Devils Lake Shoreline Erosion Study

Submitted to: Devils Lake Water Improvement District
PO Box 974
Lincoln City, OR 97367
www.DLWID.org

Submitted by: Tetra Tech, Inc.
1020 SW Taylor St., Suite 530
Portland, OR 97205
www.ttsurfacewater.com

March 08, 2012
# Table of Contents

Executive Summary ........................................................................................................... - 1 -

Introduction ....................................................................................................................... - 3 -

Historic Aerial Photography ........................................................................................... - 3 -

Shoreline Survey ............................................................................................................... - 5 -
  Vegetation ....................................................................................................................... - 5 -

Land Use, Bank Stabilization, and Shoreline Conditions ................................................... - 6 -
  Soils ................................................................................................................................. - 8 -

Inundation Mapping ......................................................................................................... - 11 -

Wave Energy .................................................................................................................... - 15 -
  Predominant Winds ....................................................................................................... - 15 -

Wind Waves ..................................................................................................................... - 23 -

Boat Waves .................................................................................................................... - 27 -
  Relative Contribution of Natural and Anthropogenic Waves ................................... - 31 -

Impacts of Dam Operations ............................................................................................. - 33 -
  Lake Level .................................................................................................................... - 33 -

Shoreline Condition ....................................................................................................... - 37 -
  Soils ............................................................................................................................... - 38 -

Vegetation ....................................................................................................................... - 39 -

Wave Energy .................................................................................................................... - 41 -

Regulations and Permits ................................................................................................. - 43 -

Approaches to Shoreline Stabilization ............................................................................. - 44 -

Recommendations and Considerations ........................................................................... - 45 -

References ....................................................................................................................... - 46 -
List of Tables

Table 1. Shoreline Vegetation Characteristics Parcel ................................................................. - 5 -

Table 2. Land Use Categories and Shoreline Conditions Parcel .................................................. - 6 -

Table 3. Soil Types and Estimated Percent Erosion ....................................................................... - 9 -

Table 4. Estimated Surface Acres due to Changes in Devils Lake Elevation (feet MSL) ............... - 15 -

Table 5. Beaufort Wind Scale and Effects on Land ....................................................................... - 19 -

Table 6. Wave Characteristics at Typical Operating Conditions (approx. 70 feet from a boat) ....... - 30 -

Table 7. Wave Energy as a Function of Boats and Percent of Total Wave Energy on the Shoreline .... - 31 -

List of Figures

Figure 1. Example of historic aerial from the D River area in 1939 (top) and 2007 (bottom) ............ - 4 -

Figure 2. Locations of non-armored and partially to fully armored shoreline based on the field inventory ............ - 7 -

Figure 3. Soil types and locations of eroding shoreline areas (yellow) ............................................. - 10 -

Figure 4. Example inundation map from the D River at 8.3 feet MSL .......................................... - 13 -

Figure 5. Example inundation map from the D River at 9.0 feet MSL ........................................... - 13 -

Figure 6. Example inundation map from the D River at 9.53 feet MSL ......................................... - 14 -

Figure 7. Example inundation map from the D River at 10.4 feet MSL ......................................... - 14 -

Figure 8. Wind roses showing the probability of winds of various speeds from each of 16 evenly spaced compass directions at the NOAA Newport Weather Station (NWP03) for the period from 1997 through 2010. Also shown, in red outline, is the probability of winds from each direction at the Lincoln City station for the period from August 2008 through September 2011 ................................................................. - 17 -

Figure 9. Wind roses showing the probability of winds of various speeds in Beaufort Category 4 and above at the Newport Weather Station (NWP03) during four seasons for the period from 1997 through 2010 ........ - 21 -
Figure 10. Wave height in relation to wind speed and fetch

Figure 11. Wave energy in relation to wave height and fetch

Figure 12. Distribution of annual wind energy around the shoreline of Devils Lake. Values less than 1 indicate less than average and values greater than 1 indicate greater than average wind energy

Figure 13. Assumed total number of recreational boats per day operating on Devils Lake

Figure 14. Typical wave climate associated with a jet boat

Figure 15. Estimated boat wave energy around the shoreline of Devils Lake on an annual basis as a percent of the local wind energy

Figure 16. Average monthly lake levels (presented as dashes) based on data for the period from January 1998 through September 2011

Figure 17. Duration curves of Devils Lake levels during the summer recreational period and the winter non-recreational period based on recorded lake levels from January 1998 through September 2011

Figure 18. Variation in Devils Lake levels during the summer recreation periods in 1998 through 2011

Figure 19. Annualized median lake level during the recreation and non-recreation periods (not to be confused with extreme storm events illustrated in Figure 16)
Executive Summary

Devils Lake is located along the Oregon coast in Lincoln County. The 685 acre lake has a mean depth of 8.4 feet and average width of 1,400 feet and length of approximately 3.3 miles. In 1998, a small impoundment was installed at the terminal end of the lake. The impoundment allows the Devils Lake Water Improvement District (the District) to store an additional 1,360 acre-feet of water for recreational purposes. This is accomplished by installing 18 inches of splashboards to the concrete substructure of the impoundment. The base of the impoundment is at 8.03 feet mean sea level (MSL) thus the top of the splashboards can be up to 9.53 feet MSL. The District exercises its recreation water right from April to October, and the lake maintains a natural elevation during the remaining months. The District retained Tetra Tech, Inc. to 1) document historic conditions around the lake and surrounding watershed based on historic aerial photography, 2) document existing shoreline conditions, and 3) obtain information that can be used to assess potential natural and anthropogenic impacts on shoreline erosion under various water level regimes.

To document historic conditions around Devils Lake and its watershed, aerial photographs for 12 years ranging from 1939 to 2007 were georectified (a method that projects an image to align with persistent landscape features) for use in ArcGIS 9.3 and assembled in interactive formats for online viewing. To document existing shoreline conditions, each parcel around the lake was photo-documented using a GPS-enabled digital camera and information on current vegetation, land use, bank stabilization, and shoreline condition was collected. Inundation maps were created to illustrate water levels at 8.3 feet MSL, 9.0 feet MSL, 9.53 feet MSL (full exercise of recreational water right), 10.4 feet MSL (ordinary high water, OHW), and the 10-year flood event and 100-year flood events at 12.9 and 14.0 feet MSL, respectively. Inundation maps were developed in ArcMap 9.3 and assembled in interactive formats for online viewing.

Operational options available to the District that would lessen shoreline erosion are limited as current controls only range 18 inches, which includes a non-impoundment level of 8.03 feet MSL at the base of the concrete sill. Using data from 1998 through most of 2011, the lake levels are typically a few tenths of feet lower during the bulk of the non-recreation period than during the recreation period, but about 10% of the time they were significantly higher due to the effects of the winter storms. Monthly data indicates that lake levels tend to decline over the course of the recreation period. As a result, historic management of the outlet dam appears to have resulted in recreational lake levels that are similar to those during most of the non-recreation period. In fact, current operations result in higher and more uniform inundation levels during the spring and early
summer than would otherwise occur. Dam operations over specific time periods have undoubtedly affected the vertical location of the shoreline, the focal point of the wave energy, and thus, the local erosion tendencies around the lake.

Natural (wind) and anthropogenic (boat) waves contribute erosive energy on the shoreline of Devils Lake. Existing information and semi-empirical relationships were applied to estimate their relative effects on shoreline erosion. During the summer, when the lake elevation is artificially maintained, strong summer northwesterly winds exert greater pressure on the east and southeast portion of the lake. Observed in these areas was relatively increased erosion, however, comparatively less bank stabilization measures were also observed compared to other areas around the lake. Conversely, during the winter when the lake is allowed to naturally fluctuate, strong storm-driven southerly and southwesterly winds coupled with increased rainfall and long fetch contribute substantially to the erosive energy along the north and western portions of the lake. Observed in these areas was relatively reduced erosion, however, comparatively greater bank stabilization measures compared to other areas around the lake. In fact, about two-thirds of the total wind-wave energy around the lake occurs during the non-recreation period (October 15 through April 15) and one-third occurs during the recreation period. Efforts to naturally stabilize shorelines through native planting, bioengineered structures, and overland erosion control measures will likely provide the most promising methods for controlling the erosion.

Based on published data on typical waves caused by waterski and wakeboard boats, boat waves account for about a fifth of the total wave energy impacting the shoreline. Using anecdotal information that typical wakeboard boats generate larger waves than are indicated by published data, the total energy associated with the boat waves of 1.5 to 2.0 feet (measured at about 70 feet from the boat) represents 40% to 50% of the total wave energy around the shoreline of the lake. The boat wave energy is the predominant erosive force around the shoreline in many areas that are not significantly impacted by wind waves.

