SUBPROJECT TITLE: MAISRC Subproject 19: Decision-making tool for optimal management of AIS
SUBPROJECT MANAGER: Dr. Nicholas Phelps
AFFILIATION: University of Minnesota Department of Fisheries, Wildlife and Conservation Biology
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WEBSITE: http://www.maisrc.umn.edu
FUNDING SOURCE: Environment and Natural Resources Trust Fund (ENRTF)
LEGAL CITATION: M.L. 2013, Chp. 52, Sec. 2, Subd. 06a

SUBPROJECT BUDGET AMOUNT: $172,465
AMOUNT SPENT: $80,469
AMOUNT REMAINING: $91,996

Sound bite of Subproject Outcomes and Results
We optimized network models for water connectivity and boater movement in Minnesota to predict zebra mussel and Eurasian watermilfoil invasion patterns. We then developed county-based recommendations to prioritize the optimal location of watercraft inspectors. The approach was piloted with Crow Wing, Ramsey, and Stearns Counties, and the results broadly disseminated.

Overall Subproject Outcome and Results
Understanding the patterns of historic AIS invasion can provide the framework for forecasting future invasions. To that end, we used a big data approach to combine hydrologic connectivity and boat movement to create a multiplex metacommunity model for both zebra mussel and Eurasian watermilfoil. We found that the hydrological corridors are important pathways of spread, even more so that previous research has suggested. While overland dispersal of AIS via boater movement is still a significant factor, additional management strategies should be developed to include intervention of hydrological pathways.

Using connectivity networks of boater movement, we developed county-based AIS management optimization models that prioritize inspection locations that will intercept the highest number of ‘risky boats’ (e.g. moving from infested to uninfested lakes). We piloted the models in Crow Wing, Ramsey, and Stearns Counties and had a very productive collaboration with county managers and citizen advisory boards during the development and evaluation for each. Ultimately, the application of this approach was well received and helped inform allocation of their inspection hours at the county level (for example: https://www.crowwing.us/1004/Aquatic-Invasive-Species-AIS).

Dissemination and usability of the models was a priority of this project. We created online tools to 1) visualize the spread risk for zebra mussels and Eurasian watermilfoil based on model predictions made in Activity 1, and 2) visualize and modify the decision optimization model at the county level based on management thresholds or funding availability. These tools and more detailed descriptions of the project have been disseminated through in-person stakeholder meetings and presentations to diverse audiences, including managers, researchers and the public.

Subproject Results Use and Dissemination
Efforts were made throughout the project to engage end-users, share findings and make deliverables broadly available. We used a combination of formal and informal dissemination strategies for this project given the
direct application to AIS managers and broad interest among other stakeholders. We held in-person meetings with County representatives and citizen advisor boards from Crow Wing, Ramsey and Stearns Counties to present results and update our models according to their input. These meetings were highly valuable to the project team and the outcomes of the project. In addition, we provided scientific and/or outreach presentations at the International Conference on Aquatic Invasive Species, the Aquatic Invaders Summit, the Cass County Watercraft Inspectors annual training, the annual AIS Roundtable, and MAISRC’s Research and Management Showcase. Several publications are currently in late-stage drafts and will be submitted for peer-review in the coming months.
Date of Report: August 16, 2019

Final Report

Date of Work Plan Approval: July 6, 2017

Sub-Project Completion Date: June 30, 2019

Project Completion Date: June 30, 2019

SUB-PROJECT TITLE: MAISRC Sub-Project 19: Decision-making tool for optimal management of AIS

Sub-Project Manager: Dr. Nicholas Phelps

Organization: University of Minnesota/Minnesota Aquatic Invasive Species Research Center

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Location: Statewide

<table>
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<th>Total ENRTF Sub-Project Budget:</th>
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<tr>
<td>Sub-Project Budget: $172,465</td>
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Legal Citation: M.L. 2013, Chp. 52, Sec. 2, Subd. 06a

Appropriation Language:
$4,350,000 the first year and $4,350,000 the second year are from the trust fund to the Board of Regents of the University of Minnesota to develop and support an aquatic invasive species (AIS) research center at the University of Minnesota that will develop new techniques to control aquatic invasive species including Asian carp, zebra mussels, and plant species. This appropriation is available until June 30, 2019, by which time the project must be completed and final products delivered.
I. **SUB-PROJECT TITLE:** Decision making tool for optimal management of AIS

II. **SUB-PROJECT STATEMENT:**
Effective management of aquatic invasive species (AIS) in complex and dynamic systems, considering variable needs, values, and constraints, has proven difficult. AIS managers at the local and state levels urgently need science-based tools to inform planning and decision-making. For example, mathematical and optimization models using robust and updated information can be used for developing effective intervention strategies, predicting impacts, testing what-if scenarios, increasing stakeholder buy-in, and designing cost-effective surveillance programs to mitigate and prevent AIS spread. We have been moving in this direction with previous and ongoing research led by the Project Manager and collaborators to describe environmental suitability and pathways of spread for high priority AIS. We have reached a point where the previously developed risk maps could be incorporated into dynamic system models to visualize risk and evaluate optimization approaches for management.

*The aim of this proposal is to build upon and refine previous research to develop and deploy a decision-making tool for optimal management intervention on a county and statewide scale to minimize the spread of high priority AIS.*

Based on the dynamics of AIS and the systems in which they live and move, we will develop models to forecast the invasion of zebra mussels and Eurasian watermilfoil in Minnesota at the lake level. These models will be subjected to strict verification and cross-validation to ensure confidence in model predictions. The risk scores for each waterbody will then be used to inform AIS management optimization models at the county level. Optimization models are a useful approach to identify a set of actions that make the best use of available resources while achieving a desired outcome. Therefore, in addition to the risk scores, values and management objectives such as types of lakes to prioritize for prevention (e.g. All lakes equally? Large/popular lakes?) will be incorporated to recommend the allocation of available funds and strategic locations for prevention and control activities to reduce the risk of new AIS introductions within each county. Similarly, cumulative risk models will be developed to help inform statewide allocation of the County AIS Prevention Aid, compared to the current approach of total boat ramps and parking spots. Local and state AIS managers will be engaged throughout the project to ensure consistency with management goals and realities. Ultimately, the models will be visualized through a user-friendly and interactive application for online or mobile viewing to empower AIS management stakeholders.

III. **SUB-PROJECT STATUS UPDATES:**

**Sub-Project Status as of January 26, 2018:**
The project is progressing largely as expected, despite a small delay in data availability. For Activity 1, the first step in developing the AIS risk estimates for each lake in Minnesota is complete, with the creation of a hydromorphological network models. As hypothesized, the model suggests that while water connectivity is important (explains ~35% of distribution for ZM and EWM), other factors are clearly influencing the spread of AIS. In the coming months, we will be adding other variables, such as environmental suitability and boat movement, to increase complexity and predictability of the models. For Activity 2, a theoretical optimization model has been created to conceptually evaluate AIS management tradeoffs, considering prevention (focus on uninfested lakes), containment (focus on infested lakes), or a mix of the two. We have found with early conversations that the DNR’s strategy has been largely focused on containment, while most local groups have largely focused on prevention. We will continue to explore various scenarios with two counties (likely Ramsey and Crow Wing) in the coming months. As expected, there has been no progress on Activity 3.

