2017 Project Abstract
For the Period Ending June 30, 2021

PROJECT TITLE:
Enhancing Spawning Habitat Restoration in Minnesota Lakes
PROJECT MANAGER: William Herb
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2017, Chp. 96, Sec. 2, Subd. 08e as extended by M.L. 2020, First Special Session, Chp. 4, Sec. 2

APPROPRIATION AMOUNT: $294,000
AMOUNT SPENT: $275,198
AMOUNT REMAINING: $18,802

Sound bite of Project Outcomes and Results

The main goal of this project was to create easily accessible information on wave energy to enable successful habitat restoration projects and increase natural fish reproduction in Minnesota lakes. We created maps, in GIS format, of wave height and energy statistics for 457 lakes in Minnesota.

Overall Project Outcome and Results

There are many ways in which healthy near-shore habitat and water quality in lakes is linked to wind and wave energy. Examples include walleye spawning habitat on nearshore gravel substrates, the distribution of submersed aquatic plants, sediment resuspension by wave action, and shoreline erosion. Successful lake habitat restoration requires good information on wind and wave energy, and this information is commonly not available. The main goal of this project was to create easily accessible information on lake wave energy to enable successful habitat restoration projects and increase natural fish reproduction in Minnesota lakes. The project partnered the University of Minnesota with the MN DNR and included field measurements of wind and wave height on four lakes ranging in size from 350 to 5000 acres, wave modeling work to map typical wave energy on the shorelines of 457 Minnesota lakes, and experimental work in a wave flume to better understand how nearshore sediment responds to wave energy in lakes. A major part of the project was to develop models for wave height and energy that consider wind sheltering by trees, so that wave height predictions could be made for smaller lakes with fetches of a kilometer or less. The wave maps created by this study can be used by state agencies and lake associations to plan lake shoreline management, including habitat restoration projects, aquatic plant management, and shoreline erosion control.

Project Results Use and Dissemination

Electronic maps of wave height and energy created in this project will be uploaded to the Data Repository for University of Minnesota (DRUM), and details of the project will be published in a St. Anthony Falls Lab project report to document the methodologies used. The project PI gave a talk on the project at a conference on Sentinel lakes in March 2019 in Alexandria, MN, and is giving a poster presentation at the 2021 Minnesota Water Resources Conference.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2017 LCCMR Work Plan Final Report

Date of Submission: **8/16/2021**

Date of Next Status Update Report: Final Report

Date of Work Plan Approval: **06/07/2017**

Project Completion Date: **6/30/2021**

PROJECT TITLE: Enhancing Spawning Habitat Restoration in Minnesota Lakes

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Location: Statewide

Total ENRTF Project Budget:	**ENRTF Appropriation:**	**$294,000**
	Amount Spent:	**$275,198**
	Balance:	**$18,802**

Legal Citation: M.L. 2017, Chp. 96, Sec. 2, Subd. 08e as extended by M.L. 2020, First Special Session, Chp. 4, Sec. 2

Appropriation Language:
$294,000 the first year is from the trust fund to the Board of Regents of the University of Minnesota, St. Anthony Falls Laboratory, in cooperation with the Department of Natural Resources to enhance efforts to increase natural reproduction of fish in Minnesota lakes by assessing wave energy impacts on near-shore spawning habitat. This appropriation is available until June 30, 2020, by which time the project must be completed and final products delivered.

M.L. 2020 - Sec. 2. ENVIRONMENT AND NATURAL RESOURCES TRUST FUND; EXTENSIONS. [to June 30, 2021]

I. PROJECT TITLE: Prioritizing shoreline habitat restoration in Minnesota lakes

II. PROJECT STATEMENT:

Fishing is big business in Minnesota, with over 1.5 million anglers spending more than 1.4 billion dollars each year. A key to maintaining healthy fish populations in Minnesota lakes is to maintain quality near-shore and shoreline habitat. Natural fish reproduction in MN lakes is threatened by watershed and lakeshore development activities, which increase erosion, sediment loading, and nutrient loading to lakes. For walleye, successful reproduction in a lake requires gravel to cobble substrates for egg incubation in near-shore waters. Development activities in a watershed or on a lakeshore can impact fish spawning habitat by increasing fine sediment and nutrient loading to a lake, filling in the substrates with fine sediment and decaying organic matter.

There are a number of ways in which healthy near-shore habitat in lakes is strongly linked to wind and wave energy. Examples include:

- Walleye spawning gravel substrates can be kept clean of fine sediment by wave energy.
- Wave energy affects the distribution of submersed aquatic plants that provide juvenile habitat for some fish species.
- Shoreline erosion is driven mainly by wind-generated wave energy.

As a result, successful lake habitat restoration requires good information on wind and wave energy, and this information is currently not available. The Minnesota DNR has approached the University of Minnesota to develop tools to provide better predictions of wave energy and near-shore habitat in Minnesota lakes.

The main goal of this project is to create easily accessible information on wave energy and near-shore habitat, to enable successful habitat restoration projects and increase natural fish reproduction in Minnesota lakes. The deliverable product will be maps (GIS-based) that can be used by lake managers to map different classes of near-shore habitat in a lake. The project will focus on walleye habitat, but the information created in this study will be applicable to many other fish species and to more general shoreline wildlife habitat restoration and erosion reduction efforts.

This project will take advantage of the experience of the Minnesota DNR in assessing and managing lake habitat, of the U of M St. Anthony Falls Lab (SAFL) in waves, sediment transport, and lake modeling, and of the UMD Natural Resources Research Institute in habitat assessment, spatial analysis, and management tools. Although wave energy models already exist for ocean coastline and large lakes, a key piece of the project will be to determine how wind-sheltering from surrounding hills and trees reduce wind speeds and wave energy on lakes of different sizes and shapes in Minnesota. Wind sheltering models previously developed at SAFL can use ENRTF-funded LiDAR data to accurately determine wind-sheltering and the corresponding reduction in wave energy. This study will take advantage of, and add to, the extensive lake data set generated by the ENRTF-funded SLICE (Sustaining Lakes in a Changing Environment) program, and will use Sentinel lakes as case study lakes.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of *November 1, 2017:*

Amendment Request

We are proposing to make a change to the project budget, to create a new line item for telecommunication charges. These funds ($500) will be used to pay for data charges for the cellular modems that will be used to download wind/wave data from the field measurement stations used in Activity 1. For this purpose, we propose to move $500 from the budget for Misc. Field Supplies ($2700). The reduced budget for Misc. Field Supplies will be handled by reusing available supplies from previous projects.

Amendment Approved by LCCMR 11/9 /2017.

Project Status as of *December 31, 2017***:**

Activity 1 is on schedule. Wind and wave data were collected at two lakes near Hutchinson, MN, in co-operation with the MN DNR, to begin the data collection effort for Outcome 3. Two wind/wave measurement stations were assembled in August 2017. One wind/wave station was installed at Belle Lake (a Sentinel lake) in mid-September, 2017, and a second station was installed in late-September in Lake Jennie. The two stations collected wind speed, wind direction, and water level data continuously, and were retrieved on November 8, 2017. Processing of the raw water level data to calculate wave statistics is in progress.

Project Status as of *June 30, 2018***:**
Activity 1 is progressing well. A wave station was installed in Swan lake, near Hutchinson, MN, in June 2018 in co-operation with the MN DNR. A second station will be installed in Ten Mile lake, near Walker, MN in July 2018. Work continues on processing the wind/wave data collected in 2017. A wave test flume has been set up at St. Anthony Falls lab, and preliminary measurements of wave height have been taken. Measurements of the corresponding water velocities and sediment resuspension for varying wave conditions will be taken in July-September 2018. A meeting was held in March 2018 between the project PI and MN DNR staff in Brainerd, MN, to discuss the application of the project results to improving aquatic plant restoration efforts at the DNR. Overall effort levels on the project will substantially increase in the second half of 2018.

Project Status as of *December 31, 2018***:**
Wind and wave data were collected from Swan Lake and Ten Mile Lake in 2018, yielding good data for a relatively small (350 acres) and relatively large (5000 acres) lake. 74 days of data were collected for Swan Lake and 41 days of data were collected for Ten Mile Lake. In addition, one day of data was collected at Belle Lake, near Hutchinson, MN, that included wind data, wave data, and nearshore water velocity data. Analysis of the wind-wave data is nearly complete for Belle, Jennie, and Ten Mile lakes. Several wave models and wind sheltering models are being evaluated, to establish a model that gives the best wave predictions for Minnesota lakes. Experimental measurements in the wave flume at SAFL (Outcome 2) were ongoing in the reporting period. Existing models to predict subsurface water velocities as a function of wave height gave good estimates of both the water velocities measured in the wave flume and those measured at Belle Lake. The wave flume is currently being used to measure sediment resuspension by waves for several different sizes and types of sediment. As the wind-wave models are finalized in January/February 2019, collaboration with the Natural Resources Research Institute will begin to determine the methods that will be used to apply the wind-wave models to a much larger set of lakes to map wave energy over the state.

Project Status as of *June 30, 2019***:**
A model has been selected for modeling wind-waves on Minnesota lakes, based on wave data from the four field measurement sites. Work is underway at SAFL and Natural Resources Research Institute (NRRI) to develop tools to calculate wave energy on a large number of lakes. NRRI personnel are compiling airport wind data state-wide to enable wind speed and direction statistics to be calculated for any lake in Minnesota. Based on preliminary work, wave energy will be calculated at a relatively high resolution (500 meters) around each lake, to better handle lakes with irregular shorelines. Wave statistics will be calculated for monthly intervals, and will include the effect of ice cover duration, which can vary by over a month over the state. The wave modeling tools are initially being applied to a set of 28 lakes that have detailed sediment surveys by the MN DNR, to enable work to begin on interactions between waves and nearshore habitat. Experimental wave-sediment measurements continue in the SAFL wave flume, with current measurements focusing on the effect of varying the bottom slope on wave-sediment interactions.

Project Status as of *December 31, 2019***:**
This reporting period included substantial work on the wind-wave models and nearshore habitat models. The previously selected wave model was first applied to a set of 28 lakes with MNDNR sediment surveys, and then to a much larger set of 457 lakes across the state, selected in cooperation with MNDNR from a list of lakes of biological significance. For both lake sets, detailed statistics on the wind speed and direction, wind fetch, and wave height were compiled for a monthly time scale, based on 16 year wind records. The fetch and wave height data for the 28 lake set were subsequently used with the MNDNR sediment surveys and other data to create empirical models relating fetch and wave parameters to the nearshore substrate (sediment) size class. This

nearshore habitat model is able to predict the variation of substrate size class around a lake with 78% accuracy. Experimental work at SAFL to relate wave height to nearshore sediment movement continued, with continued experiments to determine how the bottom slope affects sediment mobility.

Project extended to June 30, 2021 by LCCMR 6/18/20 as a result of M.L. 2020, First Special Session, Chp. 4, Sec. 2, legislative extension criteria being met.

Project Status as of *July 31, 2020***:**
This reporting period included work on wind-wave modeling and lab experiments on sediment resuspension. Experimental work at SAFL to relate wave height to nearshore sediment movement continued to March 2020, and was then put on hold due to COVID-19. It is anticipated that this experimental work will resume in late 2020. Two modeling efforts seek to improve wind-wave predictions. A two-dimensional wave model is being used to study how the shape of a lake affects the wave energy impacting shorelines, and a more detailed wind sheltering model is being used to improve the understanding of wave generation on smaller lakes. Both of these modeling efforts may be used to update wind-wave predictions and maps.

Project Status as of *December 31, 2020***:**
This reporting period included continued work on refinements to the wind-wave models. A two-dimensional wave model (SWAN) is being compared to the current one-dimensional model and is used to study how oblong or irregular lake shapes affect the wave energy impacting shorelines. A computational fluid dynamics model (FLUENT) is being used to develop more detailed relationships between shoreline vegetation, local topography, and wind sheltering on lakes, with the goal of improving the wave model accuracy for smaller lakes. Both of these modeling efforts may be used to update wind-wave predictions and maps. Experimental work at SAFL to relate wave height to nearshore sediment movement was on hold due in this period to COVID-19, but is anticipated to resume in early 2021.

