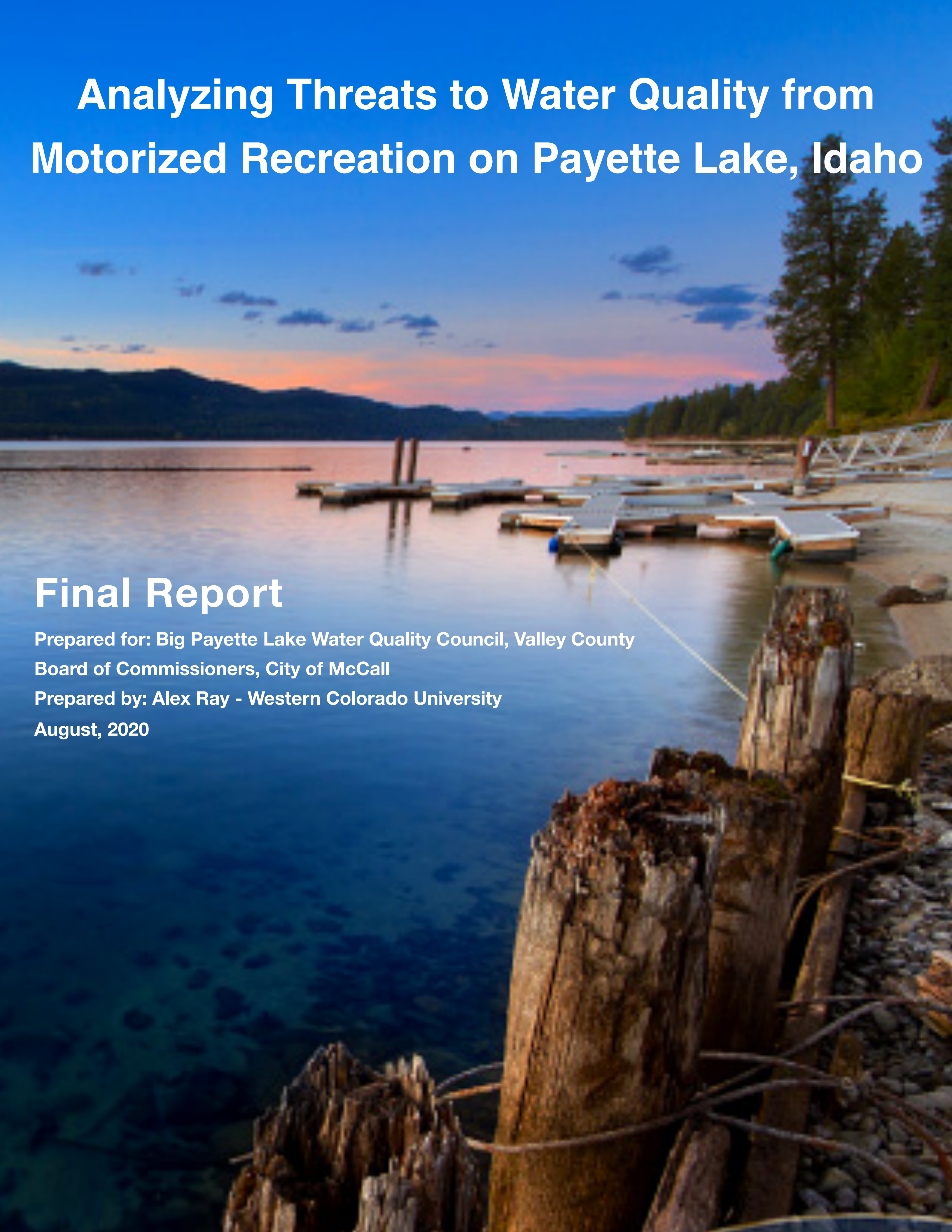
Analyzing Threats to Water Quality from Motorized Recreation on Payette Lake, Idaho



Final Report

Prepared for: Big Payette Lake Water Quality Council, Valley County
Board of Commissioners, City of McCall
Prepared by: Alex Ray - Western Colorado University
August, 2020

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Cover photo credit: Anna Gorman

Executive Summary

With the rise in popularity of boats designed specifically to produce large wakes, communities around the world have adopted policies and ordinances to mitigate the impacts that the use of these boats may cause. While a large body of knowledge exists on threats posed by recreational boating, case specific research is necessary to create informed and equitable management decisions. In pursuit of my Master of Environmental Management degree from Western Colorado University, and working in partnership with the Big Payette Lake Water Quality Council, I have started the preliminary phases of this research on Payette Lake.

Comprehensive reports on recreation management typically consider impacts towards environmental, social, and economic impacts of specific activities. These reports are often the work of a team of researchers, and take years to complete. As I am working independently, I have chosen to consider only the impacts towards environmental resources in this report. Specifically, I am investigating the potential for motorized boats to disturb bottom sediments and shorelines in Payette Lake.

In the 1997 report, “The Eutrophication Potential of Payette Lake,” Paul Woods of the USGS describes in detail hydrologic and nutrient regimes in the lake. With a water residence time of nearly 2.5 years, and high volumes of natural and anthropogenic nutrient inputs, elevated phosphorous levels are found in many areas of lakebed sediment; especially in the heavily populated and trafficked southwest basin. The danger lies in the resuspension of this phosphorous, which has been shown to be a primary (and limiting) factor of toxic blue-green algae blooms[1]. With blue-green algae affecting recreation and aquatic habitats in many Idaho waterways in recent years, including Cascade Reservoir, special attention must be paid to this threat in Payette Lake.

About the Author

Alex Ray is a McCall native (MDHS 2001), graduate of Willamette University in Salem, Oregon. (2005; B.A. Spanish/Geography) and is currently pursuing a Masters of Environmental Management degree in Integrative Public Lands Management through Western Colorado University in Gunnison, Colorado. He worked in trail, recreation, and aquatic resource management programs for the Forest Service, National Park Service, Bureau of Land Management, and various other organizations from 2001 to 2018, and currently owns and operates a recreation management consulting business. HIs work has taken him all across the West, and in addition to his scholarly pursuits, he is currently providing consulting services for the Idaho Trails Association.

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1. Pelley, J. (2016). Taming toxic algae blooms. *ACS Central Science,* 2(5), 270-273. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC488273

Introduction

Across the West, outdoor recreation is rapidly becoming the primary driver of regional and local economies. Over the last several decades, as resource extraction industries have declined in prevalence, the outdoor recreation industry has recorded drastic increases in product sales. In 2018, the Outdoor Industry Association (OIA) estimated the outdoor recreation economy saw consumer sales of $887 billion, representing a 37% increase since 2012. Likewise, 1.5 million outdoor industry jobs were created between 2012 and 2018, federal tax revenue from the outdoor industry increased by 63.5%, and state and local tax revenue increased by 49%[1,2]. During this same time period, national GDP rose by only 31.5%[3,4].

The increase in sales has directly correlated with the increase in use of public lands for outdoor recreation activities. The OIA estimated 49% of the US population age six and older participated in outdoor recreation activities in 2018, for a total of 10.9 billion outings[5]. Although not all visits occurred on public lands, reports commissioned for the US Forest Service show in 2016 at least 550 million visits occurred on lands administered solely by the USFS, the BLM, and the Park Service, many of which are concentrated in the West[6].

While nearly all sectors of the recreation industry saw increases in use, one notable example was motorized boating, and more specifically, waterskiing; between 1999 and 2009 there was a 33.1% increase in total water-skiing participants and a 20% increase in total user days (the study did not differentiate between water-skiing, wake-boarding, and wake-surfing). Since 2009, the upward trend in motorboat use has continued, and in 2016 gross sales of motorized boats and accessories reached nearly $39 billion[7]. By 2030, the US Department of Agriculture anticipates motorized water use will increase another 29.9%[8].

Needs Assessment

The increased use of motorized boats in a static number of waterways, including Payette Lake, heightens the potential for user conflict, aquatic invasive species dispersal, and water quality degradation. One particular risk from motorized boating activities is shoreline erosion and lakebed sediment disturbance, which can both lead to resuspension of phosphorous in the

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7. National Marine Manufacturers Association (NMMA). (2018). *U.S. Boating Industry Sales at a 10-Year High.* Retrieved from https://www.nmma.org/statistics/article/21974
8. US Department of Agriculture (USDA). (2016). *Federal Outdoor Recreation Trends: Effects on Economic Opportunities.* Retrieved from https://www.fs.fed.us/pnw/pubs/pnw_gtr945.pdf

water column[1,2]. Once in suspension, the availability of phosphorous can lead to toxic blue green algae and other cyanobacteria blooms, severely affecting water quality and the recreation potential of waterways[3].