The analyses performed for this study summarizes existing land use, soils, vegetation, and areas subject to the greatest wind- and boat-wave energy, thus, areas most subject to erosion. Due to variability in factors that affect wave energy that impact the shoreline, the vertical zone over which that energy is focused, and the ability of the resulting waves to cause erosion, local quantification of this process can only be done through site specific analyses. This analysis should consider the specific nearshore bathymetry of the lake, the alignment of the shoreline with respect to the predominant wind direction and angle of impact of boat waves, as well as topography, soils, vegetation, and the presence of man-made structures at and above the shoreline.
Introduction

Devils Lake is located along the coast in Lincoln County, Oregon and empties into the Pacific Ocean via the World’s Shortest River, the D River. Devils Lake is bordered to the east by the foothills of the Coast Range, to the west and south by Lincoln City, and to the north by the residential community of Neotsu. The Devils Lake watershed covers 11.1 square miles. The lake is managed by the Devils Lake Water Improvement District (the District). Devils Lake has a surface area of approximately 685 acres, with a mean depth of 8.4 feet, average width of 1,400 feet, and length of approximately 3.3 miles. In 1998, a small dam with removable splashboards was installed at the terminal end of the lake. The dam allows the District to store an additional 1,360 acre-feet of water for recreational purposes. This is accomplished by installing 18 inches of splashboards to the concrete substructure of the impoundment. The base of the impoundment is at 8.03 feet mean sea level (MSL), thus the top of the splashboards can be up to 9.53 feet MSL. The District can exercise its full recreation water right from April to October. The water regime is altered during the summer and shoulder months whereas the rest of the year the lake is not impounded.

The District retained Tetra Tech, Inc. to 1) document historic conditions around the lake and surrounding watershed based on historic aerial photography, 2) document existing shoreline conditions, and 3) obtain information that can be used to assess potential natural and anthropogenic impacts on shoreline erosion under various water level regimes.

Historic Aerial Photography

Tetra Tech obtained aerial photography of the Devils Lake Watershed from the U.S. Army Corps of Engineers and the District. Years available included: 1939, 1962, 1963, 1972, 1974, 1977, 1983, 1992, 1998, 2001, 2005, and 2007. For some years, only portions of the lake were available and, though available, not all maps were of sufficient quality to provide meaningful information. Aerials were compiled as a series of PowerPoint (.ppt) slides, in Adobe (.pdf), and .mov formats as a user-friendly “animation” (examples in Figure 1). Where possible, up to nine areas across the lake were specifically identified for maps with sufficient resolution. These areas include: the D River outlet, Devils Lake State Campground, Regatta Grounds Park, channels east of Kirtsis Park, the northwest arm below Chinook Winds Golf Resort, the northeast arm adjacent to Neotsu, Thompson Creek inlet, central eastern shoreline, and East Devils Lake State Park. Aerials included in the animation were georectified using geoprocessing tools available in ArcGIS. All electronic data files were transferred to the District on an external hard drive.
Figure 1. Example of historic aerial from the D River area in 1939 (top) and 2007 (bottom)
Shoreline Survey

A shoreline survey was conducted by Tetra Tech biologists and engineers on June 14 to 16, 2011 and June 22 and 23, 2011 when the lake was at 8.9 feet MSL. The purpose of the survey was to document current vegetation, land use, and shoreline conditions around Devils Lake. Conditions were noted by parcel and each was photo-documented using a GPS-enabled digital camera (Ricoh G700E) and transferred to ArcGIS 9.3 using PhotoLink 5.1 software. Data on the 338 parcels were provided to the District on an external hard drive.

Vegetation

Previously mapped physiographic province data (e.g. vegetation) from the U.S. Geologic Survey (USGS) identified only three communities in the vicinity of Devils Lake: Sitka-spruce-Western hemlock maritime forest, mixed conifer/mixed deciduous forest, and urban (Killsgaard 1999). During the shoreline survey, the dominant vegetation type of each parcel was described using categories in Table 1. Also included was the location of invasive plant species, particularly yellow flag iris (Iris pseudacorus), reed canary grass (Phalaris arundinacea), and Himalayan blackberry (Rubus armeniacus) which were commonly observed in mixed communities.

We found that vegetative characteristics generally varied by parcel, and that individual landowners maintained a wide variety of landscaping preferences, and hence vegetation types. More than half of the vegetation around Devils Lake is comprised of shrubs and herbaceous plants. Approximately 13% of the parcels are dominated by conifers and about 15% of the shoreline has wetland indicator species (herbaceous, shrubs, or trees). Approximately 8% are dominated by deciduous trees; however, these were commonly observed in highly mixed communities with a range of vegetation types. Of the 338 parcels observed with invasive plant species, yellow iris occurred in 86% and reed canary grass in 46%. Vegetation data were provided to the District in ArcGIS for future analysis.

Table 1. Shoreline Vegetation Characteristics Parcel

<table>
<thead>
<tr>
<th>Vegetation Types</th>
<th>Parcel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sitka spruce-Western hemlock</td>
<td>Shrub – herbaceous</td>
</tr>
<tr>
<td>Doug fir – Western hemlock</td>
<td>Emergent vegetation</td>
</tr>
<tr>
<td>Mixed conifer</td>
<td>Invasive plant species</td>
</tr>
<tr>
<td>Mixed deciduous</td>
<td>Wetland</td>
</tr>
<tr>
<td>Shrub</td>
<td></td>
</tr>
</tbody>
</table>
Land Use, Bank Stabilization, and Shoreline Conditions

During the shoreline survey, current land use, the presence and method of bank stabilization, and an assessment of the shoreline condition was documented for each parcel. Parameters presented in Table 2 were similarly stored as ArcGIS 9.3 and provided to the District.

Table 2. Land Use Categories and Shoreline Conditions Parcel

<table>
<thead>
<tr>
<th>Land Use Categories</th>
<th>Bank Stabilization</th>
<th>Shoreline Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>Rip rap</td>
<td>Eroding</td>
</tr>
<tr>
<td>Commercial</td>
<td>Concrete</td>
<td>Non-eroding</td>
</tr>
<tr>
<td>Open space</td>
<td>Vegetated</td>
<td>Bank slope</td>
</tr>
<tr>
<td>Public</td>
<td>Bare ground/lawn</td>
<td>Bank slope</td>
</tr>
<tr>
<td></td>
<td>Retaining wall</td>
<td>Smooth slope</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Terraced slope</td>
</tr>
</tbody>
</table>

Land use around Devils Lake is predominantly residential (70%), followed by open space such as parks, undeveloped land, and lake access points (28%), and only 1% commercial. Numerous parcels have multiple types of bank stabilization. For example, some parcels may have rock riprap, bare ground/lawn, and vegetated shoreline. Approximately 65% of the shoreline has some measure of armoring, consisting primarily of either concrete or wooden retaining walls or rock riprap (Figure 2). For purposes of this analysis, parcels with any engineered structures were considered “armored”, thus the estimate of percent armoring may be overestimated, depending on the degree to which a parcel is armored.
Figure 2. Locations of non-armored and partially to fully armored shoreline based on the field inventory
Differentiating “eroding” from “non-eroding” parcels proved to be more challenging than expected because the degree of erosion was highly variable (e.g. ranging from small patches to whole-parcel frontage) and because structures or vegetation obscured the view of landward erosion. We found some evidence of erosion was only visible below an existing structure, suggesting higher lake levels could limit seeing indicators of erosion. Keeping this information in mind could benefit future evaluations.

We observed numerous examples where adjoining properties with differing bank stabilization measures exhibited a range of erosional conditions. For example, between adjacent parcels, one may have a riprap bank and the other a vertical concrete retaining wall. The different types of armoring often created a discontinuity that led to erosion near the interface, and these areas were considered to be eroding. Additionally, in areas that are dominated by reed canary grass, substantial undercutting was commonly observed. While vegetated, this was also considered to be eroding.

Based on these observations, about 16% of the shoreline, or approximately 11,000 linear feet, is exhibiting at least some level of erosion, most of which (~72%) occurs in unarmored areas, although some (~28%) also occurs in areas where existing armoring has been damaged or is of limited vertical extent.

**Soils**

Based on recently published soil maps for Lincoln County (NRCS 2011), five primary soil types make up the shoreline around Devils Lake (Table 3; Figure 3). The most prevalent is the Fendall-Winema unit (19E) that represents about 39% of the total shoreline length, primarily located along the western, northeastern and north sides of the lake. A smaller percent of the shoreline (~6%) is also composed of the very similar Winema-Fendall unit (64C). These soil types are classified as low plasticity, well-drained silt loam that is composed of 30 to 45% sand, 20 to 45% silt and about 25% clay. These soil types typically occur on relatively steep (15 to 35%) slopes underlain by paralithic bedrock at depth of 20 to 40 inches. These two soil types are considered quite erodible. Of the total length of shoreline considered “eroding” during the shoreline survey, about 22% of the total length of erosion occurs in these soil types (Table 3).

The next most prevalent is the Brallier unit (8A) that makes up about 21% of the shoreline, and consists of mucky peat that is over 80% silt and clay and less than 15% fine and medium sand. This poorly-drained soil type is very erodible when bare, but tends to occur in low-lying, flat areas that are heavily vegetated, including the broad floodplain and wetland at the mouth of Rock Creek. There is
typically very little development in areas where these soils occur. Nearly half of the eroding shoreline length around the lake occurs in the soil type (Table 3).