Amendment Request (1/26/18):
For Activity 3, an amendment is being requested to reduce one service contract identified in the budget and add another service contract. Currently, the allocated contract funding for TheBlackTechGuy is $25,000 for website and app development. We are requesting that funding be split for $15,000 to TheBlackTechGuy for strictly the app development and $10,000 to SMART Solutions for Questions and Decisions model website and web-service in connection to the dynamically updated predictions of the multiplex network metacommunity model. Both contractors have been selected according to the University of Minnesota policies. This amendment request does not change the scope of the project, timeline or overall budget.

Amendment Approved by LCCMR 1/31/2018.

Sub-Project Status as of July 31, 2018:
This has been a productive phase of the project, with additional data made available with the completion of MAISRC SubProject #13. Significant progress has been made with the multiplex metacommunity model development. With the application of the model, we verified the importance of the Hydrologic Network (HN) to be higher for Zebra Mussel (ZM) than Eurasian Watermilfoil (EW); the latter seems more affected by local environmental variability and characterized by a more confined dispersal. ZM and EW fluctuate more proportionally to systemic runoff and local rainfall, respectively. Thus, runoff as an output from lakes informs a more dynamic risk determinant of species invasion vs. local lake features. Certainly, it is clear that it is not sufficient to consider only the environment as a determinant of a higher or lower chance of species invasion downstream or upstream an invasive population. Furthermore, these results emphasize once again the importance to consider physical basin boundaries rather than political lines for effective management. This paradigmatic shift creates some tension with the management of AIS because a basin can belong to different counties and decisions are typically taken at the county scale. These models are being incorporated into a new application that can be used to visualize risk of AIS.

We have also begun to evaluate ‘optimal management scenarios’ based on the data available for lake connectivity and suitability. We evaluated Ramsey and Washington counties to inform the location of a limited number of watercraft inspection sites to intercept the largest number of ‘at-risk’ boats. The mathematically optimal results have been counter-intuitive to some, demonstrating this as a valuable exercise for managers. We will continue to develop these models for other counties and a statewide approach in the months to come.

Sub-Project Status as of May 6, 2019:
This project continues to produce interesting and impactful results. Activity 1 has been wrapping up with final data analysis and preparing the manuscript for submission. It is clear from this work that a multiple risk factors must be included when estimating the risk of future AIS invasion – it is not simply only boats or water connection, rather a complex interaction between the two (and likely many more). The results from Activity 2 have been excellent, with the optimized watercraft inspection model piloted in three counties (Crow Wing, Ramsey, Stearns). The findings largely supported current plans, however there were examples in each county where the current plan could be modified to improve outcomes. We have worked closely with each county to communicate these results. We are now working on the generic model that can be applied to all counties. Lastly, progress has been made on Activity 3 with the development of an online visualization tool for the metacommunity model. However, given significant salary savings and complimentary research beyond the scope of the workplan, we feel there is a major opportunity to further develop an online tool for data visualization (see amendment request below).

This project is on schedule to end on June 30, 2019 and will not be continued in a Phase II.

Amendment Request May 9, 2019:
Amendment 1
Due to time constraints, MAISRC has withdrawn the Amendment 1 request.
Move $30,000 from Activity 1 Personnel and $10,600 from Activity 3 Personnel, to new Professional Service Contract: Epi-interactive in Activity 3.

Data visualization is a key component of this project (Activity 3) to provide a useful tool for stakeholders to understand, interpret and ultimately use our results. The massive size and complexity of our data provides a great opportunity, but at the same time has created significant challenges for our initial plan and contractor (for more details see Activity 3: Jan 31, 2019 update). We have identified another contractor (Epi-interactive: https://www.epi-interactive.com), a New Zealand based company, that has a history of creating interactive online visualization platforms for clients around the world (including the University of Minnesota; ie. https://www.epi-interactive.com/our-work) with data sets that are as large and complicated as ours.

We request a rebudget of surplus personnel funds to fund a new contract with Epi-interactive. The contract will include development of a visualization tool to see color-coded lake-level risk scores, with pop up boxes for more information and filtering options. In addition, the tool will visualize two weighted/directional network layers for boat movement and water connectivity. Stakeholders will be able to select networks and areas/lakes of interest to see connections and associated risk. The tool will also be built with the plan to add complexity and dynamic simulations in the future as funding is available. Funding for this version will be provided from significant personnel cost savings since a graduate student was not hired full time on this project.

Amendment 2
Move $10,000 from Activity 2 Personnel to Activity 2 Professional Service Contract: GAMS-CPLEX, increasing the total GAMS-CPLEX budget to $20,000.

We request a rebudget of surplus personnel funds to purchase the software GAMS-CPLEX. The software was purchased early in the project, but the license has expired. There are additional analyses we would like to run in the final two months of the project that would benefit from purchasing the software again. Funding for the software update will be provided from significant personnel cost savings since a graduate student was not hired full time on this project. At the close of Subproject 19, GAMS-CPLEX software will continue to be used for related AIS research, until the new license expires.

Amendment Approved by LCCMR: 06/13/2019

Overall Sub-Project Outcomes and Results:
Understanding the patterns of historic AIS invasion can provide the framework for forecasting future invasions. To that end, we used a big data approach to combine hydrologic connectivity and boat movement to create a multiplex metacommunity model for both zebra mussel and Eurasian watermilfoil. We found that the hydrological corridors are important pathways of spread, even more so that previous research has suggested. While overland dispersal of AIS via boater movement is still a significant factor, additional management strategies should be developed to include intervention of hydrological pathways.

Using connectivity networks of boater movement, we developed county-based AIS management optimization models that prioritize inspection locations that will intercept the highest number of ‘risky boats’ (e.g. moving from infested to uninfested lakes). We piloted the models in Crow Wing, Ramsey, and Stearns Counties and had a very productive collaboration with county managers and citizen advisory boards during the development and evaluation for each. Ultimately, the application of this approach was well received and helped inform allocation of their inspection hours at the county level (for example: https://www.crowwing.us/1004/Aquatic-Invasive-Species-AIS).

Dissemination and usability of the models was a priority of this project. We created online tools to 1) visualize the spread risk for zebra mussels and Eurasian watermilfoil based on model predictions made in Activity 1, and 2) visualize and modify the decision optimization model at the county level based on management thresholds or
funding availability. These tools and more detailed descriptions of the project have been disseminated through in-person stakeholder meetings and presentations to diverse audiences, including managers, researchers and the public.

IV. SUB-PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Development of a multiplex network metacommunity model for AIS

Description: Mathematical models can be developed to understand a wide variety of complex systems and interactions. In the case of AIS, we have previously used two primary types, Maxent models (e.g. environmental suitability) and network models (e.g. connectivity). Our research shows that these models can predict invasion far better than chance – a useful tool when prioritizing management efforts. Integrating these two models and visualizing risk on the landscape is the next step.

In Activity 1, we will develop a new multiplex network metacommunity (MnM) model to forecast the invasion of zebra mussels and Eurasian watermilfoil. To summarize our approach, we will first evaluate the role of invasion drivers, including water connectivity and boat movement. For each type of connection, we have already created a matrix of all Minnesota lakes as part of MAISRC SubProject 13. The matrix for water connectivity includes both direction and river distance, and we aim to add rate of flow as part of this Activity. The matrix for boat movement includes the number of boats and direction of travel. We will update the existing matrix with new data provided by the MN DNR watercraft inspection program during the course of this Activity. These invasion drivers will incorporate lake-specific demographics for AIS suitability developed as part of MAISRC SubProject 13 to answer the question ‘if the AIS arrives, can it survive?’ Parameters of connectivity and suitability will be incorporated into a mathematical model, similar to:

\[
\frac{dx_i}{dt} = M_0(x_i(t)) + \sum_{j=1}^{N} A_{ij} M(x_i(t), x_j(t))
\]  

(1)

We will begin with this general reaction diffusion model, where species are within defined boundaries and then include ‘noise’ to consider variability of the environment and other factors. The outputs from this model will provide a lake-specific risk score for establishment of zebra mussels and Eurasian watermilfoil.