In Cascade Reservoir, toxic blue-green algae blooms have led to summer recreation closures for many years. In 2014, the town of Toledo, Ohio had to shut down their entire drinking water system due to a toxic cyanobacteria bloom in Lake Erie[4]. In both cases, excess available nutrients in the water were found to be a contributing factor for the blooms. As recreation on Payette Lake serves as an economic engine for Valley County, and the lake is also the source of the town's drinking water, the threat of toxic algae blooms is especially relevant to our community.

While substantial research has quantified the impacts of natural and boat induced wave and slipstream energy on shoreline erosion and and resuspension of lakebed sediments, the modern generation of boats designed specifically to produce large wakes has prompted the need to better understand their effects[1,5]. Although the height of a surf-boat wake is typically no more than 50% higher than a traditional ski-boat wake, evidence has shown up to 5 times as much energy may be produced due to their shape, size, and speed[6]. Where studies have been performed to quantify the effects of wakes on shoreline erosion and slipstreams on lakebed disturbance, several pertinent data needs have emerged. These include:

- "Development of a classification scheme and delineation of sensitive and vulnerable shorelines.

- High resolution recreational boating intensity information.

- Measurements of waves and suspended sediment concentration."[7]

To help quantify the effect of boats using wave enhancing technology on shoreline erosion and lakebed sediment disturbance in Payette Lake, my project has (a) profiled waves generated by wake-surf and other boats; (b) examined wind wave regimes on the lake; and (c) delineated sensitive and vulnerable areas of the lakebed and shoreline. With this information, I then determined an appropriate no-wake zone to protect water quality resources in the lake.

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1. Beachler, M.M., & Hill, D.F. (2003). Stirring up trouble? Resuspension of bottom sediments by recreational watercraft. *Lake and Reservoir Management,* 19(1), 15-25.
2. Yousef, Y.A., McLellon, W.M., & Zebuth, H.H. (1980). Changes in phosphorus concentrations due to mixing by motor boats in shallow lakes. *Water Resources*, 14, 841-852.
3. Pelley, J. (2016). Taming toxic algae blooms. *ACS Central Science,* 2(5), 270-273. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4882738/
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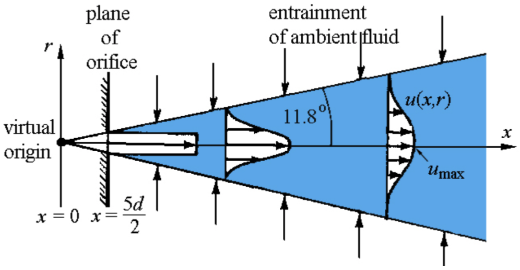
Slip-Stream Modeling Methodology

The theoretical bases for the present study were computational models developed by researchers with the Department of Civil and Environmental Engineering at Pennsylvania State University and the Department of Civil Engineering at Clemson University. Their work focused on the simulations of turbulent, non-buoyant jets, which were later validated in field studies.[1,2] Both works independently developed equations for growth rates and mean velocity decay along the stream-wise (x) axis of the jet, from which the present models were produced.

Research has shown that turbulent, non-buoyant jet streams (such as those found behind boats) develop in predictable ways. After an initial zone of establishment, the jet (slipstream) expands radially along the x-axis at a consistent 11.8 degrees, and velocity profiles across the slipstream exhibit consistent distributions (Fig. 1).

Fig. 1 - Establishment of slipstreams for turbulent, non-buoyant jets.[3]



Using the established models predicting rates of velocity decay within the slipstream (app. A), I developed velocity decay profiles and correlated them with shear forces necessary to disturb and suspend bottom sediments (app. B). Initial slipstream velocities for several boats were determined using publicly available data from boat manufacturers, publicly available data from propeller manufacturers, and data crowdsourced from wake-surf boating forums. The latter proved to be the most valuable, as it represented real world operating conditions for the development of speed to RPM curves, and thus initial slipstream velocity measurements. Information on boat trim angles under normal operating conditions was recorded on Oct. 30, 2019 on Anderson Ranch Reservoir near Mountain Home, Idaho. Data was collected with a Hobo Pendant G Accelerometer oriented along the x-axis, onboard a 2019 MB Sports F22 Tomcat surf boat.

Slip-Stream Model Results and Discussion

Charts 1-9 on the following pages display slipstream velocity profiles for three boats; a 2019 Malibu LSV22, a 2016 Malibu 22LSV, and a 2019 Axis T23. The shaded regions within the profiles are defined by the minimum velocity found in that region, and they have been correlated to crucial thresholds for sediment motion and suspension. Distance behind the source (propeller) is shown on the x-axis, and water depth is measured on the y-axis.

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1. Beachler, M.M., & Hill, D.F. (2003). Stirring up trouble? Resuspension of bottom sediments by recreational watercraft. *Lake and Reservoir Management,* 19(1), 15-25.
2. Aziz, T.N., Raiford, J.P., & Khan, A.A. (2008). Numerical simulation of turbulent jets. *Engineering Applications of Computational Fluid Mechanics.* 2(2), 234-243.
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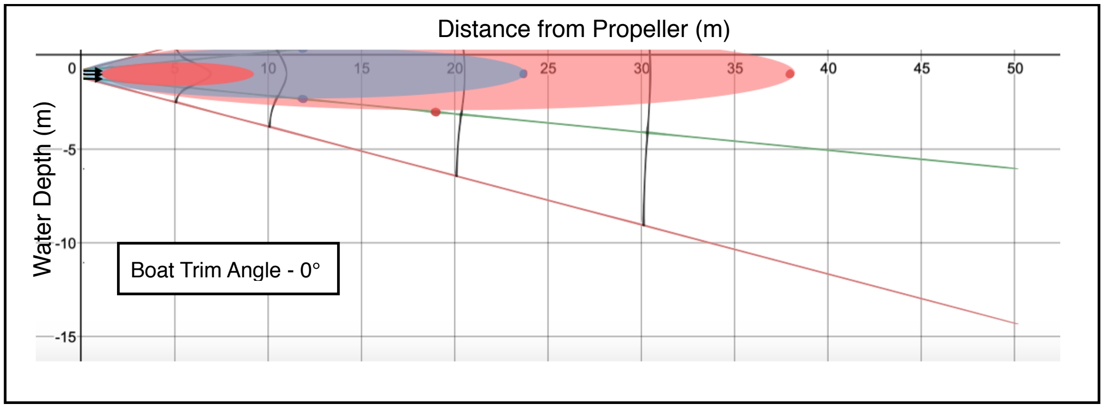
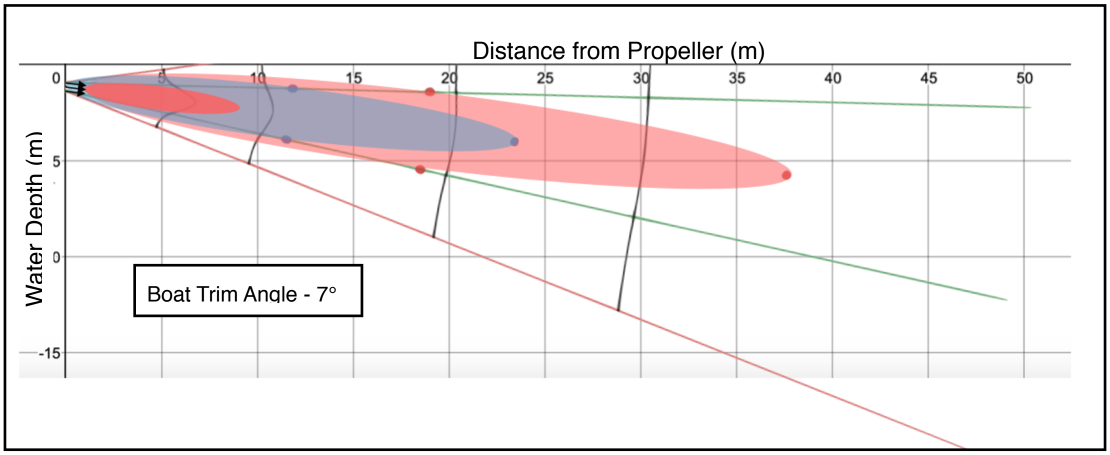
Charts 1-3: 2019 Malibu 22LSV
Max Slipstream Velocity: 4.1m/s @ 11 mph, 2300 rpm
(chart values in meters)