Overall Project Outcomes and Results:
There are many ways in which healthy near-shore habitat and water quality in lakes is linked to wind and wave energy. Examples include walleye spawning habitat on nearshore gravel substrates, the distribution of submersed aquatic plants, sediment resuspension by wave action, and shoreline erosion. Successful lake habitat restoration requires good information on wind and wave energy, and this information is commonly not available. The main goal of this project was to create easily accessible information on lake wave energy to enable successful habitat restoration projects and increase natural fish reproduction in Minnesota lakes. The project partnered the University of Minnesota with the MN DNR and included field measurements of wind and wave height on four lakes ranging in size from 350 to 5000 acres, wave modeling work to map typical wave energy on the shorelines of 457 Minnesota lakes, and experimental work in a wave flume to better understand how nearshore sediment responds to wave energy in lakes. A major part of the project was to develop models for wave height and energy that consider wind sheltering by trees, so that wave height predictions could be made for smaller lakes with fetches of a kilometer or less. The wave maps created by this study can be used by state agencies and lake associations to plan lake shoreline management, including habitat restoration projects, aquatic plant management, and shoreline erosion control.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: *<u>Wave energy and habitat mapping for Minnesota Lakes</u>*
Description: This activity focuses on developing shoreline wave energy models for small lakes and large lakes with complex shorelines in Minnesota, taking into account wind sheltering effects from local terrain and trees. Previously developed models for wind sheltering will be combined with existing wave models. Wind and wave height data will be collected at four lakes for model verification. To develop relationships between wave energy and near-shore lake habitat (substrates), laboratory tests will be conducted at SAFL to measure rates of

sediment resuspension and sorting by wave action, with emphasis on substrates favorable for walleye spawning (gravel/cobble). The laboratory data will be combined with existing DNR field surveys of near-shore substrate composition and plant communities, to develop models relating wave energy to nearshore fish habitat. The fetch, wave energy, and substrate models will be applied to a set of lakes across Minnesota. GIS-based maps of shoreline wave energy and habitat classes will be generated for a set of 500+ lakes in the state.

Summary Budget Information for Activity 1:	**ENRTF Budget:**	**$ 294,000**
	Amount Spent:	**$275,198**
	Balance:	**$18,802**

Outcome	**Completion Date**
1. Assemble preliminary models for predicting nearshore wave height and energy.	*3/2018*
2. Experimental wave tank data for nearshore sediment resuspension and transport.	*6/2018*
3. Collect field data set for wind, waves, and nearshore water velocities.	*12/2018*
4. Add sediment resuspension models to wave model to predict lake substrate types.	*3/2019*
5. Complete nearshore habitat models.	*12/2019*
6. State-wide wave energy map for 500+ lakes; hold information sessions for lake managers.	*6/2020*

Activity 1 Status as of *December 31, 2017***:**
Wind and wave data collection for Outcome 3 was initiated in Fall 2017. Two tripod-based wind/wave measurement stations were assembled at St. Anthony Fall Lab (SAFL) in August 2017. One wind/wave station was installed at Belle Lake (a Sentinel lake) on September 13, 2017, and a second station was installed on September 28, 2017 in Lake Jennie, with the assistance of the MN DNR Hutchinson office. A photograph of the wind/wave station installed in Belle Lake is given in Figure 1. Both stations collected wind speed and direction data at 1 minute intervals, and water level (wave) data 5 times per second, and utilized cellular modems to transmit the data to SAFL. The stations were retrieved on November 8, 2017, giving 55 days of data at Belle Lake and 40 days of data at Lake Jennie. Work has begun to process the raw water level data from the wind/wave stations to calculate wave statistics as a function of wind speed and direction. In general, data from the stations is good. The data logger at Lake Jennie temporarily failed at low temperatures (< 35 °F), leading to the loss of about 20% of the data. An example of wind and wave data from Belle Lake is given in Figure 1 for data taken on October 15, 2017.

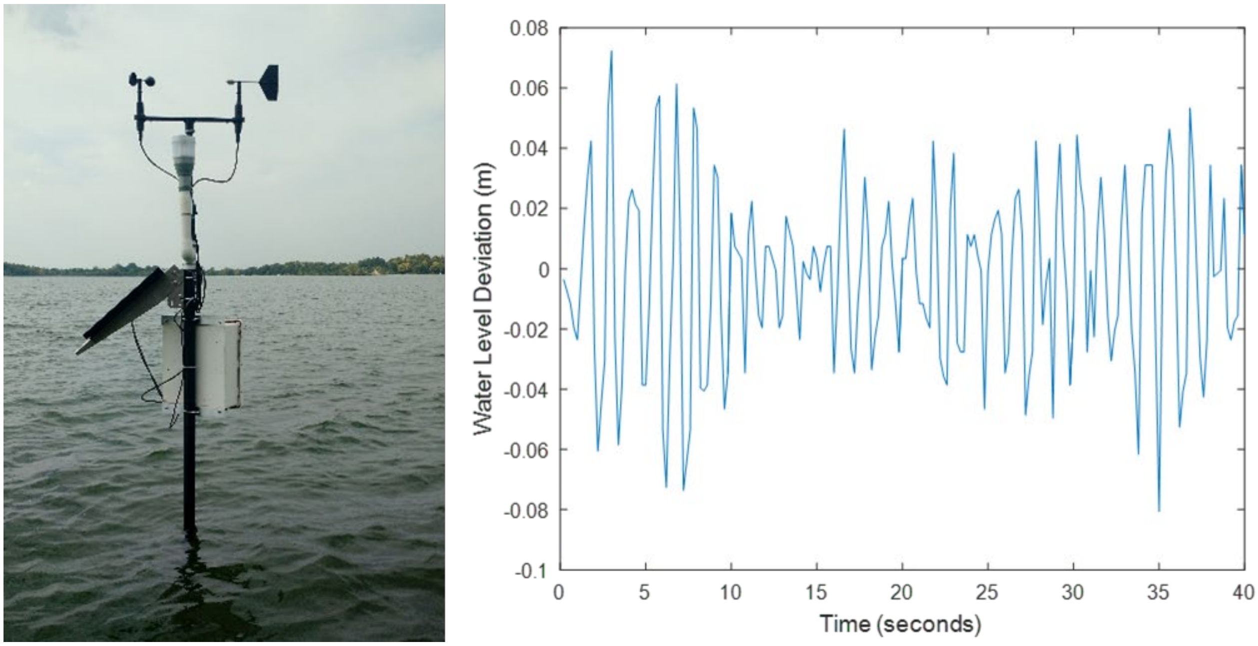


Figure 1. Left Panel: A photograph of the wind/wave measurement station installed in Belle Lake, showing the data logger, solar panel, and wind measurement instrumentation. The water level sensor is mounted beneath the data logger box, and is not visible. Right panel: A 40 second sample of the water level data taken at the station on October 15, 2017, with wave amplitudes of up to 0.13 meters (0.43 feet) driven by wind speeds of 5 m/s (11 miles per hour).

Activity 1 Status as of ***June 30, 2018*****:**
Wind and wave data collection for Outcome 3 continues in 2018. The two lakes instrumented in 2017 (Belle, Jennie) were in the range of 900-1000 acres in surface area. Two lakes to be instrumented with wave stations in 2018 include a relatively small lake (Swan Lake, McLeod County, 300 acres area) and a relatively large lake (Ten Mile Lake, Cass County, 5000 acres area), to provide wind/wave data from a broader range of lake sizes. The Swan Lake station was installed in June 2018, and the Ten Mile Lake station will be installed in July 2018. A medium sized, shallow lake (Lake Lillian, Kandiyohi County, 1000 acres) is under consideration for instrumentation later in 2018.

Processing of the wind-wave data from 2017 continues. The raw water level (wave) data from Belle Lake has been cleaned to remove bad readings and processed in Matlab to calculate wave statistics. The one hour average wave height was found to be very well correlated to the one hour average wind speed collected at the wave station, with an r^2 of 0.93 (Figure 2). The Belle Lake wave data were also compared to wind data obtained from the Hutchinson municipal airport, which is about 13 km (8 miles) south of Belle Lake. As expected, the Belle Lake wave data had lower correlation to the airport wind data ($r^2 = 0.63$). However, better correlation to the airport wind data was obtained by analyzing the data by wind direction. For winds from the northwest quadrant (west to north), the airport wind speed was well correlated ($r^2 = 0.80$) to the wave height on Belle Lake (Figure 2, right panel). The ability to correlate lake wave height to airport wind data is important, since the wave energy maps produced in this study will be based on airport wind data. Work will continue on relating measured wave heights to wind speed and direction, including the effect of lake fetch (the distance over water for wind-driven waves to build up).

To address Outcome 1, a literature search was performed to find the most relevant research on wave predictions for inland lakes and similarly sized water bodies. Work on inland lakes is very scarce, but some work on wave predictions in estuaries exists and will provide useful information on waves and sediment movement for this project. In particular, the empirical wave models in Karimpour et al. (2017) were developed for estuaries with fetches in the range of 3 km to 90 km, so that the lower fetch range of the Karimpour study is within the range of typical fetches in this study (1 to 5 km). These wave models will be tested using the 2017 wind/wave data collected in this study. Sediment resuspension models summarized in Green and Coco (2013), also focusing on estuaries, will provide the initial basis for sediment resuspension models – these models will be tested with the wave flume experiments.

Work has started on the wave flume experiments (Outcome 3). A wave flume test setup was assembled in March/April 2018, using an existing 20 in. wide by 30 ft. long flume at the St. Anthony Falls Lab. A variable speed, variable amplitude wave generator has been installed in the flume, and has been found to be capable of generating waves up to 8 inches (20 cm) in amplitude. The flume is equipped with an instrumented cart that can be used to automatically measure wave heights at different locations in the flume and make vertical profiles of the induced water velocities. Initial testing in July/August 2018 will include 1) measuring the sub-surface water velocities associated with the waves, 2) adding sediment of a known size to the flume bottom and determining the wave heights required to resuspend the sediment.

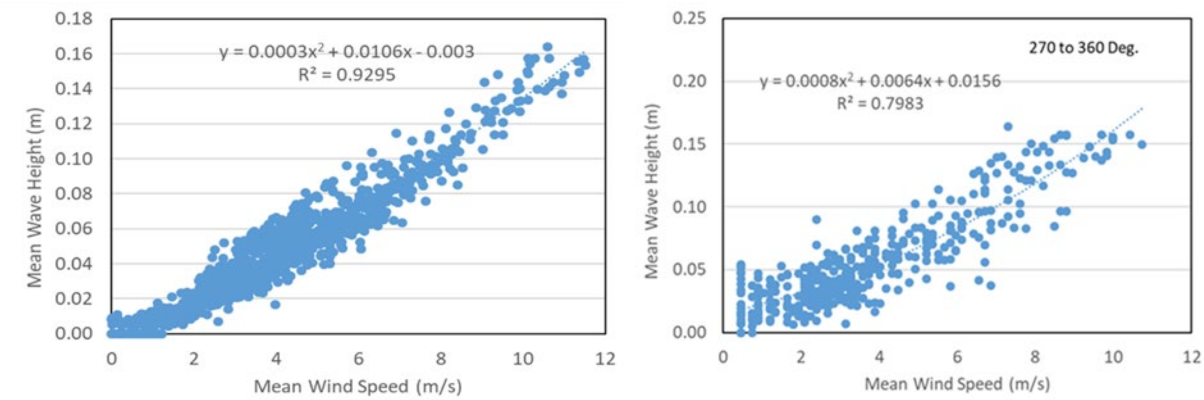


Figure 2. Left Panel: Mean hourly wave height versus mean on-lake wind speed for Belle Lake, Sept 22 to Nov 7, 2018, for all wind directions. Right panel: Mean hourly wave height versus mean airport wind speed for Belle Lake, Sept 22 to Nov 8, 2017, for westerly to notherly wind directions.

References

Green, M. O., & Coco, G. (2014). Review of wave-driven sediment resuspension and transport in estuaries. Reviews of Geophysics, 52(1), 77-117.

Karimpour, A., Chen, Q., & Twilley, R. R. (2017). Wind Wave Behavior in Fetch and Depth Limited Estuaries. *Scientific Reports*, *7*, 40654.

Activity 1 Status as of ***December 31, 2018*****:**

The wind-wave measurement stations used in 2017 were redeployed in 2018 to take wind-wave measurements in Swan Lake, a 350 acre lake in McLeod County, MN, and in Ten Mile Lake, a 5000 acre lake in Cass County, MN. Swan Lake represents a lower bound for the lake sizes of interest in this study, and is heavily wind sheltered. Ten Mile Lake is one of the MN DNR Sentinel Lakes, and has long fetches of up to 7.5 km, and represents a large lake where wind sheltering by trees is relatively insignificant. While Swan Lake was monitored from June 25 to September 7, monitoring of Ten Mile Lake was shifted later in the season (September 21 to November 1) to avoid high summer boat traffic, in co-operation with the lake association. Less-than-ideal weather conditions forced the installation of the Ten Mile Lake station to be near the boat launch, in the southwest corner of the lake. Nonetheless, good wave data was obtained for a variety of wind directions and fetch lengths, with wave heights of up to 40 cm.

