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ARTICLE

Acoustic telemetry observation systems: challenges encountered and overcome in the Laurentian Great Lakes[1]

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Abstract: The Great Lakes Acoustic Telemetry Observation System (GLATOS), organized in 2012, aims to advance and improve conservation and management of Great Lakes fishes by providing information on behavior, habitat use, and population dynamics. GLATOS faced challenges during establishment, including a funding agency-imposed urgency to initiate projects, a lack of telemetry expertise, and managing a flood of data. GLATOS now connects 190+ investigators, provides project consultation, maintains a web-based data portal, contributes data to Ocean Tracking Network's global database, loans equipment, and promotes science transfer to managers. The GLATOS database currently has 50+ projects, 39 species tagged, 8000+ fish released, and 150+ million tag detections. Lessons learned include (1) seek advice from others experienced in telemetry; (2) organize networks prior to when shared data is urgently needed; (3) establish a data management system so that all receivers can contribute to every project; (4) hold annual meetings to foster relationships; (5) involve fish managers to ensure relevancy; and (6) staff require full-time commitment to lead and coordinate projects and to analyze data and publish results.

Résumé : Le système d'observation par télémétrie acoustique des Grands Lacs (GLATOS), mis sur pied en 2012, vise à faire avancer et à améliorer la conservation et la gestion des poissons des Grands Lacs en fournissant de l'information sur les comportements, l'utilisation des habitats et la dynamique des populations. GLATOS a fait face à différents défis durant son établissement, dont l'urgence d'entreprendre des projets imposée par les organismes de financement, un manque d'expertise en télémétrie et la gestion d'une quantité massive de données. GLATOS relie aujourd'hui plus de 190 chercheurs, fournit des conseils sur des projets, maintient un portail de données sur le web, fournit des données à la base de données planétaire de l'Ocean Tracking Network, prête du matériel et fait la promotion du transfert des connaissances scientifiques aux gestionnaires. La base de données de GLATOS compte actuellement plus de 50 projets, 39 espèces étiquetées, plus de 8000 poissons relâchés et plus de 150 millions de détections d'étiquettes. Les leçons tirées comprennent l'importance (1) de demander les avis et conseils d'autres intervenants avec de l'expérience en télémétrie, (2) d'organiser les réseaux avant que ne se présentent des besoins urgents d'échange des données, (3) d'établir un système de gestion des données pour faire en sorte que tous les récepteurs puissent contribuer à tous les projets, (4) d'organiser des réunions annuelles pour renforcer les liens, (5) d'inclure les gestionnaires des pêches pour assurer la pertinence des projets et (6) de prévoir le personnel à temps plein nécessaire pour assurer la direction et la coordination des projets, l'analyse des données et la publication des résultats. [Traduit par la Rédaction]

Introduction

Acoustic telemetry has become increasingly popular for investigating behavior, habitat preferences, and population dynamics of native and invasive fish in fresh and marine waters (e.g., Hussey et al. 2015; Cooke et al. 2016*a*; Lennox et al. 2016). Ecological topics that can be investigated include, but are not limited to, home ranges, spawning locations, habitat preferences, migration pathways, and species interactions. When tags include sensors (e.g., pressure–depth, temperature, and acceleration), projects can broach subjects such as energy expenditures required for migration, swim speeds, the characteristics of the environment surrounding fish (e.g., O_2, temperature), effects of stress, bioenergetics modelling, and predation events (Cooke et al. 2004, 2016*b*; Hussey et al. 2015; Halfyard et al. 2017). Topics important to fish management can be answered as well (Crossin et al. 2017), such as evaluation of the effectiveness of marine protected areas (MPAs; e.g., Lowe et al. 2003; Lea et al. 2016), identifying critical habitats for protection (e.g., Simpfendorfer et al. 2010; Riley et al. 2014), estimating sur-

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vival rate parameters important for yield estimation (e.g., Binder et al. 2016; Hayden et al. 2018), evaluation of artificial reefs (Szedlmayer and Schroepfer 2005; Reubens et al. 2013; Marsden et al. 2016), and invasive species control (e.g., Coulter et al. 2016; Holbrook et al. 2016*a*). Acoustic telemetry can be used to address questions about populations or repeatable patterns of individual fish at scales of metres to 1000s of kilometres and at time steps of minutes to years. In addition, detection data can be used to address research questions well beyond the stated research objectives of individual projects when detection files are shared among projects. Unexpected or unanticipated movement of fish past receivers can be especially revelatory to science and management (Grothues 2009).