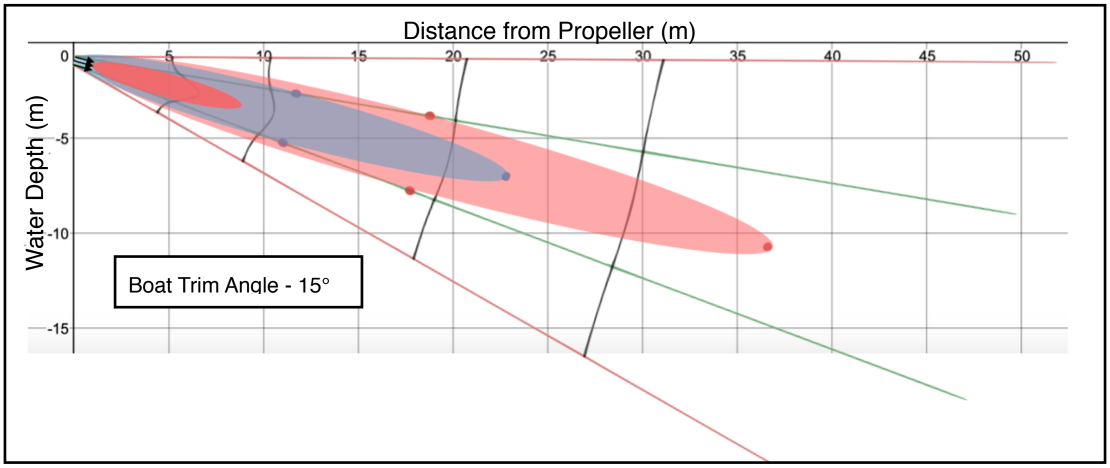
● Slipstream Velocity > .25m/s

● Slipstream Velocity > .4m/s

● Slipstream Velocity > .9m/s





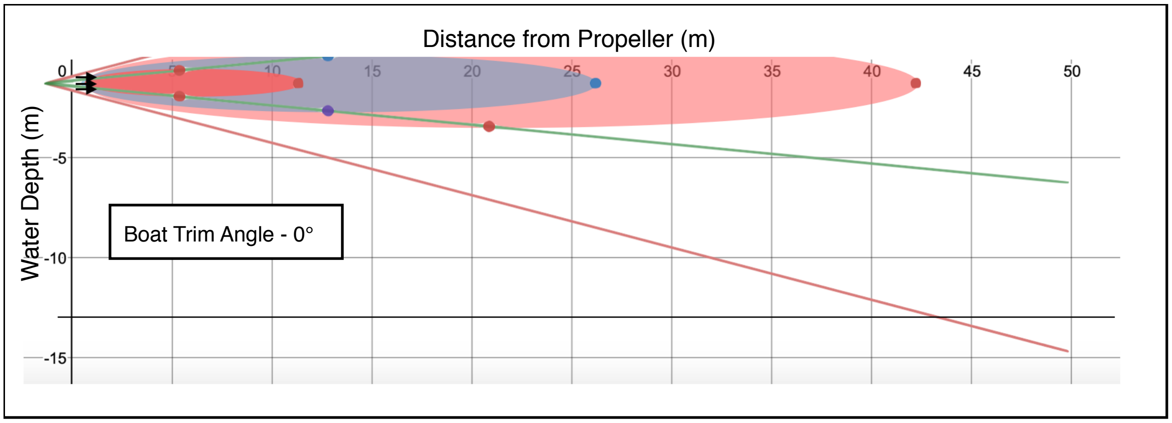


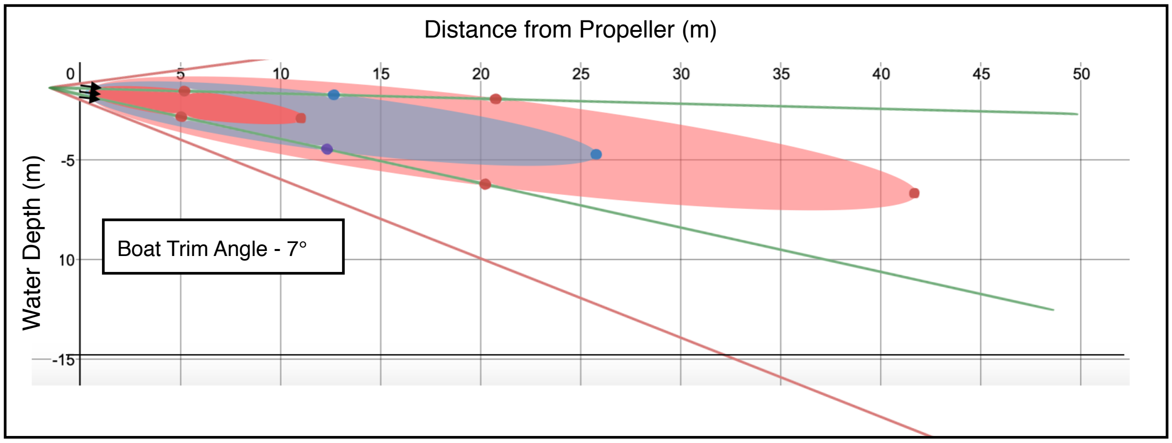
Charts 4-6: 2016 Malibu LSV22
Max Slipstream Velocity: 4.49m/s @ 11 mph, 2400 rpm
(chart values in meters)