For each model prediction, validation will be performed comparing the model’s predicted outcome with historical AIS spread within Minnesota based on speed, extent, and pervasiveness of invasion. Ultimately, by using non-linear analyses and uncertainty estimates, we will learn from the invasion histories of zebra mussels and Eurasian watermilfoil in Minnesota to forecast future areas associated with high risk. Generating these risk maps is critical to informed and optimized decision-making in Activity 2.

All findings will be widely available through MAISRC communications (i.e. website, newsletter, social media, presentations, etc), one scientific presentation and one peer-reviewed open access publication.

Summary Budget Information for Activity 1:

| ENRTF Budget: $62,250 |
| Amount Spent: $15,678 |
| Balance: $46,572 |

Activity Completion Date:

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<th>Outcome</th>
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<tr>
<td>1. Development and validation of multiplex network metacommunity (MnM) model</td>
<td>May 2018</td>
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<tr>
<td>2. Result dissemination: MAISRC communications, scientific presentation, peer-reviewed publication</td>
<td>August 2018</td>
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Activity Status as of January 26, 2018:
The first step of the MnM model was the creation of a high resolution hydrogeomorphological network from the Digital Elevation Model. We created this network that is the most detailed representation of the hydrological connections between areas in the state of Minnesota. These hydrological connections are useful within hydrologic units (HUs) that described connected by independent subcatchments in MN. The Watershed Boundary Dataset (WBD), that provides information of the full areal extent of surface water drainage for the U.S., uses a hierarchical system of nesting hydrologic units at various scales, each with an assigned hydrologic unit code (HUC). These codes have been used to identify HUs. Below in Figure 1 we report the “HUC 8” map that comprises the subbasins whose scale is analogous to medium-sized river basins, and predictions that were made assuming only the hydrological network were responsible for AIS spread.

Figure 1. Preliminary results of the MnM model for AIS in MN. The model is run considering the yearly data and the HUC spatial scale. In red and in blue the data and cumulated confirmed invaded HUs are shown. The predictions are only based on the hydrologic network (Eq. 1) without the incorporation of the local suitability and the boat mobility network. On average for both Zebra Mussel (ZM) and Eurasian watermilfoil (EW) we predict 35% of total invaded HUs as reported by data. The plots show the total invaded HUs considering the total HUs in MN. Thus, we see that in MN about 33% of HUs are invaded by ZM and 55% by EW. The gap between model predictions and data is larger for EW since EW is less mobile than ZM whose dispersal can be more easily facilitated by water flow; in other words, ZM has a higher dispersal ability than EW through the river network as confirmed by the average dispersal factor inferred from data. Despite the lower dispersal ability of EW we notice a relatively higher spread velocity of EW than ZM; however, this is only partially reported by the model.

The further overall goal of the study is to provide a mid-level complexity model with respect to previously developed statistical (see Kanankege et al., 2018) and physical-based models (see Mari et al., 2011). This goal is carried out by identifying the optimal transmission networks along which AIS spreads; these networks are also optimal information networks (OINs) for the constructed predictive models. Optimal transmission networks are the most informative networks derived from data analytics or raw data at an optimally identified spatio-temporal scale that predict with the highest accuracy the AIS invasion patterns. These networks are typically coinciding with OINs derived via data analytics on the spreading patterns.

As a future step, we also wish to quantify the information, complexity, scale trade-off landscape where: (i) information is dictated by the amount of data included in the model; (ii) complexity is related to the level of sophistication used to characterized each variable (which may be related to the quantify of data); and (iii) scale refers to the spatial and temporal scales used to represent AIS patterns. As a last step we will perform a non-
linear analysis of time series data to determine other quantities such as the regularity and average persistence time of AIS in a location, as well as to perform a global sensitivity and uncertainty analysis of the model. This exercise can identify areas where to have better monitoring of AIS either because of the intrinsic uncertainty in data or because of the consistent departure between reports and model predictions. A web application will be developed as part of Activity 3 to post all AIS spread predictions based on updated report and hydrological data determining the local suitability layer and affecting the effective hydrologic network. An app will also be developed to report AIS.

**Activity Status as of July 31, 2018:**

Significant progress has been made in development of the multiplex metacommunity model (“M3”) by representing the Minnesota ecosystem in pixels, from the NASA Digital Elevation Model (DEM) whose minimum resolution is 25m² (8/9/19: this has been updated to 90 m² considering the resolution invariance up to 90 m²). Pixels are associated to river basins and the model is run at the USGS hydrologic unit (HU) scale. The river network is derived from the DEM and the boat network is calculated considering the radiation model on previous boat density data. Via the application of the model we, verified the importance of the Hydrologic Network (HN) to be higher for Zebra Mussel (ZM) than Eurasian Watermilfoil (EW); the latter seems more affected by local environmental variability and characterized by a more confined dispersal. ZM and EW fluctuate more proportionally to systemic runoff and local rainfall, respectively. Thus, runoff as an output from lakes informs a more dynamic risk determinant of species invasion vs. local lake features. Certainly, it is clear that it is not sufficient to consider only the environment as a determinant of a higher or lower chance of species invasion downstream or upstream an invasive population.

Without the consideration of the river network (RN) the risk of invasion that is calculated by the model is about 30% lower than the risk with RN and that underestimation affects the network dependent zebra mussel more than EW. Additionally, we find that the amount of risk/presence related to streams vs. lakes is 65% vs. 35%; the latter seems to concentrate on lakes belonging to the Upper Mississippi basin where invasion of EW is very widespread. These results underline the importance of considering the hydrological network vs. just lakes (or lake connectivity); the hydrological network is acting not just as a spreading corridor for AIS but also as an ensemble of connected host sites with high persistence time for AIS.

As for assessing the importance of “inter-basin risk transfer” (that occurs when one or more “infected” boats are moved from one basin to another) a calculation can be made by considering the full boat network (both within and between river basins) and the boat network only along the hydrological networks. It results that the difference in the predicted risk in both scenarios is only 5% more or less. This result highlights the fact that at least with these data available the inter-basin transfer of boat is really a secondary issue (at least in a predictive risk sense). These models will be updated with the revised and now available boater network created as part of MAISRC SubProject #13.

In this study we identified fewer clusters (4) than previous studies, where one cluster is for the Upper Mississippi Basin, and the other 3 are disconnected and in northern Minnesota (not belonging to the Mississippi Missouri River Basin). The basins associated to these clusters are disconnected from each other so the only possibility of AIS “inter-connection” is via inter-basin human dynamics (overland boat transfer from one basin to another). This result emphasizes once again the importance to consider physical basin boundaries rather than just defining clusters based on purely statistical models or political lines that do not consider the true feasible spreading corridors. This paradigmatic shift creates some tension about management of AIS because a basin can belong to different counties and decisions are typically taken at the county scale.