Acoustic telemetry projects use receivers (with integrated hydrophones), usually anchored to the bottom that continuously "listen" for tagged fish. Acoustic tags, typically affixed externally to the fish or surgically implanted within the peritoneal cavity, transmit unique codes that identify individual fish. Tag life depends on several variables, including battery size, transmission power, and transmission frequency, with some transmitters lasting up to 10 years (Heupel et al. 2006). Projects conducted in large bodies of water usually have lines and arrays of receivers recording data 24 h a day from tags affixed to fish that transmit every few minutes. Receivers are deployed and maintained at fixed positions for variable lengths of time depending on a project's objectives. Receivers can be placed in a variety of configurations to detect fish at specific locations of interest (e.g., several in a line perpendicular to a shoreline) or throughout an area of interest (e.g., a grid of receivers throughout an embayment; Heupel et al. 2006). Closely spaced receiver grids with overlapping detection ranges can also provide two-dimensional positions accurate to within a few metres based on time-difference-of-arrival of the coded transmission at three or more receivers and, with repeated detections, provide paths or tracks over time (Espinoza et al. 2011). Three-dimensional positions in the water column are possible using coded depth-sensing transmitters (Cooke et al. 2005) or when water depth is sufficient to estimate depth based on time-difference-of-arrival among depth-stratified receivers (Ehrenberg and Steig 2003).

With the power of acoustic telemetry comes many challenges to researchers of projects using this technology. First, an individual researcher's ability to fund and manage a large network of receivers over an extended period is usually limited. Second, researchers often lack knowledge about spatial and temporal scales at which to deploy receivers. Third, when a large network of receivers is used, the spatiotemporal complexity of the data can generate an extensive set of potential questions for investigation, sometimes well beyond the original project's objectives. These data sets require a sophisticated level of data manipulation and analysis beyond the level of most graduate training. Identifying and prioritizing the most important and timely sets of questions for analysis involves advanced planning, discipline, and communication with resource managers.

A unique challenge of acoustic telemetry is that tag transmission data from multiple projects can be recorded by receivers shared across several projects. Receivers do not discriminate from among acoustic signals specific to a project, but record transmissions from all compatible tags within listening range, thus creating an opportunity to broaden the scope of individual projects through data sharing among researchers. Indiscriminate detection of all compatible transmitters by receivers within detection range also creates a need for coordination among projects to prevent overwhelming receivers with too many detections, which can result in data loss due to destructive code collisions (which occur when too many tags are within range of a receiver, overloading memory capacity of receivers and the ability of the receiver to properly decode the signal; Lacroix and Voegeli 2000; Heupel et al. 2006). When detection data are shared among multiple investigators and projects, a project's scope and scale can extend well beyond what could be justifiably budgeted for in a single project (Grothues 2009). Data sharing in concept, and the protocols used in data-sharing systems, present a challenge to project leaders, who may be possessive of research data, skeptical of large data systems, and not accustomed to conforming to common standards for data collection (Nguyen et al. 2017). Herein rests, in part, the motivation for establishment of telemetry observation systems to serve as networks that connect projects within a geographic area, to facilitate deployment of receivers to serve the needs of multiple projects, and to assist with data sharing among participating projects and investigators.

Over the past 15 years, acoustic telemetry observation systems have become established worldwide. Observation systems connect telemetry projects and their leaders with each other and provide opportunities to share equipment and data. In North America, these systems include Pacific Ocean Shelf Tracking project (POST; Welch et al. 2002; Jackson 2011), California Fish Tracking Consortium, Atlantic Cooperative Telemetry Network (ACT; Maine to Florida), Florida Atlantic Coast Telemetry (FACT) Network, and the Integrated Tracking of Aquatic Animals in the Gulf of Mexico (iTAG). Inland North America contains the Champlain Acoustic Telemetry Observation System (Lake Champlain; CATOS) and Great Lakes Acoustic Telemetry Observation System (Laurentian Great Lakes; GLATOS). Elsewhere globally, systems occur in Australia (Integrated Marine Observing System; IMOS) and South Africa (Acoustic Tracking Array Platform; ATAP). Some of these observation systems are hierarchically organized at a national level, such as within the US Animal Telemetry Network (Block et al. 2016). The global Canadian-led Ocean Tracking Network (OTN) links many of these regional, national, and international systems (e.g., IMOS, ATAP, and GLATOS) together through a global database and by providing personnel, advice, statistical tools, and equipment loans to researchers that participate in the network (O'Dor and Stokesbury 2009; Cooke et al. 2011; Hussey et al. 2015).

The Laurentian Great Lakes has lagged behind marine systems in the application of acoustic telemetry to fish ecology and management questions. Landsman et al. (2011) provided a review on fish movement studies in the Great Lakes and listed only seven of 112 papers as using acoustic telemetry, of which six used active tracking with hydrophones to follow fish, often for a duration of only minutes to hours before the tracking session was terminated (e.g., Kelso 1974). Only McGrath et al. (2003) used fixed station acoustic telemetry to test the potential feasibility of tracking American eels (*Anguilla rostrata*) adjacent to a hydroelectric plant in the St. Lawrence River, the outflow from the Great Lakes into the Atlantic Ocean. With few acoustic telemetry projects in the Great Lakes basin, little need existed during the early 2000s for the organization of a telemetry observation system. However, with advancements in telemetry technology combined with the research successes in the marine sector, use of acoustic telemetry in the Laurentian Great Lakes rapidly expanded during the next decade (e.g., Toronto Harbour project; Peat et al. 2016; Rous et al. 2017; sea lamprey (*Petromyzon marinus*) navigation; Holbrook et al. 2015; Meckley et al. 2014, 2017), which provided the motivation to organize an observation system and eventually led to the creation of GLATOS.

