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ASSESSING THE IMPACT OF FLOOD INUNDATION IN THE DEVILS LAKE AREA: A REMOTE SENSING APPROACH

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ABSTRACT: *Devils Lake is a naturally occurring, closed water body located in northeastern North Dakota. Since the early 1990's, it has experienced a rise in surface elevation of over 8 meters (m). The result of this change in water elevation has been the destruction of hundreds of homes, thousands of acres of farmland, and over 450 million dollars in expenses incurred to relocate roads, bridges, power-lines, and levees. While recently the rise in water has appeared to have stabilized, there is no guarantee that the water will not continue to rise in the near future. The purpose of this study is to use a combination of remote sensing and geographic information system techniques to determine the type of land cover that has been affected by the rise in elevation of Devils Lake and to project what land will be damaged in the future should Devils Lake continue to rise until it reaches its natural spill elevation of 444.7 m.*

Keywords: *Remote sensing, Land cover change, Supervised classification, Tasseled cap, Principal components*

INTRODUCTION

Devils Lake is located in the Devils Lake Basin, a 9,870 square-kilometer (km^2) sub-basin of the North Basin. As a closed drainage basin, Devils Lake has no outlet to the ocean; the only water that leaves it is in the form of evaporation (Ryan and Wiche, 1988). When Devils Lake reaches a height of 440.89 m above mean sea level (ASL) it begins to spill into Stump Lake, and if the water continues to rise to 444.70 m both Devils Lake and Stump Lake begin to overflow into the Sheyenne River (Wiche et al., 2000). While there have been reports on the extent of the flooding that has occurred, and the monetary cost associated with rebuilding, there has not been a study detailing precisely what type of land has been affected. Further, it is pertinent that an analysis be performed in regards to assessing the type and amount of land that will be affected should Devils Lake reach its peak elevation of 444.70 m. It is the objective of this study to assess, quantitatively, the spatial extent of current and future flooding for the Devils Lake area and to address, specifically, what land cover types will be affected.

Figure 1. Devils Lake, Stumpe Lake, and the Sheyenne River. Devils Lake water elevation of 441.4 meters. (Image: Landsat ETM+ Date: 04/15/05).

History

Geologists from the North Dakota State Geological Survey (NDSGS) have been able to use radiocarbon techniques to date samples of sediments that they collected along the beaches of Devils Lake (Murphy et al., 1997). As a result, they were able to determine that sometime in the past 1,800 years Devils Lake has spilled into the Sheyenne River. Furthermore, they have concluded that Devils Lake has overflowed at least twice, if not more, into the Sheyenne River in the last 4,000 years. An accurate count of the number of times Devils Lake has overflowed has not been possible due to the erosive action of the water on the dating material as it rises. North Dakota State Geologist John Bluemle has stated that the natural state for Devils Lake is one of rising and falling. This is verified by measurements taken in the past century (Bluemle, 1991).

While there are no records of water elevation for Devils Lake prior to 1867, research has been able to verify that water flowed from Devils Lake into Stump Lake sometime in the years between 1820 and 1840 (Wiche et al., 2000). When Stump Lake was originally surveyed in 1881, the surface elevation of Stump Lake ranged between 432.82 and 434.34 m ASL. This is higher than the water level of Stump Lake in August of 2000 (429.65 m ASL) – when Devils Lake had already begun to flow into Stump Lake. Since Stump Lake has a very small drainage area, it is reasonable to conclude that a significant amount of water flowed into Stump Lake prior to 1881 (Wiche et al., 2000).

Since the early 1940's, the waters of Devils Lake have been on a rising trend (Wiche et al., 2000). By the early 1980's, Devils Lake had risen to an elevation of 434.34 m ASL, causing an increased interest in the funding of federal and state projects to construct levees in order to protect the town of Devils Lake. The goal of these levees was to retain the waters of Devils Lake up to a height of 438.91 m ASL. This did not prove to be high enough, as an unusually high amount of precipitation from the summer of 1993 to the fall of 1999 caused the waters to rise to a height of 441.06 m ASL (Wiche et al., 2000). The consequence of this precipitation was more than 283 km^2 of flooded land. Since then, state and federal highways have been raised while other roads have been made impassable (Wiche et al., 2000). As of January 31, 2008, the current water level of Devils Lake is 440.97 m ASL (USGS, 2008).