About 15% of the shoreline consists of the Grindbrook unit (23C), which is also classified as a moderately well-drained soil of low plasticity silt loam, consisting of 10 to 25% medium to fine sand, 55 to 85% silt and about 15% clay. This soil type occurs primarily on the terraces along the eastern shoreline in the south half of the lake. Of the total length of shoreline considered to be “eroding”, about 24% occurs in this soil type (Table 3).

Other less prevalent soil types include Netarts (47C) and Nelscott (42C) that represent about 10% and 6% of the total shoreline length, respectively. The Netarts unit is derived from Aeolian (wind-blown) sand dunes, consists primarily of well-drained fine sand, with up to 15% silt and clay, and is highly erodible. This soil type occurs on the small peninsula on the northeast side of the lake. The Nelscott unit is classified as a moderately well-drained silt loam derived from Aeolian material over stratified marine deposits, and includes a layer of somewhat erosion resistant material. This soil type occurs in two areas along the west shoreline. Of the total length of shoreline considered “eroding”, about 6% occurs in the Nelscott soil type (Table 3).

**Table 3. Soil Types and Estimated Percent Erosion**

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Code</th>
<th>Approximate Length (Ft)</th>
<th>Estimated % of Shoreline</th>
<th>Erosion Length (Ft)</th>
<th>% Erosion Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fendall-Winema Unit</td>
<td>19E</td>
<td>25,695</td>
<td>39%</td>
<td>1,912</td>
<td>18.9%</td>
</tr>
<tr>
<td>Winema-Fendall unit</td>
<td>64 C</td>
<td>3,955</td>
<td>6%</td>
<td>329</td>
<td>3.2%</td>
</tr>
<tr>
<td>Brallier Unit</td>
<td>8 A</td>
<td>13,835</td>
<td>21%</td>
<td>4,873</td>
<td>48.1%</td>
</tr>
<tr>
<td>Grindbrook Unit</td>
<td>23 C</td>
<td>9,880</td>
<td>15%</td>
<td>2,463</td>
<td>24.3%</td>
</tr>
<tr>
<td>Netarts</td>
<td>47 C</td>
<td>6,590</td>
<td>10%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nelscott</td>
<td>42 C</td>
<td>3,955</td>
<td>6%</td>
<td>562</td>
<td>5.5%</td>
</tr>
</tbody>
</table>

*Note: See text for method to determine erosion; soil data based on NRCS 2011*
Figure 3. Soil types and locations of eroding shoreline areas (yellow)
Inundation Mapping

As previously mentioned, the elevation of Devils Lake can be controlled between 8.03 feet and 9.53 feet MSL. The ordinary high water (OHW) is 10.4 feet MSL and the 10-year and 100-year flood events are estimated at 12.9 and 14.0 feet MSL, respectively\(^1\) (FEMA 2009). Inundation maps for the various lake levels (referenced to MSL, NGVD29) were developed for the immediate vicinity of Devils Lake. To accomplish this, representative topographic maps of Devils Lake were developed, based on the combination of overbank LiDAR data and surveyed bathymetry data.

The LiDAR dataset was produced by the Oregon LiDAR Consortium from LAS files covering the area around Lincoln City, and provided in the form of 1-foot resolution ESRI raster grids. Based on associated metadata, the LiDAR was collected between April 21 and July 16, 2009, and provided in the horizontal coordinate system of NAD 1983 Harn Lambert Conformal Conic and the North American Vertical Datum of 1988 (NAVD88). The lake elevation when the LiDAR data were collected averaged 9.57 feet MSL (median = 9.66 feet MSL).

Bathymetric data were collected on March 24 to 25, 2004 when the lake level was at 8.75 feet MSL (NGVD29) (Eilers et al. 2005). The bathymetric data included depth, latitude, and longitude. To create elevations, the depth of each sounding was subtracted from the lake elevation of 8.75 feet (NGVD29). In addition to the bathymetric data, a shoreline survey of the edge-of-water was also conducted, and since only the X-Y coordinates were provided, an elevation of 8.75 feet (NGVD29) was applied to all of the edge-of-water survey points.

To develop a comprehensive topographic map, the vertical datum of the LiDAR data was converted from NAVD88 to NGVD29 (MSL), which effectively lowered all LiDAR elevations by approximately 3.44 feet, and the horizontal projection of all data was converted into the Oregon North NAD83 State Plane coordinate system. A breakline around the perimeter of the lake was created from the edge-of-water survey points, and the breakline was used to clip the boundary and remove all LiDAR data within the footprint of the lake and as a breakline to facilitate triangulation of the topographic map. Using ESRI ArcGIS, the edge-of-water breakline and bathymetric data were combined and a triangulated irregular network (TIN) surface was created. The TIN surface was then converted into a

---

\(^1\) Lake levels reported by the District as MSL are referenced to the National Geodetic Vertical Datum of 1929 (NGVD29). The FEMA-published values for the 10- and 100-year floods of 16.3 feet and 17.4 feet, respectively, are referenced to North American Vertical Datum of 1988 (NAVD88), which is 3.44 feet higher than the datum for NGVD29; thus, the equivalent 10- and 100-year lake levels are 12.9 feet and 14.0 feet NGVD29. Unless otherwise specified, MSL and NGVD29 are used interchangeably throughout this report. To convert from NGVD29 to NAVD88, add 3.44 feet.
raster grid dataset with a 1-foot pixel resolution, and this TIN surface was then inserted into the LiDAR raster data.

In general, available overbank LiDAR data intersected very closely to the edge-of-water survey that was conducted at an elevation of 8.75 feet MSL. However, based on the depths recorded during the bathymetric data collection, the survey vessel did not enter portions of the lake with depths less than about 2 to 3 feet. As a result, a gap in data typically exists between the lateral extent of the bathymetric data and the edge-of-water around the lake. In most situations, the interpolation across this gap during development of the TIN appears to be reasonable, especially where the shoreline is relatively uniform. However, in some situations such as near the mouth of an inlet, it was necessary to estimate the channel bottom elevation in localized areas to prevent the interpolation from producing unreasonably high elevations.

This issue should only affect the accuracy of the low water height at 8.3 feet. The other elevations are above the lake level of 8.75 feet that was present during the Eilers et al. (2005) edge-of-water survey. As a result, the inundation boundary at the higher lake elevations under consideration fall outside the interpolated area, and the accuracy of the mapped inundation boundary will be consistent with the accuracy of the LiDAR data (1-foot interval). Based on the limitations in the data, the horizontal locations of the inundation boundaries should be treated as approximate. To determine the specific location of the water’s edge at the resolution of an individual parcel, a site specific survey is required. The relative location and differences between the mapped boundaries should, however, provide a reasonable representation of how the shoreline will change at the scale of several parcels.

The inundation map for the 100-year flood event was taken directly from the electronic version of the Digital Flood Insurance Rate Map (DFRIM) generated from FEMA (2009). The inundation map for the 10-year event was developed for the FEMA-published elevation of 16.3 feet NAVD88 and converted to 12.9 feet NGVD29 using the same procedures that were used to map the lower lake levels. Flood events of a magnitude that are expected to be equaled or exceeded once on the average during any 10 and 100 year flood have a 10% and 1% chance, respectively, of being equaled or exceeded during any year (FEMA 2009). That is, these represent a statistical probability of an event being equaled or exceeded during any year and this does not mean these events will occur exactly once every 10 or 100 years. Additionally, this information represents the average period between floods of a specific magnitude. Rare floods could occur at short intervals or even within the same year (FEMA 2009).
Examples of inundation maps are provided in Figures 4 to 7 and all electronic data, including the 10 and 100-year events (12.9 feet and 14.0 feet MSL, respectively) were provided on an external hard drive to the District in ArcGIS 9.3 as a user-friendly animations in .pdf and .mov formats similar to the historic aerials.

Figure 4. Example inundation map from the D River at 8.3 feet MSL

Figure 5. Example inundation map from the D River at 9.0 feet MSL
Figure 6. Example inundation map from the D River at 9.53 feet MSL

Figure 7. Example inundation map from the D River at 10.4 feet MSL
Based on available data for the inundation mapping exercise, the estimated differences in acres inundated between the various water levels are provided in Table 4.

### Table 4. Estimated Surface Acres due to Changes in Devils Lake Elevation (feet MSL)

<table>
<thead>
<tr>
<th>Feet MSL</th>
<th>Increase in Surface Acres between Lake Levels (feet MSL)</th>
<th>Estimated Surface Acres*</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.3</td>
<td></td>
<td>655</td>
</tr>
<tr>
<td>9.0</td>
<td>25</td>
<td>680</td>
</tr>
<tr>
<td>9.53</td>
<td>27 2</td>
<td>682</td>
</tr>
<tr>
<td>10.4</td>
<td>39 15 12</td>
<td>694</td>
</tr>
<tr>
<td>12.9</td>
<td>155 130 127 115</td>
<td>809</td>
</tr>
<tr>
<td>14.0</td>
<td>278 253 250 238 123</td>
<td>943</td>
</tr>
</tbody>
</table>

*The accuracy of these data are determined by previously described limitations in the inundation maps which have not been ground-truthed.