Most of the wind-wave data obtained in 2017 and 2018 has been analyzed, with the goal of selecting the best method for modeling wave height as a function of wind speed, fetch, and tree sheltering in Minnesota lakes. In general, measured wind speeds are not available for each lake, so wave height predictions need to be made using wind data from the closest airport. The raw wind and wave data were processed to give mean hourly wind speed and direction, and the observed hourly significant wave height for each lake. For each hourly measurement, the fetch was determined based on the lake geometry and the wind direction. The tree height surrounding each lake was estimated from the MN State LiDAR data. The measured wind speed, fetch, and tree height were then used as input to wave models, and the predicted wave height was compared to the measured wave height.

Good wave prediction results have been obtained using data from Belle Lake, Lake Jennie, and Ten Mile Lake. Several wave models are being evaluated, including two versions of wave models developed by the US Army Corps of Engineers. Since these models were developed based on wind speeds measured over water, corrections need to be made for the case where wind speeds are measured at land-base airports. Examples of the relationships between modeled wave height and measured wave height are given in Figure 3 for Ten Mile Lake. For Ten Mile Lake, the relationship between measured and modeled hourly wave heights has an r^2 of about 0.65. We expect even better wave model correlations for longer time scales, e.g. daily and monthly. As the wave models are finalized in January/February 2019, work will begin with the Natural Resources Research Institute to develop methods to apply the models to a larger set of lakes in Minnesota.

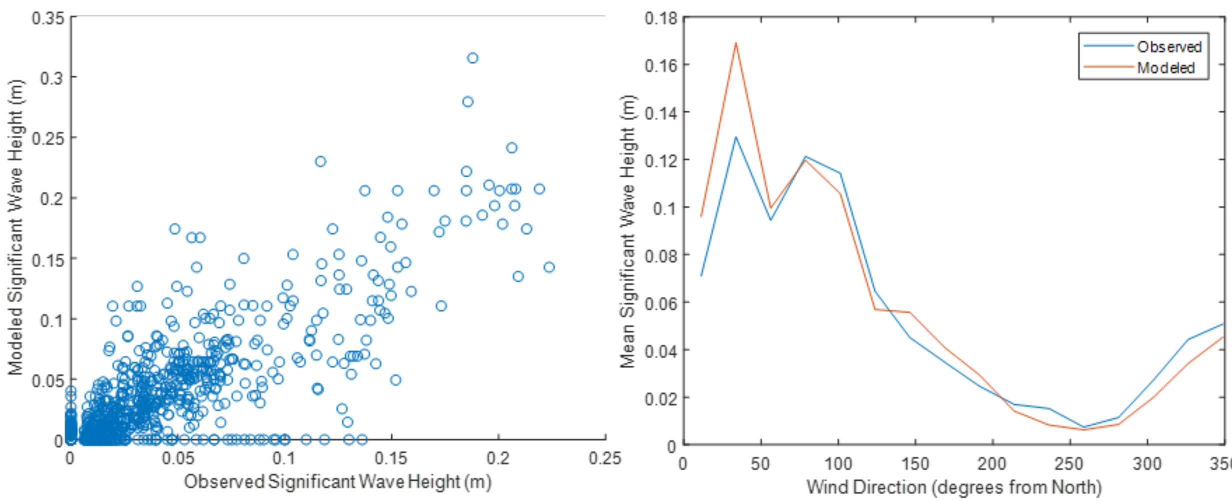


Figure 3. Comparisons of modeled and observed wave height on Ten Mile Lake, Sept 21 to Nov 1, 2018. Left Panel: Modeled versus observed mean hourly wave height, for all wind directions. Right panel: Modeled and measured mean wave height versus wind direction.

Several experiments have been completed in the wave flume at SAFL (Figure 4), as part of Outcome 2. High resolution surface wave time series and sub-surface water velocity profiles were measured for a number of different speed and amplitude settings of the wave generator, using an ultrasonic distance sensor and an acoustic doppler velocimeter. Existing theory to predict sub-surface water velocities as a function of wave height was found to be in good agreement with the wave flume data. The wave flume was then used to measure the required wave height required to resuspend a sand layer with 0.2 mm median diameter. The observed wave heights (9.5 cm) needed to resuspend the sand were reasonably close to the theoretical value of 7.8 cm (Green and Coco 2014). Experiments are currently underway to measure the wave resuspension characteristics of larger sediment sizes and mixed sediment sizes.

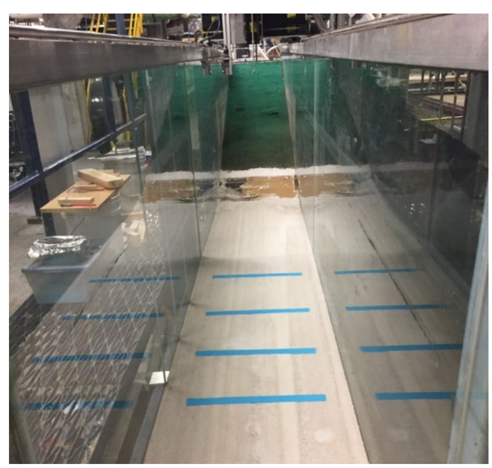


Figure 4. Photo of the interior of the wave flume. Stripes of colored sand were used to observe the onset of sediment movement.

Activity 1 Status as of *June 30, 2019***:**

A wind-wave model for Minnesota lakes has been finalized, based on a wave model from the US Army Corps of Engineers Shore Protection Manual, which gives a relationship between wind speed, fetch (open water distance), and wave height. To appropriately apply this model to inland lakes, airport wind speeds are modified to take into account the change in surface roughness from land to water, using a model developed by Taylor and Lee (1984). This roughness correction reduces wind speeds over short fetches, to take into account wind sheltering, but also increases wind speed over long fetches (> 1 km), as the wind speeds up over the smooth water surface. The wave model will be used to calculate wave heights and wave energy along the shoreline of each lake at approximately 500 meter intervals, based on the local wind conditions and the fetch (open water distance) for each wind direction. An example of the mean September wave height calculated for Ten Mile Lake (Cass County) is given below in Figure 5. The 500 meter resolution for the wave calculations is needed to capture the highly variable wave heights along the relatively complex shoreline.

Wave statistics will be calculated for each lake for each month, to capture the seasonal variability of winds at each location. The effect of ice cover will be included in the wave analysis. A regression equation for ice-in and ice-out dates will be used to determine the typical ice cover period for each lake based on latitude and lake depth. Wave statistics will be calculated only for the open water period, which can vary by more than a month from North to South in Minnesota. The Natural Resources Research Institute is compiling airport wind data over the state, so that wind statistics needed for wave calculations can be determined for any location in the state. Preliminary wave modeling work at the four study lakes has demonstrated that using spatial averages from multi airports surrounding a lake gives better results compared to using a single airport. Initially, wave statistics will be calculated for 28 lakes in Minnesota which have detailed sediment surveys by the MN DNR. This task will be completed in July 2019, to enable work to begin on relating wave height to nearshore sediment and habitat features (Outcome 5). We anticipate mapping wave energy on 500+ lakes, per the original plan, by the end of the year.

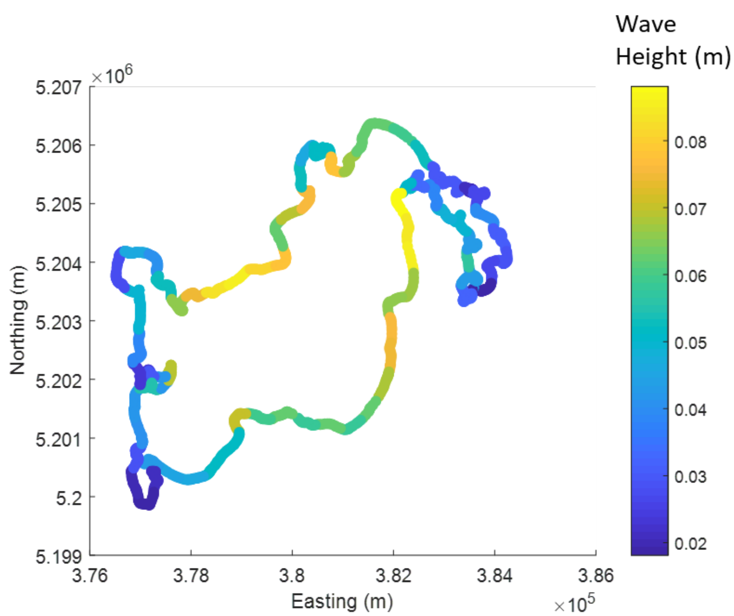


Figure 5. Map of mean September wave height for the shoreline of Ten Mile Lake in Cass County, MN.

Work continues on wave flume experiments at SAFL. Experiments on wave-induced sediment resuspension have been completed for different sand grain sizes, including mixed grain sizes. An experiment with a mixture of larger (1 mm mean diameter) and smaller (0.1 mm diameter) sand found that the larger sand grains had an armoring effect, inhibiting the resuspension of the small sand grains. The wave flume is currently being set up with an adjustable ramp, so that the effect of bottom slope on sediment resuspension can be measured.

References

Taylor, P. A. and R. J. Lee, 1984. Simple guidelines for estimating wind speed variations due to small-scale topographic features. Climatological Bulletin (Canada), 18(22), 3-32.

Activity 1 Status as of *December 31, 2019***:**

The wind-wave model developed previously in this study was first applied to a 28 lake set with detailed MNDNR substrate surveys and then to 457 lakes classified by the MNDNR as lakes of biological significance (LOBS), with the lake locations shown in Figure 6. Wind data was compiled from National Weather Service stations for 2002-2018 and spatially interpolated for each lake location, for use as input to the wind-wave model. An empirical model was developed for lake ice-in and ice-out dates, based on the lake latitude and maximum depth, which was used to modify the monthly wave statistics in spring and autumn to take into account the open water period. Outputs of the wind-wave model included mean and maximum fetch, and monthly wave statistics at 200m increments around each lake shoreline (Figure 5). Wind-wave data for the 28 lake set was used for a nearshore habitat model described below. The 457 lake set is a subset of about 1500 LOBS lakes in Minnesota with surface area greater than 100 acres, a maximum depth of at least 15 feet, and with the required data for the wind-wave model. The calculated wave statistics include monthly and annual significant wave height, the 50, 75, 90, and 95th percentile wave height, and the duration of waves exceeding thresholds of 5, 10, and 15 cm. The wave data for the 457 lake set will subsequently be made into GIS-based maps as one of the project deliverables, with the possibility of adding additional lakes for analysis.

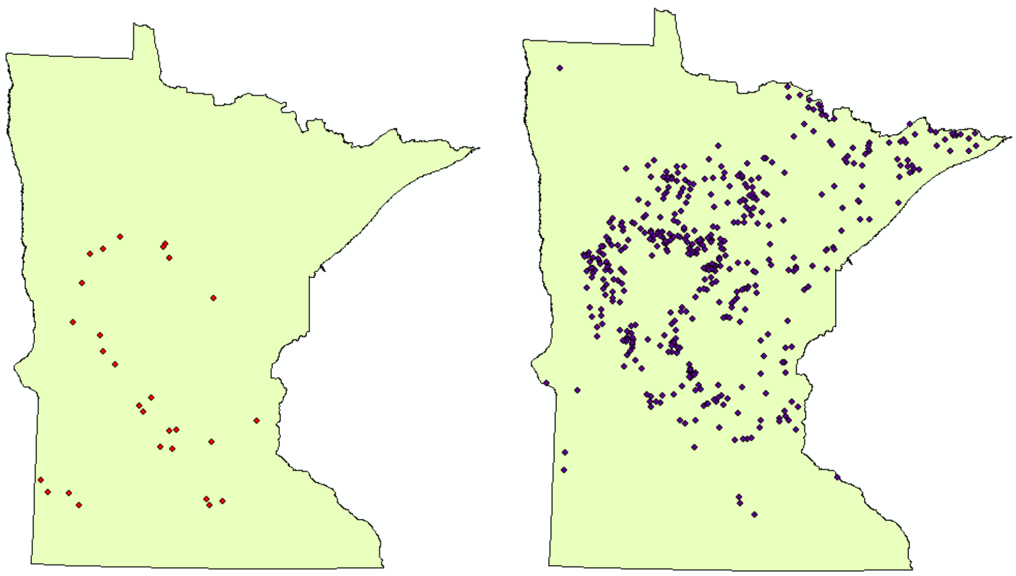


Figure 6. Location of the 28 lakes with detailed MNDNR substrate surveys (left) and the location of the 457 lakes of biological significance for which wind-wave analysis was performed (right).