The North Dakota State Water Commission and the U.S. Army Corps of Engineers have created several plans to combat the flooding in the Devils Lake area. These plans involve providing an emergency drain outlet to the Sheyenne River through the West Bay of Devils Lake, management and storage of water in the Devils Lake Basin, and a continuation of infrastructure protection to include building more levees and raising roads (Wiche et al., 2000). Without the ability to accurately predict the future rise in the waters of Devils Lake, these solutions become temporary at best.

Climatology

The extreme fluctuations in the surface elevation of Devils Lake are attributed to climatic variability, specifically changes in movement of the jet stream (Wiche et al., 2000). This high-velocity tunnel of air is located 9.1 km above the Earth's surface. Devils Lake is extremely susceptible to long-term shifts in this jet stream current, due to the fact that the lake level is influenced by many years of previous evaporation, precipitation, and runoff (Wiche et al., 2000).

Thrust into the American public's consciousness in the last ten years are the phenomena known as El Niño and La Niña. These occurrences mark a deviation in sea surface temperature, which then alters the amount of precipitation across South and North America. These changes in circulation patterns have a direct influence on the jet stream, thereby affecting the amount of precipitation incident upon Devils Lake (Montoy, 1997).

El Niño and La Niña did not have a significant effect on the Devils Lake area until recently. Starting in the late 1970's, El Niño activity began to increase, bringing increased amounts of moisture from the Gulf of Mexico. In addition, the position of the jet stream has caused early spring-like temperatures, resulting in a somewhat shorter winter. This is contrasted with a lower overall average annual temperature due to increased cloud cover and precipitation. An increase in precipitation amounts during May, June, and the early fall have contributed to the onset of the most recent rise in lake water elevation (Wiche et al., 2000).

Hydrology

The Devils Lake Basin is located in the Red River Basin of the North Basin. It is bordered by the Lower Red Basin to the north and east, the Upper Red and Sheyenne Basins to the south and southeast, and the Souris Basin to the west. Approximately 8,600 km^2 of the 9,870 km^2 basin is tributary to Devils Lake, the rest of which flows into Stump Lake. Seven interconnected lakes are tributary to Devils Lake: Sweetwater Lake, Morrison Lake, Mikes Lake, Dry Lake, Chain Lake, Lake Alice, and Lake Irvine. Devils Lake's eastern, western, and northern boundaries serve as marginal drainage divides. The southern edge of Devils Lake consists of several recessional moraines and, in fact, most of the topography in the area is due to glacial activity in the past. Stump Lake serves as the only natural outlet for Devils Lake (Wiche, 1986).

In addition to Devils Lake itself, the Devils Lake Basin contains numerous smaller lakes known as prairie potholes. These indentations are often times connected by intermittent channels. When runoff enters these prairie potholes, their water level begins to raise until this water in turn experiences runoff, traveling further down the basin. Often times, the water elevation in these potholes is not enough to overcome the necessary elevation for runoff to occur, in which case the water is stored (Ryan, 1988).

The bays that make up Devils Lake are semi-isolated during times of low surface elevation. The concentration of dissolved solids increases, for the most part, from west to east along these bays. This is due to water entering the western side of the lake and slowly becoming more concentrated, due to evaporation, while the water moves east. Between 1988 and 1989, the average concentration on the western side of the lake was approximately 3,400 mg/L compared to 10,000 mg/L for the eastern side. Due to increased precipitation and runoff experienced after 1993, the concentration of dissolved solids in 1999 was 1,140 mg/L for the western shore and 1,350 mg/L in Main Bay (North Dakota Department of Health, 2001).

