GIS Analysis of Groundwater Transport of Septic Tank Phosphorous in Lake Nebagamon, Wis.

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Introduction

Lakes in Wisconsin have long been a source for recreation and relaxation – a focal point for gatherings of family and friends. One such lake is Lake Nebagamon, a 950 acre mesotrophic lake[1] located in far northern Wisconsin (Figure 1), which holds special significance because my family has owned a shore side cabin there for over fifty years. Principle to the continued enjoyment of Lake Nebagamon is thoughtful stewardship of the waters and surrounding environment. A recent study by the Wisconsin Department of Natural Resources (WDNR) found the lake to be "relatively healthy", with a diverse aquatic ecosystem and limited land development within the watershed[1]. Protection of Lake Nebagamon is a concern shared by a majority of lake users. 70% of respondents to a 2015 survey stated willingness to alter the way in which they manage their property in order to protect Lake Nebagamon[1]. One such modification would be a reduction in the number of homes employing septic systems.

Figure 1: Location of Lake Nebagamon

The Village of Lake Nebagamon, on the north shore, is serviced by a sanitary sewer system. However, because the sewer system does not extend to most homes and cabins around the lake, these dwellings are forced to rely on individual septic systems for wastewater disposal. Seepage from septic tanks can enter Lake Nebagamon through groundwater transport with the primary pollutant of concern being phosphorous. Though septic systems represent a small portion of the overall phosphorous budget, approximately 44% of the annual phosphorous load is retained by the lake[1]. Therefore, any reduction in phosphorus inputs will positively affect the long-term health of Lake Nebagamon. However, given the small size of the community and the large, irregular shape of the lake, providing sewer service to all residents is likely cost-prohibitive. A more modest plan would involve providing wastewater treatment to a greater portion of homes around Lake Nebagamon with the extended service area informed, in part, by potential reductions in phosphorous transport.

This report presents a GIS based method for the analysis of phosphorous loading of Lake Nebagamon through groundwater transport. By modeling the soil surrounding Lake Nebagamon as an unconfined aquifer, it is possible to utilize the built-in groundwater analysis tools in ArcGIS Pro. Based on the analysis of groundwater flow at each address point around Lake Nebagamon several regions of developed shoreline are identified as candidates for extended sewer service.

Methods

Study Area

The area of study was determined to be the land area draining through the outlet of Lake Nebagamon into Nebagamon Creek. A point feature was created at the outlet of Lake Nebagamon and the web-based Watershed tool in ArcGIS Pro was utilized to delineate the area draining to that point. Additionally, a 100-meter buffer was created by employing the Buffer geoprocessing tool. The watershed buffer was used in subsequent data layer extractions to prevent edge effects from impacting further analyses. The NHD waterbody class was used to extract the polygon shapefile corresponding to the shape of Lake Nebagamon (Figure 2).