### Wave Energy

Energy, and hence, erosional stress on the shoreline around Devils Lake is caused by a combination of natural and human-induced wave action. Natural waves are caused primarily by wind while anthropogenic effects are assumed to result primarily from boat waves. Using the information gathered from the shoreline survey, available meteorological data, and information on the range of typical boat types that use Devils Lake, semi-empirical relationships were applied to estimate the effects of natural and anthropogenic waves on shoreline erosion around the lake.

#### Predominant Winds

The relative intensity and duration of wind-driven waves was quantified using computational procedures outlined in the U.S. Army Corps of Engineers Coastal Engineering Manual (USACE 2008). Available wind data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Newport Weather Station (NWP03), for which detailed, long-term records are available, and from Windfinder.com (2011) for which wind directions are available for the past approximately three years.

Wind roses showing the percentage of time that the wind blew from each of 16 evenly spaced compass directions during each month of the year from August 2008 through September 2011 were obtained from WindFinder (2011). These data generally indicate that the winds blow predominantly
from the northeast\(^2\) during the winter months (December through February), with a lower, but substantial probability of south to southeasterly winds (Figure 8). The winds tend to shift to a predominantly southerly direction in March, and can be quite strong during this period (~25 percent probability of exceeding 4 on the Beaufort scale). During the spring and summer (April through August), when most of the recreational boat activity occurs, the winds tend to blow from the northerwesterly direction. During the early fall (September and October), the winds also tend to originate predominantly from the northwest, but this period also sees a transition toward more southerly to southwesterly winds.

The available wind data at Lincoln City (Windfinder 2011) provides the wind direction; however, these data only include the average monthly wind speed and probability that the wind exceeds Category 4 on the Beaufort Scale (i.e., winds greater than 11 knots) (Table 5). Data at much higher temporal resolution are required to assess the overall wind climate and erosive energy around the lake boundary. The closest station with detailed, longer-term records suitable for this analysis is located at Newport, Oregon, approximately 25 miles south of Devils Lake (NOAA Gage NWP03). While the topography appears to affect the prevailing winds during non-storm periods, the storms that provide the vast majority of the erosive energy over the course of the year cause the winds to blow from essentially the same direction at both Newport and Lincoln City (Paul Robertson, personal communication, 2011); thus, it is assumed for purposes of this analysis that the detailed data from the Newport gage can be used for this analysis. The available detailed data for the Newport gage extend from Calendar Year 1997 through 2010, and it includes both the direction and wind speed at hourly intervals throughout the period. These data were obtained from the NOAA historical data archives and analyzed using the Lakes Environmental WRPLT V 7.0 program to quantify and graphically display the probability distribution of wind speeds from each of the 16 compass directions (Figure 9).

Except for the frequent, relatively light, easterly and east-northeasterly winter winds that tend to blow down Yaquina Bay at Newport, the wind patterns for the short Lincoln City records and the longer term Newport records are reasonably consistent. Closer evaluation of the data indicates that the stronger winds (Beaufort Category 4 and above) tend to originate from consistent directions during each of four seasons defined from November through February, March through May, June through August, and September through October (Figure 9).

\(^2\) Wind directions discussed in this report refer to the direction from which way the wind is blowing, as is standard in meteorological reporting.
Note: this plot is intended to provide an overview of the prevailing wind directions during each month of the year and not monthly wind speed.

Figure 8. Wind roses showing the probability of winds of various speeds from each of 16 evenly spaced compass directions at the NOAA Newport Weather Station (NWP03) for the period from 1997 through 2010. Also shown, in red outline, is the probability of winds from each direction at the Lincoln City station for the period from August 2008 through September 2011.
<table>
<thead>
<tr>
<th>Beaufort Number</th>
<th>Wind Speed (knots* / mph)</th>
<th>Seaman’s Term</th>
<th>Sea State</th>
<th>Effects on Land</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Less than 1 (0.5)</td>
<td>Calm</td>
<td>Sea like glass, flat, calm</td>
<td>Calm; smoke rises vertically</td>
</tr>
<tr>
<td>1</td>
<td>1 to 3 (1 to 3.5)</td>
<td>Light Air</td>
<td>Ripples with appearance of scales, no foam crests</td>
<td>Smoke drifts with wind direction; weathervanes do not move</td>
</tr>
<tr>
<td>2</td>
<td>4 to 6 (4.5 to 7)</td>
<td>Light Breeze</td>
<td>Small wavelets (6”-8”); crests begin to break; scattered whitecaps</td>
<td>Wind is felt on face; weathervane do not move; leaves rustle</td>
</tr>
<tr>
<td>3</td>
<td>7 to 10 (8 to 11.5)</td>
<td>Gentle Breeze</td>
<td>Large wavelets (2”); crests begin to break; scattered whitecaps</td>
<td>Leaves, small twigs move; small flags extended</td>
</tr>
<tr>
<td>4</td>
<td>11 to 16 (12.5 to 18.5)</td>
<td>Moderate Breeze</td>
<td>Small waves (3’) with numerous whitecaps</td>
<td>Dust, paper, leaves raised up; small branches move</td>
</tr>
<tr>
<td>5</td>
<td>17 to 21 (19.5 to 24)</td>
<td>Fresh Breeze</td>
<td>Moderate wave (6’) and many whitecaps and some spray</td>
<td>Small trees in leaf sway; large flags ripple</td>
</tr>
<tr>
<td>6</td>
<td>22 to 27 (25 to 31)</td>
<td>Strong Breeze</td>
<td>Large waves (10’); whitecaps everywhere with much spray</td>
<td>Large branches of trees in motion; whistling can be heard in wires and sailboat rigging</td>
</tr>
<tr>
<td>7</td>
<td>28 to 33 (32 to 38)</td>
<td>Moderate Gale</td>
<td>Large waves (13’); foam blown in streaks; sea heaps up</td>
<td>Whole trees in motion; resistance felt while walking against the wind</td>
</tr>
<tr>
<td>8</td>
<td>34 to 40 (39 to 46)</td>
<td>Fresh Gale</td>
<td>Moderately high waves with longer length (18’); crests break into spindrift</td>
<td>Small branches and twigs are broken off; hard walking against wind</td>
</tr>
<tr>
<td>9</td>
<td>41 to 47 (47 to 54)</td>
<td>Strong Gale</td>
<td>High waves (23’); sea begins to roll; visibility is affected</td>
<td>Light structural damage occurs; shingles torn from roof</td>
</tr>
<tr>
<td>10</td>
<td>48 to 55 (55 to 63)</td>
<td>Whole Sale or Storm</td>
<td>Very high waves (30’); sea looks white as foam is blown in dense streaks; heavy sea roll; visibility is restricted</td>
<td>Moderate structural damage occurs; some trees uprooted</td>
</tr>
<tr>
<td>11</td>
<td>56 to 63 (72.5 to 72.5)</td>
<td>Violent Storm</td>
<td>Exceptionally high waves (35’); visibility is poor</td>
<td>Heavy widespread structural damage; large trees uprooted</td>
</tr>
<tr>
<td>12</td>
<td>Over 64 (74)</td>
<td>Hurricane</td>
<td>Waves may reach 45’ in height; air if filled with foam and spray, visibility very poor</td>
<td>Very heavy structural damage; coastal areas evacuated; very large trees broken or uprooted</td>
</tr>
</tbody>
</table>

*1 knot equals approximately 1.15 miles per hour
Figure 9. Wind roses showing the probability of winds of various speeds in Beaufort Category 4 and above at the Newport Weather Station (NWP03) during four seasons for the period from 1997 through 2010.
Wind Waves

For the bathymetric characteristics and shape of Devils Lake, the wave height is primarily a function of the fetch (i.e., distance across the water over which the wind blows) and the wind speed (Figure 10). The wave energy that is the primary driver of erosional stress is proportional the square of the wave height and is also affected by the wave period that is related to the fetch (Figure 11). As is clearly evident from the logarithmic vertical scale in Figure 11, even modest increases in the wind speed and the resulting wave height have a dramatic effect on the wave energy and, thus, erosion potential.
The distribution of wind wave energy around the shoreline of Devils Lake was assessed by computing the total annualized energy at a series of points evenly spaced at 500 foot intervals along the shoreline. The local fetch from each of the 16 compass directions and the associated probability of winds of various speeds from each direction were included in the computations. The average annual energy directed at the shoreline around the lake by wind waves varies from negligible in sheltered areas to about 50,000 megawatts (MW) per foot of shore length (north end of the lake near NE Neotsu Drive), and averages about 9,900 MW per foot.

About 65% of the total wind-driven wave energy occurs during the non-recreation (October - April) period, most of which occurs along the north shoreline. Conversely the bulk of the wind energy during the recreation period (April - October) occurs along the south and east shore. Since the raw
magnitude of the energy has meaning only in the context of the site-specific characteristics of the shoreline (e.g., slope, soils, presence or absence of armoring, vegetation), the average annual energy values were normalized to the average value (Figure 12). That is, values less than 1.0 receive less than the average energy due to wind and locations with values greater than 1.0 receive more than the average (Figure 12).