**Activity Status as of January 31, 2019:**

We have made some refinements in the multiplex metacommunity model (“M3”) described above and have now begun to draft the manuscript, tentatively titled “A multiplex metacommunity model for aquatic invasive species in Minnesota”. Below are a couple of the draft figures from this manuscript.
This figure provides comparisons between the data (e.g., confirmed number of new infestations over time) and various model outputs that consider E (static conditions), HN (hydrologic network), and E+HN+BN (previous conditions+boater network). This shows that the spread of AIS is driven by multiple factors.

This figure provides the average model accuracy results (red line; 89% accurate), compared to random chance (black line; 50% accurate). The network as an inset is showing the functional interdependence of the model factors as derived from the global sensitivity and uncertainty analysis. The importance of each factor is proportional to the size of the node and interdependence is proportional to the width of each link.

In the last six months of this project we will finalize this manuscript and submit for peer-review.

**Final Report Summary:**

We have created an ecohydrology-based multiplex metacommunity model that forecasts the spread of zebra mussels (ZM) and Eurasian watermilfoil (EM) in Minnesota considering hydrological factors and boater movement (see Activity 3 for visualization). In addition to serving as a useful tool to understand current risk, the framework developed here can be modified if additional data become available (e.g. other vectors) or spatial resolution of underlying landscape data are refined. A few main takeaways from Activity 1:

1. Understanding the risk of various pathways for AIS dispersal is crucial for effective AIS management. Here, we show that hydrological corridors (streams of different orders connecting hydrologic units (HUs), such as lakes) are important pathways for the spread of ZM and EM. When evaluating risk, managers should consider streams and connected HUs rather than individual lakes solely.

2. The importance of the delineating subbasins to define dependence and independence of invaded areas, coupled to the boat movement network, is important. We found that statistical analyses that do not consider hydrological dependence provided an inaccurate clustering and invasion predictions, again emphasizing the importance of more than just boater movement to understand risk. Therefore, hydrological networks were derived from high resolution Digital Elevation Models (DEM) in Activity 1 and used for the multiplex models.

3. The exceedance probability distribution (epdf) of invasion magnitude or AIS incidence (e.g. related to the predicted abundance of AIS) is the most important signature for the criticality of invasion; the observed epdf is a truncated power-law that highlights the fact that the majority of systemic risk is dependent on the multiplex network connections, and local susceptibility of lakes is a second-order factor. The latter would have been predominant if the edpf was an exponential or Poisson distribution reflecting local environmental dynamics (EW seems more sensitive to niche condition than the neutral dispersal-dominated ZM). Thus, this supports the centrality of streams/hydrologic pathways vs. lakes in the effective management of AIS.

**SPECIFICS**
A deeper characterization of the dynamics of AIS dispersal has been investigated as well as the creation of a pattern-oriented systemic index of co-invasion of EW and ZM. For both AIS, the exceedance probability (epdf) shows combined exponential baseline dynamics and weak power-law dynamics (see figure below). This implies that there is a regular seasonal baseline (corresponding to local runoff) and systemic dispersal related to long range factors (such as boat movement). However, the latter is not sufficient to establish true criticality defined by the scale-free regime (power-law pdf). EPD is higher for ZM (lower scaling exponent) that shows higher criticality for ZM and how systemic factors are affecting ZM more than EW.

Figure. Exceedance probability (EPDF) distribution function of ZM and EW predicted incidence (Zipf’s law). Incidence can be defined as predicted abundance or predicted invaded HU. This probability defines the likely persistence of invasion but does not provide necessarily a risk characterization that considers size of the community invaded, its multiplex connection and local invasion suitability.

The systemic invasion risk is then predicted considering the size of invasion in the hydrologic community (e.g. HU) that is considered, the probability function of local invasion susceptibility P(HU), the inverse of the exceedance probability of invasion (based on the invasion magnitude, such as AIS abundance) defining the persistence time t(HU), and the connectivity of the community to other “nearest neighbor” communities considering boat and hydrological connectivity. Note that all these factors trade-off different aspects of the systemic risk that is then characterized as a rate function [size/time] if it is considered that, strictly speaking, persistence time is not truly a temporal variable, but a return period and each function can be evaluated at incremental time steps, in particular HU. The invasion risk is then more properly defined as the rate of change (of effective invasion velocity) of AIS with respect to the temporal frame of reference. In all these calculations the slope of the epdf is a first order factor in determining the invasion risk; in particular if t(HU) is power-law distributed the risk is mostly determined by systemic network connections rather than local susceptibility.

In the figure below, C(HN,BN) is the number of connections along the (HN,BN) multiplex network, where HN = hydrologic network and BN = boater network. The two networks are not related to each other because boat movement can occur even where the drainage network is not connected, thus considers the terrestrial possibility of moving AIS from one HU to another by boats. P(HU > hu) is the exceedance probability for an invasion of size hu to reoccur. hu is the abundance of ZM or EW that can be characterized by ‘bursting dynamics’ with endemic and epidemic periods. Small values of T(HU) are associated with “endemic-like” dynamics with high probability of invasion; small values of T(HU) correspond to very high and long lasting invasions with high persistence. Note that the exceedance probability is independent (computationally speaking) from the local susceptibility and the multiplex connectivity. If local susceptibility and connectivity are included in the model, then the exceedance probability can be informative of the systemic risk. Note that the risk below is formulated as a convolution function because in principle each function is characterized by different time delays.

The innovative characterization of the systemic risk shown in the figure below (risk of communities) is reflecting the classical conceptual formulation of risk encompassing hazard (magnitude and frequency of AIS defined by HU), exposure (defined by persistence time and connectivity t and C) and vulnerability (defined by the susceptibility of the community P(HU)).
Based on the above definition of risk we determined the risk attributed to river pathway (extracted from the Digital Elevation Model at 90 m² resolution) and lakes. This shows that about 70% of the risk of invasion is attributed to streams/hydrologic pathways that are either the favorable habitat or predominant corridors of invasion. This result highlights the extremely high importance of developing effective management strategies for streams connections, in addition to individual lakes.

Considering the potential for co-invasion of the AIS considered, synchronization is here defined as the co-predictability of one AIS when the other is predicted. EW predictability based on ZM is higher than ZM predictability based on EW due to the higher percent of invaded communities with EW and lower dispersal of the latter. $u_H$ and $u_B$ are average dispersal factors related to the hydrologic network and boat network. The incoherent phase is the AIS invasion state related to the inability of the two species to predict each other (complete independence). The bistable phase means that one or the other exists at a critical transition in the parameter values. Boat movement adds randomness to the coupled dynamics.

The calculation of the risk with the consideration of the hydrologic connectivity also identifies clusters of invasions that make physical sense. This result emphasizes the contradictory findings of previous studies that were only based on data and statistical methods without the incorporation of the macroecological drivers/hydrogeomorphological constraints defining invasion pathways. In this way we identify 3 (maximum of 4) major independent clusters of invasions dependent on both the hydrological and boat networks.
Considering the average synchronization we developed a Systemic Invasion Index (SII) created by the non-linear combination of model factors after Global Sensitivity and Uncertainty Analyses (GSUA). SII is expressing the likelihood of species invasion considering the systemicity dictated by the combination of system-scale multiplex dispersal networks, multiple hydro-geomorphological factors defining species environmental suitability, and the combination of all these factors.