Recent Flooding

In the summer of 1993, above average precipitation caused extreme flooding in nine mid-western states, including North Dakota. Between June 10th and September 28th, Devils Lake experienced an increase in surface elevation of 1.2 m. This change in surface elevation resulted in a 370,050,000 m^3 increase in water volume. Past summer floods had resulted in an increase of only 37,050,000 m^3 in water volume (Williams-Sether, 1996). During the spring of 1997, Devils Lake experienced another damaging flood. Between mid-April and early-June, lake water levels increased another 1.2 m. This further damaged the region and suggested that the flood of 1993 was not an isolated incident. These summer floods, while severe, were not isolated incidents. The waters of Devils Lake continued to rise during the rest of the year resulting in a total water elevation increase of 8 m from 1993 to 2003. This 8 m increase in water level has created a very real problem for the state of North Dakota. The lake's surface area has increased by more than 360 km^2 and the total volume has increased by 2.5 km^3. The damage from this increase in water has affected homes, highways, and cropland at an estimated cost of more than $400 million (Vecchia, 2002).

METHODS

A remote sensing approach was chosen to determine the damage caused by the rising waters in the area of Devils Lake. Remote sensing is generally defined as a way to capture information about phenomena without actually coming into physical contact with it (Lo, 1986). Remote sensing also allows the user to process large amounts of data over large pieces of land in a repeatable and consistent way. Due to the large area of interest in this study, a semi-automated process was used.

Data

Landsat images were obtained for the years 1989, 1991, and 1992. A comparison to water levels of those years reveals water elevations heights of 434.49, 433.80, and 433.70 m respectively. Given this information, the image from 1992 would have been the preferable choice. A visual inspection of the image revealed prominent cloud cover, so the 1991 image was chosen instead for the pre-flood analysis. This allows for an accurate portrayal of the water's spatial extent prior to the later flooding. The acquisition date for this image was August 31, 1991.

It was desirable to get the most current imagery available for the post-flood analysis. The second major flood of the Devils Lake occurred in 1997, but waters have been continuously rising since then, albeit at a more relaxed pace. Originally a Landsat ETM+ image from 2005 was obtained from the NDSGS. However, it proved to have unacceptable levels of registration error and every effort to geometrically correct this image to the 1991 image resulted in a degradation of registration accuracy for both images. Instead, an image taken in 2000 was used. This was sufficient for addressing the effects of the flooding that occurred in 1997. The differences in water elevations for the 2000 and 2005 images is 0.54 m, which is significant, but greater registration accuracy between the pre- and post-flood images was deemed more important than the disparity in water levels. When trying to determine changes in land cover for an area, proper registration of data becomes critical. It has been shown that in order to maintain an error level of less than 10% when performing change detection on images, the registration error between the two images must be no more than 0.20 pixels (Townsend, 1992). In the case of Landsat imagery, these 0.20 pixels of error correspond to 6 m of distance on the ground. The acquisition date for the second image was July 30, 2000.

In order to predict what land may be affected by rising flood waters in the future, elevation data was used. The first dataset considered was a Light Detection and Ranging (LiDAR) image obtained from the NDSGS for the Devils Lake area. Upon closer inspection there were several discrepancies including a ‘striping effect’ that is sometimes present in LiDAR data, which eliminated some of the area with which this study was concerned. Instead of the LiDAR data, a digital elevation model was obtained.

Several other datasets were indirectly used in an effort to aid in the classification of land cover. These include Digital Ortho Quadrangle images from various dates, the National Agriculture Imagery Program datasets from 2005 and 2006, and the United States Department of Agriculture’s National Agriculture Statistics Service land cover datasets from 1997 to 2006.

Methods

Prakash et al. (2006) outlined a procedure for drought assessment that involved performing several spectral enhancement techniques in order to assess drought impact. Their main concern was with the detection of water, or lack thereof, and crop loss assessment. Since this study is concerned with water and crop detection, this was considered to be a logical technique to use. Specifically, the technique involves performing a tasseled cap transformation, principal components analysis (PCA), and normalized difference vegetation index (NDVI) on the image in question. Then the appropriate layers from these three separate transformations are stacked together to produce a final multi-band image consisting of all the information of the different transformations (Prakash et al., 2006).

NDVI can be thought of as measuring the health, or stress, of vegetation. An inherent characteristic in healthy plants is an increased reflectance in the near-infrared portion of the spectrum. NDVI uses a ratio of near-infrared reflectance with that of visible red reflectance. This ratio can be expressed mathematically as,

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

where NIR is near infrared red reflectance and RED is visible red reflectance. The result of this calculation is a value between -1.0 and 1.0, with higher plant productivity corresponding to higher positive values (Tucker, 1979; Singh, 1989).