Here we describe the origins and history of the development of GLATOS, including problems, solutions, and lessons learned. The goal of this review is to highlight successes and failures, providing guidance and an organizational pathway and framework to establish new, viable telemetry observation systems elsewhere.

Genesis of the Great Lakes Acoustic Telemetry Observation System (GLATOS)

The events that led to the establishment of GLATOS began in March 2009 when the opportunity arose to apply for funding from the Great Lakes Restoration Initiative (GLRI), through the US Environmental Protection Agency (Fig. 1). An earlier planning document highlighted the need for observation systems to monitor biotic and abiotic parameters in the Great Lakes (EPA 2005, p. 56). Building on this recognized need, the Great Lakes Fishery Commission (GLFC) submitted a proposal to the GLRI program to establish three acoustic telemetry projects in the Great Lakes basin, which would in combination form a small observation system comprising only these projects. At the time, a basin-wide observation system serving hundreds of projects such as GLATOS was not envisioned. The GLFC was awarded US$2.1 million in 2010 for these projects. Unlike most research and monitoring programs, the funds received from GLRI were for only 1 year with final reports due late in 2011 and no assurance of additional funds. Therefore, expenditures of GLRI funds were always premised on the possibility that the current year could be the last year of funding.

A program development plan was adopted to ensure that the initial funds would provide lasting benefits if no other funds were received. The intent was to address high priority fishery management questions that required observations of fish at resolutions and scales that were not feasible with other technology (e.g., nets, traps, sonar). To be successful, such projects required procurement of substantial telemetry infrastructure (e.g., receivers and rigging, boats, water quality loggers), technical expertise, and data management systems. Thus, funds received in 2010 were used primarily to secure equipment and expertise needed to conduct studies of fish movement and with the hope that such investment would pay dividends long into the future regardless of future funding. Later, as these first three projects matured and more funding was secured, we came to recognize the need to develop a basin-wide telemetry observation system, not just for the original GLFC projects, but for all Great Lakes projects. However, the application of this technology in new projects and the establishment of a basin-wide acoustic telemetry network in the Great Lakes (GLATOS) faced several challenges.

Problem 1: urgency to get projects in the water

Based on the GLRI proposal, three projects were to be conducted from 2010 funds that focused on lake trout (*Salvelinus namaycush*), sea lamprey, and walleye (*Sander vitreus*) spanning Lake Huron, Lake Erie, the St. Marys River (connecting lakes Superior and Huron), and the St. Clair River – Lake St. Clair – Detroit River systems connecting Lakes Huron and Erie (SCDRS). The sea lamprey and lake trout studies were to focus on survival, behavior, and habitat use during spawning and would share receivers (i.e., receivers deployed in spring for sea lamprey would be removed and redeployed for lake trout in autumn). Notably, the lake trout study was to be achieved with the largest fine-scale telemetry array ever used to collect 2D fish tracks (140 receivers, ~25 km^2; Vemco Positioning System). In contrast, the walleye study was designed to monitor year-round movements throughout Lake Huron, the SCDRS, major spawning tributaries to Lakes Huron and Erie, and Lake Erie itself. Another project focused on lake sturgeon (*Acipenser fulvescens*) was begun in 2011 that leveraged GLRI-funded receivers with funds from the Great Lakes Fishery Trust. Like the walleye study, the lake sturgeon study required year-round receiver operation at sites throughout Lake Huron, the SCDRS, and Lake Erie. Notably, the walleye and lake sturgeon projects were overseen by two different project leaders and field crews in offices about 400 km apart, but required sharing data from the same receivers. Thus, a data management system was needed to receive, process, and distribute data between project leaders.

The difficulty of implementing these ambitious first projects was that no infrastructure existed within the GLFC or its partners to support such a large-scale endeavor. No experienced telemetry personnel were dedicated to the projects at the start. No equipment was available, such as receivers for deployment. All equipment for the projects were new purchases. No ongoing telemetry