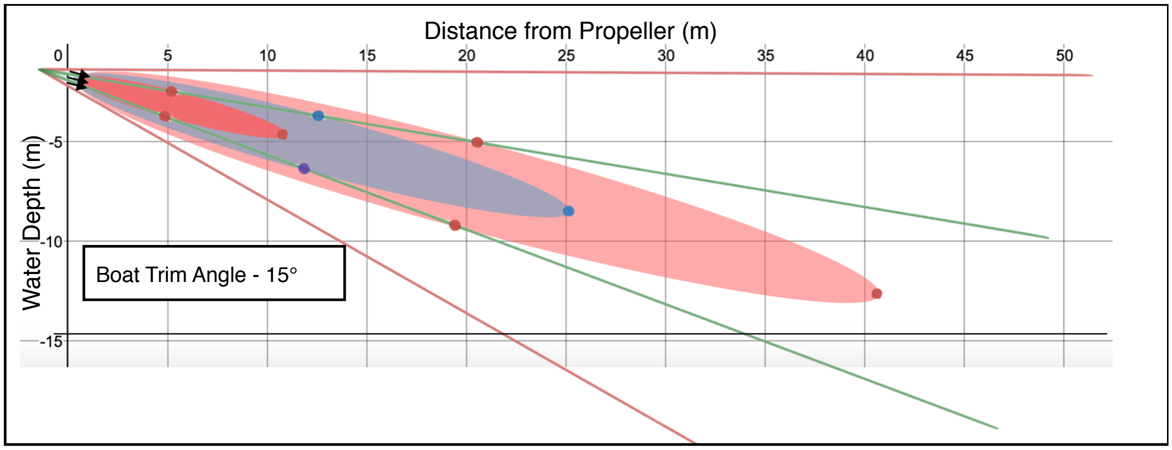
● Slipstream Velocity > .25m/s

● Slipstream Velocity > .4m/s

● Slipstream Velocity > .9m/s





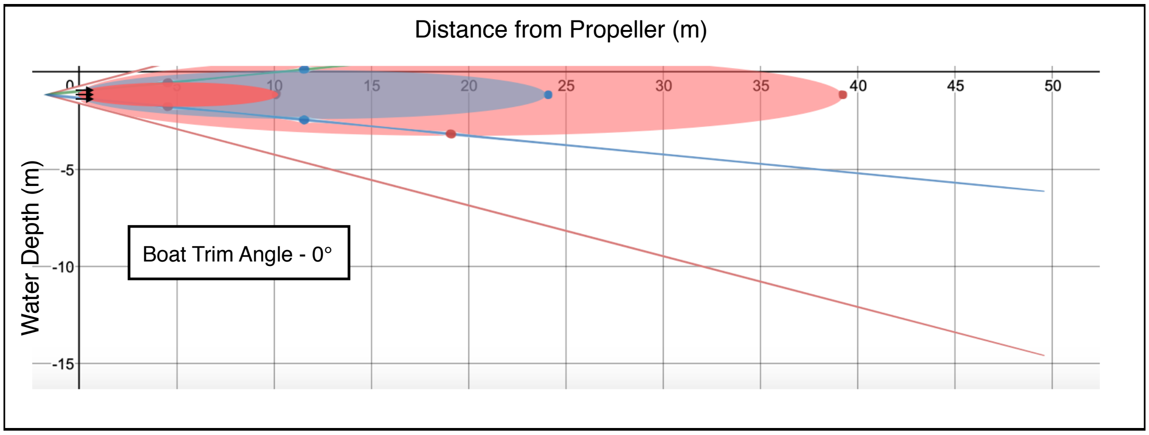


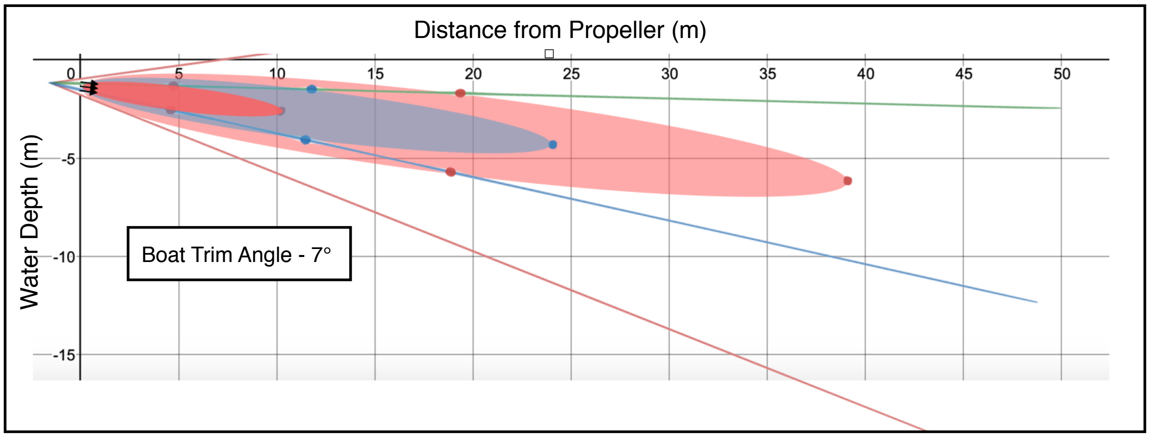
Charts 7-9: 2019 Axis T-23
Max Slipstream Velocity: 4.21m/s @ 10.2 mph, 2500 rpm
(chart values in meters)

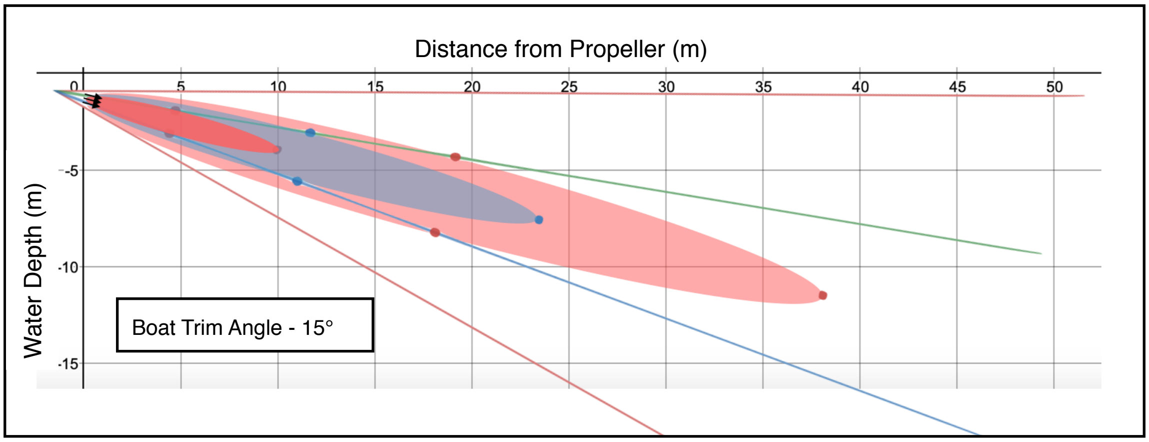
● Slipstream Velocity > .25m/s

● Slipstream Velocity > .4m/s

● Slipstream Velocity > .9m/s



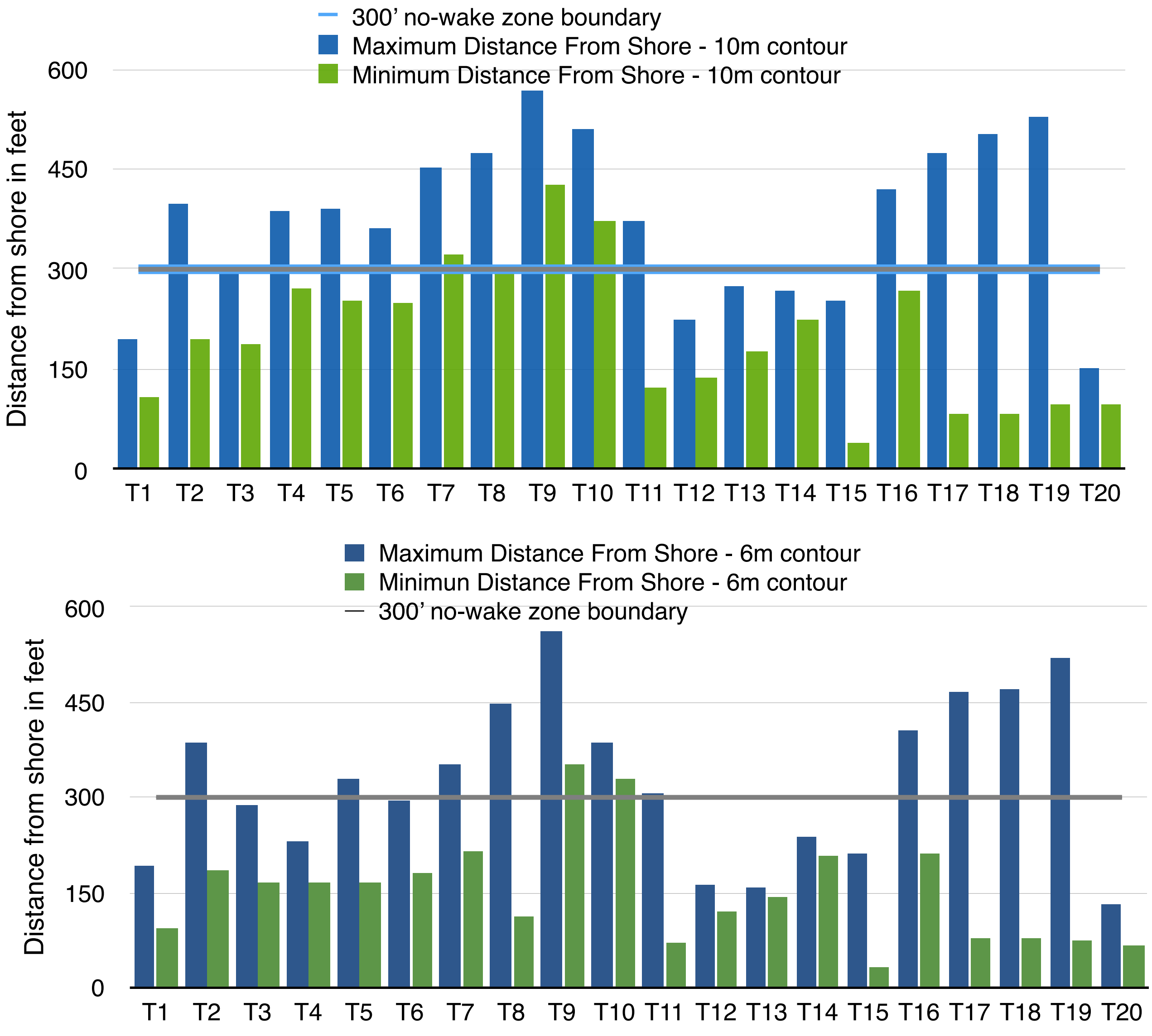




According to modeling results, wake boat slip-streams have the potential to affect bed sediments at 33' of depth. To correlate the above findings with water depths at the 300' no-wake zone boundary, a survey was performed using publicly available bathymetric information from the USGS. This data assumed a full-pool elevation of 1,519.7m (4986'). 5 miles of lakeshore in the Southwest basin was then divided in to approximately quarter mile intervals, and minimum and maximum distances from shore were estimated for the 6m (20') and 10m (33') contours in each transect.