In the figures below, the SII of ZM shows a more fat-tailed distribution highlighting the higher criticality and dispersal. In the GSUA plots, $S_{ij}$ is the interaction among model factors and $S_i$ is the one factor importance when each factor is independent from all others. The higher $S_{ij}$ and $S_i$ the more important the factor is. $u$ are mean dispersal factors (scale factors of the dispersal kernel), and $p$ is the dispersal shape (shape parameter). $R$ is the runoff, $TI$ is the topographic wetness index, $w$ is the dispersal bias (for upstream movement), and $\mu$ is the speciation factor. Dispersal factors are defined for both networks.
A manuscript has been submitted to Environmental Modeling and Software that describes these models in more details.

**ACTIVITY 2:** Development of county and statewide optimization models for AIS management

**Description:** In 2014 the State of Minnesota created the AIS County Prevention Aid Program, with annual support of $10,000,000 direct to counties. The use of these funds has varied widely, based on expertise, local values, concerns, and total funding available. Specific activities have included new personnel, education, watercraft inspection, and decontamination units to name a few. While there is little doubt these activities help in the fight against AIS, counties are asking for help in determining the most effective use of their funds.

In Activity 2, we aim to develop risk-based optimization models to inform county AIS prevention and management activities. To that end, we will intensively interview representatives from two Minnesota counties and the MN DNR to better understand management objectives, ongoing activities and associated costs, personnel requirements, tradeoffs and budget constraints. We will use this information, combined with lake-level risk from Activity 1, to develop an optimization model for each county. The models will be spatially explicit, including location of lakes, pathways of boat movement, and locations for potential intervention activities. The participating managers will review the final models for relevance and consistency with their expectations. We will also socialize the models with representatives from all other counties and receive feedback during regional AIS coordination meetings hosted by the MN DNR. Assuming the management objective (e.g. prevent the introduction of AIS into new lakes) is widely accepted, we will build generic optimization models for all counties based on local AIS risk and funding levels.
In addition, we aim to develop an alternative strategy for statewide allocation of the AIS County Prevention Aid Program. Currently, the funding allocation is based on the number of boat ramps and parking spots within each county as a crude measure of risk. Through the research in Activity 1 and Activity 2, we will estimate cost curves for management and levels of cumulative risk for each county to quantify total need. This approach will be compared against the status quo.

All findings will be widely available through MAISRC communications (i.e. website, newsletter, social media, presentations, etc), one scientific presentation and one peer-reviewed open access publication.

Summary Budget Information for Activity 2:

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Activity Completion Date:

<table>
<thead>
<tr>
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<th>Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Development of county-based AIS management optimization models</td>
<td>September 2018</td>
</tr>
<tr>
<td>2. Development of risk-based statewide funding allocation model</td>
<td>September 2018</td>
</tr>
<tr>
<td>3. Deploy models at AIS manager workshops</td>
<td>October 2018</td>
</tr>
<tr>
<td>4. Result dissemination: MAISRC communications, scientific presentation, peer-reviewed publication</td>
<td>January 2019</td>
</tr>
</tbody>
</table>

Activity Status as of January 26, 2018:
There was a modest delay in this activity due to available data from a complementary project (MAISRC SubProject #13). We now have the data and will be working in earnest in the coming months. Regardless, progress has continued and several notable things were accomplished. We ordered, received, and installed GAMS/CPLEX optimization software. We developed a prototype optimization model for a fictitious county using information about the location of infested and un-infested lakes, number of boats moving between lakes, boat infestation rate, species detection rate, and susceptibility of establishment of invasive species in un-infested lakes. The optimization model locates boat inspection stations at either infested or un-infested lakes to maximize the number of boats that are inspected and treated prior to entering un-infested lakes. The evaluation of management strategies (i.e., containment, prevention, or a mix) depends on boat flux (i.e., boat movement into and out of lakes) and lake parameters (i.e., boat infestation rate of infested lakes, susceptibility of un-infested lakes). We have found with early conversations that the DNR’s strategy has been largely focused on containment, while most local groups have largely focused on prevention. During the next period, we will apply the model to two different counties using lake and boat movement data with aim to present results to local managers in March, 2018.

Activity Status as of July 31, 2018:
Having received a matrix of boat movement rates among lakes in Minnesota from MAISRC SubProject #13, we formulated and solved a boat inspection location problem for two counties in the Twin Cities metropolitan area: Ramsey and Washington. For each county, we have the locations of 25 infested and un-infested lakes and the number of boats moving from infested lakes within and outside the county into un-infested lakes in the county. The circles in the map below represent the numbers of incoming boats from zebra-mussel infested lakes inside or outside the county.
For each county, the problem is to locate a fixed number of boat inspection stations to minimize the risk of AIS moving into and establishing in un-infested lakes. We quantify risk as the number of un-inspected boats that move from infested lakes to un-infested lakes. We allow inspection stations to be placed at either infested or un-infested lakes within the county. Our only constraint is an upper bound on the number of inspection stations, which represents a budget limitation.

In Ramsey County, there is one lake infested with zebra mussel (Pleasant Lake), and almost no movement of boats from Pleasant Lake to other lakes in the county. Almost all of the incoming boats from infested lakes originated from outside the county. In this case, the best solution is to locate stations at un-infested lakes that receive the most boats from out-of-county infested lakes. This is an example of a prevention strategy. The top three un-infested lakes for the location of inspection stations are Bald Eagle, Turtle, and Johanna.

In Washington County, there are two lakes infested with zebra mussel (Forest and White Bear), and some movement of boats from those lakes to un-infested lakes in the county. However, most incoming boats from infested lakes originated from outside the county. In this case, the best solution is again to locate stations at un-infested lakes that receive the most boats from out-of-county infested lakes. The top three lakes are Big Marine,
Elmo, and Clear. If the budget allows ten or more stations, then the best solution locates stations at the two infested lakes—White Bear and Forest—as well as 8 un-infested lakes. This is an example of a combined prevention and containment strategy.

During the next period, we will continue to apply the optimization model to different counties using the lake and boat movement data that we have. We will look at the potential gains from cooperation among adjacent counties for inspection station location given information about boat movement between counties. We will also look at refining the optimization model to include estimates of the costs and efficacies of different types of inspections as well as different management objectives.

**Activity Status as of January 31, 2019:**
In September 2018, we presented our modelling approach and results for Ramsey and Washington County to attendees of the MAISRC Aquatic Invasive Species Research and Management Showcase. The title of our presentation was, “Assigning Watercraft Inspection Stations to Minnesota Lakes: An Operations Research Approach.” In the days following the presentation, we were contacted by planners from three counties interested in experimenting with our model: Jacob Frie of Crow Wing County, Justin Townsend of Ramsey County, and Elizabeth Leitch-Sell of Stearns County. Working with each partner, we crafted a county-level optimization model that met their specific needs. Below we highlight model innovations and results provided to each county.