In general, the locations with the greatest wind energy (shown in yellow-orange-red in Figure 12) occur along the north shore of the lake where the fetch associated with the winter-storm driven southerly and southwesterly wind is greatest. Here, the maximum energy has a normalized value of about 5.2 (i.e., this location receives over five times more wave energy due to wind that the average). High wind wave energy also occurs along portions of the east and southeast shoreline due to the long fetch associated with the strong, northwesterly summer winds. As anticipated, locations that are sheltered from the wind or have relatively short fetch receive low erosional energy due to the wind.

The fetch values used for the above analysis were based on a lake elevation of 9.0 feet MSL. The difference in surface area between the lowest level of about 8.3 feet MSL and the OHW level of 10.4 feet MSL is about 39 acres (Table 4). Spread over the approximately 12.2 mile perimeter of the lake, this represents an average difference in fetch of less than 5 feet; thus, differences in fetch for the range of typical lake levels have an insignificant effect on the wave energy estimates. As a result, the relative values shown in Figure 12 would change by an imperceptible amount if other lake levels had been used; the relative erosional energy indicated in Figure 12 is valid for the range of lake levels that are of concern in this study.

It is important to note, however, that while lake level does not significantly affect the amount of wave energy, the vertical location at which it impacts the shoreline may be significant in specific areas, depending on the local characteristics at the point of impact. It is also important to note that the wave energy values shown in Figure 12 assume that the water depth up to the shoreline sufficiently prevents significant interaction with the bottom and dissipation of wave energy. That is, the lake bottom profile approaching the shoreline is highly variable and, therefore, the relative energy values shown in Figure 12 represent the upper limit for the assumed conditions.
Note: Numbered locations referenced in text

Figure 12. Distribution of annual wind energy around the shoreline of Devils Lake. Values less than 1 indicate less than average and values greater than 1 indicate greater than average wind energy.
Boat Waves

Waves associated with recreational boat traffic on Devils Lake are also a source of significant erosional energy. The approximate intensity of boat-driven waves was estimated using computational procedures in USACE (2008), data from published literature on the characteristics of waves generated by boats that are similar to those typically using Devils Lake, and assumptions regarding the amount of recreational boat traffic on the lake.

Based on information provided by the District, most of the boats used on the lake fit into one of two categories: wakeboard and waterski, with the wakeboard boats accounting for approximately 75% of the traffic and waterski boats the remaining approximately 25%. Based on available information, it is reasonable to assume that there are typically 20 to 40 boats operating on the lake at any given time during the summer months, with a peak of about 60 on holiday weekends, and a smaller number operating during the latter half of May and through September and the first half of October (Figure 13). This information also indicates that a typical boat will operate for about three hours on any given day and make about six turns per hour. Based on these assumptions, the total number of turns during a typical season ranges from about 37,000 to 72,000, and averages about 54,000. Based on the 75:25 percent ratio of wakeboard to waterski boat, this indicates about 13,500 waterski turns and about 40,500 wakeboard turns per season.
The characteristics of the waves generated by these boats was evaluated using semi-empirical relationships that describe the spectral characteristics and energy of the wave bursts associated with boats passing at different distances from the shoreline. When a power boat passes a particular area, a series of waves is generated that exerts energy on the shoreline by disturbing the local flow pattern. The wave train associated with a single boat pass will typically consist of about 15 waves that increase in amplitude to a maximum height and then diminish back to the still water level (Mussetter Engineering, Inc. 2006) (Figure 14). The height of the waves diminishes at a rate proportional to about the one-third power of the distance from the sailing line to the boat. The magnitude of the disturbance caused by the waves depends primarily on the wave height. The wave height is related to a variety of factors including the size and speed of the boat, hull shape, draft of the boat (which is strongly influenced by the amount of ballast and number of passengers, particularly in the case of the wakeboard boats), water depth, and distance from the boat to the shoreline. The waves typically radiate from the boat at an angle of 18 to 20 degrees to the sailing line.
line. If the boat is traveling parallel to the shore, this also indicates that the waves will impact the shoreline at about 18 to 20 degrees.

![Image of wave climate data]

**Figure 14. Typical wave climate associated with a jet boat**

Data on the wave characteristics of the specific boats that use Devils Lake are not available; however, data have been collected by others on boats that have similar characteristics. Of the available data that were identified in the literature, studies by Glamore and Hudson (2005) and documented in Glamore (2008) appears to be the most directly relevant to conditions in Devils Lake (Table 6). In these studies, the investigators measured the wave climate for a wide range of conditions for six different types of wakeboard boats and five different types of waterski boats. Based on these tests, the typical wave climate associated with the waterski boats, measured at approximately 70 feet from the boat, had maximum wave height of about 0.4 feet, period at the peak of 1.5 seconds and total energy of about 62 Kw/ft of length along the wave crest. The waves
associated with the wakeboard boats, also measured 70 feet from the boat, were significantly larger, with maximum height of about 0.8 feet, peak period of about 1.6 seconds and total energy of about 296 Kw/ft.

Table 6. Wave Characteristics at Typical Operating Conditions (approx. 70 feet from a boat)

<table>
<thead>
<tr>
<th>Boat</th>
<th>Boat Speed (knots)</th>
<th>Boat Speed (mph)</th>
<th>Maximum Wave Height (ft)</th>
<th>Peak Wave Period(s)</th>
<th>Boat Length (ft)</th>
<th>Energy (Kw/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterski</td>
<td>30</td>
<td>35</td>
<td>0.4</td>
<td>1.5</td>
<td>20.0</td>
<td>62</td>
</tr>
<tr>
<td>Wakeboard</td>
<td>19</td>
<td>22</td>
<td>0.8</td>
<td>1.6</td>
<td>20.0</td>
<td>296</td>
</tr>
</tbody>
</table>

Source: Glamore 2008

The data from Glamore (2008) and the above relationships were used to assess wave energy expended on the Devils Lake shoreline by boats operating at different distances from the shoreline. As noted above, the wave height diminishes with about the one-third power of the distance from the boat. It was assumed that the boats typically travel parallel to the long axis of the lake (except when turning), and they could be at any location on the lake that is more than 100 feet from the shoreline. The average width of Devils Lake is about 1,500 feet; thus, the operating zone for the boats averages about 1,300 feet wide. The relative impact of the boats was estimated assuming that, over the course of the year, the boat traffic would be uniformly distributed within this zone. Based on the wave characteristics reported by Glamore (2008), the average energy of the boat-driven waves around the shoreline is about 2,000 MW per ft, or about 20% of the average annual wind energy (or ~17% of the total wave energy considering the combination of wind and boat waves). Boat-driven waves account for about 40% of the total wave energy during the recreation period.

Review of the available information on wakeboard boats, including photographs and videos of these boats in operation, as well as comments from reviewers of the initial draft of this report, indicates that waves generated by these boats may be significantly larger than is indicated by Glamore (2008). Repeated attempts to obtain better information from a variety of boat manufacturers were unsuccessful; thus, direct data that can be used to provide more refined estimates of the wave characteristics are not available.

To provide a quantitative sense of how the relative impacts of the boat waves would change if the typical waves are larger than those indicated by Glamore (2008), a sensitivity analysis was performed which assumed maximum wave heights of 1 foot, 1.5 feet and 2.0 feet at the same 70
foot distance from the boat. A typical recreational rider will use a tow-line that is in the range of 40 feet long. Based on the rate at which the maximum wave height in a typical wave burst declines with distance from the boat, the 0.8 foot maximum height indicated by Glamore (2008) and used in the above estimates, would be about 1.1 feet at the location of the rider and about 1.6 feet at a distance of 10 feet from the boat. Based on the sensitivity analysis for the three assumed larger maximum wave heights, the wave heights at the location of the rider (40 feet) range from 1.3 feet to 2.6 feet. Further, the annual energy expended on the shoreline for these wave heights ranges from about 2,800 MW per foot to about 8,600 MW per foot (Table 7). These estimates represent 31% to 95% of the average wind wave energy and 23% to 49% of the total wave energy along the shoreline.