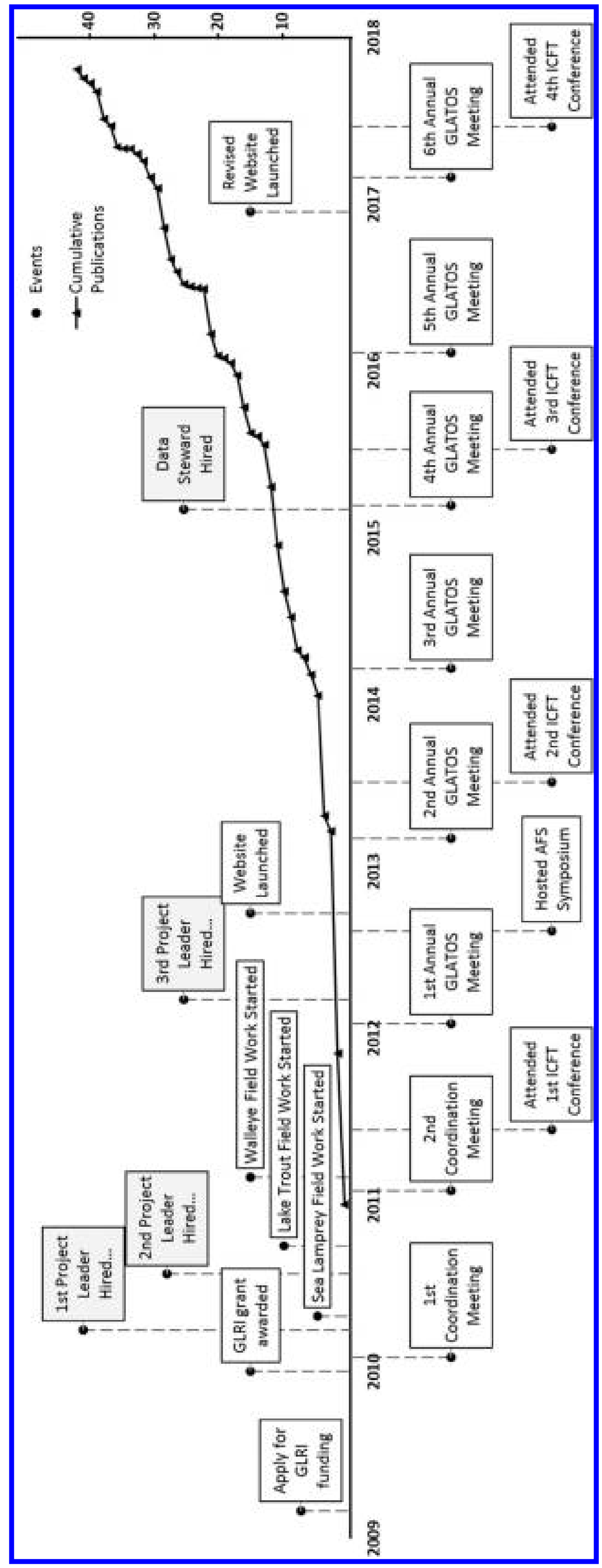


Fig. 1. Timeline of key developments in the establishment of the Great Lakes Acoustic Telemetry Observation System (GLATOS) and cumulative number of publications (as of 17 November 2017).

projects existed from which to immediately enhance and then be able to report some easy early results. This new large program, albeit well-funded, had to begin from a cold start and produce useful outcomes by the end of 2011.

The solution used, and not without considerable risk, was to begin immediately the sea lamprey, lake trout, walleye, and lake sturgeon projects. Ideally, pilot projects, consisting of thorough studies investigating equipment performance (e.g., range detection studies; Hayden et al. 2016) would have been conducted prior to project initiation; however, the short timeline precluded the possibility of pilot work. Instead, study designs, including estimating fish sample sizes, receiver array configurations, and tag specifications (e.g., nominal delays) required to address study objectives, were based on short-term field tests and simulation models. The simulation models have since been developed into data analysis tools in an R package for GLATOS members (see https://gitlab.oceantrack.org/GreatLakes/glatos). Some problems did arise as a result of not conducting pilot projects. For example, too many lake trout from Lake Huron were tagged, code collisions occurred when they returned to the Drummond Island spawning area, and substantial data loss resulted. The rush to conduct projects also resulted in other problems, such as the purchase of animation software to visualize tag detections through time that was overly complicated to use and limited in scope and receiver and synchronizing tag moorings that failed due to galvanic corrosion from using incompatible materials. In some cases, the rush to projects resulted in purchases of software and hardware and use of field methods that were not thoroughly tested, which ultimately hindered project implementation. These errors were quickly corrected after discovery.

Nevertheless, full-time personnel began to be hired in 2010 through the GLFC partners — Michigan State University and the US Geological Survey (USGS; Fig. 1). The first acoustic transmitters went into sea lamprey in May 2010, lake trout in August 2010, walleye in March 2011, and lake sturgeon in July 2011. A strategic decision was made to base most field operations out of USGS's Hammond Bay Biological Station on Lake Huron, because of its centrality in the Great Lakes basin. Risk associated with starting large projects immediately was somewhat ameliorated by successfully addressing the next challenge — the need to immediately import telemetry expertise.

Problem 2: lack of acoustic telemetry experts working in the basin

Whereas operating acoustic telemetry equipment may seem straightforward, successful application of acoustic telemetry to management problems requires careful consideration of tag specifications, receiver placement, choice of data analysis tools and methods, and writing papers for publication (Heupel et al. 2006; Grothues 2009). Thus, we discovered that tasking 10% or 20% of an existing personnel's time was insufficient for leading a project. Full-time attention to each project was required for successful implementation and completion.

Telemetry expertise was captured early in the form of project leaders (co-authors C.M. Holbrook and T.R. Binder) and advisors to projects (co-author S.J. Cooke; Fig. 1). However, in what was later considered a misstep, the walleye project was begun as a collaborative program, without a single leader for more than a year before a leader was recruited (co-author T.A. Hayden). Similarly, the project leader for the SCDRS lake sturgeon project had extensive additional agency responsibilities that slowed data analysis until additional personnel were hired to assist. In both cases, data analyses and paper publications were hampered until the personnel issues were addressed. Eventually, our strategy resulted in a team of project leaders with a range of telemetry expertise and Great Lakes experience so that those with less expertise and experience could learn from those with more. All project leaders received administrative supervision from their respective organizations and research direction from the GLFC and eventually from the GLATOS Director (co-author C.C. Krueger). To improve regional telemetry expertise, GLATOS personnel also attended the 1st International Conference on Fish Telemetry, Sapporo, Japan, in 2011 and hosted "Advances in telemetry in the Great Lakes and beyond" symposium at the 142nd Annual Meeting of the American Fisheries Society in St. Paul Minnesota, 2012 (Fig. 1).