An updated empirical model to relate fetch, wave height, and other spatial parameters to the nearshore habitat (substrate size class) has been developed by staff at the Natural Resources Research Institute. The substrate model is based on previous work by the MNDNR and others; the predicted lake substrate size information given by the model is useful for determining fish habitat suitability, including walleye spawning habitat (e.g. Schall et al. 2017). The model was developed based on detailed MNDNR substrate surveys for 28 lakes in Minnesota, with a series of transects on each lake (810 transects total) to measure the relative fractions of silt-clay, sand, gravel, cobble, rubble, and boulders in the lake substrate. Potential variables for predicting these substrate size classes (predictor variables) include wind speed, fetch, and wave height (from the wind-wave model), along with the slope and orientation of the shoreline, tree height, and some watershed variables such as land cover and soil types.

Several different statistical model types were explored to relate the observed substrate size classes to the predictor variables, including cluster analysis, generalized additive models (GAM), and classification trees. GAM models were used to predict the percentage of each substrate size class based on three predictor variables for each (Table 1). The coefficient of determination (R^2) for the GAM models ranged from 0.21 for cobble to 0.54 for silt-clay. Better predictions of substrate size classes were achieved using cluster analysis and classification trees. Cluster analysis was used to determine that three generalized substrate classes (denoted silt-clay, sand, and rock-gravel) were adequate to represent the variation of the six substrate sizes, and classification trees were then used to predict the presence/absence of the three generalized substrate classes (Figure 6). Some data for the analysis were unavailable for 2 of the 28 lakes, so that the analysis presented here is based on 26 lakes. The classification tree shown in Figure 6 was able to predict the presence of the substrate size classes with an overall correctness of 79%.

Table 1. The three predictors applied in GAM model to predict the percentage of each substrate component. GCV is generalized cross-validation score used in GAM. N=810. Ave_Fetch is the average fetch, Depth_5m is the water depth in the transect 5 m from shore, Depth_Avg_0_2m is the average water depth for sites, ndays is the average number of ice-free days, Slope_20m_MAX is the maximum slope for 20 m buffer around substrate stations, and UTM_x is the east-west location in the state.

Response variable - substrate	Predictor 1	Predictor 2	Predictor 3	r.sq	GCV	AIC
Boulder	Depth_Avg_0_2m	ndays	Ave_Fetch	0.4130	283	6874
Cobble	Depth_5m	UTM_x	Ave_Fetch	0.2085	109	6098
Gravel	Depth_5m	Depth_Avg_0_2m	UTM_x	0.2699	271	6837
Rubble	Depth_5m	Depth_Avg_0_2m	ndays	0.3773	181	6509
Sand	Depth_5m	Depth_Avg_0_2m	ndays	0.3344	666	7566
Silt_Clay	ndays	Ave_Fetch	Slope_20m_MAX	0.5444	510	7349

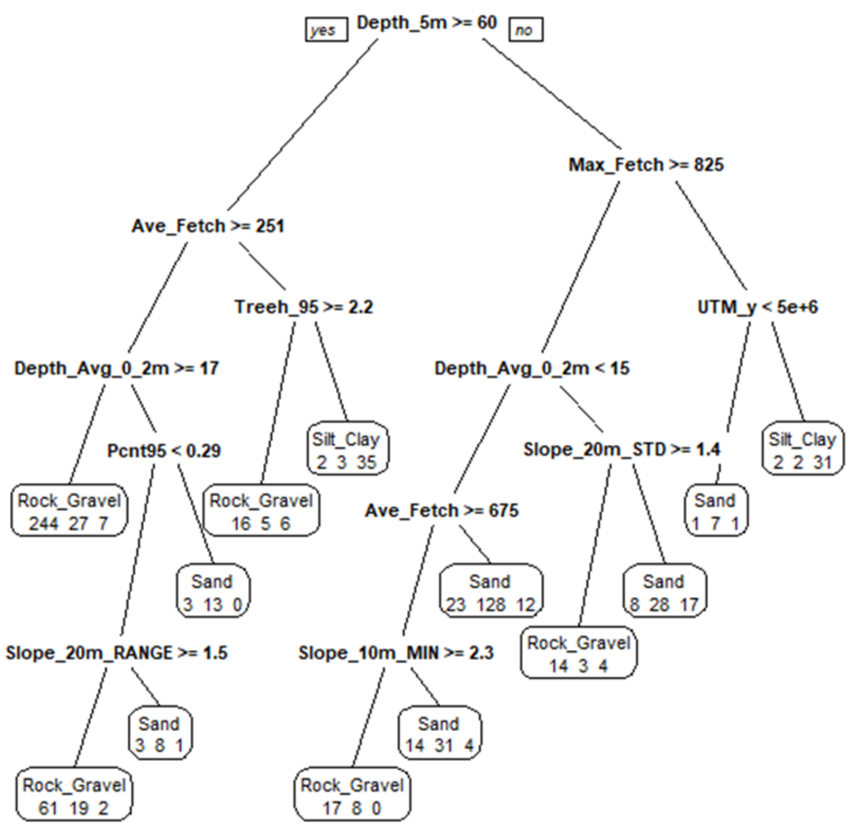


Figure 7. Classification tree for predicting the substrate size classes.

References

Schall, B. J., Cross, T. K., Katzenmeyer, E., & Zentner, D. L. (2017). Use of wind fetch and shoreline relief to predict nearshore substrate composition in a north temperate lake. North American Journal of Fisheries Management, 37(4), 935-942.

Activity 1 Status as of ***July 31, 2020*****:**

A two-dimensional (2D) wave model (SWAN) is being used to better understand how the shape of a lake and the orientation of the lake shape to the wind direction affects shoreline wave energy. A 2D model has been assembled for Belle Lake, to test the model against existing wave measurements. The model is currently being calibrated, and then will be used to predict shoreline wave energy over a range of wind directions, for comparison to the 1D wave models previously used in this study. It is expected that additional 2D wave models will be set up for lakes with irregular or oblong shapes (length much greater than width), to assess the wave field for different wind directions, compare the wave predictions to the 1D model, and determine if corrections need to be made to the 1D wave modeling results.

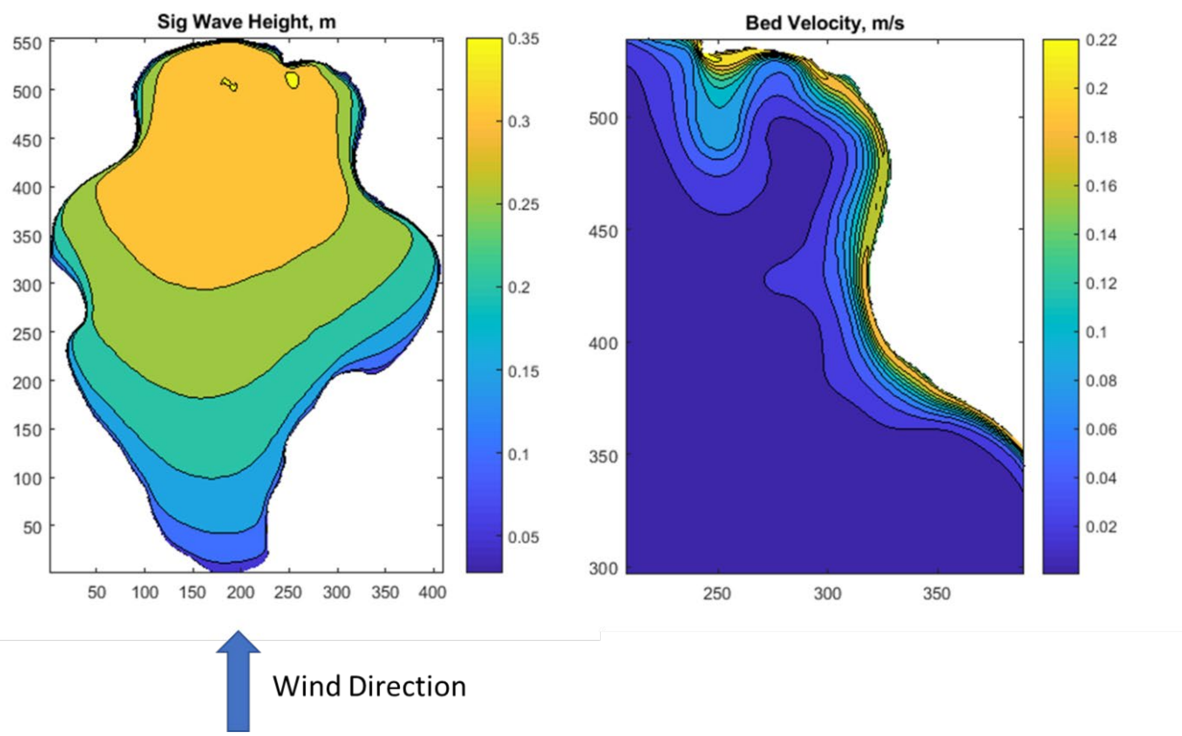


Figure 8. Sample output from the 2D wave model (SWAN) for Belle Lake, including a map of the significant wave height over the lake and a detail of the predicted nearshore bed velocity.

A second modeling exercise is focusing on the effect of wind sheltering on wind-waves. In previous work in the project, a simple model for wind sheltering based on the change in roughness from the land surface to the water was used to correct the observed wind speed to take into account wind sheltering. Wind sheltering is a more significant effect on small lakes, so that an improved wind sheltering model would enable better wave predictions on small lakes and lakes with short fetches in one direction. Two and three-dimensional models for wind flow over a row of trees and onto a lake surface are being used to map the wind-generated shear stress on a lake for different types of shoreline vegetation. The results from these simulations will be compared to the wind-sheltering model previously used in this study, and the need and ability to improve the simple wind sheltering models will be assessed.

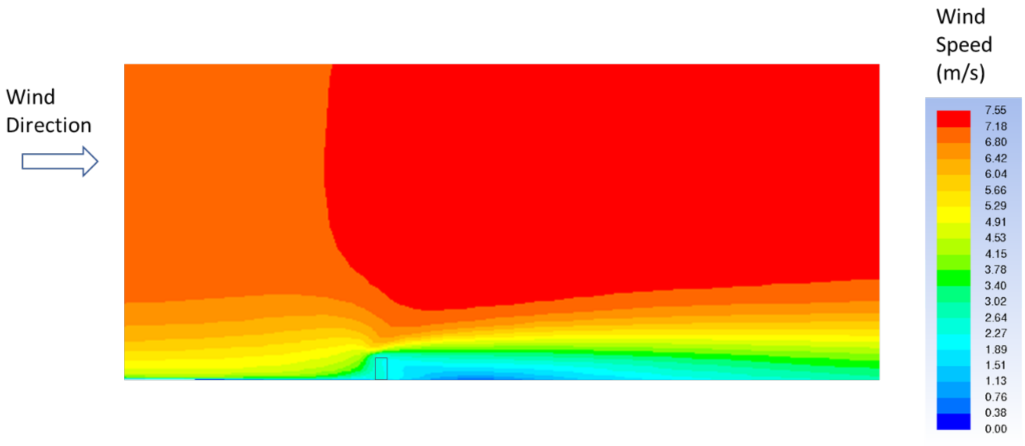


Figure 9. Two-dimensional simulated velocity field for wind flow over a line of trees adjacent to a pond or lake, showing the wind sheltering (speed reduction) downwind of the tree line. ANSYS-Fluent is being used for the simulations.

The lab experiments at SAFL to study sediment resuspension by waves continued into March 2020, but are currently on hold due to COVID-19. It is expected that testing will restart in October 2020. Tests in early 2020 focused on sediment movement on a sloped shoreline impacted by waves, by characterizing both local movement of the sand particles and migration of the sand down the slope.