### Table 7. Wave Energy as a Function of Boats and Percent of Total Wave Energy on the Shoreline

<table>
<thead>
<tr>
<th>Maximum Wave Height (ft)</th>
<th>Distance from boat</th>
<th>Average Annual Wind Energy at Shoreline (MW/ft)</th>
<th>Percent of Average Annual Wind Energy</th>
<th>Percent of Total Wave Energy</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70 feet</td>
<td>40 feet (location of rider)</td>
<td>10 feet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td></td>
<td>1.1</td>
<td>1.6</td>
<td>2,000</td>
<td>22%</td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td>1.3</td>
<td>1.9</td>
<td>2,800</td>
<td>31%</td>
</tr>
<tr>
<td>1.5</td>
<td></td>
<td>1.9</td>
<td>2.9</td>
<td>5,400</td>
<td>59%</td>
</tr>
<tr>
<td>2.0</td>
<td></td>
<td>2.6</td>
<td>3.9</td>
<td>8,600</td>
<td>95%</td>
</tr>
</tbody>
</table>

Relative Contribution of Natural and Anthropogenic Waves

As shown in Table 7, the average contribution of boat waves to the total wave energy at the shoreline ranges from about 17% based on the wave data from Glamore (2008) to nearly 50% if the typical boat waves from wakeboard boats operating on Devils Lake are 2 to 2.5 times larger. The impact of the boats waves relative to the wind driven waves, of course, varies depending on the location around the lake (Figure 15). In general, the areas with the greatest relative impact from boat-generated waves tend to occur where the wind energy is lowest.
Figure 15. Estimated boat wave energy around the shoreline of Devils Lake on an annual basis as a percent of the local wind energy.
In assessing these results, it is important to note that there is considerable uncertainty in many of the assumptions, particularly the number of boats and the specific locations on the lake within which they operate. It is also important to note that the wave analysis was performed for individual wave trains, and did not explicitly consider the effects of wave refraction or interference (or wave building) among waves generated from different sources. A more detailed assessment could be performed using a wave simulation model that can take into account the combined effects of multiple wave sources. In spite of these limitations, the results presented here provide a reasonable indication of the primary source and distribution of erosional energy around the shoreline of the lake.

**Impacts of Dam Operations**

This section discusses the overall impacts of dam operations as they relate to lake level, general shoreline conditions, soils, vegetation, and wave energy.

**Lake Level**

As previously stated, lake levels during the summer recreation period that typically extends from early- to mid-April through mid-October are controlled by a small dam with removable splashboards that was constructed at the lake outlet in 1998. Prior to a water-rights evaluation by the Oregon Water Resources Department (WRD) in March 2009, the District used up to three 7.5 inch high splashboards that had the collective ability to raise the lake level by up to 22.5 inches above the dam sill. The March 2009 evaluation found that raising the lake to this level impounded more water than is allowed by the District’s water right and the height of the dam was subsequently restricted. Under current operations, the lake level can be raised during the summer months to a level that is up to 18 inches higher than would otherwise occur in the absence of the dam. Since the splashboards are removed during the winter, non-recreational season from mid-October through early-April, the lake levels during this period are controlled primarily by precipitation and inflow from the local watershed.

Although the lake level has an insignificant effect on the amount of wave energy approaching the shoreline, it can have a significant impact on the erosional characteristics of those waves depending on the specific vertical location at which they impact. For example, vertical walls have been constructed in a number of areas around the lake to limit shoreline erosion. During the shoreline survey (conducted at lake level of approximately 8.9 feet MSL), the still-water level was at or near the bottom of the wall in several areas, with little or no protection below the wall. In these areas, much of the wave energy that impacts the wall is reflected back into the lake and/or down the shoreline where it can combine with and enhance other waves. The trough of the waves, however, exposes at
least several inches of the unprotected shoreline below the wall to erosion. Significant waves can also overtop some of the walls, absorbing, rather than reflecting that part of the wave energy and subjecting the unprotected areas behind the wall to erosion. Additionally, artificially raising the water level to one specific point on a yearly basis artificially isolates the still water line, potentially increasing erosion to one area that would otherwise change throughout the year.

Differences in lake level can also affect the erosional characteristics of unarmored or partially armored areas within the elevational range of the wave energy - particularly where vegetation is limited (e.g., bare ground/exposed lawn) and soil stability may be compromised. This occurs because the depths in the nearshore region affect the amount of wave energy that actually reaches the shoreline. In shallow areas where the depth is less than about 1.25 times the wave height, the waves break, causing significant turbulence and dissipating energy before the wave reaches the shoreline. Turbulence in the breaker zone tends to entrain sediment from the lake bottom that affects turbidity and can alter the lake bottom profile. However, turbulence also reduces the wave energy that actually reaches the shoreline, particularly where the breaker zone extends well out into the lake. Where the flow is deeper than about 1.25 times the wave height, most of the wave energy directly impacts the shoreline. Where the topography of the lake bottom is flatter than above the shoreline, the approaching waves will impart more erosive energy in the wave impact zone at higher lake levels because there will be less tendency for breaking and energy dissipation prior to reaching the shoreline.

To provide a basis for assessing the potential impact of dam operations on shoreline erosion, the available lake level data were analyzed to quantify the typical range of lake levels over the course of the year. The data used in the analysis were provided by the District, and included recorded lake levels from January 1998 through mid-September 2011. An initial analysis was performed by computing the average, minimum, and maximum monthly lake levels for the period of record (Figure 16). This analysis indicates that the highest monthly average levels typically occur in May and June (averages of 9.7 feet and 9.6 feet MSL, respectively), and the levels tend to decline over the summer to the lowest levels that typically occur in October (average of approximately 9 feet MSL). The lake levels then increase to their maximum winter levels that average about 9.5 feet MSL during December and January as a result of increased precipitation.

Variability in lake levels can also impact the erosional characteristics of the waves. Variability during the winter months is significantly greater than during the summer (see vertical bars in Figure 16), largely due to the effects of the periodic winter storms compared to lack of precipitation events and control at the outlet dam during the summer months. Prior to 1998, winter rains, which account for
about 75 inches from October to April in Lincoln City created higher water levels during the winter than summer compared current operations.

![Graph showing average monthly lake levels and precipitation](image)

Note: Vertical black lines indicate the range of lake levels during each month. Purple line represents the average monthly precipitation (values on right vertical axis)

**Figure 16. Average monthly lake levels (presented as dashes) based on data for the period from January 1998 through September 2011**

To provide additional information on the variability and duration of lake levels, mean daily duration curves were developed from the data set for the recreation (assumed Apr 15 to Oct 15) and non-recreation periods (assumed Oct 16 to Apr 14). The curves shown in Figure 17 indicate the percentage of time that the lake level equals or exceeds the indicated elevations (e.g., mean high water or maximum summer level). The number of days corresponding to the range of exceedence percentages for the two approximately 180 day periods is also indicated. For example, at least 30% of the time, or roughly 58 days of the year, the water level was greater than 9.53 feet MSL during the non-recreation period when the lake was not controlled by the District’s water right.

Based on this analysis, the median lake level (i.e., level equaled or exceeded 50% of the time) during the period of record was about 9.4 feet MSL during the recreational period, decreasing to about 9.2
feet MSL during the non-recreational period. The lake levels are typically a few tenths of feet lower during the bulk of the non-recreation period than during the recreation period, but about 10% of the time they were significantly higher due to the effects of the winter storms. The lake levels during the recreational period were between 8.4 feet MSL and 10.0 feet MSL about 98% of the time, and during the non-recreational period, they ranged between 8.5 feet MSL and 10.8 feet MSL about 98% of the time (elevation ranges of 1.6 feet and 2.3 feet, respectively.)

Figure 17. Duration curves of Devils Lake levels during the summer recreational period and the winter non-recreational period based on recorded lake levels from January 1998 through September 2011

Available lake level data were also used to assess whether the operational changes resulting from the 2009 WRD evaluation changed the typical recreation period lake levels (Figures 18). This analysis indicates that the median lake level ranged from a low of about 9.0 feet MSL in 2003 to a
high of about 9.6 feet MSL in 2004, 2007 and 2008, with the median levels in 2009, 2010, and 2011 slightly below the average for the full period. The variability in lake levels since the 2009 evaluation was also somewhat less compared to the period prior to the evaluation.

![Graph showing lake levels from 1998 to 2011](image)

**Figure 18.** Variation in Devils Lake levels during the summer recreation periods in 1998 through 2011

**Shoreline Condition**

During the shoreline assessment the lake was at 8.9 feet MSL. Based on observations at that level, we found that parcels with shoreline protection (largely manmade structures) exhibited the least erosion; however, it is important to note that under lower water conditions, those structures may not provide sufficient stabilization if the bottom of the structure is in the path of wave energy, particularly for highly erodible soils. In fact, the vast majority of existing vertical structures were constructed prior to the 1998 recreation impoundment. That is, they were built to conditions that assumed a summer ordinary low water less than current operations. Conversely, at higher water levels, overtopping of vertical structures can result in overland erosion that can cut from the bank side.
As previously mentioned, specific shoreline conditions (e.g. manmade protection, vegetation, and bottom approach) are highly variable between parcels at Devils Lake. The erosional response of the shoreline is, therefore, determined by synergistic effects of site specific conditions. By extension, a discussion of the relative impacts of wave energy on various shoreline conditions is largely based on general, rather than specific, changes in lake level. Erosion is occurring in some areas protected by manmade structures and/or vegetation; however, the mechanism by which erosion occurs between them are variable. The combined influences of wave energy, bottom approach, erodibility of the soils, and vegetative communities are stronger drivers for erosion potential for vegetated shorelines. Conversely, for armored structures, other factors such as structural integrity and structure height play a larger role in determining shoreline stability. For example, as previously mentioned, there are locations where existing bank stabilization is present and appears to effectively protect the upper part of the bank; however, at least a portion of the bottom of the wall is above the area that is impacted by the waves, and the wall is being undercut.