In Crow Wing County, the problem is to locate a fixed number of watercraft inspection stations at lakes/landings to maximize the number of inspected watercraft that move from zebra mussel (zm) infested to zm uninfested lakes from within and outside the county. We obtained information on the location of zm infested and uninfested lakes within the county and average boats per hour inspected (2016-18) at 28 ramps in infested lakes from Jacob Frie. We also obtained the number of watercraft moving from zm infested lakes to uninfested lakes within the county, within the county to outside, and outside the county to within the county, from MAISRC SubProject #13. From these data, we estimated the numbers of boats per day leaving infested lakes, number of boats per day leaving a given infested lake and entering each uninfested lake within the county and uninfested lakes out of county, and number of boats per day entering each uninfested lake in county from infested lakes out of county. Using these estimates, we computed optimal inspection locations given upper bounds of 10, 20, and 30 stations.
With 30 public access ramp landings identified for inspection stations in the results, the model predicts coverage of at least 85% of watercraft moving from infested to uninfested waterbodies. Twenty four stations are located at zm infested lakes and six are located at zm uninfested lakes. The access points selected for inspection stations were largely consistent with Crow Wing County’s lake risk classification. Thirteen of 15 “very high risk” lakes are covered (Lower and Upper South Long Lakes are not), 15 of 24 “high” risk lakes are covered, and 2 “moderate” risk lakes are covered (Hubert and Little Rabbit). Both of these are zm infested with moderate risk and have large proportions of outgoing boats heading to zm uninfested lakes. These results informed the development of the 2019 Crow Wing County AIS Prevention Plan http://www.crowwing.us/DocumentCenter/View/15432/2019-CWC-AIS-Prevention-Plan?bidId.

In Ramsey County, Justin Townsend provided us with estimates of the average number of boats per day inspected at four zm infested lakes/ramps (White Bear City Ramp, White Bear County Ramp, Bald Eagle, Johanna) and during each of three 4-hour time periods in May through August. We combined these estimates with boat movement among lakes obtained from MAISRC SubProject #13. We modified our inspection optimization model to locate a fixed number of inspection stations at county lakes by time period to maximize the number of inspected watercraft that move from zm infested to uninfested lakes. We allow inspection stations to be placed at either infested or uninfested lakes in each 4-hour time interval: 6am-10am, 10am-2pm, 2pm-6pm. Our only constraint is an upper bound on the number of inspectors, which represents a budget limitation. We addressed this problem with budget constraints ranging from 1 to 30 inspectors, assuming that each inspector can work a 12-hour shift.

With an upper bound of four stations, the best solution is to locate one station at each of the three infested lakes, Johanna, Bald Eagle, and White Bear, because together they supply 10 boats per day to uninfested lakes in Ramsey county and 52 boats per day to uninfested lakes outside the county. The fourth station is located at Turtle Lake, which receives 16 boats per day from infested lakes outside Ramsey County, much more than any other uninfested lake in the county. The location of the inspection stations varies by time period. From 6am-10am, an inspector is allocated to Lake Johanna but not White Bear City Ramp. In the other two periods, inspectors are located at White Bear City and County ramps, Bald Eagle, and Turtle, but not Johanna. With four inspectors, 79% of the boats are inspected. With five or more inspectors, locations do not change by time period and greater than 90% of the boats can be inspected. Justin Townsend is using these results to inform his 2019 AIS prevention plan.
Working with Elizabeth Leitch-Sell of Stearns County, we formulated our optimization model to maximize the number of inspected watercraft that move from zebra mussel and starry stonewart (ss) infested lakes to uninfested lakes within or outside Stearns County. We populated the model with estimates of boat movements among Stearns County lakes obtained from MAISRC Subproject #13. We allowed inspection stations to be placed at either infested (zm or ss) or un-infested lakes within the county and solved the problem with budget constraints ranging from 1 to 30 inspection stations.

With an upper bound of four stations, the best solution is to locate two stations at zm infested lakes (Clearwater and Sylvia), because together they supply over 4,000 boats per year to zm uninfested lakes outside Stearns county. The other two stations are located at ss infested lakes (Koronis and Rice), which together receive over 7,000 boats from zm infested lakes inside and outside of Stearns county and supply over 2,000 boats to ss uninfested lakes outside of Stearns County.
Stearns County

Optimal Inspection Locations

<table>
<thead>
<tr>
<th>Lake</th>
<th>Number of Inspection Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clearwater (zm)</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>Big Fish (zm)</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>Watab (zm)</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>Sylvia (zm)</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>Otter (zm)</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>Koronis (ss)</td>
<td>X X X X X X X X X</td>
</tr>
<tr>
<td>Rice (ss)</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>Grand (ss)</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>Horseshoe</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>Big Watab</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>Two Rivers</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>Proportion boats inspected</td>
<td>0.26 0.38 0.49 0.57 0.65 0.72 0.78 0.83 0.87 0.91</td>
</tr>
</tbody>
</table>

This table shows which lakes to locate an increasing number of inspection stations, if additional resources were available for inspections. In most cases, for each incremental increase in inspection stations, a new lake is added to the list of locations. For example, with a budget for two stations, the optimal locations are Koronis and Rice Lakes. With two stations, approximately an estimated 38% of the boats county wide moving from zm or ss infested lakes to uninfested lakes will be inspected. Increasing the budget from two to three stations, the model adds Clearwater Lake to the list of stations while increasing inspections from 38% to 49% of the boats leaving zm or ss infested lakes and entering uninfested lakes. Ten stations located at the lakes listed in the table will inspect 91% of the boats that leave zm and ss infested lakes and enter uninfested lakes. Note that Big Fish Lake, which is zm infested, is not selected for an inspection station when the upper limit is ten stations. Big Fish had the lowest number of boats moving to uninfested lakes inside and outside the county among the list of infested lakes. We are currently working with Elizabeth Leitch-Sell of Stearns County to modify our model based on up-to-date lake access information.

Final Report Summary:
Since the beginning of this project in January 2018, we have developed a county-based AIS management optimization model, demonstrated the model at AIS manager workshops, and disseminated the work through MAISRC communications and scientific presentations. The county-based management optimization model seeks to locate boat inspection stations to maximize the number of inspected boats that move from infested to uninfested lakes, both within and outside the county. The model uses estimates of the annual numbers of boats moving between lakes within and outside counties and locations of infested and uninfested lakes. We applied the model to Ramsey, Crow Wing, and Stearns County, focusing on zebra mussel and starry stonewort prevention (see results detailed above). The results were presented to AIS committees in each of the three counties and the models were adjusted based on their feedback. The results for Crow Wing County were used to help justify boat inspection location decisions documented in their 2019 plan: https://www.crowwing.us/1004/Aquatic-Invasive-Species-AIS. A research paper documenting the model and its application is being prepared for submission to a peer-reviewed scientific journal.

The development of a risk-based statewide funding allocation model was not completed within the timeframe of this project; however, the framework to make that happen has been under development. We plan to complete this work in the coming months as part of a requested legislative report.

**ACTIVITY 3:** Development and deployment of visualization tool for the AIS decision-making
Description: The Questions and Decisions (QnD) model system has previously been used for other systems by project collaborators to provide an effective and efficient, open-source, decision research and education tool that can visualize scenarios of model outputs that incorporate management decisions. This would be a very useful tool to empower AIS managers with real-time access to our models.

We aim to construct a QnD model using a combination of occurrence data and interactions of ecosystem elements embedded in the MnM model developed in Activity 1 and the management optimization Activity 2. The model will include real-time information of AIS infestations (e.g. new reports from EDDmapS) and produce updated model predictions. For visualization of the QnD model, we will develop an online interface and mobile app written in object-oriented Java.

We will socialize the interface throughout the course of the Activity to ensure usability. Ultimately, the online QnD interface and mobile app will be deployed to county and MN DNR AIS managers during a final project workshop, MAISRC communications (i.e. website, newsletter, social media, presentations, etc) and peer-reviewed publication.