Activity 1 Status as of ***December 31, 2020*****:**

Significant work was done over the period on detailed modeling of wind sheltering, with the goal of improving the wave model accuracy for smaller lakes. A commercial computational fluid dynamics package (ANSYS-Fluent) was used to simulate wind flow from land surfaces with vegetation and topography on to lakes. The main outputs of the models are the wind velocity distribution over the lake and the shear stress distribution on the lake surface (a surrogate for wave generation). For example, a decrease of shear stress on a lake surface indicates more wind sheltering and lower wave energy generation. An example simulation output is given in Figure 10, showing the wind velocity distribution as it transitions from a land surface to a water surface, with a line of trees and an embankment at the shoreline. A series of model runs simulated a range of tree and embankment heights, tree densities, single tree lines versus continuous forests, and the distance of the trees from the water edge. The results are being compiled into design curves that show the importance of the different variables on the average shear stress on the water surface. Examples of these design curves are given in Figure 11, showing the dependence of shear stress on the width of the forest strip and the height of the embankment. The moderate dependence on embankment height shows the importance of the local topography surrounding the lake on wind sheltering. The next step in this modeling effort will be to try to compile and simplify these relationships into a form that can be tested with existing field data and implemented into the wave model.

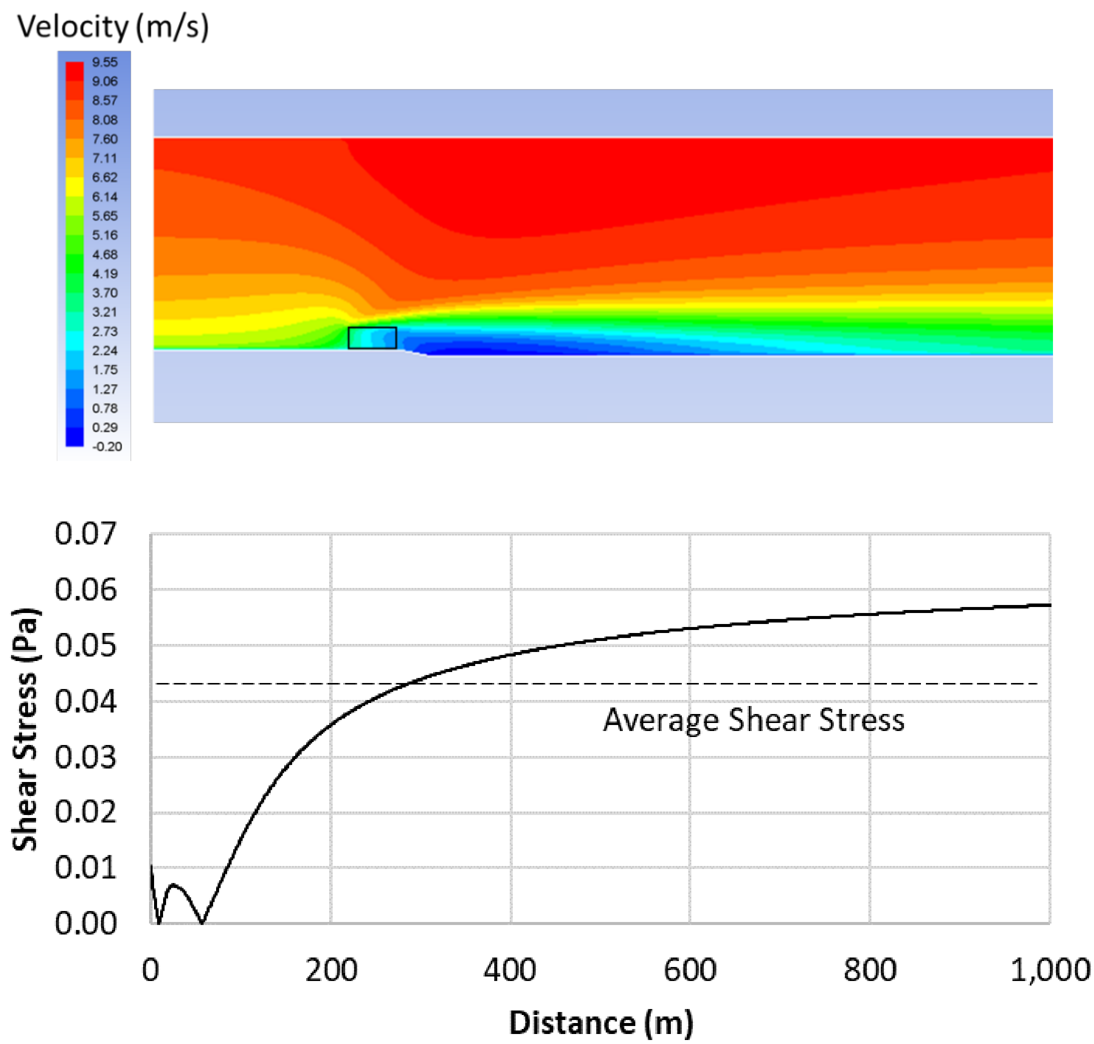


Figure 10. Sample output from a Fluent model, showing the wind velocity distribution (upper panel) going from upwind (left), over a 20 m wide line of trees, and onto a lake surface, and the corresponding shear stress distribution on the lake surface (lower panel). The dashed line on the lower plot indicates the average shear stress over the lake.

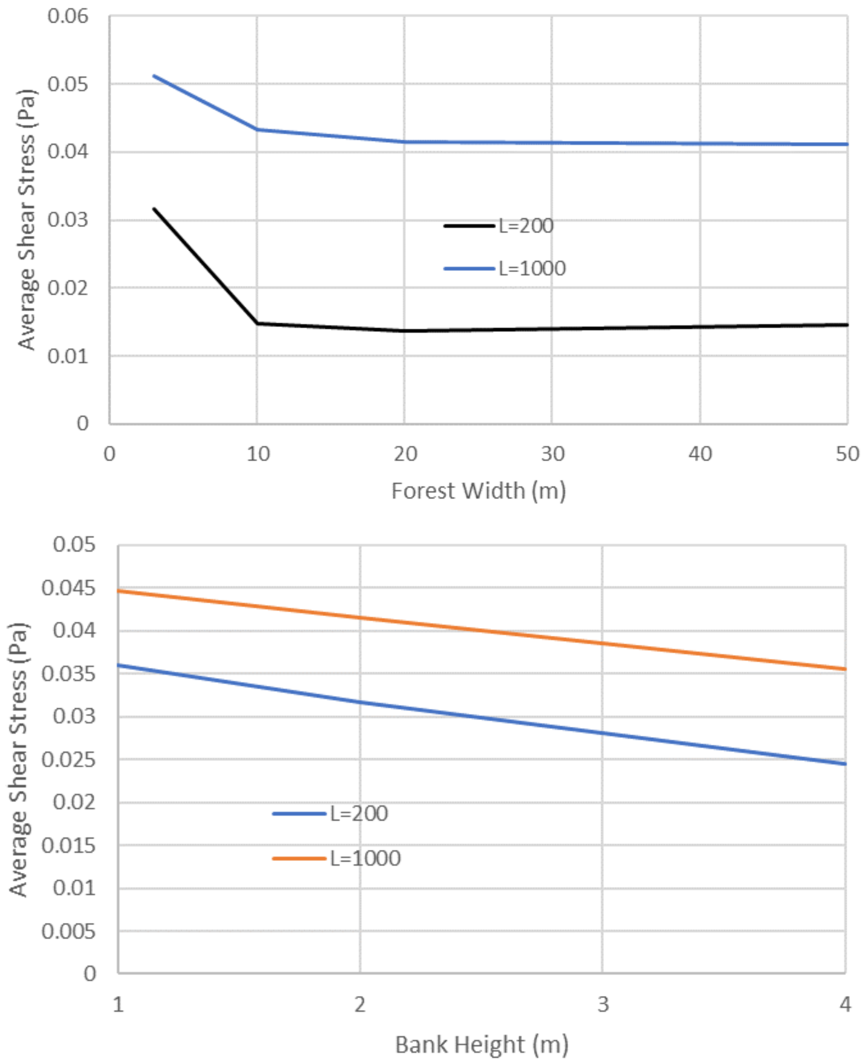


Figure 11. Average shear stress over a water body versus the width of the adjacent forest strip (upper panel) and average shear stress versus bank height (lower panel for 200 m long and 1000 m long water bodies.

Significant progress was also made on the 2D wave modeling effort using the SWAN model. The goal of this effort is to better understand how the shape of a lake and the orientation of the lake shape to the wind direction affects shoreline wave energy, and how these shape effects limit the accuracy of the 1D wave model currently being used for state-wide wave energy predictions.

A series of SWAN wave model simulations were made for Belle Lake and for a simple rectangular shape to compare SWAN predicted wave heights to the 1D wave model over a range a fetch, wind velocities, and model options in the SWAN model. Overall, it was found that there is reasonable agreement between the SWAN model and the USACE model at moderate to high wind speeds (e.g. 5 m/s and higher), as shown in the wave height plots for the two models at Belle Lake (Figure 12). but more discrepancy between the two models at low wind speed, e.g. < 5 m/s (Figure 13). With these results in mind, we will focus upcoming SWAN simulations on moderate to high wind speeds, which are also of more interest for the overall goals of the project.

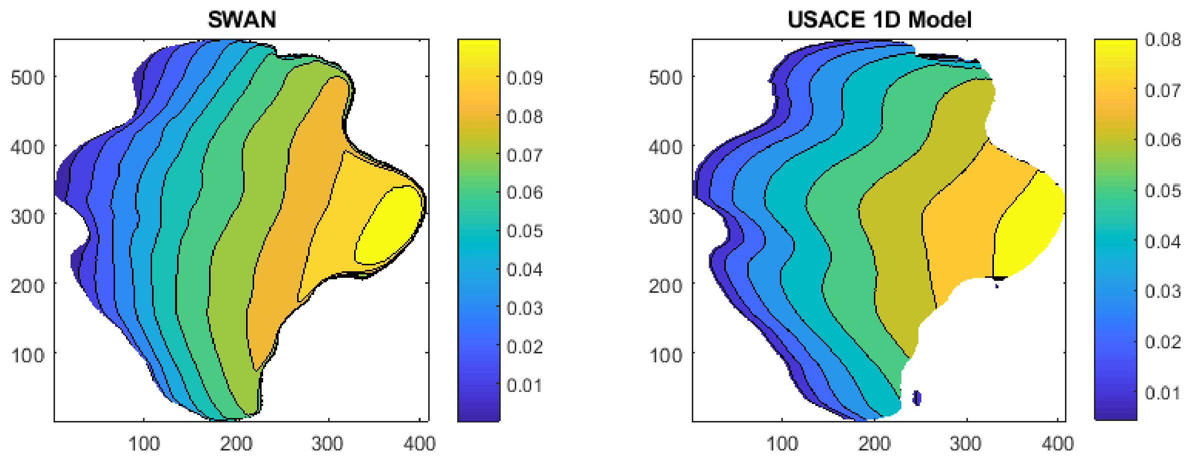


Figure 12. Simulated significant wave heights on Belle Lake for a wind event on Oct 4, 2017, with mean wind speed of 4.2 m/s at 285˚ CCW from the north. SWAN was used with wave setup Model B, with wind distributed on the lake per fetch distance predicted by the USACE model and wind speed reduction from roughness transition at the shore per Taylor and Lee (1984).

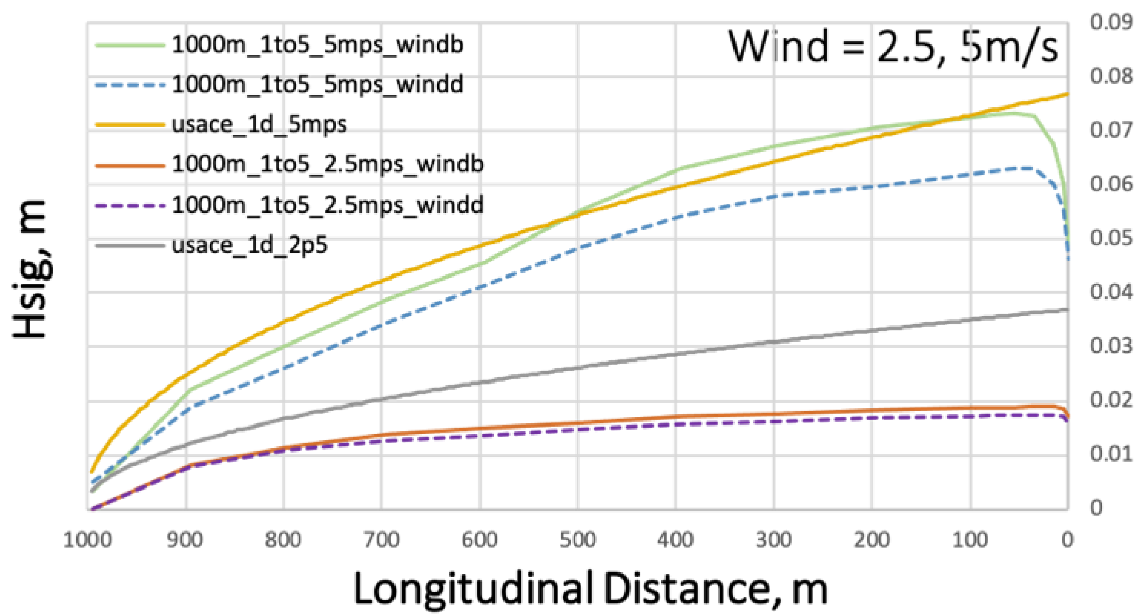


Figure 13. Comparison of significant wave height predictions from SWAN models B and D vs. USACE 1-D wave model for a 1000m-long domain for wind speeds of 2.5 m/s and 5 m/s wind speed. Note the larger differences in open water wave height prediction at low wind speeds (2.5 m/s).