PCA can be used in remote sensing to reduce data size, enhance the image, detect change, and to assess “underlying multi-temporal dimensionality of data sets” (Singh, 1989). It is a linear transformation that uses statistics about the data to rotate the axes of the image so that the new axes are perpendicular to one another and are pointed to the direction of decreasing variance. This has the effect of producing as many individual components as there are image bands, with the added benefit of absolutely no correlation between them (Singh, 1989). In basic terms, PCA reduces the number of image bands to work with, mostly eliminating noise and unnecessary data. The first principal component contains most of the information of the original image bands with each further principal component containing less and less information until the last few bands, which contain mostly atmospheric noise (Jensen, 2005). To perform a PCA, first the covariance matrix must be calculated using the desired input image. Next the eigenvalues and eigenvectors are calculated, leading to the calculations of the actual principal components (Singh, 1989).

The final image transformation to be performed was that of the tasseled cap. The tasseled cap transformation is similar to the PCA transformation in the fact that it reduces redundancy in the data layers by compressing the majority of information into the first few bands. In fact, 95 to 98% of the information contained in the six bands of Landsat imagery is contained in the first two tasseled cap bands. The tasseled cap transformation obtains its name from the fact that when the brightness and greenness bands are plotted on a Cartesian axis, the resulting data points resemble that of a cap (Jensen, 2005). The tasseled cap transformation, like PCA, changes the vectors of the original Landsat data so that they are oriented in orthogonal planes of Brightness (B), Greeness (G), and Wetness (W) (Crist, 1984). The B band is representative of the brightness, or albedo, of all six spectral bands. The G band is best compared to vegetation indices, as it is a comparison between the visible blue, green, and red bands with the near-infrared band. The W band is a comparison between the bands representative of visible light, near-infrared, and mid-infrared. As such, it can be viewed as representative of vegetation and soil moisture. A significant difference in the tasseled cap transformation, compared to PCA, is that the tasseled cap method uses fixed coefficients that can be independently applied to different images (Seto, 2002).

After these three transformations were performed, it was necessary to combine them into one master image as outlined in Prakash's drought assessment. The tasseled cap bands of B, G, and W were assigned to bands 1, 2, and 3. The principal components bands 1, 2, and 3 were assigned to bands 4, 5, and 6. Lastly, the NDVI image was assigned to band 7. The additional three bands for the tasseled cap and principal component images were discarded. As previously mentioned, these bands are mostly representative of atmospheric noise and do not add significantly to the classification process.

A supervised classification technique was decided upon to produce the 1991 land cover map. The classes were based on the United States Geological Surveys' National Land Cover Data (NLCD) 2001 classification system and included: open water, developed (open space), developed (low intensity), developed (medium intensity), developed (high intensity), deciduous forest, grassland/herbaceous, pasture/hay, cultivated crop, and emergent herbaceous. One hundred training sites were selected – ten for each class. Training sites were selected based on visual interpretation from aerial photos, a NLCD 1992 dataset, and the image itself. After the training sites were processed, the preliminary output map was examined for accuracy. Final pixel counts were obtained for each land cover type in order to determine land cover area for the entire map (Figure 2). The purpose of this study was to assess the impact of rising water elevation in the Devils Lake area, so a land cover classification of the post-flood image was deemed unnecessary. What was needed was an analysis of the spatial extent of the flood waters. A similar method was used to classify the image from 2000, with the difference being that the there need be only two classes: land and water.

To assess the future impact of the rising lake elevation on land cover, it was necessary to use elevation data. First, there was a concern about accounting for the different elevation heights of water in Devils Lake compared to Stump Lake. However, it was found that Stump Lake is quickly approaching the water level height of Devils Lake and that by the summer of 2007 the difference in water elevation between the two lakes could be within 15 cm of each other (Connelly, 2007). With this in mind, the elevation between the two lakes in the near future is negligible and not a factor after the water elevation has increased another 3.5 m. The elevation dataset was classified into two categories, elevations below 444.7 m and above 444.7 m and a simple two-bit map was created. When projecting the spatial extent of the rising flood waters, it was assumed that existing levees and roads would be raised accordingly to avoid damage to the town of Devils Lake and to maintain existing transportation corridors (Figure 3).