Summary Budget Information for Activity 3:

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Activity Completion Date:

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</thead>
<tbody>
<tr>
<td>1. Development of visualization tool for AIS management</td>
<td>April 2019</td>
</tr>
<tr>
<td>2. Deployment of visualization tool to AIS managers</td>
<td>June 2019</td>
</tr>
<tr>
<td>3. Result dissemination: MAISRC communications, peer-reviewed publication</td>
<td>June 2019</td>
</tr>
</tbody>
</table>

Activity Status as of January 26, 2018:
No progress during this period. We will be working in February to set up the service contracts to construct the online visualization tool. We are requesting an amendment to the budget to move funds within the service contract category. This will not result in a change to the deliverables or overall budget.

Activity Status as of July 31, 2018:
An online dashboard for almost real-time model runs is being developed as well as a model-based app for the individual use of the model and data reporting. We are on schedule to complete this app as expected.

Activity Status as of January 31, 2019:
The massive size and complexity of our data provides a great opportunity, but at the same time has created significant challenges for our initial plan and contractor. Our goal was to create a tool that could visualize out model outputs with an online user-friendly interface. While progress has been made, the developers have exceeded their estimated time to create the application and future progress is uncertain. Below is a screenshot of the current version.
The current tool will provide value for model simulations, but does not have the usability/resolution that could be achieved with a further development. Given the progress to date, short time period for completion, significant savings in personnel funding, and analysis of new data, we feel it is best to include an alternative option to improve our outcomes. We have identified a highly experienced global company with a strong track record working with the University of Minnesota to create v2.0 of the online tool. For details, see amendment request 5/6/19.

**Final Report Summary:**
We exceeded expectations for this activity, creating two visualization tools (instead of one), one for each activity (summarized below). Two manuscripts are currently in late stages of drafts and will be submitted soon. There are major opportunities to expand on this work and we will be seeking funding to facilitate that as soon as possible.

**Model Dashboard (SMART Solutions)**
The underlying model for the visualization is a QnD model that allows one to select data and scenarios in input of the M3 predictive model of Activity 1, as shown in the previous update. All data coming from official reporting and app-based reporting can be visualized, reported and implemented. A preliminary version of the model (whose data interface is reported below) is accessible at

http://admin.lakelifechat.com/#/adminlogin; Username: admin, Password: 123

Current visualizations that are available are provided at a resolution of 90 m² as supported by the underlying Digital Elevation Model from which the drainage network is extracted.
Figure. Zebra mussel average probability of exceedance considering the whole time period for which ZM has been tracked. The map shows the situation for the probability of exceedance of 20 years. This approach is considering additional areas at risk compared to previous conservative or non-physical calculations. In white the recorded occurrences are reported while in purple some other points are added considering a bias in reporting. The map is a QnD map based on the M3 model calculations of Activity 1.

Figure. Eurasian watermilfoil average probability of exceedance considering the whole time period for which EW has been tracked. The map shows the situation for the probability of exceedance of 20 years. This approach is considering additional areas at risk compared to previous conservative or non-physical calculations. In white the recorded occurrences are reported while in purple some other points are added considering a bias in reporting. The map is a QnD map based on the M3 model calculations of Activity 1.

Reporting Application (BlackTechGuy)
The App has been finalized and allows any user to report AIS occurrences as well as to visualize M3-based QnD model predictions. A built-in social app has been included to enhance the reporting of AIS by people recreating on lakes as well as any other stakeholder involved in lake activities. Additional development will be needed to automatically link reports made here to other reporting systems. We believe that social participation is a key factor for citizen science initiative and environmental sustainability. The app is connected to the interface of the
QnD model in almost real time (update every 48 hrs) by uploading data on the cloud and receiving AIS risk prediction.


**Visualization tool for the decision optimization model**

We created a user-friendly App written in the open-source programming language R (e.g. RShiny) The app runs a heuristic version of the CPLEX/GAMS model developed in Activity 2, in which the boater movement data is described using a social network approach. The output provides a ranked list of waterbodies to prioritize for watercraft inspection at the county-level and the proportion of boats inspected (cost-benefit curve). An example is given in the screenshot below, where a manager selected the county of interest (Crow Wing) and a desired management threshold of risky boats inspected (90%). In seconds, results are generated that provide a list of 30 waterbodies (only the first five shown in screenshot) in ranked order needed to meet that threshold. These results will help inform the decision-making process for effort allocation. If the management threshold or available funding change, the model can by simply modified with the drop-down menu and be re-run for an updated list of lakes. We are currently in the process of developing additional options (i.e. removing lakes that are not of interest within the county) for this tool and making it available the MAISRC website.

![Optimal Inspection Stations](image_url)

### V. DISSEMINATION:

**Description:** Dissemination of project findings is a critical component of this project. Efforts will be made throughout the project to engage end-users, share findings and make deliverables broadly available. Specifically, at least three peer-reviewed manuscripts are expected to be published in open-access scientific journals. Results will be presented at two scientific conference, including the Upper Midwest Invasive Species Conference (location TBD, likely Duluth, MN) and the International Conference on Aquatic Invasive Species (ICAIS; location TBD). If ICAIS is located outside of the USA, another conference will be selected. The project team will also
contribute to MAISRC communications, including information for the website, newsletter, social media, presentations at the annual Research Showcase, news media, etc. We will share downloadable material (i.e. maps, tables, reports) on the MAISRC website.

**Status as of January 26, 2018:**
An overview of the project, along with complementary research efforts, was presented at the International Conference on Aquatic Invasive Species in Tampa Florida in October 2017. The presentation was titled “The use of co-spatial modeling to inform aquatic invasive species management”. Project funds were not used for travel. Updates on the project were also presented at the Aquatic Invaders Summit, the Cass County Watercraft Inspectors annual training, and the AIS Roundtable held in Crosslake, MN. Early project results and plans for future research were also presented at a workshop (as part of MAISRC Subproject #13) with MN DNR, County and watershed district managers.

**Status as of July 31, 2018:**
No updates to report as of 7/31/2018

**Status as of January 31, 2019:**
We continue to pursue a combination of formal and informal dissemination strategies for this project given the direct application to AIS managers and broad interest among other stakeholders. We presented two talks at MAISRC’s 2018 Research and Management Showcase focused on 1. “Estimating AIS risk for Minnesota lakes”, and 2. “Locating boat inspection stations on Minnesota lakes”. Both presentations are available on MAISRC’s webpage. We have numerous conversations with MN DNR, Ramsey County, Stearns County and Crow Wing County to discuss applications of Activity 2 to their watercraft inspection programs. We are currently drafting several manuscripts, with the goal of submission prior to the end of the project.

**Final Report Summary:**
Efforts were made throughout the project to engage end-users, share findings and make deliverables broadly available. We used a combination of formal and informal dissemination strategies for this project given the direct application to AIS managers and broad interest among other stakeholders. We held in-person meetings with County representatives and citizen advisor boards from Crow Wing, Ramsey and Stearns Counties to present results and update our models according to their input. These meetings were highly valuable to the project team and the outcomes of the project. In addition, we provided scientific and/or outreach presentations at the International Conference on Aquatic Invasive Species, the Aquatic Invaders Summit, the Cass County Watercraft Inspectors annual training, the annual AIS Roundtable, and MAISRC’s Research and Management Showcase. Several publications are currently in late-stage drafts and will be submitted for peer-review in the coming months.