The lab experiments at SAFL to study sediment resuspension by waves is currently on hold due to COVID-19. It is expected that testing will restart in late January 2021. Tests in early 2020 focused on sediment movement on a sloped shoreline impacted by waves, by characterizing both local movement of the sand particles and migration of the sand down the slope.

Final Report Summary:

Wave Flume Experiments

Beginning in late 2019, experiments were run in the SAFL wave flume to investigate movement of fine sediment (median diameter = 0.1mm) along a sloped bed, for a range of wave heights (~3 cm to ~7.5 cm) and slope conditions (0%, 5%, 7.5%, and 10%). These experiments were intended to simulate waves impacting a shoreline (in contrast to earlier experiments in which the sediment bed was flat), and due to changing water depth along the slope, the impact on sediment movement of a range of near-bed velocities and wave heights (due to shoaling and breaking) could also be observed. A fine sediment was chosen to ensure observable sediment movement occurred for the limited range of wave conditions the flume could produce. A schematic of the setup is shown in Figure 14.

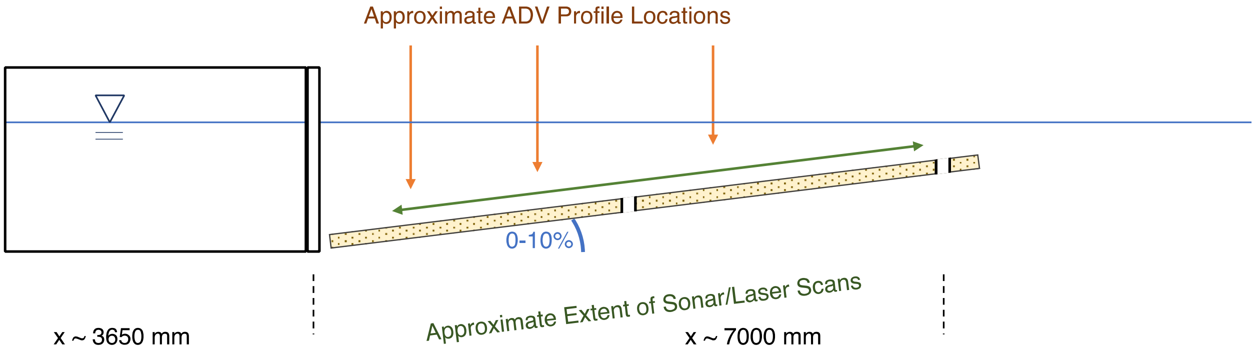


Figure 14. Schematic of SAFL wave flume with adjustable-slope bed. Wavemaker apparatus located off-diagram to the left at a location of roughly x=1000mm. Rock was placed at the upslope end of the adjustable bed where it met the fixed ramp ("beach") to prevent unrealistically high scour from occurring at the abrupt junction.

As in previous experiments, data were collected with the use of a cart mounted to the top of the flume, and included wave height (ultrasonic distance sensor), velocity fields in a vertical profile at three lateral locations (acoustic doppler velocimeter, or ADV), 3-D scan of the bed elevation between trials (sonar), and a fine-scale scan of the bed elevation while dry, before and after the run (laser). Collected data were aimed at addressing several goals: (1) compare measured velocities within the water and near the bed to velocities predicted from wave conditions and water depth, using approaches from the literature; (2) determine wave and water velocity conditions that lead to sediment movement, and compare these observations to predictions from the literature; (3) quantify movement of sediment downslope and relate to wave conditions or water velocities near the bed if possible. While several trials of this set of experiments were run in Nov 2019 and Feb 2020, work was put on hold due to Covid restrictions from March 2020 until April 2021.

A sample of the results are shown below (Figure 15) for the 10 percent slope case to illustrate data collection and analysis. This result was typical for the trials with greatest wave heights (usually around 6.0 – 7.5cm in each slope scenario), in which scour was most severe near the beach and deposition greatest near the downslope end of the bed, and distinct sinusoidal bed forms were produced along the slope (these can be seen in the upslope area of the sonar scan as vertical lines and patches in Figure 15).

Across the experiments, water velocity profiles observed with the ADV were very similar to velocity profiles predicted from linear wave theory (Green and Coco (2014) and Dean and Dalrymple (1991)) using the observed wave heights and water depth as inputs, except for the locations nearest the beach, where shoaling and breaking of waves violate model assumptions. Importantly, the water velocities near the sediment bed that are crucial to sediment movement, were also well-predicted by the modeling approach (RMSE = 18 mm/s; Figure 16a). Note that the scenarios (points) with poorest fit were generally in shallowest locations close to the beach where wave energy is lost due to shoaling, and the model over-predicts observed velocities, illustrating an important limitation of the model. Wave height and slope did not explain the outliers, further suggesting an effect of depth.

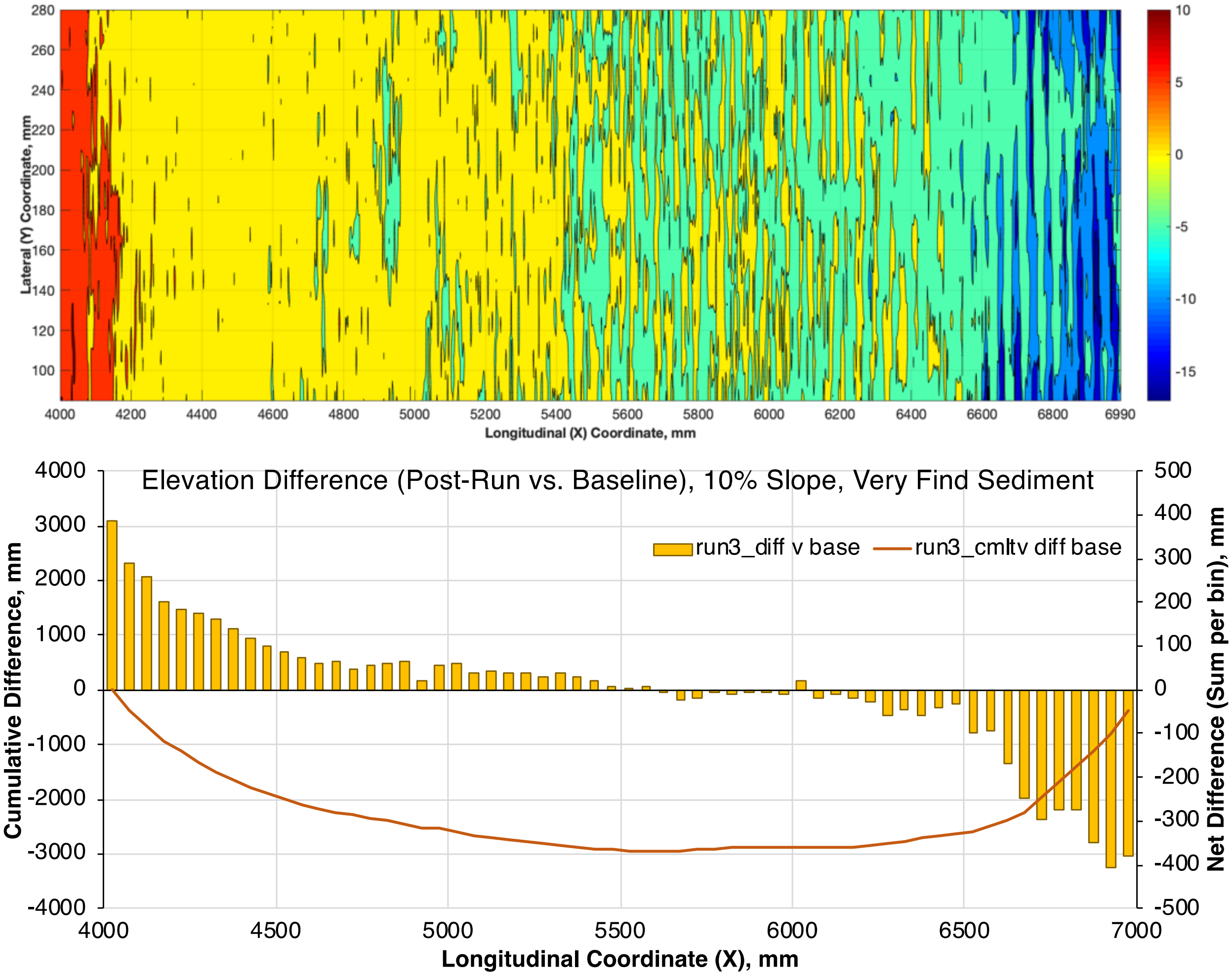
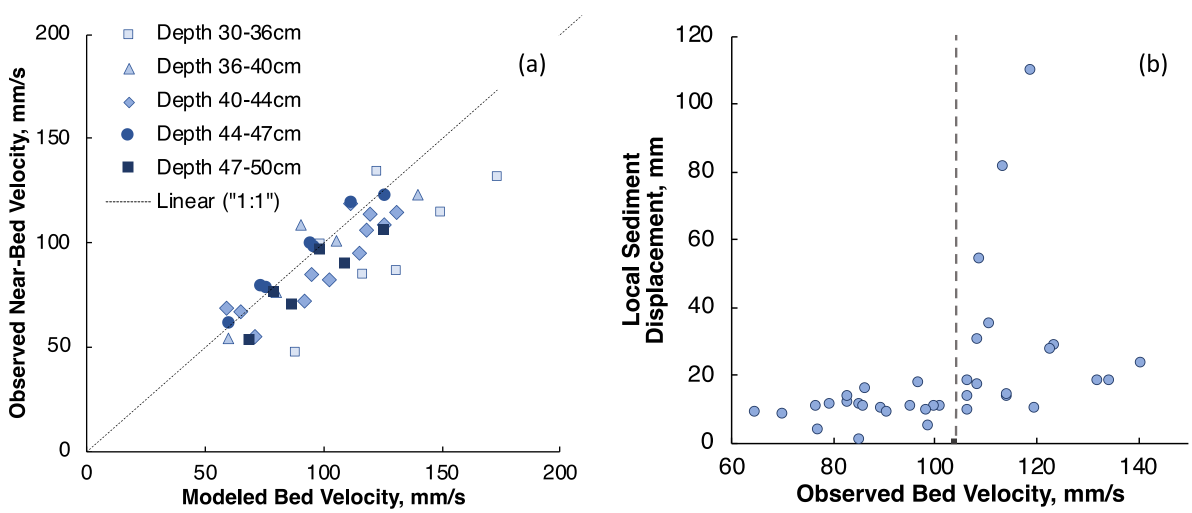


Figure 15. Top: elevation map of the sediment bed in the 10% slope case from sonar, following a run with mean wave height = 6.0 cm, plotted as change in elevation (in mm) vs. the baseline case of an undisturbed (smooth) bed. Blue colors indicate scour (mostly near the beach) and red indicates deposition (near the bottom of the slope). Bottom: lateral (Y) average of elevation difference along the slope (yellow bars); positive = deposition, negative = scour. Cumulative deposition shown (orange line) relative to the beach (x=7000mm).