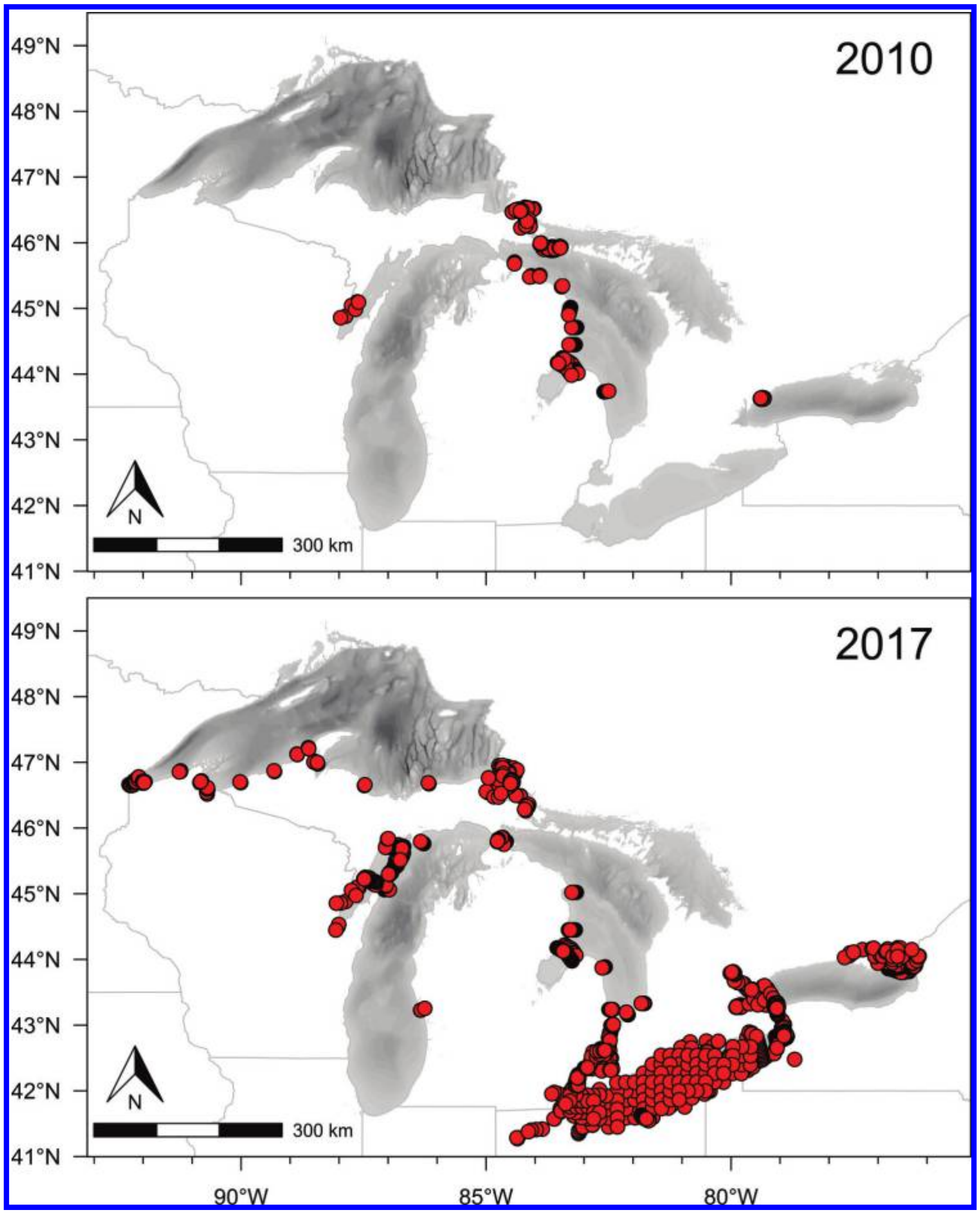
Problem 3: managing millions of tag detections and ephemeral receiver stations

Early in 2010, we recognized an impending data flood at scales that exceeded the training and experience of the typical fisheries scientist. The lake trout project alone recorded more than 7.2 million detections during September–November 2010, and by December 2011, 1153 receiver deployments had occurred for the three GLFC projects. The complexity and dynamic nature of receiver station data alone presented a challenge to data management and communication, much less managing the millions of tag detections. Unlike many other observation systems, operating schedules varied among receiver stations, ranging from a few months for sea lamprey and lake trout projects to year-round for walleye and lake sturgeon projects. For seasonally operated stations, the timing and location of each deployment was imperative to record and disseminate, as well as the status of data during the associated time interval. Even year-round deployments presented challenges as receivers were constantly shuffled among locations. In addition, new acoustic telemetry projects unrelated to the three GLFC projects were being implemented throughout the basin. We expected tags from these new projects would be detected by the core projects of the GLFC, and similarly, tagged lake trout, sea lamprey, walleye, and lake sturgeon would be detected on new receivers from other projects. The expanding use of acoustic tags created a critical need to share data and a need for investigators to discover other projects in the basin so they could interact and coordinate their projects to maximize potential benefits (e.g., sharing resources) and minimize negative interactions (e.g., code collisions and duplication of receiver deployments).