As seen by the first graph below, portions of the lake were shallower than 10m (33') at the 300' no-wake zone boundary in thirteen out of twenty transects. At the 300' no-wake zone boundary in four of these transects, the lake was shallower than 10m across the entire quarter mile segment. In the second graph, it can be seen that in ten out of twenty transects, portions of the lake were shallower than 6m (20') at the 300' no-wake zone boundary. In two of these transects, the lake was shallower than 6m at the 300' no-wake zone boundary across the entire quarter mile segment

Graph 1-2 - 10m and 6m depth contour max. and min. distance from shore.



Sediment samples were then taken from various locations around the Southwest basin of the lake to determine general substrate types and sizes. Sediment analysis from Legacy Beach revealed an average sand particle size of approximately 0.25mm, with a high distribution of particles near the 0.15mm size. This sediment is characteristic of a majority of the transects sampled. Sediment analysis at Ponderosa Park revealed a slightly larger average particle size of approximately 0.4mm. However, the general lakebed substrate at both sites was characterized by gravel, cobble, and woody debris in a matrix of find sand and silt. Sediment samples were not taken from a third location, Rotary Beach, as the general substrate was observed to be cobble, gravel, and woody debris in a matrix of fine silt.

Sand is characterized by a particle size of .0625 to 2 mm; Silt is characterized by a particle size of .0039mm to .0625 mm. The chart in Appendix B denotes general shear forces necessary to initiate motion and suspend sand particles of various sizes (although other studies have found particles as large as 0.3mm can be suspended by currents as low as .25 m/s.[1]). It does not show shear forces necessary to initiate motion and suspend silt particles, which are lower than those necessary to initiate motion and suspend sand particles. As displayed, it can be seen that **the turbulence imparted by the modeled slipstreams is sufficient to disturb sediments of the size classes commonly found in Payette Lake, at depths regularly encountered at or beyond the 300' no-wake zone boundary.**

It is worth noting that although the boats used to develop models were typical of boats available for rent through local dealers and commonly used on Payette Lake, the information used to develop speed to RPM curves and slipstream velocity profiles was recorded from boats with no passengers, and at elevations between 500' and 700'. At higher elevations, the same motors will run at higher RPM for the given speeds, and thus create higher slipstream velocities (and depth influence) than are displayed here. Adding passengers and ballast also creates higher slipstream velocities, as it increases drag on the boat. Additionally, while most boats pass through the RPM band correlating to the highest slipstream velocities (during acceleration to planing mode), surf-boats are often continuously operated at the speed where displacement, slipstream velocities, and trim angle are highest.

Boat Wake and Wind Wave Analysis

Boat wake analyses occurred on Anderson Ranch Reservoir, near Mountain Home, Idaho, on Oct. 30, 2019, and on Payette Lake across several days in July, 2020. Due to logistical challenges and weather constraints, deep and open water measurements of wake surf boat waves proved difficult. The few results recorded lacked the integrity necessary to provide conclusive results. However, shallow water testing of boat and wind waves on Payette Lake proved to be highly successful, and the data collected may provide more realistic insight on near and on-shore wave conditions, as well as their potential to induce shoreline erosion.

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1. Beachler, M.M., & Hill, D.F. (2003). Stirring up trouble? Resuspension of bottom sediments by recreational watercraft. *Lake and Reservoir Management,* 19(1), 15-25.

Boat and wind waves were measured using a Global Water WL-16 Water Logger, factory calibrated to measure water depths up to 50 feet. The design of the unit allowed for automatic compensation for barometric pressure, and the logger was programmed to collect water depth readings 10x/second during sampling periods. Wind data was collected during two months in the fall of 2019 using two RainWise Inc. WindLog Wind Data Loggers, programmed to collect wind speed, gust speed, and wind direction 6x/hour. The units were deployed at the West end of Rotary Park and near the Ponderosa State Park visitor center. Other relevant wind data was collected from the National Oceanographic and Atmospheric Administration (NOAA) website.

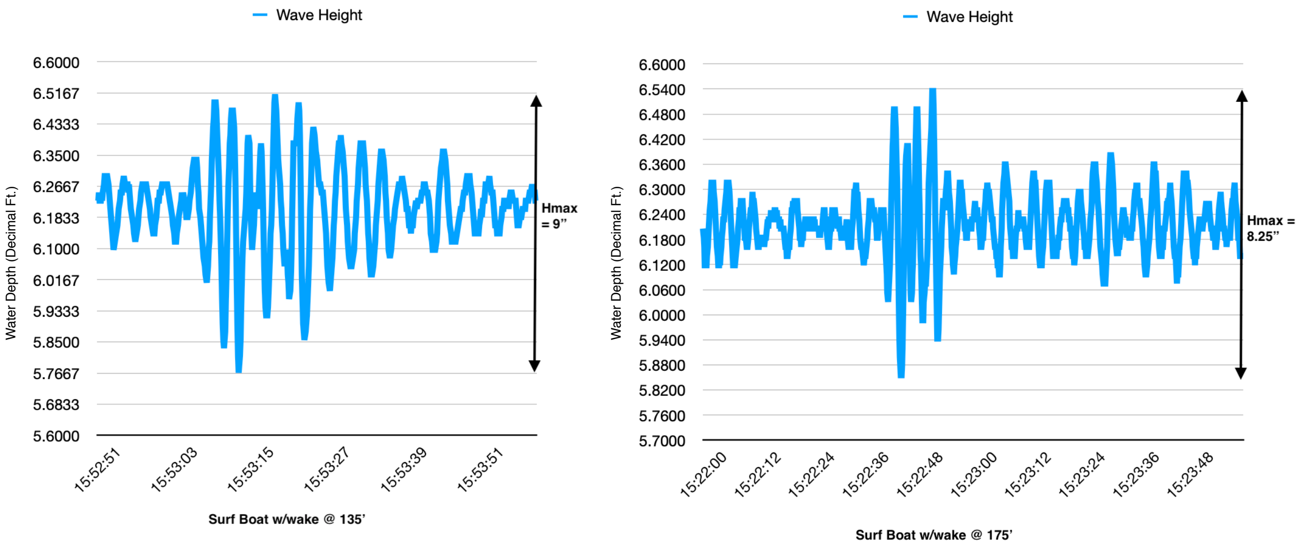
Boat Wake Study Results and Discussion

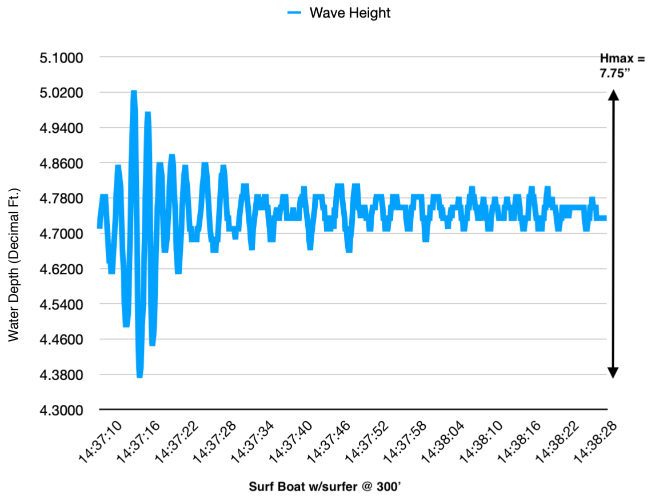
On July 3, 2020, boat wakes were measured for five hours on a small, rocky point immediately north of the cliffs swimming area. Boat traffic was moderate to heavy during the entire sampling period. As wave-height data was collected at 10x/second during the entire sampling period, and nearly 180,000 data points were collected during the 5 hour sampling period on July 3rd alone, only relevant data has been included in this report.