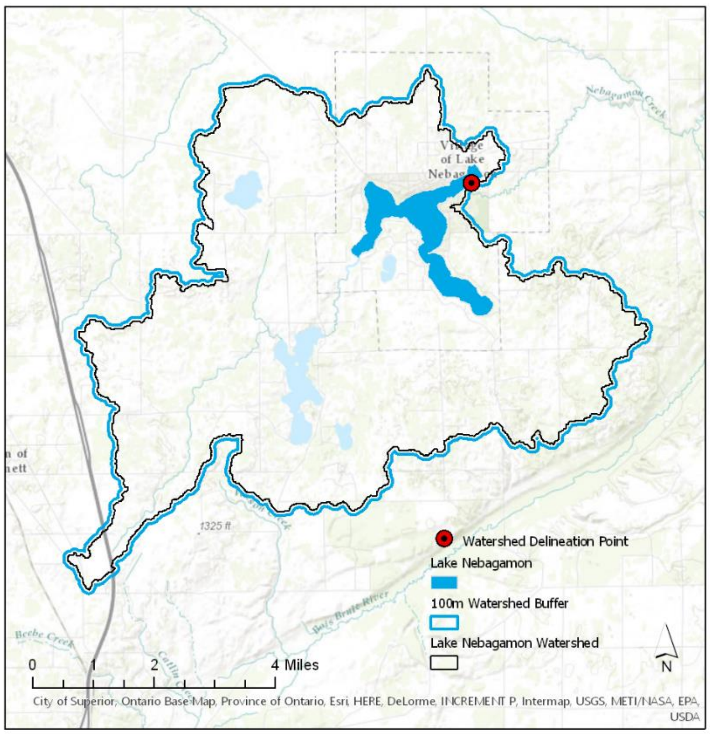

Figure 2: Lake Nebagamon Watershed Boundary and 100 Meter Buffer

The study area was further refined to include only those address points within 50 meters of Lake Nebagamon. Fifty meters was chosen to maximize the number of shore-adjacent address points while minimizing the number of non-shore adjacent properties in the analysis. A 50-meter buffer of Lake Nebagamon was created similarly to the 100-meter watershed buffer as described above (Figure 3).

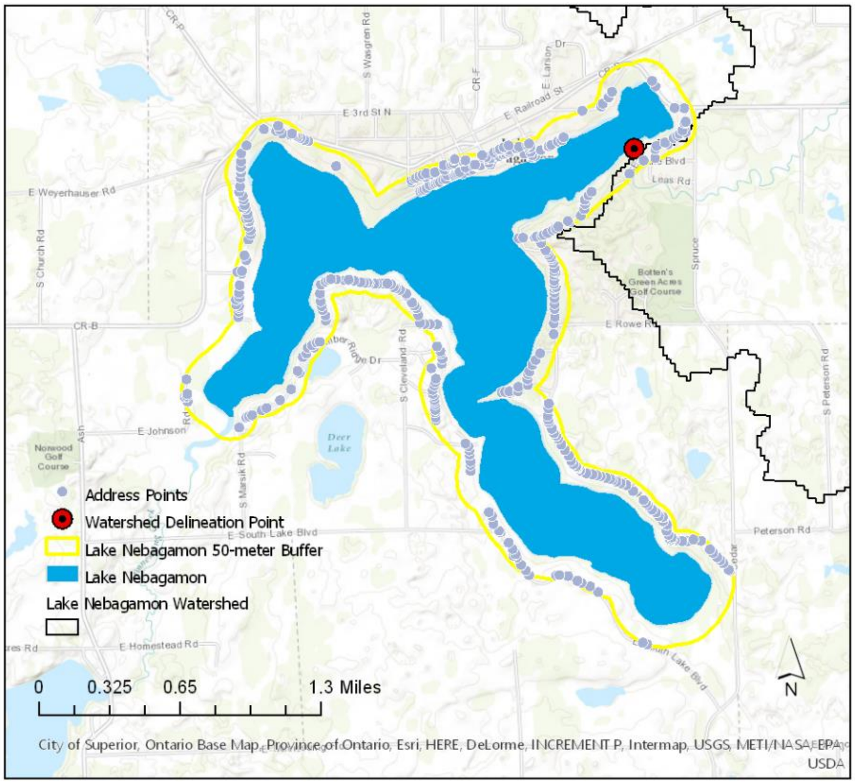

Figure 3: Lake Nebagamon and 50-meter buffer with associated address points

Data Sources

The National Map, Digital Elevation Model

The National Map, provided by the U.S. Geological Survey (USGS), contains various elevation products for the United States. The 1/9 arc-second (ten meter) bare earth digital elevation model (DEM) for the state of Wisconsin was downloaded directly from The National Map website[2].

Gridded Soil Survey Geographic (gSSURGO) Database

The gSSURGO database, provided by the USGS, contains soil geographic data as a raster in geodatabase format at ten meter resolution. Tabular data from the National Soil Information System (NASIS) represent included soil attributes and the associated soil mapping unit identifiers (MUKEY). Data for the state of Wisconsin were downloaded from the Geospatial Data Gateway website[3].

Value Added Look Up (VALU) Table Database for the (gSSURGO) Database

Tabular data containing area- and depth- weighted averages of select soil properties provided by the USGS. The "Layer" dataset was downloaded and contained all parameters required for groundwater flow analysis. Parameters used were saturated hydraulic conductivity (AVG_KSAT) and porosity (AVG_POR)[3,4].