Project coordination and data sharing were addressed primarily through encouraging communication in three ways: face-to-face meetings, a website, and a data management system. First, early in 2010, a meeting of a small group of investigators assisting with the three GLFC telemetry projects was held in late winter to discuss project designs and to plan field operations (Fig. 1). This meeting was held again early in 2011 with a broader group of participants than before, including investigators not funded through GLRI funds, and was deemed highly successful due to its practical focus and discussion format. The meeting then was expanded in 2012 to include any Great Lakes investigators using acoustic telemetry. The purpose of these expanded "coordination meetings" was to invite leaders of new projects to present and discuss their research plans, for others to deliver progress reports of ongoing projects, and to provide the opportunity to attend workshops focused on a wide variety of topics from anchoring and recovering receivers to data analysis using R programming. Thus, 2012 began the expansion from an observation system that served only the needs of the GLFC projects to a broader system, GLATOS, that supported acoustic telemetry research basin-wide.

The successes of the new GLATOS meetings starting in 2012 have been such that researchers from outside the Great Lakes basin have participated, including researchers from Halifax, Nova Scotia (OTN), Lake Champlain (CATOS), Lake Winnipeg, and the Northwest Territories. Attendance has grown from 46 participants in 2012 to 95 participants in 2017, and in recent years attendance has been capped by the meeting venue's room capacity. Because of the informal format, leaders of Great Lakes projects have been able to directly interact with each other and to develop relationships and build trust, which has helped to minimize problems associated with data protectionism (i.e., instances where te-

Fig. 2. Active acoustic telemetry receiver deployments in the Great Lakes Acoustic Telemetry Observation System (GLATOS) in 2010 and 2017 (as of 17 November 2017).



lemetry users are unwilling to share detection data with the rest of the network) and has resulted in new collaborations and projects.

Second, a website was launched in 2012 that described the organizational structure of the newly formed GLATOS, offered general information about acoustic telemetry in the basin, and provided a map of receiver locations (Figs. 1–2), a tag search–query function, and descriptions of ongoing and recently completed projects. Projects were listed and described by location, species, receiver sites, and study objectives. The intended audience of the website was research investigators and the general public. The website later provided a data submission, retrieval, and sharing platform (see http://glatos.glos.us/). Instead of maintaining its own separate domain and server, GLATOS partnered with the Great Lakes Observing System (GLOS) to assist with web site development and hosting of the GLATOS web site. GLOS is a regional partnership of academic institutions, industry, state and federal agencies, and nongovernment organizations who collaborate to deliver Great Lakes water and weather information. GLOS is the Great Lakes node of the Integrated Ocean Observing System (US IOOS), which works with regional partners to ensure compatible and consistent ocean and coastal data collection and management.

Third, a data management system was developed to allow project leaders to submit, retrieve, and later share data. Learning from the experiences of OTN and ACT and recognizing the need to gain buy-in from project leaders, the data system was intentionally designed to be as simple as possible and to provide a service to researchers. Initially, the database only contained receiver station, fish, and tag information; detection data were added in 2014. To simplify data submission and ensure global interoperability, the data structure adopted was based on the OTN data structure after slight GLATOS-specific modifications, and receiver and tag metadata were entered and submitted via a standardized spreadsheet. The data format used allows Great Lakes data to be easily exported to OTN's global database, and in 2015 GLATOS announced plans to become the Great Lakes node for OTN. Over time, the data system has been expanded and improved as needs have been identified and funding had been secured. A full-time data manager (co-author N. Nate) was hired in 2015 due to the increasing data management workload caused by the growth of acoustic telemetry in the basin (Fig. 1). Currently, investigators registered with GLATOS have access to a secure data portal for uploading their tagging, receiver, and detection data; basin-wide summaries of all receiver locations; and a mechanism for searching for mystery tag identification codes (i.e., an unknown tag ID detected by a project's receiver) from a summary of all tag identification codes compiled across projects. Only project leaders, or members authorized by a project leader, can access detections of their tagged fish. Access to detections of tagged fish from other projects without permission is not allowed. In this way, project leaders maintain control over their own research data. Recognizing that data sharing is a sensitive topic and policies about data ownership may differ among institutions and funding sources, GLATOS developed a data-sharing policy that defers decisions about data sharing to the individual researcher and their home institution. This approach has resulted in a high rate of participation among researchers in the Great Lakes basin. Website and data management have become key strategic issues for GLATOS that require full-time focused attention and effort from a data manager. The ability to access detection data of any tagged fish across the entire receiver network is a keystone service of the GLATOS data system.