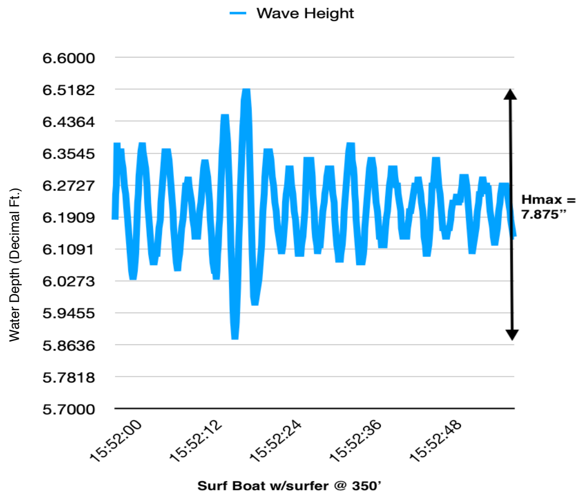
The graphs below display wave height data for wake boats operating in displacement mode that passed the sampling station on July 3rd. The wave height recorder was placed in approximately 6’ of water and approximately 12’ off-shore. Boat distance from shore was measured using a Nikon Aculon 6x20 digital range finder.

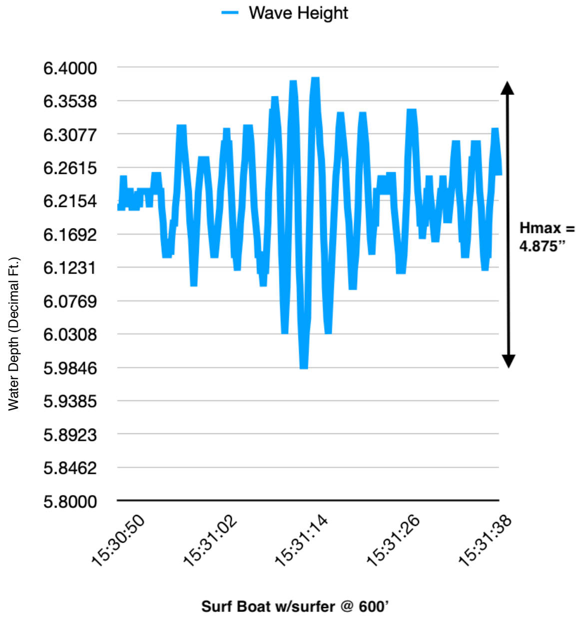
As displayed in the graphs a wake boat operating at the 300’ no-wake zone boundary can produce a wave that is still 7.75 inches high when it reaches shore. A wake boat operating at 135’ from shore can produce a wave that is still 9 inches high when it reach shores. Measurements also showed wake boats operating nearly 1000’ from shore could produce a wave that was still 4 inches high when it reached the sensor.

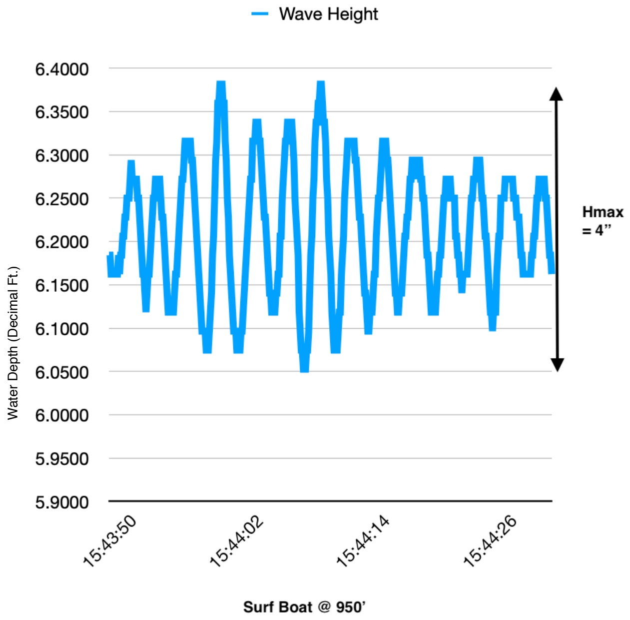
Graphs 3-8 - Surface wave measurements for wake boats at varying distances from shore.











The results of this field sampling are consistent with data collected by C.A. Goudey & Associates in 2015[1], which measured waves from wake boats at heights of 7.5 inches at 300' from the source of propagation. The results are also consistent with results from University of Quebec studies, which showed waves created by wake boats could propagate 1000' or further[2]. Wave height data was collected during the sampling period on July 3rd for other boat types as well, which in comparison also showed wake boats created the longest and largest wave trains.

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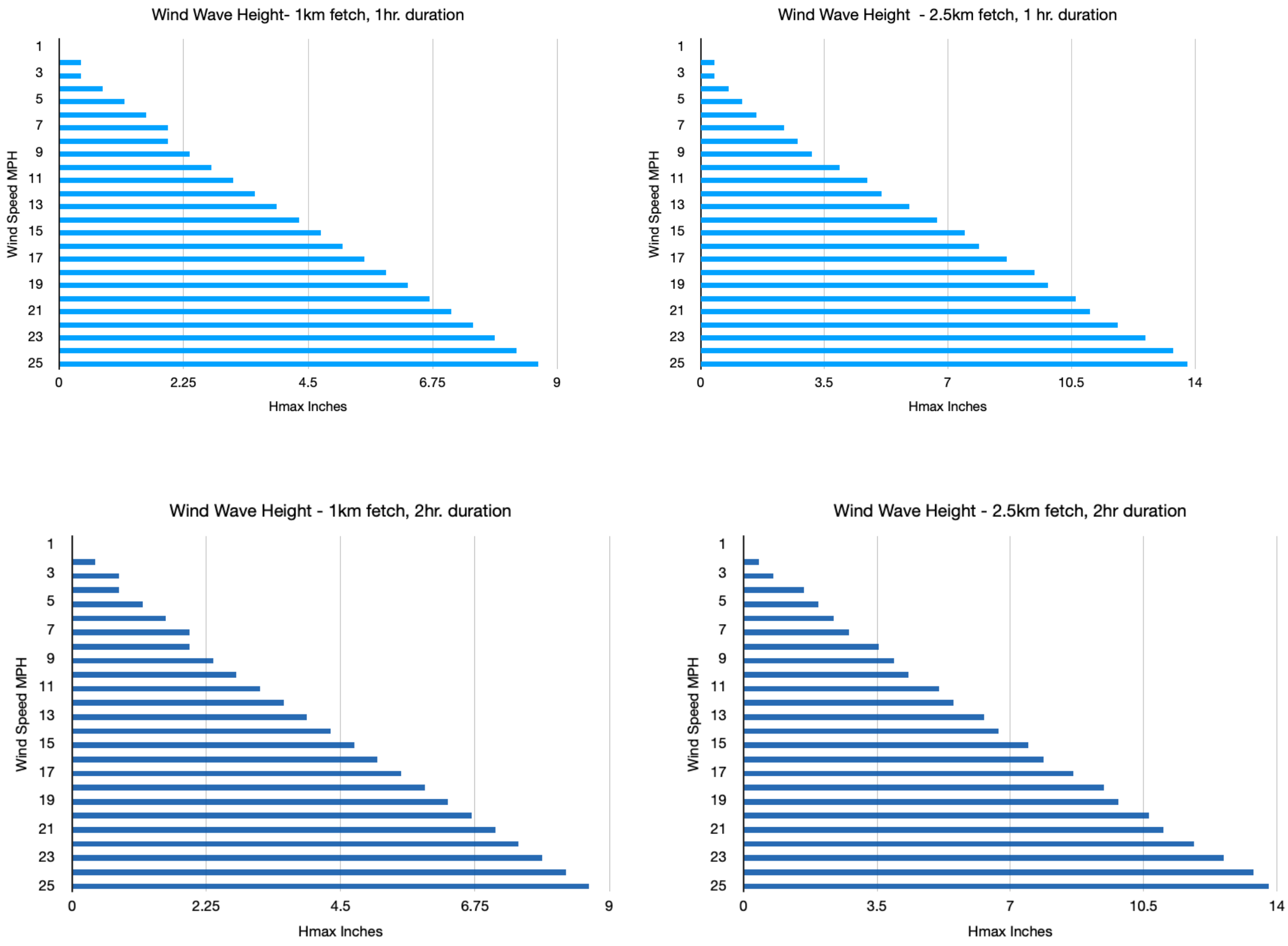
1. Goudey, C.A. & Associates. (2015). *Characterization of Wake-Sport Wakes and Their Potential Impact on Shorelines.* Report commissioned for the Wave Sports Industry Association. Retrieved from http://www.wsia.net/wp-content/uploads/2019/04/Wave-Energy-Study-C.A.-Goudey-Assoc.-Final.pdf
2. Mercier-Blais, S., & Prairie, Y. (2014). *Projet d'évaluation de l'impact des vagues créées par les bateaux de type wakeboat sur la rive des lacs Memphrémagog et Lovering.* Société de Conservation du Lac Lovering, Memphrémagog Conservation Inc et Service aux collectivités de l'UQAM. Retrieved from https://vite.memphremagog.org/files/userfiles/files/Centre_de_documents/FR/Rapport-Vagues-Wakeboard-2014.pdf

Wind Wave Study Results and Discussion

The size of wind waves is determined by three factors; wind speed, wind duration, and fetch.The last factor, fetch, is the length of open water the wind is blowing across. As Payette Lake contains only relatively small areas of open water, the lake is considered fetch limited. In other words, the relatively short spans of open water limit the size of wind waves that can be formed, regardless of the duration of the wind.