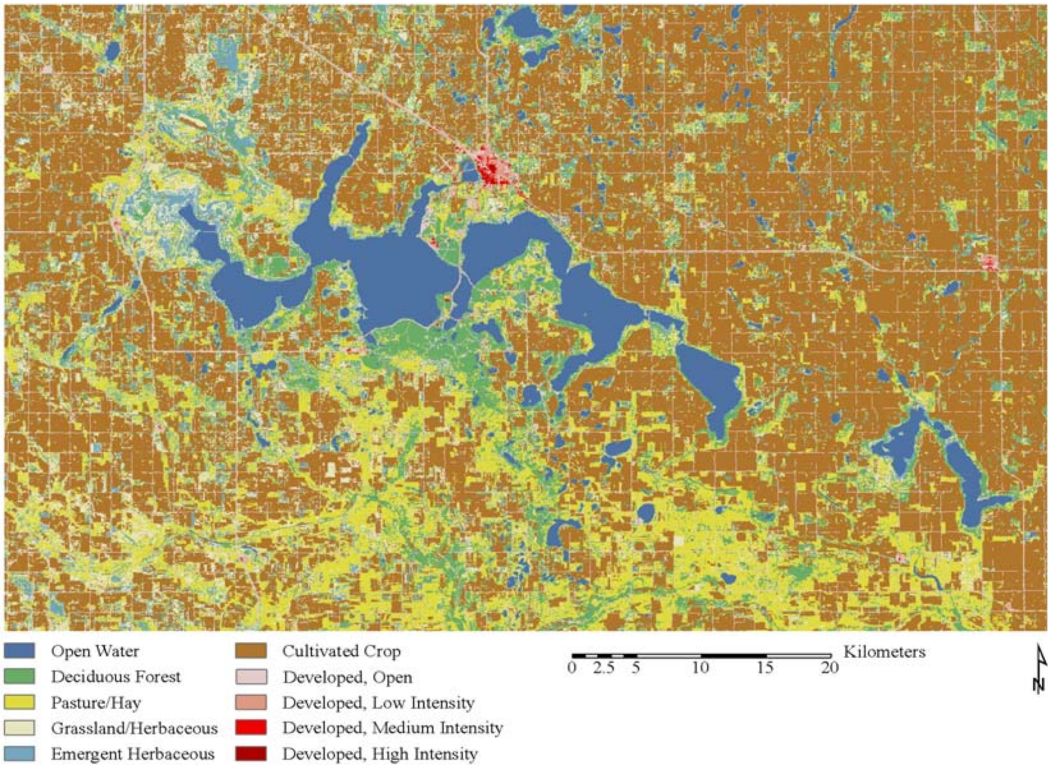


Figure 2. Land cover class map created from 1991 Landsat TM Image.