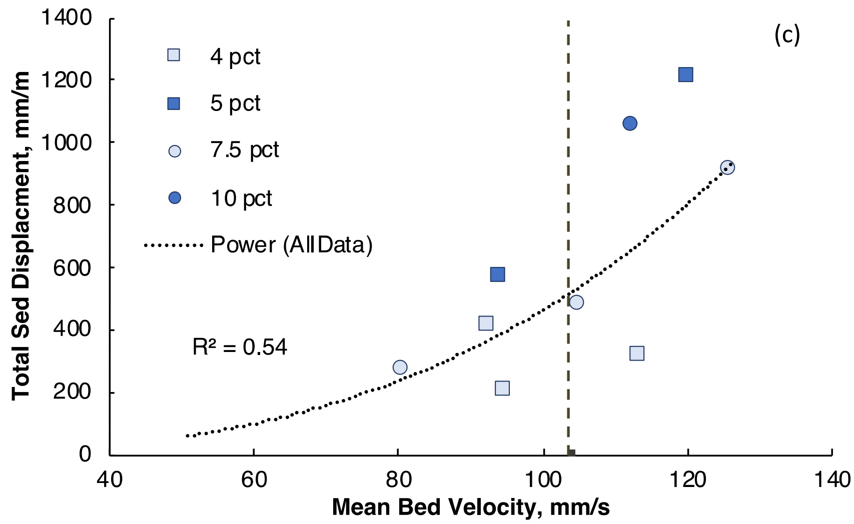


Figure 16. (a) Observed vs. Modeled bed velocity for all measurement locations across experiments (0% - 10% slope) with the fine sand (median diameter 0.1 mm), binned by water depth; (b) Local sediment displacement (mm; estimated from sonar) vs. observed bed velocity; (c) Total sediment displacement along the slope (mm displacement per m of slope) vs. mean observed bed velocity, with each point representing a given scenario of wave and slope conditions (lowest wave height scenarios omitted).

Using the sonar data, we characterized sediment movement (displacement) at all locations where bed velocities were measured during the experiments; these results are shown in Figure 16b along with the critical bed velocity required to initiate motion of sediment (104 mm/s for the sediment we used in the experiments; Green and Coco (2014)). The critical velocity for sediment motion does appear to coincide with an increase in observed sediment displacement, though the observed displacement at lower velocities is harder to explain. However, across the experiments, sediment movement was generally more difficult to detect at the lower wave heights (typically < 5 cm) from the sonar scans, or even from visual inspection, due to the small range of motion of the sediment and limitations of the sonar to detect these movements.

Total sediment displacement along the entire sloped bed was also estimated from sonar data (as total sediment displacement in mm per length of slope in m) and compared to the average bed velocity across the three locations within each run (Figure 16c). As with the local estimates, the lower wave height scenarios are not included (though bed velocities were marginal for sediment movement). As mean bed velocity increases, so does total sediment displacement, as expected. Slope did not seem to indicate greater or lesser likelihood of motion, though scan data did seem to indicate greater downslope deposition for the higher slope cases (10% slope especially).

2-D Wave Models

Earlier work in this study established that the SWAN and the USACE wave models were generally in agreement at moderate to high wind speeds (> 5 m/s). The last stage of this modeling effort was to use the 2D capabilities of the SWAN model to investigate wave refraction (bending towards shore as waves transition to shallower areas, especially when moving parallel to shore), in particular as it affects wave formation on lakes with irregular or oblong shapes. Results presented here are therefore mostly preliminary and may serve to inform future research.

SWAN was tested for a series of scenarios of increasing “ellipticalness” for a hypothetical, perfectly circular lake. The base scenario was a round lake with diameter (fetch) of 3000 m and max depth 20 m and a bowl-like bathymetry; the second scenario was an ellipse with major and minor axes of 3600 m and 2625 m, respectively, and the third scenario had axis lengths of 4200 m and 2460 m (Figure 17). All scenarios had the same diagonal

(NW to SE) distance of 3000 m; this was the fetch over which the scenarios were compared for an 8 m/s constant wind out of the NW (45° CCW from N).

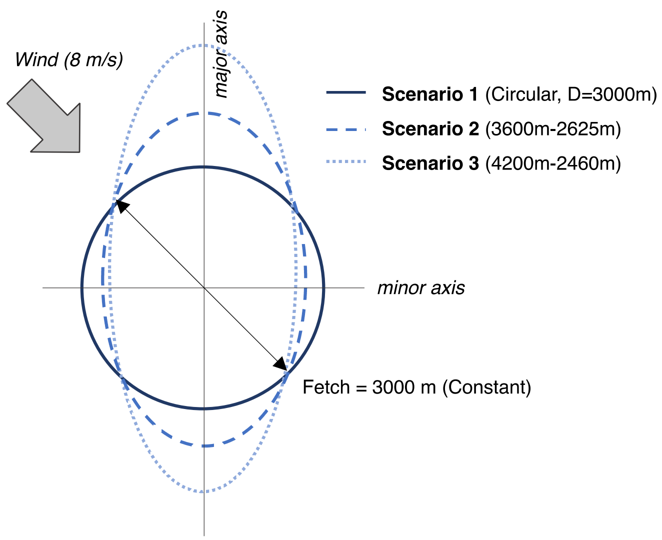


Figure 17. Schematic of lake geometries used to test wave refraction in lakes with irregular (oblong) shapes. Scenarios set up so that wind-aligned fetch (NW-SE) had a constant distance of 3000m among scenarios. Wind constant from NW at 8 m/s.

The results given in Figure 18 show that despite having a constant fetch distance, there was a slight increase in wave heights for the more oblong scenarios: Scenario 3 (most oblong) produced roughly 7.4% greater wave heights than Scenario 1 (circular lake) in the NW-SE transect. Interestingly, the minor axis transect (W-E), which was shortest in the most oblong case (Scenario 3), produced waves that were roughly 6.2% higher than the circular case, with the greatest difference at the upwind (lee) side of the transect. These simulations, though limited in scope, illustrate the potential two-dimensional effects of wind and wave interaction in irregularly-shaped lakes, in that greater fetch distance in directions that are not perpendicular to the shore and/or not in alignment with the wind direction, can still impact near-shore areas due to wave refraction.

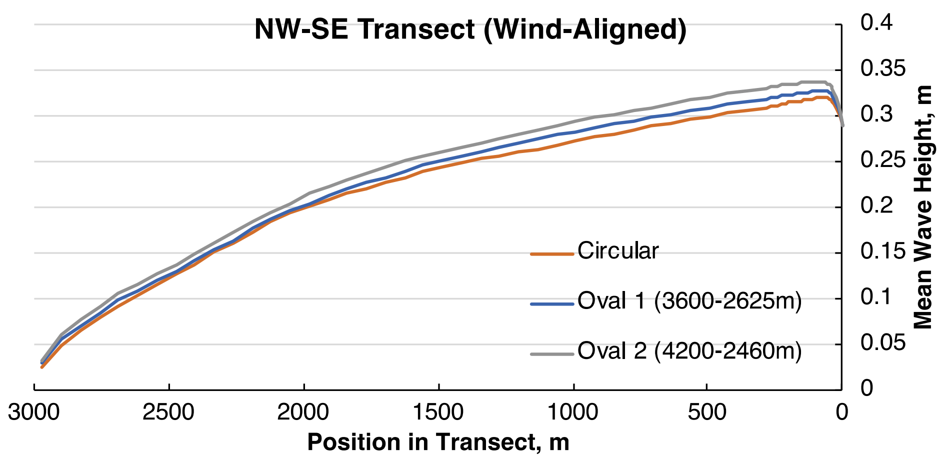


Figure 18. Simulations of mean wave height (m) versus position using the 2-D SWAN wave model along the wind-aligned direction.

Wind-sheltering models

In the last six months of the project, some additional work was performed to use CFD (computational fluid dynamics) to study wind sheltering on smaller lakes and ponds in more detail. 2-dimensional models (similar to the model shown previously in Figure 10) were used to simulate the wind field over the smallest lake from the field study, Swan Lake. Each hourly wind speed measured at the wave station was divided the observed airport wind speed to calculate a wind speed ratio. The wind speed rations were placed in 8 bins, by wind direction, and averaged over the 3-month time record. The observed wind speed ratios were then compared to modeled wind speed ratios, for both the CFD model and the simple roughness change model previously used to calculate wave heights. For the Swan Lake data, neither model performed well in predicting the wind speed ratio (Figure 19). Both model results show the expected effect of fetch on wind speed, while the observed wind speed ratio stays below 0.5 in directions with high fetch (bins 7 and 8). Some of this discrepancy is likely due to the airport wind measurement, which is approximately 12 km away from Swan Lake.

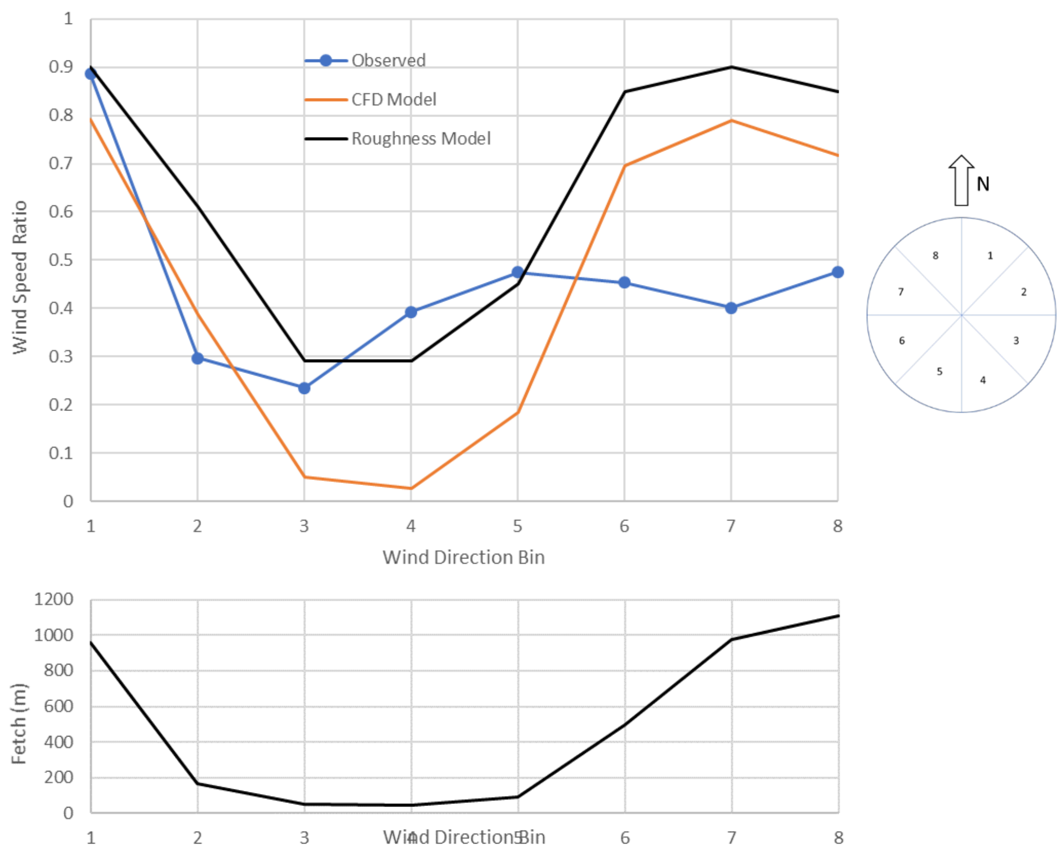


Figure 19. Observed and simulated wind sheltering (wind speed ratio) for Swan Lake (upper panel) and wind fetch versus direction (lower panel). The wind direction bins are numbered 1 through 8, as shown in the diagram to the right.

References

Dean, R. G., & Dalrymple, R. A. (1991). Water Wave Mechanics for Engineers. World Scientific Publishing Company, Teaneck, NJ.

Green, M. O., & Coco, G. (2014). Review of wave-driven sediment resuspension and transport in estuaries. Reviews of Geophysics, 52(1), 77-117.

Summary – Activity 1

Wind and wave measurements were collected at four lakes in the study, ranging in size from Swan Lake (350 acres) to Ten Mile Lake (5000 acres). A wind-wave model was developed based on previously USACOE work to predict wave height and wave energy statistics on the shorelines of inland lakes using wind data from local airports. The model was used to map wave height and wave energy on the shorelines of 457 Minnesota lakes. GIS layers with the simulated wave data for 457 lakes have been created. Wave statistics have been summarized both for mean annual time periods and for seasonal (monthly) periods, including the effects of ice cover. A key problem for wave prediction on inland lakes is availability of wind data in proximity to a lake of interest. Several methods for adjusting local airport wind speeds for wind sheltering around a lake were explored, from simple roughness change models to more complicated computational fluid dynamics models. We found that with limitations of reginal airport wind measurements and the complexity of terrain and tree canopies around lakes, more complex wind sheltering models were no better than simple models at predicting wind speeds and wave heights on lakes. A preliminary exploration of 2-dimensional (2D) wave models to take into account non-circular lake shapes showed that long fetches in directions different than the wind direction may increase wave heights on the order of 5-10%. 2D wave models are promising tools for exploring particular lakes, but would be difficult to apply to a large lake set.