Current status of GLATOS

GLATOS established a purpose statement in 2012 as follows: to advance and improve conservation and management of Great Lakes fishes by providing information on fish behavior, habitat use, and population dynamics. In support of this purpose, GLATOS now provides and supports the following:

- **A network of researchers** — GLATOS connects 195+ investigators using telemetry in the basin representing 45+ agencies and universities via annual coordination meetings, workshops, the website, and the database.
- **Consultation services** — GLATOS personnel facilitate collaboration and coordination within and among projects to (1) maximize capital resources such as receivers, (2) ensure study objectives are well defined and compatible with other projects, (3) minimize conflicts in study designs among projects, (4) improve aspects of study designs such as receiver locations and tag specifications, and (5) advise on data analyses. An R package, hosted by OTN, also has been developed to assist users of acoustic telemetry with data manipulation and exploration.
- **Data archiving and management** — GLATOS maintains a database of acoustic telemetry data that includes tag IDs, receiver locations and schedules, and tag detections. Receiver and project-specific tag detection data are shared among investigators. A full-time data manager facilitates data submission and retrieval. To encourage participation, GLATOS simplified requirements for data submission and protected data ownership. Thus, the data management system was developed as both a service to project leaders and as a data warehouse.
- **Equipment** — GLATOS has an inventory of equipment, notably acoustic receivers. Receivers are provided on loan to individual projects. Projects raise funds independently to purchase tags and support project-specific field operations. Loans of receivers allow small projects with minimal funds to be realized without the large capital investment of receivers. GLATOS has also benefited from a long-term loan of receivers from OTN, which further enhanced tag listening capabilities in the Great Lakes.
- **Science transfer** — GLATOS promotes scientific publication and encourages presentations at scientific symposia and meetings of Great Lakes fish management committees. Forty-two peer-reviewed journal articles were published from 2010 to 2017 (Fig. 1). Publications are highlighted and available for download via the GLATOS website. Presentations are made annually to lake managers who attend the Lake Committees meetings organized by the GLFC (http://www.glfc.org/joint-strategic-plan-committees.php).

As of November 2017, a total of 59 projects were registered with GLATOS, with projects occurring in all five Great Lakes. These projects have tagged 39 species, made 7800+ receiver deployments, released 8000+ tagged fish, and provided more than 150 million fish tag detections to the GLATOS database. Over the past 8 years, the GLATOS receiver network has grown throughout the Great Lakes basin (Fig. 2; see https://youtu.be/6y_oO7cM8PE).

GLATOS has affected fish management in the Great Lakes. For example, results from sea lamprey studies contributed to decisions (1) not to pursue lock-and-dam refurbishment to block migrating sea lampreys in the Cheboygan River but to pursue evidence of a landlocked population upstream (Holbrook et al. 2014; Johnson et al. 2016); (2) to discontinue releases of sterile male sea lampreys in the St. Marys River (Bravener and Twohey 2016; Holbrook et al. 2016*b*); and (3) to consider sterile-male releases as a possible control method in the St. Clair River (Holbrook et al. 2016*a*). Cormack–Jolly–Seber models used to estimate annual spawning site fidelity rates for tagged lake trout in the Drummond Island Refuge, Lake Huron (Binder et al. 2016) produced annual adult survival estimates that were incorporated into Lake Huron harvest models used by the management agencies for evaluating fishery regulations. Similarly, Hayden et al. (2018) used the GLATOS network to estimate spawning site fidelity rates for the Maumee River walleye stock in Lake Erie, information that was unknown to fishery managers responsible for setting safe harvest quotas for this multistock fishery (Vandergoot et al. 2010; DuFour et al. 2015; Hayden et al. 2018). Finally, the finding that most walleye tagged during spawning in a Saginaw Bay tributary moved to Lake Huron after spawning (Hayden et al. 2014, 2018) was instrumental in the recent management action to liberalize walleye angler bag limits in Lake Huron.

Lessons learned

Six lessons are provided to summarize what we have learned over the past 8 years about organization of a telemetry observation system and reflect our experiences and observations concerning the rapid adoption of acoustic telemetry in the Great Lakes and the concurrent development of GLATOS. Some of these lessons may be self-evident based on the information provided above or are intuitive, yet we list them here to emphasize our belief of their importance when establishing a large-scale, collaborative telemetry observation system. The lessons may be transferrable to existing observation systems, especially those that, like GLATOS, are networks of people, agencies, and data and with receiver stations constantly changing. The last two lessons also relate to conducting and managing telemetry projects in general.

Seek advice

Be willing to take advice and learn from others experienced in telemetry. With the rapid adoption of acoustic telemetry for marine and freshwater research and the establishment of coastal observation systems, several of which have been in place for more than 10 years, a wealth of experience is available to help guide the establishment of new telemetry observation systems. As an example, in 2010 and afterward, we sought advice from leaders within POST and OTN and from VEMCO (Halifax, Nova Scotia, Canada), a major supplier of acoustic telemetry equipment (https://vemco.com/). In addition, we sought advice from individual researchers about how to get our projects started.