Wind wave analysis during ice free months on Payette Lake revealed long periods of relatively calm wind across the lake, punctuated by (storm) events with average wind speed in the 10-15 mph range, and gusts in the 15-25 mph range. The graphs below display the maximum wave heights for winds based on various fetch, wind speed, and wind duration parameters, and the specific parameters to produce these graphs were selected based on wind and fetch conditions observed to regularly occur on Payette Lake.

Graphs 9-12— Wind Wave H_{max} Reference



According to (a) wind data collected on Payette Lake, (b) direct measurements of wind waves, and (c) the laws governing wind wave formation, typical wind regimes on Payette Lake produce waves with average heights of 2-4 inches. Storm events can produce waves up to 8 inches high, and wind conditions may occur at rare times that could produce waves up to 12 inches high. However, while the height of these waves may be similar to those produced by wake boats, the wave length of even the largest wind waves is far less than the wave length of waves produced by motorized boats.

Modeling shows wind waves on Payette Lake 4 inches high have a maximum wavelength of approximately 6'. Eight inch waves have a maximum wavelength of approximately 10'. Conversely, the wavelength of waves produced by wake boats can be 15' to 25'. These factors become significant when considering the relative energy of waves, and their potential to disturb bottom sediments.

General Discussion

While wave theory is well established, and much can be learned from the size, shape, and speed of a wave, I did not attempt to calculate wave energies produced by wind waves or boat wakes for this study. However, based on physical properties of boat induced waves, such as their considerably longer wave length, they carry far more energy than the type of wind waves that are formed on Payette Lake. Thus, they pose a much greater threat to bed sediments. Furthermore, while some of the differences in wave heights recorded during the study may seem inconsequential, wave energy grows exponentially; A wave of 8 inches contains four times the energy of a 4 inch wave, and sixteen times the energy of a 2 inch wave[1]. Energy also increases as wavelength increases, indicating boat induced waves carry far more energy than wind waves on Payette Lake.

To determine the exact amount of wave energy reaching the shores of Payette Lake, from both wind waves and waves propagated by motorized watercraft, a far more in depth study would be necessary. However, given what we already know about the lake, the shoreline bathymetry, and nutrient loading in lakebed sediments, the results of this study indicate the threats to lakebed sediments, shorelines, and water quality posed by motorized recreation on Payette Lake are not negligible. Furthermore, because McCall's drinking water is sourced from the lake, special attention should be paid to the threat.

Given the results of my research, and the physical dynamics of the types of waves seen on Payette Lake, three important and case specific details are evident regarding motorized recreation (and the use of wake surf boats) on the lake:

1. the 300' no-wake zone boundary likely does not provide sufficient protection against accelerated shoreline erosion due to the large waves propagated by motorized watercraft, and specifically wake boats.
2. Lakebed sediments at depths of up to 7'-12' are likely to be disturbed by boat propagated waves, while wind waves are likely only to regularly disturb sediments at depths up to 5'.
3. Slip-streams from wake boats may disturb lakebed sediments at depths of up to 33'.

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[1] University of Hawaii (U of H). (2020). Wave energy and wave changes with depth. Retrieved from https://manoa.hawaii.edu/exploringourfluidearth/physical/waves/wave-energy-and-wave-changes-depth

As previously discussed, the disturbance of lakebed sediments is of special concern in Payette Lake, as it could potentially cause cyanobacteria or other algal blooms. While the concentrations of nutrients in shoreline and near-shore lakebed sediments is unknown, and may be negligible due to continual disturbance, updated information should be gathered regarding nutrient loading in bed sediments since the last testing 25 years ago.

Management Implications and Recommendations

Given the findings presented in the preceding text, two especially important and case specific conclusions regarding motorized recreation on Payette Lake have become evident:

- **The turbulence imparted by a wake boat slipstream is sufficient to disturb lakebed sediments in Payette Lake, at depths regularly encountered at or beyond the 300' no-wake zone boundary.**

- **Due to the large waves propagated by motorized watercraft, and specifically wake boats, The 300' no-wake zone boundary likely does not provide sufficient protection against accelerated shoreline erosion and near-shore lakebed sediment disturbance.**

Based on these conclusions and the other results of my research, and to best protect water quality from threats posed by motorized boats, **I recommend extending the no-wake zone in Payette Lake to 500 feet.**

Although opponents of extending the no-wake zone contend that substantial portions of of the lake would become off limits to boats, GIS data revealed that moving the no-wake zone to 500' would only decrease usable area in the Southwest basin of the lake by less than 200 acres, or approximately 7%. There is little evidence suggesting use is approaching the carrying capacity of Payette Lake, therefore this decrease in usable area is likely to have negligible effect on motorized recreation. Furthermore, expanding the no-wake zone would open a larger corridor for higher-density, non-motorized use, increasing the overall recreation potential of the lake.

It is also worth noting that during the sampling period on July 3, 25% of boats observed creating a wake were operating within the 300' no-wake zone boundary. Sampling on July 15 revealed 20% of boats were operating inside the no-wake zone. This further exemplifies the need to expand the no-wake zone, as it could help provide a larger buffer to deter users from operating too close to shore.

Areas of Further Research

This research was conducted to determine specific threats to water quality on Payette Lake posed by motorized recreation. Other potential threats from motorized recreation on the lake include: User displacement, user conflict, over-crowding, noise pollution, invasive species dispersal, and shoreline infrastructure damage. While over-crowding may not be especially relevant at this time, user displacement has occurred on the lake, and anecdotal evidence suggests shoreline infrastructure damage and erosion is occurring. The water ballast used in wake boats also raises concerns about invasive species dispersal. Given these additional threats, I recommend the following areas of further research to fully inform a comprehensive lake management plan:

- Updated information on nutrient concentrations in lakebed sediments.
- High resolution recreational boating information, such as user day surveys, visitor use surveys, and carrying capacity research.
- Information concerning the economic effects of shoreline erosion and shoreline infrastructure damage.
- Strategies to reduce the risk of invasive species dispersal.

Conclusion

As resource utilization changes over time, and our toys become more and more powerful, management schemes must also adapt. This data-driven approach to analyzing the effects of motorized boat use was designed to bring an objective look at recreation management in Payette Lake, and to inform decision makers with the most relevant and up-to-date data. Although this research informs perhaps the most important aspect of resource management on Payette Lake, protecting water quality, I urge the City of McCall and Valley County to address the other gaps in information concerning recreation and resource protection on the lake. With use of the lake destined to grow in the future, I also urge decision makers to act before the threats are realized. This includes promptly extending the no-wake zone to 500’.