National Hydrography Dataset Plus

Extensive data set built by the Environmental Protection agency containing hydrography data for the United States. NHD Plus V2 was accessed via an ArcGIS server from which the polygon shapefile for Lake Nebagamon was extracted[6].

Address Points

Address points for the State of Wisconsin were obtained via the Link Wisconsin website. Address points for the most recent year (2014) were provided in geodatabase format and extracted for the area of interest[7].

Spatial Reference

NAD 1983 Albers Equal Area was used as the projected coordinate system for all raster files in this analysis. Those raster files with a different native projected coordinate system were re-projected using the nearest neighbor setting of the Project Raster tool. Additionally, all raster files were snapped to the gSSURGO grid. Meters were used as the unit of length in all cases.

Geoprocessing

All geoprocessing was completed using ArcGIS Pro – either directly within the program or via the IDLE Python interface. Darcy Flow, Particle Track, and Porous Puff from the Spatial Analyst Groundwater toolbox were used extensively in the analysis.

Darcy Flow

Darcy Flow was utilized to generate groundwater volume balance residual, groundwater flow direction, and groundwater flow magnitude raster files. The inputs files were produced using the following procedures:

Groundwater Head Elevation Raster: The NED 10-meter raster was pre-processed using the Pit Fill tool and projected and snapped as described above.

Effective Formation Porosity Raster: AVG_POR from the VALU table was joined to the gSSURGO raster using MUKEY as the join parameter which allows matching of soil types with the appropriate average porosity value. The Reclassify tool was then used to assign the AVG_POR values to the raster cells. The AVG_POR parameter is provided as a percent, so Raster Calculator was used to divide each cell by 100.

Saturated Thickness Raster: The saturated thickness was approximated as the elevation above average lake elevation. The NED raster was extracted using the Lake Nebagamon feature shapefile and an average elevation of 337.2 meters was obtained from the raster statistics section of the properties table. Raster Calculator was used to subtract the average lake elevation from the original NED raster.

Formation Transmissivity Raster: Defined as the hydraulic conductivity multiplied by the saturated thickness. AVG_KSAT values from the VALU table were joined to the gSSURGO raster and reclassified as described above. The AVG_KSAT parameter is provided as µm/s and was scaled to m/hr using the Raster Calculator function before again using Raster Calculator to compute the product of the saturated thickness and hydraulic conductivity raster files.

The Darcy Flow geoprocessing tool produces three output raster files:

Groundwater Volume Balance Residual is a measure of the net accumulation in each raster cell and is an indication of the internal consistency of the input raster files, with cells closer to zero indicating more consistency within the inputs. (Figure 4)

Groundwater Flow Direction represents the direction of flow clockwise from East in degrees. (Figure 5)

Groundwater Flow Magnitude is the groundwater analogue of slope in surface water models. (Figure 5)