Organize your network early

GLATOS was established in 2012 prior to widespread adoption of acoustic technology within the Great Lakes basin. We believe early establishment of the GLATOS network helped to enhance researcher participation, as evidenced by the numbers of registered researchers and projects and widespread participation in the data-sharing platform. As new projects were established, we routinely interacted one-on-one with individual researchers to explain the importance of data sharing to their projects (i.e., access to basin-wide tag detection data) and to counter reluctance and concern among some to share their data. Advice from others (see above) warned of the problems that can occur when trying to organize an observation system after the data-sharing need becomes acute. We did not wait until the issue became critical, but foresaw the problem on the horizon and addressed it.

Establish a centralized data management system

A data system provides a wide range of services, including mechanisms for data discovery, archiving, recovery, and distribution. A dedicated support person within GLATOS facilitates the process of data formatting, submission, and retrieval, thereby minimizing the burden on individual researchers. Data sharing leverages resources from individual projects and yields synergistic benefits by having all receivers contribute to every project. As a result, data sharing enhances and promotes participation in the network because of the increase in geographic coverage for every project and the ability to better assess the fate of tagged fish. Importantly, data sharing is not limited to fish detections, and project leaders also benefit from standardized, automated, repeatable methods for distributing receiver station data to other project leaders and members.

Face-to-face communications are essential

Whereas email and the internet provide easy communication channels, face-to-face communication allows researchers to connect a name with a face and personality. GLATOS annual coordination meetings and workshops promote project discovery and help new investigators get advice and learn from experienced telemetry researchers. Immediate feedback is provided on new projects and their designs prior to implementation. In particular, we discourage participants from falling into "let's tag some fish and see where they go" type projects, but instead encourage new investigators to have clear, concise study objectives, often working with them to formulate research questions, hypotheses, and objectives. Pilot studies are also encouraged as a first step of new projects so as to identify unexpected logistical difficulties prior to full-scale project implementation. In addition, during annual meetings, experiences are shared, problems presented, and solutions suggested via project presentations and the discussions that follow. As a result of our meetings, relationships were formed among investigators, and likely this aspect contributed to building trust among investigators and ultimately promoted GLATOS membership and data sharing.

Directly involve fishery managers

Each of the original four projects undertaken in 2010–2011 had fishery managers as co-investigators on the project proposals, and their involvement continued throughout project execution, including co-authorships on journal publications. Managers helped to ensure that research was relevant to the decision-making process and created agency buy-in to the project and to the credibility of the information being obtained. Agency ownership in the projects led to contributions of personnel, vessel time, and additional funds to purchase tags and receivers. Managers regularly attend GLATOS annual meetings, and several have initiated telemetry projects with funding from sources outside the GLFC.

Plan and budget sufficient time and money for data analysis

One exceptional challenge across projects has been the size and complexity of data sets generated from telemetry studies creating a data analysis burden. Of the project leaders brought initially into the GLATOS program, each have said at one time or another that data management was a major challenge. One approach to address this issue was the development of publication plans. Plans listed specific questions, hypotheses, and objectives that formed the basis for potential papers, often including papers beyond the original scope of individual projects relying on combined data sets across more than one project (e.g., Binder et al. 2017). This approach helped to clarify and focus data analyses and clearly identified who would lead the analyses (typically the project leader).

Data analyses often required that millions of tag detections were filtered for false detections, bundled into appropriate time intervals, and organized geographically to address specific questions. These activities cannot be efficiently performed with typical spreadsheet software and require a high level of sophistication in data handling. Such intensive analysis is often difficult for individuals tasked with other obligations such as stock assessment and fishery management-related activities (e.g., public outreach). Instead, near full-time attention to a project is required if telemetry data are to be properly analyzed and interpreted and to ensure timely reporting of project results in manuscripts and presentations. As a result, a high proportion of GLATOS financial resources was dedicated to supporting full-time scientists to lead and conduct projects and to disseminate study findings.

Some promising new projects, while relevant and of management importance, were not undertaken to ensure sufficient funds were available to support personnel to complete analysis and publication of existing data sets. Early telemetry results were exciting and sometimes stimulated investigators to want to tag more fish and deploy more receivers, but would have resulted in needing to add additional staff to cover the additional workload. With varying levels of success, this type of "project-creep" was discouraged or slowed.

Conclusion

Acoustic telemetry projects organized within an observation system with data sharing provide extraordinary data sets suitable to answer a variety of ecological and management questions at a scope and scale never before possible in fishery science. Telemetry projects in the Great Lakes are not independent entities, but have a dependency on other projects to access tag detections from receivers from other projects. Development and operation of GLATOS was guided by adaptive learning when errors were made and on the advice of others already conducting telemetry projects and managing observation systems. Undoubtedly, some of the success of GLATOS has been due to consistent funding over 8 years from GLRI, although GLATOS financial management has been guided by the uncertainty of future funding. With benefits to science and fishery management accruing, our hope is that GLATOS will persist into the future, that it will continue to address questions relevant to the sound management of Great Lakes fisheries, and that it may serve as a model for other regional telemetry observation systems.

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