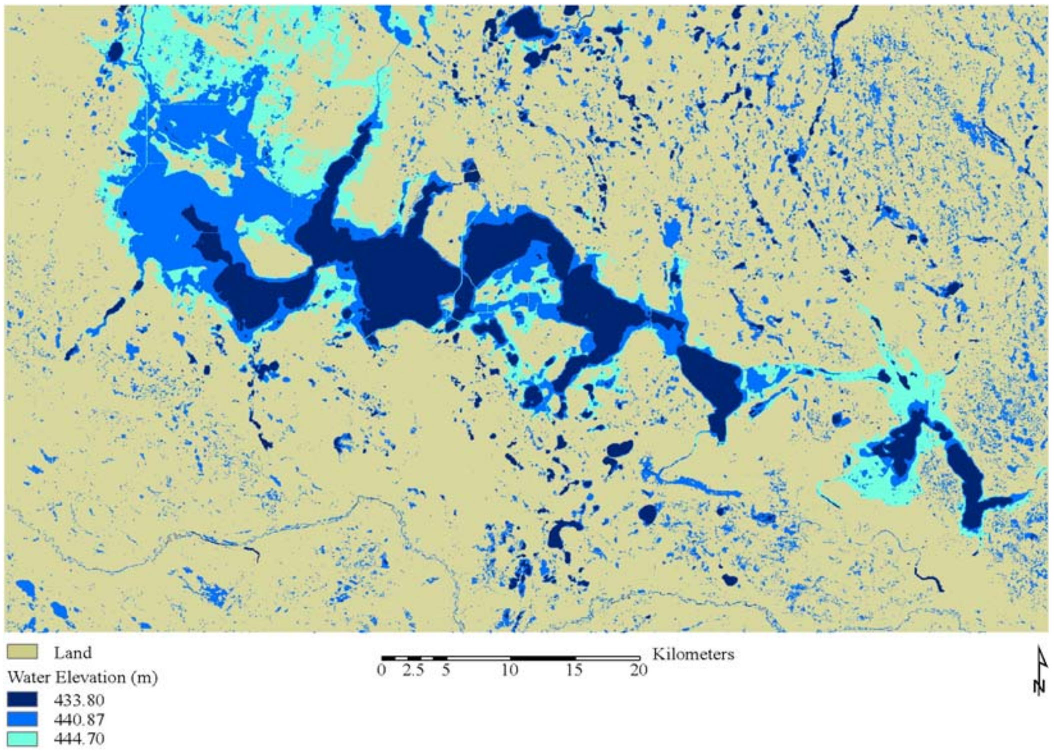


Figure 3. Spatial extent of open water for the three elevations examined in this study.

RESULTS

(1) The impact of flooding between the years of 1991 and 2000 resulted in not only an increase of surface area of Devils Lake of 301.69 km^2, but an increase of total water surface area of 597.88 km^2 (assuming a flat groundwater table) for the entire area that was analyzed.

(2) The two land cover types most affected by flooding in the 1990's were cultivated crops and deciduous forests. Cultivated crops experienced a loss of 126.95 km^2 (6% of total) to flooding and 103.74 km^2 (28% of total) of deciduous forests were affected.

(3) When Devils Lake has reached its spill elevation of 444.70 m it will have expanded by another 292.62 km^2.

(4) Cultivated crops and deciduous forests will also potentially be the most affected land cover types should Devils Lake reach its spill elevation. A further 115.05 km^2 of cultivated crops and 33.82 km^2 of deciduous forests will potentially be flooded.

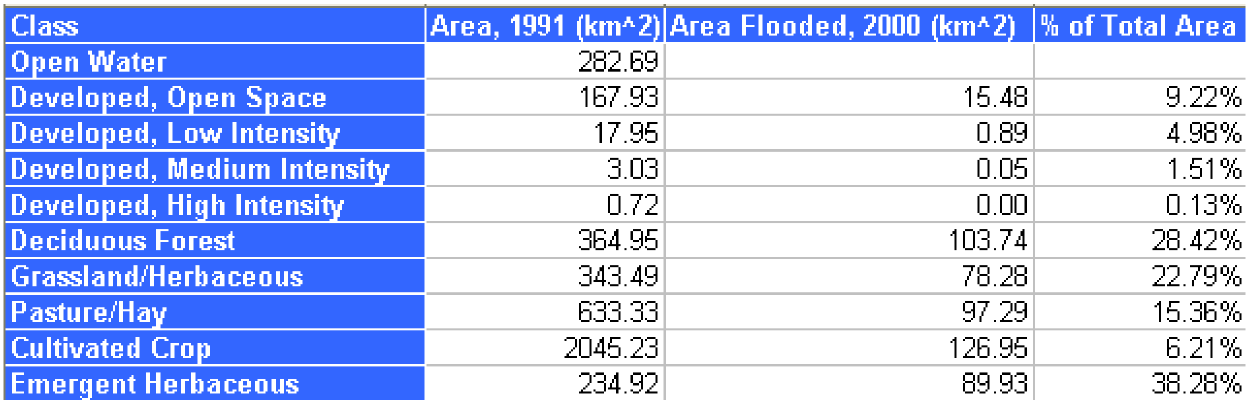
Changes in Water Surface Area, 1991 to 2000

Total water surface area increased from 282.69 km^2 in 1991 to 880.57 km^2 in 2000. Upon closer examination, it was found that the combined increase in Devils Lake and Stump Lake's surface area was 222.33 km^2 for this time period. This indicates that the remaining increase in surface water area, 375.55 km^2, can be attributed to lakes and prairie potholes. In many ways, the increase in surface area of these lakes and prairie potholes can be seen as more damaging to cropland as these water level increases occur somewhat randomly across the landscape, as opposed to increasing water levels around the lake which only affect adjacent land cover.