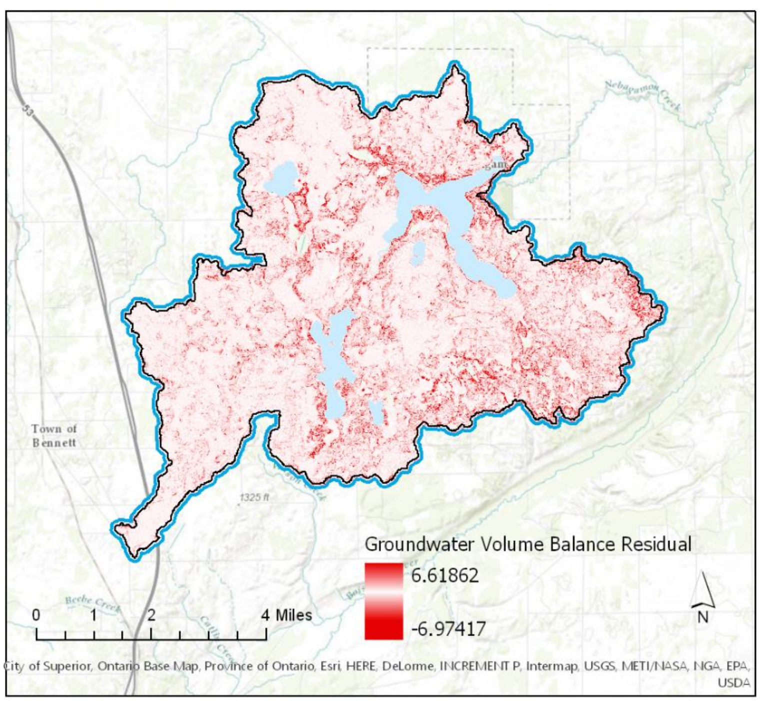

Figure 4: Lake Nebagamon Watershed Groundwater Volume Balance Residual

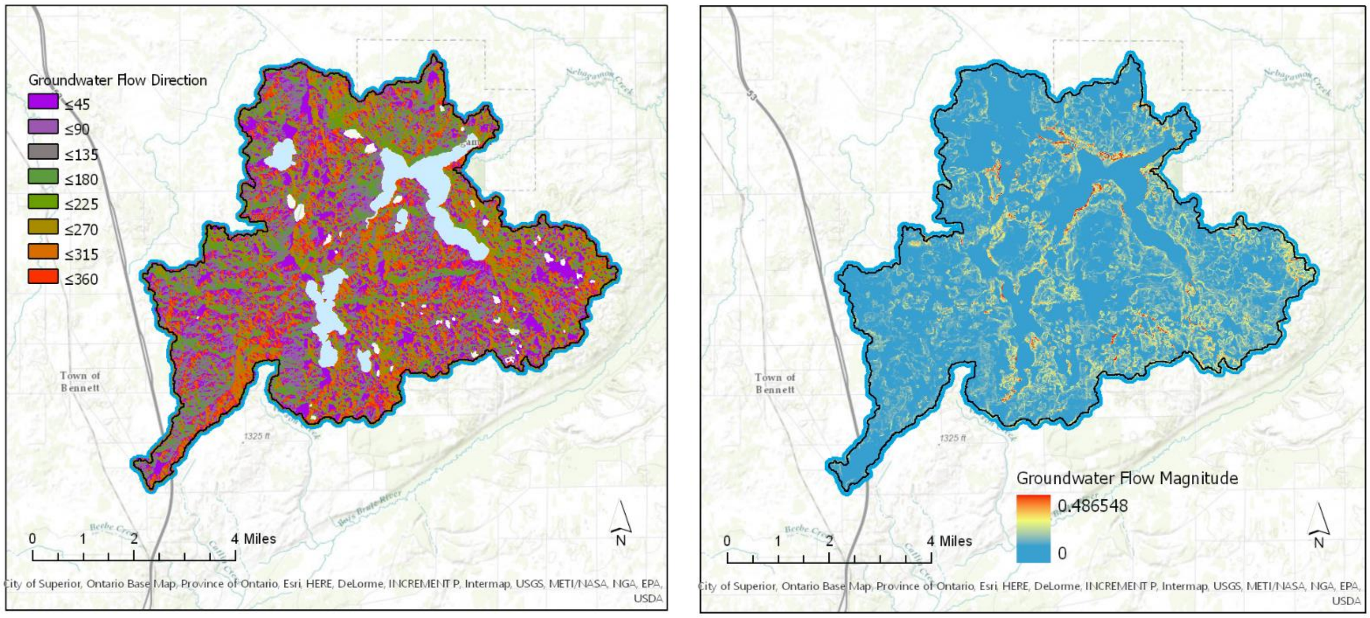

Figure 5: Lake Nebagamon Watershed Groundwater Flow Direction (left) and Groundwater Flow Magnitude. Groundwater Flow Direction is in degrees clockwise from East

Particle Track

Particle Track uses the Groundwater Flow Direction and Magnitude raster files as inputs to calculate a particle track from a specified starting point within spatial domain of the inputs. The tool produces an ASCII file and an optional polyline file as outputs. (Note: ArcGIS Pro consistently crashed if an output file was not specified for the polyline feature.) The ASCII file is used as the input of the Porous Puff tool. Each point of interest must be run individually (Figure 6).

time	x	y	length	flow dir	flow mag
0.0000000000	331848.7092	2621882.887	0.0000000000	44.07555760	0.01985578621
657.9670092	331856.9348	2621888.574	10.00000000	66.29455996	0.01519833040
1318.752288	331866.4316	2621891.706	20.00000000	75.70104918	0.01513350904
2045.716422	331876.3850	2621892.670	30.00000000	93.38157957	0.01375583683
2704.739505	331886.2526	2621891.049	40.00000000	105.4337236	0.01517397531