**Soils**

Much of the natural shoreline of Devils Lake is composed of parent materials that are inherently erodible, largely due to the high sand content associated with the lake’s proximity to the Pacific Ocean. The shoreline survey indicates that about 35% of the shoreline is not armored, and most of this area is vegetated, while about 65% of the shoreline has at least some measure of armoring.

Though some level of shoreline erosion is natural, the combined effects of existing soil conditions, proximity to shoreline stabilization features, and location with respect to wave energy synergistically causes erosion to be worse in some areas than it would be in the absence of the stabilization measures. This occurs because waves that are reflected off the hardened structures can combine with the waves originating from other locations within the lake, causing increased wave energy in adjacent areas.

It could be hypothesized that artificially raising the lake level during the recreation period above the typical winter levels could increase shoreline erosion by later exposing saturated soils during the winter when the strongest storm-driven winds occur. Conversely, if natural hydrology was allowed, where the highest water levels occurred during the winter, then boat-driven waves could increase shoreline erosion in the summer by impacting saturated soils in which vegetation growth is inhibited by short growth season and winter inundation. Confounding this assessment is the fact that while the lake level analysis indicates typical levels are only slightly higher during the recreational period compared to the non-recreational period (Figure 17), the regime would be reversed without current operational controls.
During the five years preceding the 2009 WRD water-rights evaluation, the median lake level averaged about 0.5 feet higher during the recreation period than during the non-recreation period (Figure 19). Although the median lake level during the recreation period dropped by about 0.2 feet in 2009 compared to the previous years, it still remained about 0.5 feet higher than during the non-recreation period. During the past two years, the median lake level was somewhat lower than in 2009, reflective of a systematic change in operations in response to the WRD evaluation. During these years, however, the non-recreation median level increased to among the highest during the period of record. As is clearly illustrated in Figures 16 and 17, the variability in lake levels during the non-recreation period is significantly greater than during the recreation period. In addition, the lake levels during the winter likely tend to be higher during storm periods when the strongest winds occur.

![Figure 19. Annualized median lake level during the recreation and non-recreation periods (not to be confused with extreme storm events illustrated in Figure 16)](image)

**Vegetation**

Native vegetation along shorelines provides increased habitat structure for fish and wildlife, contributes nutrients to the system (e.g., leaf detritus), provides shade, traps sediment deposition
due to waves and overland flow, traps and absorbed nutrients from upland soils, and is generally aesthetically pleasing. Natural recruitment of submersed vegetation, and even some emergent vegetation, along the shoreline of Devils Lake faces a number of challenges. Non-native grass carp currently limit the establishment of most all submersed plant species. Grass carp were intentionally stocked in Devils Lake 1986, 1987, and 1993 to control invasive Eurasian watermilfoil (*Myriophyllum spicatum*), Brazilian elodea (*Egeria densa*), and coontail (*Ceratophyllum demersum*) (Bonar et al. 1993; Buckman and Daily 1993). The lake is now largely void of submersed vegetation; however, scattered patches are increasingly found around the lake. For example, in the canals on the far southwest side of the lake, near the D River, including Canadian waterweed (*Elodea Canadensis*), wild celery (*Vallisneria americana*), flat-stemmed pondweed (*Potamogeton zosteriformis*) and water starwort (*Callitriche sp.*) - most of which were observed throughout Devils Lake prior to grass carp stocking (Bonar et al. 1993). It is not known what emergent vegetation grew in the shallow areas of Devils Lake prior to grass carp stocking. Aerials from 1983 suggest dense vegetation north of the Devils Lake State Recreation Area; however, the species is unknown. Floating-leaved spatterdock (*Nuphar luteum*), which is not preferentially fed upon by grass carp, is one of the few conspicuous rooted macrophytes currently found in Devils Lake. As previously mentioned, parcels around Devils Lake exhibit a range of shoreline conditions such that even armored shorelines may have some beach area lakeward that would allow for emergent vegetation. In addition to the invasive reed canary and yellow flag iris observed, the native bulrush (*Scirpus sp.*) was also observed where bathymetry favors establishment.

Operational changes in water level are unlikely to affect foraging behavior by grass carp in Devils Lake. While increasing the lake level from 8.3 feet MSL to 9.53 feet MSL provides an estimated additional 27 surface acres (Table 4), this increase is largely spread around the perimeter of the entire lake where plants are not likely to establish in the short window of time due to the low propagule bank. The grass carp population, however, is compromised and unlikely to persist beyond approximately 2016. In the absence of grass carp, plant establishment could conceivably be influenced by changes in water level. That is, recreational water levels could inundate shorelines at a time when they might otherwise be open to plant propagules that require saturated, but not inundated, sediment. The period of recreational water level also corresponds to increasing day length which is important in plant establishment and growth, particularly seed germination and flowering.

Yellow flag iris, which is widespread around Devils Lake, may be reducing some erosional effects and can withstand prolonged periods of exposure and inundation. Unfortunately, yellow flag iris is an undesirable non-native species that spreads aggressively by seeds and rhizomes, and thus it is likely
it would be pervasive under any operational scenario. It is particularly adapted to wide ranges in inundation, sediment types, and soil oxygen levels and can grow as an emergent in nearly 2 feet of water or survive up to 3 months under dry conditions (Sutherland 1990). It can tolerate thin organic, dry sandy or even peaty soils (Sutherlin 1990, Thomas 1980). Additionally, yellow flag iris is an ecosystem engineer, meaning it changes its own habitat as the rhizomes grow and mat together – eliminating suitable habitat for other plant species.

Secondary to direct consumption of aquatic plants by grass carp is the erosive energy of waves that physically undermines the highly erodible soils in which plants can become established. Specific strategies for establishing conditions that will support native vegetation vary by parcel and an understanding of site-specific attributes is needed. Example approaches include “soft” structures, described below, but must consider wave energy, bottom approach/bathymetry, available space to set back/decrease the slope.

**Wave Energy**

The primary focus of the wave energy occurs in a zone near the still-water level (water level that would occur in the absence of the waves); the vertical distance over which significant erosional energy occurs depending on the bank slope, surface roughness, and the wave height. As previously mentioned, changes in lake level certainly contribute to changes in surface area (e.g. fetch) and the point of contact at the still water level. In general; however, areas around the shoreline where the depth is greater than about 1.25 times the wave height (e.g., along vertical retaining walls or areas where the bank is steep and composed of erosion-resistant material), the wave energy is transmitted directly into the structure where the energy is sent downward toward the base of the wall, potentially crumbling into the lake (Schiereck 2001). Further, as these vertical bulkheads erode, overland flow builds behind the structure to exert additional strain, particularly during freeze-thaw cycles. In shallow areas where the depth is less than about 1.25 times the wave height, the waves break, causing significant turbulence that can entrain sediment that would not otherwise be mobile. In relatively deeper areas outside the influence of the breaking waves, the orbital velocity of the wave can cause a significant increase in the local bed shear stress that can also entrain sediment that would not otherwise be mobile. In short, as a waves approach the shoreline, differences in lake bathymetry, in combination with the steepness of the bank (e.g., steep concrete, gradual vegetation, broad riprap), have differential effects on dissipation of wave energy along the shoreline.

Though not specifically evaluated in this analysis, operating the lake under full exercise of recreational water right (9.53 feet MSL) could theoretically increase the probability of waves overtopping existing shoreline stabilization structures. Overtime, this could cause erosion on the
landward side of existing structures. Conversely, operating the lake at a substantially lower level could cause erosion beneath some of the existing armoring, and could also expose erodible soils that are saturated during the winter to more erosion.

Because of the variability of the lake bottom topography in the near-shore region, the characteristics of both the armored and non-armored shoreline, and the variability in shoreline alignment with respect to the typical wave directions, more specific conclusions regarding the effects lake levels and waves on shoreline erosion cannot be made without a site-specific evaluation. The information presented here, however, identifies the locations around the lake where the erosional stresses are highest, provides information on the relative effects of boat- and wind-driven waves, and identifies the key factors that will affect erosion. This information, thus, provides a starting point for the site specific analyses.

In considering options to prevent erosion along the shoreline, the strength of the waves is a key factor. Based on the measured wake boat wave data from Glamore (2008), the waves impacting the shoreline in areas where the depth approaching the shoreline is sufficient to prevent breaking will have heights ranging from about 0.5 feet when a wakeboard boat passes at the edge of the assumed operating zone (i.e., ~100 feet from the shoreline), decreasing to about 0.3 feet at 600 feet and to about 0.2 feet at about 1,200 feet. If the boat in the above example is throwing off a 2-foot wave at the 70-foot measurement point, the wave heights impacting the shoreline would be about 1.2 feet, decreasing to about 0.7 for a boat 600 feet away and to about 0.5 feet for a boat 1,200 feet away.