Land Cover Affected by Flooding, 1991 to 2000

Of all the land cover types affected by flooding, the developed set of classes suffered the least. Deciduous forests experienced extreme inundation with 103.74 km^2 being affected. A significant portion of the forested areas around Devils Lake are clustered around the shoreline of the lake itself, and the expanding shoreline accounts for a majority of the land damaged. The grassland/herbaceous land cover class is relatively dispersed among the Devils Lake area. Flood waters inundated 78.28 km^2 of this land cover type, mainly due to the increased area of the Devils Lake shoreline. The pasture/hay and emergent herbaceous

Table 1. Land Cover Classes Affected by Flooding in the 1990's



Class	Area, 1991 (km^2)	Area Flooded, 2000 (km^2)	% of Total Area
Open Water	282.69		
Developed, Open Space	167.93	15.48	9.22%
Developed, Low Intensity	17.95	0.89	4.98%
Developed, Medium Intensity	3.03	0.05	1.51%
Developed, High Intensity	0.72	0.00	0.13%
Deciduous Forest	364.95	103.74	28.42%
Grassland/Herbaceous	343.49	78.28	22.79%
Pasture/Hay	633.33	97.29	15.36%
Cultivated Crop	2045.23	126.95	6.21%
Emergent Herbaceous	234.92	89.93	38.28%

land cover types were hit equally hard by flooding. The pasture/hay class had 97.29 km^2 flooded, while emergent/herbaceous land lost 89.93 km^2 due to inundation. Cultivated crops were most devastated during this time period with 126.95 km^2 subjected to flooding. This is not surprising, as cropland is the most prominent land cover type in the Devils Lake area. Damage to cropland is almost exclusively due to the increase in surface area of the prairie potholes since most of the planted crops are relatively far away from the shorelines of Devils Lake and Stump Lake.

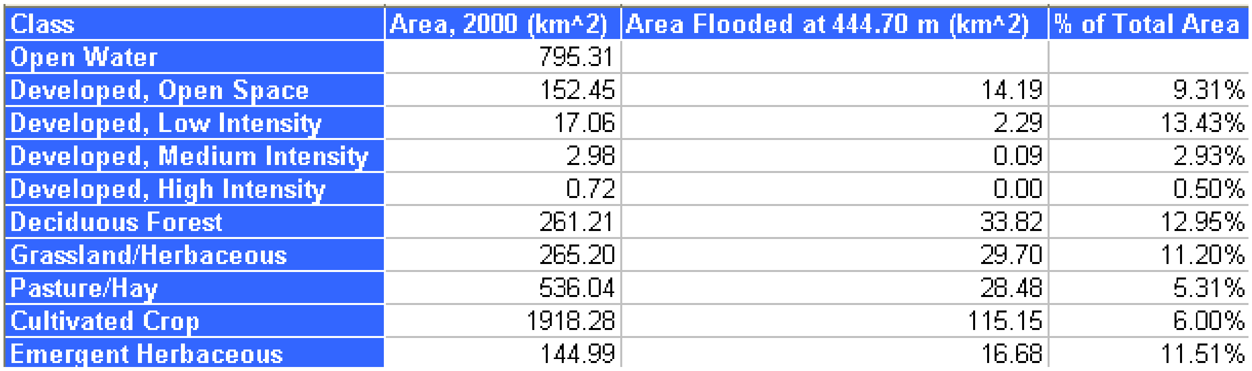
Changes in Water Surface Area, 440.87 m to 444.70 m

While the change in water surface area in this analysis is not as drastic as it would be if extraneous water bodies could be included in the calculation, Devils Lake and Stump Lake nevertheless impact a large amount of land before they spill into the Sheyenne River. With a rise in elevation from 440.87 m to 444.70 m, the two lakes increase in surface area by another 292.46 km^2. In some locations, such as Stump Lake, this has the effect of increasing the shoreline by 1.5 km from its location in 2000.

