimization as well as a backbone for scaled implementation. In this way, the Smart Lake Erie initiative can serve as an incubator for sensor and software development and implementation, accelerating regional evaluation of and response to shifts in water quality challenges facing our communities, and establishing Lake Erie as a hub in the water technology ecosystem. Within this frame of continual innovation, the Smart Lake Erie pilot can serve as a model for the larger *Smart Great Lake*s to support water management in the larger Great Lakes region and can inform similar smart initiatives in the ocean environment.

Keep the Larger Picture in Mind

Issues of nutrient pollution, algal blooms (as indicated by increase in chlorophyll), and hypoxia are all too common across the Great Lakes and beyond. By leveraging the activation seen around Lake Erie to develop, test, and validate solution architecture for a smart lake system, we believe that we will be able to demonstrate the value of such a data infrastructure to other stakeholders across a wider bi-national, geographic region. Building on the foundation of Smart Lake Erie, we anticipate scaling this project to include all five Great Lakes and their watersheds.

FUTURE DIRECTIONS

Success of the Smart Lake Erie project will serve as a model for GLOS and presents a tremendous opportunity. As water security awareness increases at multiple levels of government, corporations and the general public, GLOS has the unique opportunity to take a leadership role in serving these diverse communities. The data platform of the pilot will be a window into what is needed to serve new contributors, service providers, stakeholders and consumers of the data and information service paradigm. At the very least this will include the ability to ingest data from a variety of data sources and providers into a common interface leveraging public and private APIs (Application Programming Interfaces). The opportunity for the new technology ecosystem however, does not just suggest that data alone can come into the system from providers, but also directly from acquisition sources. Additionally, GLOS has the opportunity to work with hardware and sensor manufacturers to innovate new technology that has the means to automatically connect with GLOS. This innovation could spur and encourage "edge" computing, the ability the automatically process data at the time of acquisition and send processed results. This has the added benefit of shortening the data to information timeline; critical in the context of water security and getting information to decision makers quickly.

By building a data platform that allows incoming data and information from a variety of technologies (sensors, devices) and contributors (water authorities, citizen science, non-government organizations, research, and academia), GLOS' impact can be amplified. By developing an agnostic data platform for the consumption, processing, delivery and dissemination of data and information, GLOS partners indirectly become part of an interconnected network. This network would naturally lead to the promotion of information sharing, rapid decision making and ultimately a better "system" for information communication that could include not only water managers and other top-level decision makers, but anyone with a stake in the Great Lakes from city planners to parents to businesses and researchers. This is the penultimate goal of a smart ecosystem, and done on the scale of the Great Lakes, this serves as a model for large regional ecosystems around the world.

The Great Lakes Observing System anticipates that the concepts, technology, and approaches for *Smart Great Lakes* will scale well to coastal management areas around the U.S. and the world. With Lake Erie as ground zero, we anticipate seeing this technology making positive impacts on seaboards and coasts for decades to come.

CROSS REFERENCES

This Community White Paper intersects with a number of other OceanObs'19 topic areas:

- The Great Lakes Observation System is part of IOOS ("IOOS: Lessons Learned") and GOOS ["Global Ocean Observing System (GOOS)"].
- The primary driver for the Smart Lake Erie pilot is harmful algal blooms ("Regional to Global Perspective: Harmful Algal Blooms").
- The desired agility and interoperability of the monitoring system will be underwritten by consistent adherence to and implementation of sound data management principles ("FAIR Principles: Data Services").
- There is a strong focus on stakeholder/end user perspectives for development of effective products ("Sensor and User Product Integrations: Innovation and Vision").

AUTHOR CONTRIBUTIONS

KP, BS, MH, and TS contributed conception and design of Smart Lake Erie pilot. MH and BP wrote the first draft of the manuscript. TK, TS, MH, and KP wrote the sections of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version of the manuscript.

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Conflict of Interest: TS was employed by company LimnoTech.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

GLOSSARY

Distributed Sensing - Distributed sensing is a technology that enables continuous, real-time measurements within a geographic area.

Automated Control - A control system manages, commands, directs, or regulates the behavior of other devices or systems using control loops. It can range from a single home heating controller using a thermostat controlling a domestic boiler to large Industrial control systems which are used for controlling processes or machines.

For continuously modulated control, a feedback controller is used to automatically control a process or operation. The control system compares the value or status of the process variable (PV) being controlled with the desired value or setpoint (SP), and applies the difference as a control signal to bring the PV output of the plant to the same value as the SP (from Wikipedia).

Interoperability - Interoperability is a characteristic of a product or system whose interfaces are able to work seamlessly with a defined set of other products or systems. Smart Cities Council, https://smartcitiescouncil.com/master-glossary.