**VI. SUB-PROJECT BUDGET SUMMARY:**

**A. Preliminary ENRTF Budget Overview:**

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<tr>
<td>Professional/Technical Services and</td>
<td>$39,774</td>
<td>Contract with TheBlackTechGuy (Mondo Davidson) for website/app development to visualize outputs ($25,000), purchase GAMS-</td>
</tr>
<tr>
<td>Contracts:</td>
<td></td>
<td></td>
</tr>
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</table>
CPLEX optimization software essential for Activity 2 ($10,000), and peer-reviewed publications ($2,000).

<table>
<thead>
<tr>
<th>Equipment/Tools/Supplies:</th>
<th>$1,784</th>
<th>One macbook pro ($1,500; Computer will be retained by MAISRC at the end of the project), two external hard drives ($500), and materials for final workshop ($1,000).</th>
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</thead>
<tbody>
<tr>
<td>Capital Expenditures over $5,000:</td>
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<td>None.</td>
</tr>
<tr>
<td>Travel:</td>
<td>$0</td>
<td>Travel within Minnesota to participate in regional AIS coordination meetings ($1,000) and domestic travel outside of Minnesota to present the findings of this project at two scientific conference and get feedback from other experts and to learn about the newest developments in the field – expected conferences include the Upper Midwest Invasive Species Conference and the International Conference on Aquatic Invasive Species (only if location is domestic) ($4,000).</td>
</tr>
<tr>
<td>Other:</td>
<td>$0</td>
<td>None.</td>
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**TOTAL ENRTF BUDGET:** $80,469

**Explanation of Use of Classified Staff:** NA

**Explanation of Capital Expenditures Greater Than $5,000:** NA

**Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation:** 2.1 FTE

**Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation:** 0.25FTE

**B. Other Funds:**

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<th>$ Amount Spent</th>
<th>Use of Other Funds</th>
</tr>
</thead>
<tbody>
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<td>Non-state</td>
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<td>$0</td>
<td></td>
</tr>
<tr>
<td>State</td>
<td>$0</td>
<td>$0</td>
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<tr>
<td><strong>TOTAL OTHER FUNDS:</strong></td>
<td><strong>$0</strong></td>
<td><strong>$0</strong></td>
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</tbody>
</table>

**VII. SUB-PROJECT STRATEGY:**

**A. Sub-Project Team/Partners:**

This highly collaborative project will be managed by Dr. Nicholas Phelps (Project Manager; MAISRC). He will be involved in all aspects and provide overall guidance for the project. Dr. Phelps has ongoing research efforts focused on modeling the establishment and introduction risk of AIS in Minnesota, as well as intervention strategies at all levels of management. Dr. Matteo Convertino (UMN-School of Public Health and Systems Engineering) will lead Activity 1 and 3 and has research expertise that broadly focuses on modeling and management of nature-inspired complex systems (using information, network, and decision theories) to inform decision-making. Dr. Robert Haight (US Forest Service) will lead Activity 2 and has research expertise in optimal control of invasive species and building models to allocate scarce resources for prevention, detection, control and rehabilitation. A postdoctoral associate will assist with all aspects of the project.
MN DNR and County-based AIS managers will be included during the early stages of the project to solicit management objectives informing the models. The same individuals will be re-engaged at the end of the project to discuss findings. The project team has a history of successful collaboration with agency partners.

**B. Sub-Project Impact and Long-term Strategy:**
MAISRC’s 2017-2018 Research Needs Assessment identified this type of project as a High Priority Research Need. This project will fill key knowledge gaps and provide immediate and long-term benefits to resource management and allocation at the state and county levels. Working closely with AIS managers at all levels will help facilitate the translation of the research into action. This is the third phase of a long-term effort (previous two projects funded by MnDRIVE and MAISRC).

In addition, the outputs generated will also have value beyond the management of the considered AIS. Other AIS can be used in the same modeling framework and the partnership with DNR can lead to systemic ecosystem health management, where all species are taken into account simultaneously. The multidisciplinary and collaborative nature of this project will enhance the collaboration among AIS management agencies including the MN DNR and county-based managers, and the research efforts of MAISRC.

Importantly, as management goals change and new data becomes available, the optimization models will need updating to remain relevant. Future research to refine and update this tool based on the discovery of new species/locations, changes in introduction risk or environmental suitability, and other information gained overtime would be warranted.

**C. Spending History:**

<table>
<thead>
<tr>
<th>Funding Source</th>
<th>M.L. 2008 or FY09</th>
<th>M.L. 2009 or FY10</th>
<th>M.L. 2010 or FY11</th>
<th>M.L. 2011 or FY12-13</th>
<th>M.L. 2013 or FY14</th>
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**VIII. ACQUISITION/RESTORATION LIST:** N/A

**IX. VISUAL ELEMENT or MAP(S):** N/A

**X. ACQUISITION/RESTORATION REQUIREMENTS WORKSHEET:** N/A

**XI. RESEARCH PROPOSAL:**

**XII. REPORTING REQUIREMENTS:**
Periodic work plan status update reports will be submitted no later than January 31, 2018, July 31, 2018 and January 31, 2019. A final report and associated products will be submitted within two months of the anticipated sub-project completion of June 30, 2019.
**Environment and Natural Resources Trust Fund**

**Final Report** M.L. 2013 Sub-Project Budget of M.L. 2013-06a: Aquatic Invasive Species Research Center

**Project Title:** Aquatic Invasive Species Research Center Sub-Project #19 Decision-making tool for optimal management of AIS

**Legal Citation:** M.L. 2013, Chp. 52, Sec. 2, Subd. 06a

**Project Manager:** Dr. Nicholas Phelps

**Organization:** Minnesota Aquatic Invasive Species Research Center

**Sub-Project Budget:** $172,464

**Sub-Project Phase 1 Length and Completion Date:** 2 years, June 30, 2019

**Project Length and Completion Date:** 6 Years, June 30, 2019

**Date of Report:** August 16, 2019

### ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET

<table>
<thead>
<tr>
<th>BUDGET ITEM</th>
<th>Activity 1: MnM model development</th>
<th>Activity 2: Optimization model development</th>
<th>Activity 3: Model visualization</th>
<th>TOTAL BUDGET</th>
<th>TOTAL SPENT</th>
<th>TOTAL BALANCE</th>
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<tbody>
<tr>
<td></td>
<td>Amount</td>
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<tr>
<td>Personnel (Wages and Benefits) - Total</td>
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<td>Dr. Matteo Convertino, Assistant Professor:</td>
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<td>Professional Services and Contracts: Contract with TheBlackTechGuy (Mondo Davidson) for app development</td>
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<td>Equipment/Tools/Supplies - Total</td>
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<td>Supplies - Office &amp; Gen Operations: Workshop materials (flip charts, paper, markers, etc)</td>
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<td>Equipment - Non-Capital Lab and/or Field: One MacBook Pro, two external hard drives</td>
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<td>Travel - MN: Travel to attend five workshops hosted by MN DNR, mileage and lodging for five nights total for one person. Travel to host one workshop, mileage and lodging for three people for one night.</td>
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<td>Travel - Domestic: Travel to attend two scientific conferences to present the findings of this project and get feedback from other experts and to learn about the newest developments in the field – expected conferences include the Upper Midwest Invasive Species Conference and the International Conference on Aquatic Invasive Species (only if location is domestic)</td>
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