Appendix A - Model Formulas[1,2]

1. Slipstream Velocity

$$V_s = \omega P - V_b$$

V_s = Slipstream Velocity
w = Propeller Angular Velocity (rps)
P = Pitch of Propeller (m)
V_b = Boat Speed (m/sec)

2. Slipstream Velocity Decay

$$u(x, r) = 7\,\frac{M_0^{1/2}}{x}\,\exp\left[-\left(\frac{r}{0.107x}\right)^2\right]$$

x = streamwise coordinate
r= radial distance from jet axis
$M_o = \pi(V_s{}^2)(D^2)/4$
V_s = Slipstream Velocity (m/s)
D = Prop Diameter (m)

3. Slipstream Velocity Decay

$$\frac{u_m}{u_o} = \frac{A_4}{x/d + \alpha_2}$$

u_m = Slipstream Velocity at point *x* (m/s)
u_o = Initial Slipstream Velocity (m/s)
A_4 = 6.3 (constant)
x = streamwise coordinate
d = diameter of jet (m)
a_2 = correction for virtual origin

4. $U_{max}{}^{1/2}$ Velocity Decay

$$b/d = A_2\left(x + \bar{x}\right)/d$$

b = distance to $.5U_{max}$ from centerline
d = diameter of jet (m)
A_2 = .097 (constant)
x = streamwise coordinate
$\bar{x}$ = distance to virtual origin (m)

5. Radial Velocity Decay Profile

$$\frac{u}{u_m} = \exp\left(-0.693\lambda^2\right)$$

u_m = Slipstream Velocity at point *x* (m/s)
u = Initial Slipstream Velocity (m/s)
λ = r/b
r = radial coordinate
b = distance to $U_{max}{}^{1/2}$ from x-axis (m)

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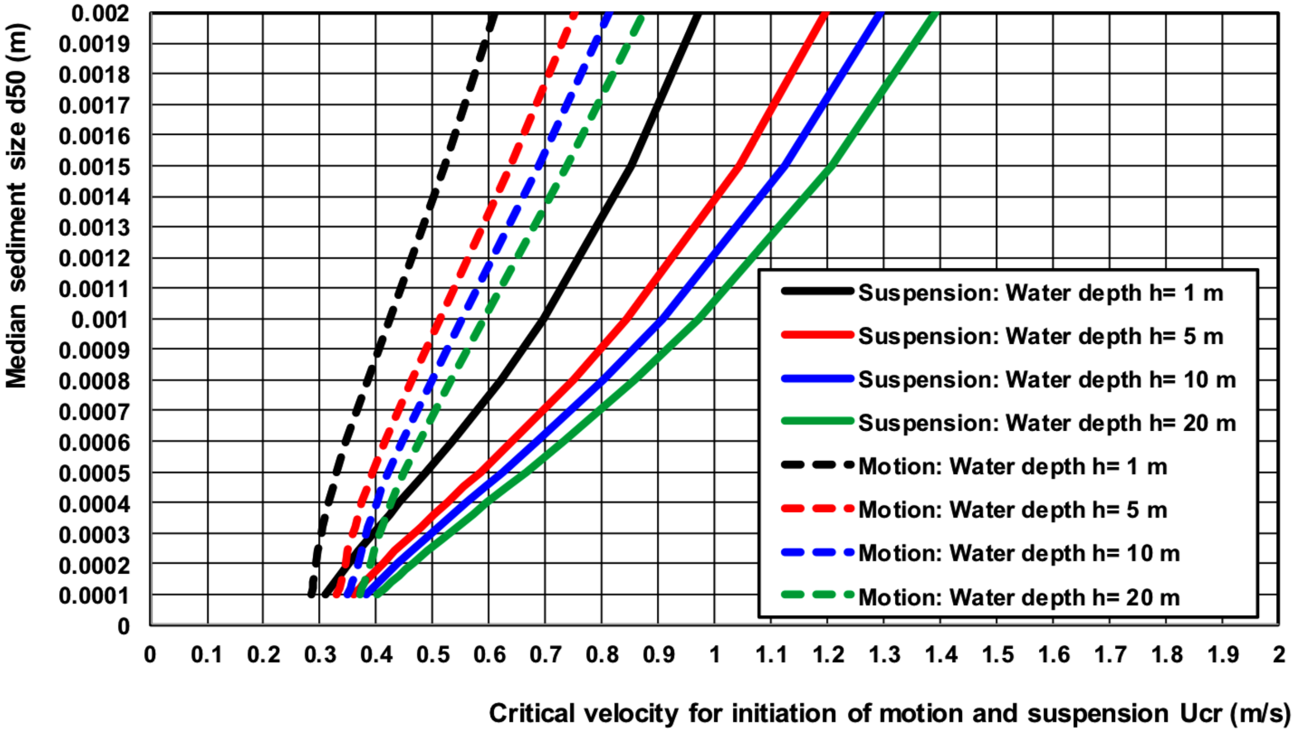
1. Beachler, M.M., & Hill, D.F. (2003). Stirring up trouble? Resuspension of bottom sediments by recreational watercraft. *Lake and Reservoir Management,* 19(1), 15-25.
2. Aziz, T.N., Raiford, J.P., & Khan, A.A. (2008). Numerical simulation of turbulent jets. *Engineering Applications of Computational Fluid Mechanics.* 2(2), 234-243

Appendix B - Sediment Shear Forces[1]



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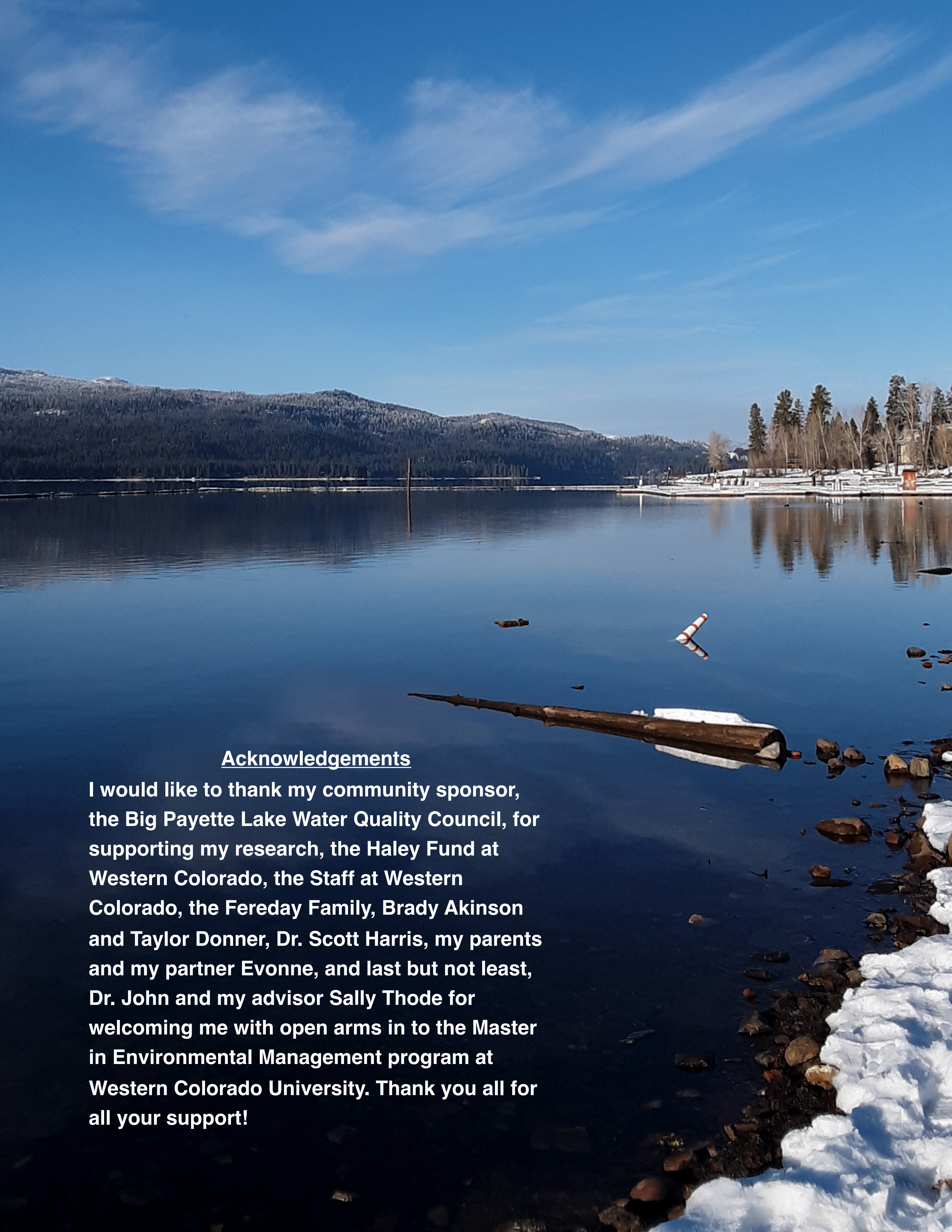
1. Van Rijn, L.C. (2020) Simple general formulae for sand transport in rivers, estuaries, and coastal waters. Retrieved from www.leovanrijn-sediment.com



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