Land Cover Affected by Flooding, 440.87 m to 444.70 m

The amount of land affected by a future flood is similar to the amount affected in the flooding experienced during the 1990's – if inundation due to other lakes and prairie potholes is not included. As in earlier floods, developed land cover types are the least affected by the flooding. Deciduous forests fared better this time with only 33.82 km^2 being affected, while pasture/hay areas also experienced a decrease in damaged land with 28.48 km^2 caught in flooding. Grassland/herbaceous lost 29.70 km^2 to flood damage and emergent herbaceous saw 16.68 km^2 affected. Cultivated crops were again the most damaged land cover type with 115.15 km^2 being subject to flooding. Undoubtedly, should other open water bodies be included in these calculations, cultivated crops would be considerably more affected. In this regard, these estimates should be considered extremely conservative, as the prairie potholes and separated lakes accounted for

Table 2. Land Cover Classes Affected by Flooding at a Water Elevation of 444.70 m



Class	Area, 2000 (km^2)	Area Flooded at 444.70 m (km^2)	% of Total Area
Open Water	795.31		
Developed, Open Space	152.45	14.19	9.31%
Developed, Low Intensity	17.06	2.29	13.43%
Developed, Medium Intensity	2.98	0.09	2.93%
Developed, High Intensity	0.72	0.00	0.50%
Deciduous Forest	261.21	33.82	12.95%
Grassland/Herbaceous	265.20	29.70	11.20%
Pasture/Hay	536.04	28.48	5.31%
Cultivated Crop	1918.28	115.15	6.00%
Emergent Herbaceous	144.99	16.68	11.51%

63% of the flood damage area in the 1990's. It could be assumed that these water bodies would play a similar role in future flood events. If the past magnitude of their effect is any indication, the amount of area damaged by flood waters could easily be doubled once these other water bodies are taken into account.

CONCLUSIONS

The area of Devils Lake is one that has experienced a great deal of change, and if trends continue, it is likely that a great deal more is in store. While mainly rural, the change in climate patterns has a significant effect on the local economy due to the large amount of land devoted to agriculture. With 6% of cropland underwater as a result of the flooding in the 1990's and at least 6% more (more liberal estimations would put it at greater than 12%) likely to be affected by future flooding, clearly preventative measures need to be taken.

To date over $450 million worth of damage can be attributed to the flooding and it is likely that at least that much damage will be incurred again if current trends persist. The State of North Dakota completed an outlet for Devils Lake in 2005 that flows into the Sheyenne River. The maximum drainage for this outlet is 2.8 m^3/s and it would not be used until lake elevations rose higher than 440.43 m (current elevation is at 440.97 m) (ND-0026247). However, the State of Minnesota and the Canadian Province of Manitoba have fought the implementation of this outlet, citing water quality concerns. The North Dakota Supreme Court struck down a challenge to the outlet that had been raised by the Government of Manitoba, the Attorney General of Minnesota and several environmental groups (Flanders, 2006). This drainage has yet to be implemented, however, due to ongoing litigation.

To fully assess the impact of flooding at Devils Lake further spill elevation study needs to be done concerning the geographically separated lakes and prairie potholes in the region. These water sources contribute significantly to the overall flood damage and their impact on future flooding will likely be more devastating than the expansion of Devils Lake itself. This presents a problem for the area, as no outlet constructed for Devils Lake will have an effect on these water bodies. Further analysis of the topography surrounding these features would allow for the prediction of what land will be affected in the future and help develop strategies to minimize the damage and plan agricultural procedures for the future. While constructing barriers and levees on a small-scale, individual basis may be a viable option, the massive infrastructure needed to protect all agricultural land in the area from water rise would most likely prove to be cost prohibitive. Recent measurements have revealed a cessation in the rise of flood waters in the Devils Lake area. Hopefully this respite will give engineers and planners more time to address this pressing issue.

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