The effect of waves on near-shore sediment was explored using a series of laboratory wave flume experiments, which showed that simple linear wave theory is largely successful is predicting sub-surface water velocities and movement of sediment driven by waves, particularly for the case of a flat and level lake bottom. Water velocities and sediment movement becomes more complicated and less predictable on sloped boundaries, as the water depth is reduced to values similar to the wave height, due to wave shoaling, breaking, and reflection from the beach. For flat bottoms, wave-driven sediment movement was mainly in the form of sand ripple formation. For sloped bottoms, some evidence of bulk sediment movement down slope or off slope, but the small changes in bed elevation due to bulk movement were difficult to measure reliably.

The predicted wave heights were also used in an attempt to model observed distributions of different sediment sizes (silt, sand, gravel, cobble) in the near-shore are of lakes, as a first step towards, for example, a fish spawning habitat model. A previously developed (by the MN DNR) empirical model for near-shore sediment sizing was modified to include the modeled wave height and wave energy variables. Somewhat surprisingly, the addition of the wave variables did not improve the prediction of sediment sizing. The implication is that the fetch variable included in the original sediment size model effectively captured the effects of waves. More reliable models for nearshore lake substrates may need to include longshore transport of sediment by wind-driven currents, which was out of the scope of this study.

The GIS maps of wave height and energy created in this project will be uploaded to the Data Repository for University of Minnesota (DRUM). Details of the project will be published in a St. Anthony Falls Lab project report to document the methodologies used. The project PI attended a conference on the Sentinel lakes, organized by the MN DNR, in March 2019 in Alexandria, MN. Current results and future plans for this project were presented to the group, which included MN DNR, MPCA, and USGS personnel, and some feedback on the project deliverables was obtained. The PI is also giving a poster presentation at the 2021 Minnesota Water Resources Conference. A small, independently-funded project is underway at SAFL to measure boat wake impacts on Minnesota lakes, in co-operation with a number of Minnesota lake associations. Results on wind-driven waves from the LCCMR project will be used as a basis for comparison in the boat wake project and presented to lake owners associations that are involved in the boat wake project.

V. DISSEMINATION:

Description: We will disseminate the results of our project in several ways. Scientific results from Activity 1 will be published in peer-reviewed journals, and presented at regional conferences, e.g. the Minnesota Water Resources Conference, and Minnesota DNR meetings, e.g. the annual fisheries research meeting. In addition, we will hold several informational sessions for lake managers to describe the wave and habitat mapping products as the study concludes.

Status as of ***December 31, 2017*****:**
No dissemination activities to report in this period.

Status as of ***June 30, 2018*****:**

A meeting was held in March 2018 between the project PI and MN DNR staff in Brainerd, MN, to discuss the application of the project results to improving aquatic plant restoration efforts at the DNR. A poster has been created to summarize the project for public and private tours of the St. Anthony Falls lab.

Status as of *December 31, 2018*:
No dissemination activities to report in this period.

Status as of *June 30, 2019*:
The project PI (William Herb) attended a conference on the Sentinel lakes, organized by the MN DNR, in March 2019 in Alexandria, MN. Current results and future plans for this project were presented to the group, which included MN DNR, MPCA, and USGS personnel, and some feedback on the project deliverables was obtained.

Status as of *December 31, 2019*:
No dissemination activities to report in this period.

Status as of *July 31, 2020*:
No dissemination activities to report in this period.

Status as of *December 31, 2020*:
A journal manuscript summarizing some of the wave measurement and modeling work has been started, with the goal of submitting the manuscript by 6/30/2021. A small, independently-funded project is underway at SAFL to measure boat wake impacts on Minnesota lakes, in co-operation with a number of Minnesota lake associations. Results on wind-driven waves from the LCCMR project will be used as a basis for comparison in the boat wake project and presented to lake owners associations that are involved in the boat wake project.

VI. PROJECT BUDGET SUMMARY:
A. Preliminary ENRTF Budget Overview:
***This section represents an overview of the preliminary budget at the start of the project. It will be reconciled with actual expenditures at the time of the final report.**

Budget Category	$ Amount	Overview Explanation
Personnel:	$ 277,099	1 project manager at 28% FTE for 3 yrs ($83,470); 3 research associates (SAFL and UMD) at 39% FTE 3 yrs ($94,098), 15% FTE 3 yrs ($42,513) and 5% FTE 3 yrs ($14,086); 1 assistant scientist at 7% FTE for 3 yrs ($15,679); 1 junior scientist at 6% time for 3 yrs ($12,178); 1 undergraduate at 22% FTE for 3 yrs ($15,075)
Equipment/Tools/Supplies:	$ 12,825	6 ultrasonic distance sensors $400 each ($2,400), 6 anemometers $375 each ($2,250), 3 Data Loggers $1625 each ($4875), Tripods, Misc. field supplies ($2700), Misc. Lab Supplies ($600)
Printing:	$300	Materials for informational seminars
Travel Expenses in MN:	$3366	Travel to field sites ($646), UMD personnel travel to Twin Cities for meetings ($972), In-state conferences ($924), Informational seminars ($824).
Other:	$410	NRRI GIS Lab fees ($410)
TOTAL ENRTF BUDGET:	**$294,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: N/A

Total Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 3.6 FTEs

Total Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: N/A

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
	$	$	
State			
University of Minnesota (in-kind support)	$152,880	$	Unrecovered F&A at 52% MTDC
Minnesota DNR	$45,000		The MN DNR will provide in-kind support as labor and expenses for ongoing collection of shoreline habitat data, and for testing and evaluation of the products produced in this study.
TOTAL OTHER FUNDS:	**$197,880**	**$**	

VII. PROJECT STRATEGY:

A. Project Partners: Drs. William Herb and Heinz Stefan (*UMN-SAFL)* will be the overall lead in the project, develop wave energy and lake sediment models, relate wave energy to shoreline habitat features, and assist in the development of the habitat assessment tool. UMD-NRRI staff (Lucinda Johnson's group) will assist in evaluating shoreline habitat features and in producing the deliverable maps. Herb, SAFL support staff, and NRRI staff will be funded by the ENRTF, while Stefan will contribute time to the project. All personnel funded by the ENRTF are soft-funded research staff and students.

The MN DNR will contribute in-kind staff time, equipment, and data for characterization of near-shore substrate composition and aquatic plant communities, coordinated by Tim Cross (Fisheries Research Scientist) and John Hiebert (Shoreland Habitat Manager).

Partners receiving ENRTF funding

- *University of Minnesota Duluth, NRRI (Lucinda Johnson's group), $56,600 for habitat mapping.*

Partners NOT receiving ENRTF funding

- *Tim Cross, Fisheries Research Scientist, Minnesota DNR, nearshore fish habitat assessment*
- *John Heibert, Shoreland Habitat Manager, Minnestoa DNR, shoreline management*
- *Heinz Stefan, Emeritus Professor, University of Minnesota, assisting with technical management*

B. Project Impact and Long-term Strategy: Information on wave energy affecting shoreline habitats of Minnesota lakes is critical for lake managers using limited resources to improve sustainable lake habitat conditions. Using the study results to bolster critical natural reproduction processes for fish in lakes where shoreline habitats have been compromised is a likely outcome. The wave energy maps will have a number of applications, including, for example, mitigation of shoreline erosion for lake property owners and for reestablishing submerged and emergent aquatic plants in lakes. The results of this study may also form the basis for additional research on fish habitat, e.g. targeting particular sport fish or endangered species.

C. Funding History:

Funding Source and Use of Funds	Funding Timeframe	$ Amount
Minnesota DNR, preliminary wave measurements and analysis	6/1/15 – 6/30/16	$ 25,000
		$
		$

VIII. REPORTING REQUIREMENTS:

- **The project is for 4 years, will begin on July 1, 2017, and end on June 30, 2021.**
- **Periodic project status update reports will be submitted** *6/30* **and** *12/31* **of each year.**
- **A final report and associated products will be submitted between June 30 and August 15, 2021**.

IX. VISUAL COMPONENT or MAP(S): see attachment

X. FEE TITLE ACQUISITION/CONSERVATION EASEMENT/RESTORATION REQUIREMENTS:

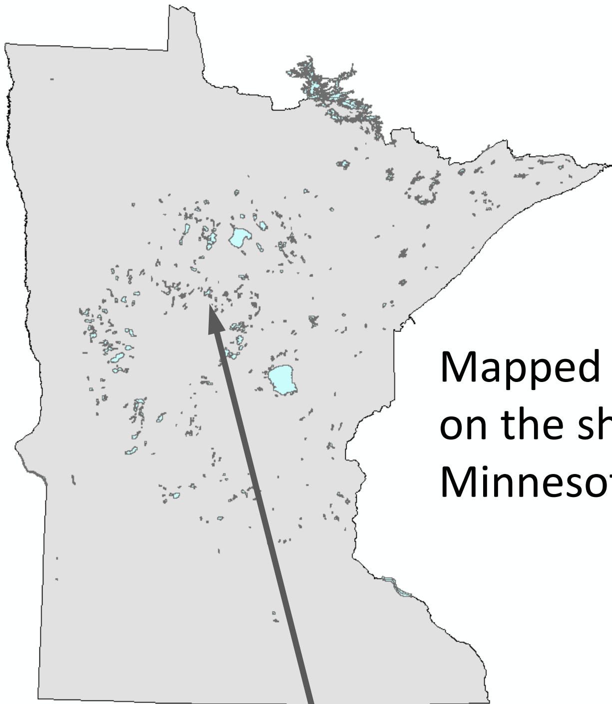
A. Parcel List: N/A

B. Acquisition/Restoration Information: N/A

Environment and Natural Resources Trust Fund
M.L. 2017 Final Project Budget

Project Title: Enhancing Spawning Habitat Restoration in Minnesota Lakes
Legal Citation: M.L. 2017, Chp. 96, Sec. 2, Subd. 08e
Project Manager: William Herb
Organization: University of Minnesota
M.L. 2017 ENRTF Appropriation: $ 294,000
Project Length and Completion Date: 4 Years, June 30, 2021
Date of Report: August 16, 2021

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Revised Activity 1 Budget 8/3/2020	Amount Spent	Activity 1 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM					
Personnel (Wages and Benefits)	$277,099	$263,895	$13,204	$277,099	$13,204
William Herb (PI): Project management, wave modeling, 28% fte, 66% Salary, 34% Fringe, 36 months ($83,470)					
NRRI Res. Assoc.: Map development, 15% fte, 66% Salary, 34% Fringe, 36 months ($42,513)					
Meijun Cai, Res. Assoc., Habitat model, 5% fte, 66% Salary, 34% Fringe, 36 months ($14,086)					
Erickson, B., Assist. Scient.: Field measurements,7% fte, 74% Salary, 26% Fringe, 36 months ($15,679)					
Res. Assoc.: Wave modeling, 39% fte, 66% Salary, 34% Fringe, 36 months ($94,098)					
Mielke, S., Jun. Scient.: Lab measurements, 6% fte, 74% Salary, 26% Fringe, 36 months ($12,178)					
Undergrad: Lab and field measurements, 22% fte, 100% Salary, 0% Fringe, 36 months ($15,075)					
Equipment/Tools/Supplies	$12,325	$9,681	$2,644	$12,325	$2,644
6 ultrasonic distance sensors $400 each ($2,400), 6 anemometers $375 each ($2,250), 3 Data Loggers $1625 each ($4875), Tripods, Misc. field supplies ($2200), Misc. Lab Supplies ($600)					
Printing	$300	$90	$210	$300	$210
Materials for informational seminars					
Travel expenses in Minnesota	$3,366	$1,389	$1,977	$3,366	$1,977
Travel to field sites ($646), UMD personnel travel to Twin Cities for meetings ($972), In-state conferences ($924), Informational seminars ($824).					
Other	$910	$143	$767	$910	$767



Mapped wave height and energy on the shorelines of 457 Minnesota lakes