Figure 6: Representative Particle Track ASCII File

Porous Puff

Porous Puff models an instantaneous release of a pollutant at a specific location in a vertically mixed aquifer. The Particle Track ASCII file is used as the basis for the direction and magnitude of the flow of the pollutant. The dispersion is calculated using the effective formation porosity and saturated thickness raster files from the Darcy Flow tool. A standard mass of 50 was used as the input value for each address point. Use of a standard value allowed for direct comparison of the individual Porous Puff result.

Python Scripting

Due to the large number of address points in the study area, Python scripting was used to automate the analysis of the address points near Lake Nebagamon. The address points were saved in a .CSV file with x- and y-coordinates tabulated in terms of the projected coordinate system. Following initialization, a loop is run such that, for every address point, Particle Track and Porous Puff are run in succession. The resulting Porous Puff raster files are combined to form an aggregate raster containing the Porous Puff data from each address point in a single file. Additionally, each address point produces an ASCII track file and a polyline track file. (Figure 8)

The aggregate porous puff raster is the final output of the script and serves as the basis for the analysis of phosphorous loading from septic tanks near Lake Nebagamon. (Figure 7)

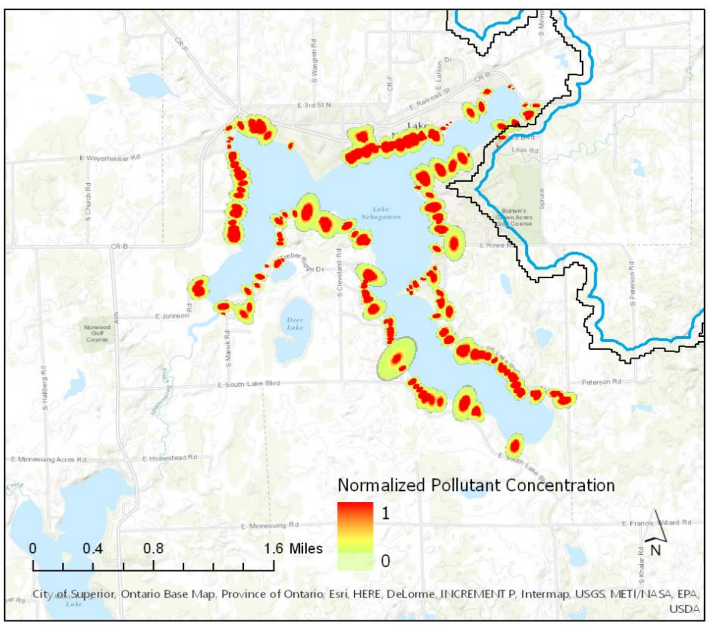

Figure 7: Normalized Aggregate Porous Puff Raster

```python
import arcpy, os
from arcpy import env
from arcpy.sa import *


# Set local variables
folder = r"C:\Users\andre\Documents\GIS F2016\Nebagamon2\Nebagamon\python\output"
ws = r"C:\Users\andre\Documents\GIS F2016\Nebagamon2\Nebagamon\Nebagamon.gdb"
ds_name = "Tracklines"
inDirectionRaster = r"C:\Users\andre\Documents\GIS F2016\Nebagamon2\Nebagamon\NewDDir"
inMagnitudeRaster = r"C:\Users\andre\Documents\GIS F2016\Nebagamon2\Nebagamon\NewDMag"
stepLength = 10
trackingTime = 10000000
csv_file = r"C:\Users\andre\Documents\GIS F2016\Nebagamon2\Nebagamon\python\AdPtsShort.csv"
env.workspace = ws
inPorosityRaster = r"C:\Users\andre\Documents\GIS F2016\Nebagamon\porosity-100"
inThicknessRaster = r"C:\Users\andre\Documents\GIS F2016\Nebagamon2\Nebagamon\depthuse"
mass = 50
dispersionTime = ""
longitudinalDispersivity = ""
dispersivityRatio = 3
retardationFactor = ""
decayCoefficient = 0
zeroRaster = r"C:\Users\andre\Documents\GIS F2016\Nebagamon2\Nebagamon\zeroraster"



# Check out the ArcGIS Spatial Analyst extension license
arcpy.CheckOutExtension("Spatial")

i = 0
with open(csv_file ,'r') as infile:
    for line in infile:
        i += 1
        if i != 0:
            x = line.split(',')[1]
            y = line.split(',')[2]
            id = line.split(',')[0]
            sourcePoint = arcpy.Point(float(x),float(y))

            outTrackFile = os.path.join(folder, "xy_{0}.txt".format(id))