As discussed above, the height (and strength) of wind-driven waves is a function of the wind speed and fetch, and the wave energy that actually impacts the shoreline is also a function of the near-shore depth. Due to the highly variable fetch around the lake and the variability of the wind direction, it is necessary to consider the characteristics at each individual location of concern to understand the wind wave climate and to provide quantitative information with which to select appropriate protection measures. Four locations where wind waves appear to exert significant energy on the shoreline were selected to illustrate this point (see Figure 12). At Location 1, about two-thirds of the annual wind wave energy occurs during the winter, non-recreation season due to winds blowing from the SSW. About half of the total wave energy is caused by winds in the 21 mph to 47 mph range (approximately equally distributed between each of the three Beaufort scale categories covered by this range). At this location in the lake, the waves associated with these wind speeds range from 0.8 feet to 1.5 feet in height. At Location 2, where the annual wave energy is less than half that at Location 1, the winds responsible for the most energy are in the same range of speeds and also
originates from the SSW during the winter, non-recreation season, accounting for about 30% of the total wind wave energy at this location. Because the fetch is significantly shorter at Location 2 than at Location 1, the wave heights are somewhat less, ranging from 0.5 feet to 0.9 feet. Locations 3 and 4 are also subject to high wind wave energy, but most of this energy occurs during the summer recreation season due to winds from the N and NNW. The range of wind speeds that are responsible for the most wave energy at these locations are in the range of 11 mph to 21 mph, considerably lower than at Locations 1 and 2. The wave heights at Location 3 for this range of wind speeds ranges from 0.3 feet to 0.4 feet, and they are even lower at Location 4, ranging from 0.2 feet to 0.3 feet, due to the shorter fetch for winds from this direction.

Because water depth affects the amount of wave energy that actually reaches the shoreline, the lake level can significantly affect the amount of energy available to drive the erosion process. The most significant energy dissipation occurs when the waves break; coinciding with water depth less than about 1.25 times the wave height. For the range of predicted wave heights, this means that the full energy of the waves will impact the shoreline when the nearshore depths are greater than a few feet. As a result, holding the lake at a higher level during periods of high natural or boat-induced wave activity will increase the tendency for erosion.

Based on the above information, aggressive efforts to dissipate wave energy before it reaches the shoreline is probably necessary to prevent shoreline erosion at locations similar to Locations 1 and 2, but softer, bio-engineering treatments may be effective at locations similar to Locations 3 and 4. It is important to understand; however, that design of appropriate treatments at any specific area requires a site specific evaluation of the local wind- and boat-wave climate and the characteristics of the shoreline at that location, including the soil type, shoreline slope perpendicular to the shoreline, and the bathymetry in the near-shore region. The data compiled for this study provides the initial basis for quantifying the wind-wave climate and the approximate contribution of boat wave to the overall wave energy approaching the shoreline around the lake.

**Regulations and Permits**

Oregon's Removal-Fill Law (ORS 196.795-990) requires any person who plans to "remove or fill" material within "waters of the state" to obtain a permit from the Oregon Department of State Lands (DSL). Removal means taking rock, gravel, sand, silt and other inorganic substances from the bed or banks of a waterway, or their movement by artificial means within the bed or banks, including channel relocation. Fill means the deposit by artificial means of any material (organic or inorganic) at any one location in the bed or banks. Waters of the state include wetlands on private and public land.
Two types of permits may be submitted to DSL for removal-fill projects related to shoreline stabilization. An Individual Permit (IP) is issued for projects that 1) have more than minimal adverse effects on waterways and wetlands, 2) are more complicated and often involve more than one removal-fill activity, 3) may involve substantial mitigation obligation, and 4) do not qualify for any of the General Authorizations or General Permits. Oregon Department of Fish and Wildlife (ODFW) reviews all individual permits submitted to DSL. Conversely, General Authorizations (GAs) are an expedited process for specific types of removal-fill activities that have minimal adverse effects on wetlands and waterways, including, but not limited to, certain minimal disturbance activities within essential fish habitat (ESH) and waterway bank stabilization. In addition to permit(s) required by DSL, the U.S. Army Corps of Engineers (USACE) will likely also require a permit. Currently DSL and the USACE use the same joint application; however, separate permits are issued. Additional permits could also be required by the National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (USFWS). Detailed information the DSL's removal-fill guidance is provided at http://oregonstatelands.us/DSL/PERMITS/rfg.shtml.

**Approaches to Shoreline Stabilization**

There are a variety of armored structures (e.g. cement retaining walls, rock riprap) currently used around Devils Lake to stabilize the shoreline; however, recent DSL - approved permits have been limited to “soft” structure approaches. Examples of “soft” structures include large wood, engineered logs with root wads, vegetated buffers, bioengineered slopes, and log toe placements. The use of soft structures is highly encouraged by ODFW as a more natural approach to stabilizing shorelines while maintaining and/or improving habitat.

ESH is the habitat necessary to prevent the depletion of native anadromous salmon species during their life history stages of spawning and rearing. The designation applies only to those species that have been listed as Sensitive, Threatened, or Endangered by a state or federal authority. Devils Lake is considered ESH due to its use by federally threatened Coho salmon (*Oncorhynchus kisutch*) for rearing and survival. Any amount of removal-fill in ESH requires a permit, except for prospecting and other non-motorized activities and activities customarily associated with agriculture.

As previously mentioned, ODFW reviews all individual permits submitted to DSL. In fact, ODFW encourages site meetings prior to initiating the permit process to discuss design plans and evaluate habitat benefits provided by those plans. ODFW recognizes that while some degree of hard structures may be necessary, the use of soft structures is highly preferential. Specific examples include 1) the use of 18 to 22 inch logs with in-tact root wads to provide increased structure and habitat, 2) planting native vegetation as a means of increasing bank stabilization, or 3) providing...
appropriate slope set-backs on steep banks. A list of native plants appropriate for use at Devils Lake is available from the District in the *Shoreline Planting Guide: Devils Lake* (Tetra Tech 2010). As a follow-up to site visits with ODFW, DSL encourages pre-design permit scoping to identify all necessary permit and requirements in order to avoid project delays.

**Recommendations and Considerations**

Tools developed from this effort may be used by the District in evaluating a wide variety of projects for future planning efforts and in assessing potential natural and anthropogenic impacts on shoreline erosion under various water level regimes. Some examples may include:

- Identifying areas at high risk for erosion,
- Identifying factors that contribute to erosion,
- Assessing the function of bioengineered structures,
- Evaluating the success of invasive plant species control measures,
- Assessing the feasibility of restoration efforts, and
- Documenting changes in shoreline and watershed condition.

Based on data from 1998 to 2011, the average lake level is typically only a few tenths of feet different between the recreation and non-recreation periods. Almost 10% of the time, however, lake levels were above the OHW due to the effects of the winter storms (Figure 17). This period also coincides with periods of strong winds and increased precipitation, strongly suggesting that winter conditions set up the greatest potential for erosion.

Assessing shoreline conditions and recommending erosion control measures requires a detailed understanding of the site including the specific near-shore bathymetry of the lake. This includes the alignment of the shoreline with respect to the predominant wind direction and angle of impact of the boat waves, and the topography, soils, vegetation, and presence of man-made structures at and above the shoreline that synergistically determine its current and erosion potential. That is, due to the variability in all of the factors that affect wave energy impacting the shoreline, local quantification of this process can only be done through site specific analyses. Where new construction of shoreline stabilizations are needed, it is recommended that lakefront property owners consider these factors and conduct preliminary design discussions with ODFW and DSL to expedite the permit process and create an opportunity to explore the most appropriate solutions. Projects should also consider reducing overland flow of water that can undermine existing shoreline stabilization features.
An active shoreline restoration program that involves removal of invasive plant species followed by planting of native species that can withstand both natural and/or operational changes in fluctuation may prove most beneficial in protecting shorelines. In the absence of operational controls, there would still be natural fluctuations in water level at Devils Lake; however, current operations seasonally shift the lake inundation regime (Figure 18). Without further investigation, it is purely speculative whether overall changes in water level, or the seasonal shift due to operations, play a greater role in favoring the establishment of yellow flag iris. Under either water control regime, however, it is likely that herbaceous species such as sedges, bulrush, and cattails more likely to become established compared to woody native species.

Operational options available to the District that would lessen shoreline erosion are limited as controls only range 18 inches, which includes a non-impoundment level of 8.03 feet MSL at the base of the concrete sill. During the summer, when the lake elevation is artificially maintained, strong summer northwesterly winds exert greater pressure on the east and southeast portion of the lake (e.g., zones 3 and 4 in Figure 12). Observed in these areas was relatively increased erosion, however, comparatively less bank stabilization measures were also observed compared to other areas around the lake. Conversely, during the winter when the lake is allowed to naturally fluctuate, strong storm-driven southerly and southwesterly winds coupled with increased rainfall and long fetch contribute substantially to the erosive energy along the north and western portions of the lake (e.g., zones 1 and 2 in Figure 12). Observed in these areas was relatively reduced erosion, however, comparatively greater bank stabilization measures compared to other areas around the lake. In areas that are more sheltered from the wind (e.g., Figure 15, west side of NW arm), boat-driven waves are estimated as the most significant source of erosive energy during the summer.

References