            outTrackPolylineFeatures = os.path.join(folder, "xy_{0}.shp".format(id))

            # Execute ParticleTrack
            ParticleTrack(inDirectionRaster, inMagnitudeRaster, sourcePoint,
                          outTrackFile, stepLength, trackingTime, outTrackPolylineFeatures)
            print(id)

            inTrackFile = outTrackFile

            # Execute PorousPuff
            outPorousPuff = PorousPuff(inTrackFile, inPorosityRaster, inThicknessRaster,
                                       mass, dispersionTime, longitudinalDispersivity,
                                       dispersivityRatio, retardationFactor,
                                       decayCoefficient)

            outPorousPuff.save(r"C:\Users\andre\Documents\GIS F2016\Nebagamon2\Nebagamon\python\output\Puff_{0}".format(id))

            print(id)

            # Execute Raster Addition
            if i == 1:
                rasterSum = outPorousPuff + zeroRaster
                rasterSum.save(r"C:\Users\andre\Documents\GIS F2016\Nebagamon2\Nebagamon\python\output\Sum_{0}".format(i))
                print(rasterSum)

            else:
                oldRaster = r"C:\Users\andre\Documents\GIS F2016\Nebagamon2\Nebagamon\python\output\Sum_{0}".format(id)
                rasterSum = outPorousPuff + oldRaster
                rasterSum.save(r"C:\Users\andre\Documents\GIS F2016\Nebagamon2\Nebagamon\python\output\Sum_{0}".format(i))
                print(rasterSum)

# Re-check the ArcGIS Spatial Analyst extension license
arcpy.CheckInExtension("Spatial")
```

Figure 8: Python Script

Shoreline Map

Further geoprocessing was performed on the aggregate raster file to aid in visualization of the results. The Lake Nebagamon polygon shapefile was converted first to a polyline and then to a raster with 10 meter cell size and given a value of one for every cell. Using raster algebra, the lake outline raster was multiplied by the aggregate porous puff raster to produce an outline of the lake containing the relative phosphorous concentration at the shoreline. Conversion from a raster to a polyline shapefile requires the raster data be in integer form. The shoreline raster was multiplied by 1000 and values truncated to integers using the Int tool before the raster was transformed back to a polyline and again normalized to one (Figure 9).

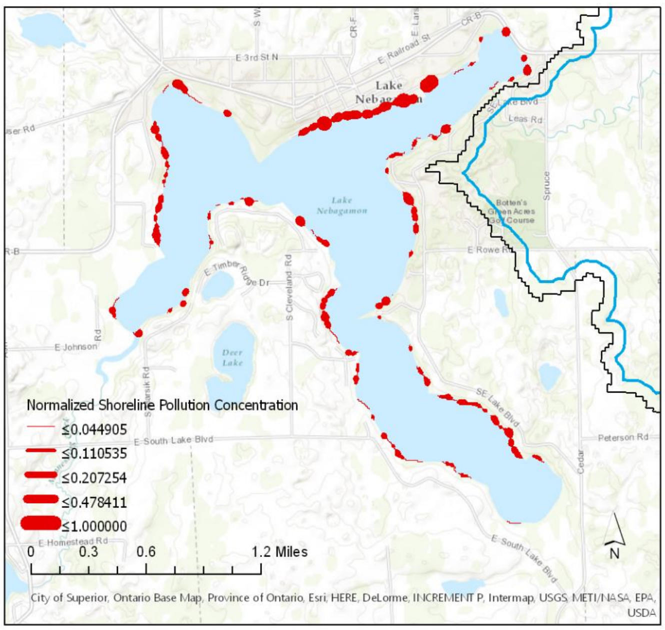

Figure 9: Normalized pollutant concentration at the shoreline of Lake Nebagamon

Results and Discussion

This analysis has focused on septic tank phosphorous loading of Lake Nebagamon via groundwater transport. Modeling the soil layer as an unconfined aquifer allowed for the use of the ArcGIS tools Darcy Flow, Particle Track, and Porous Puff. Utilizing a Python script, each address point near the lake was analyzed and the resulting Porous Puff raster files were combined and normalized. A map highlighting the relative phosphorous concentration at the shoreline provided an easily interpreted visualization of the results.

Based on Figure 9, there are several areas of shoreline that could be considered for service under an expanded sanitary sewer system. The area of greatest relative phosphorous concentration, on the north shore of Lake Nebagamon, corresponds to the Town of Lake Nebagamon. The structures in this area are connected to the existing sewer system and therefore can be neglected for this discussion. The western edge of the lake features an area of higher phosphorous concentration over a discrete section of shoreline. Given this area's proximity to the Town of Lake Nebagamon, this area is a strong candidate for extended wastewater service. Both the eastern and western sides of the southern arm of the lake have sections with concentrated areas of phosphorous pollution; however, these areas are farthest from the town center and would likely be the costliest to connect to the sewer system. The remaining sections of shoreline show only sporadic sections of phosphorous pollution indicating there would be little decrease in the amount of phosphorous entering the lake through groundwater flow in these areas if homes were connected to the sewer system.

Future Work

There are several ways in which the methods described above could be improved upon that relate to data either data quality, geoprocessing inputs, or model improvements.

Data Resolution, Specificity, and Accuracy

The data sources used were all ten-meter resolution raster files. Improved resolution will increase the accuracy of all analyses. As Lake Nebagamon is relatively sparsely populated, it is unlikely that the NED and gSSURGO will both be updated to a higher resolution any time soon.

The gSSURGO VALU data are based on average properties for each soil class; therefore it would be beneficial to obtain local values for the soil properties used in the analysis.

The address points used to calculate particle track and porous puff are positioned at the street and not at the precise physical location of each building. Moreover, each septic system is an unknow distance from the structures they serve. Precise location data for each septic tank would improve the accuracy of the particle path and porous puff outputs. As it stands, the majority of septic tanks are likely closer to the lake than the address points obtained and it is possible that the calculated pollution profiles underestimate the amount of phosphorous impacting the lake through groundwater transport.

Geoprocessing Inputs

The groundwater volume balance residual output of the Darcy Flow tool can be interpreted as a measure of the internal consistency of the input data. Under ideal conditions, the output raster file would be zero for all cells in the watershed. ESRI documentation suggests that inputs to Darcy Flow be modified and checked for consistency in an external groundwater modeling program, noting that a head raster consistent with other input data could differ substantially from measured and/or interpolated head data[8]. Utilizing groundwater modeling software on the NED elevation data used in this analysis would result in improved data consistency and increase the accuracy of the resulting flow direction and magnitude raster files.

Model Improvements

The transport of phosphorous through groundwater was examined by modeling the soil layer around Lake Nebagamon as an unconfined aquifer. The assumptions built into this model include steady flow and vertical mixing. While this is an appropriate first attempt to model the impact of phosphorous released from septic tanks, there are also obvious shortcomings – primarily the steady flow assumption. An improved model would ideally consider the effects of intermittent precipitation on the flow of water through the soil. Following that, local estimates of precipitation could then be incorporated to further increase accuracy.

Conclusions

This project has demonstrated a GIS based method for the analysis of groundwater transport of phosphorous into Lake Nebagamon, Wisconsin. By modeling surface soil as an unconfined aquifer, it was possible to employ the groundwater tools built-in to ArcGIS Pro. Though the results are not strictly quantitative, they provide a sense of which areas of the lake might be considered for expansion of the existing sewer system with the goal of reducing pollution from septic tanks. The use of the IDLE Python interface in ArcGIS Pro greatly aided in the completion of the analysis of over 300 address points. Though there are several improvements that would increase the accuracy of the results, the current analysis provides a general sense of the spatial distribution of groundwater phosphorous into Lake Nebagamon.

Acknowledgments

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References

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