From Farm to Lake:

Modeling Phosphorus Sources in the Lake Mendota Watershed

Dave Huwe, Jack Plasterer, and Mike Smale

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Capstone Statement

Lake Mendota is a culturally eutrophicated water system that is susceptible to phosphorus runoff, particularly from nonpoint agricultural areas. We have performed a surface analysis of the lake's watershed using the Soil and Water Analysis Tool (SWAT), which allows for a prediction of agricultural sites that are most naturally susceptible to contributing phosphorus into the lake system.

Introduction & Background

Madison, the "City of Four Lakes", takes pride in the lakes surrounding the Isthmus. The largest of the lakes, Lake Mendota, is a hot spot for local recreation in Madison and Southern Wisconsin, as fishing, swimming, and boating are sought-after recreational activities over the summer months within the lake. Yet, the lake often has low water clarity and quality and is subject to rancid algal blooms. These blooms can occasionally be overwhelming, producing odious scents and dank water. In May 2017, a massive cyanobacteria "algae" bloom put the lake into a toxic and unsightly state, preventing any human contact for days and has been blamed for the deaths for several animals. (Hinterthuer 2017) These explosive algae blooms occur because the lake contains excessive amounts of nutrients, which is described as being "eutrophic". Since the lake is filled with nitrogen-fixing bacteria, phosphorus is the limiting nutrient in Mendota (Carpenter 2008).

Within the lake's watershed, agriculture is the predominant land use, constituting about 53% of the lake's watershed as of 2011 (Betz 2014). Farms within the watershed will apply external phosphorus to ensure high agricultural productivity. Since terrestrial systems are nitrogen-limited, common practice, especially for dairy farmsteads which produce large amounts of P-saturated manure, is to apply fertilizer or manure to raise the amount of available nitrogen on the soil, without regard to the amount of phosphorus. The result is a large amount of unused terrestrial phosphorus and causes excess P to be leaked into the nearby aquatic system.

Thus, agricultural areas are the primary source of phosphorus (P) into the lake, which can be transported in two related, yet distinct, processes. First, the phosphorus can be dissolved in water runoff from the agricultural area and flow its way into a nearby steam and make its way to the lake. This form of P loading allows for uptake-ready phosphate to directly flush into the lake system, allowing for rapid growth of P-limited organisms (Daniel, 1994). Second, P can move off the land and into the water via particulate transportation. Since P is a charged compound, it will readily bind to other materials such as clay or silt particles. In agricultural areas, phosphorus from applied fertilizer of manure can sorb to soil particles and raise the amount of minerally-bound P in a soil to a considerable degree more than would naturally exist (Combs, 1992). When erosion and transportation of this P-coated sediment makes its way into a stream, it will eventually flow its way into Lake Mendota. Organically-bound P is transported to the lake in a similar way. While particulate and organic phosphorus are not readily available for algal uptake, microbial and chemical processes taking place within Lake Mendota’s oxygenated and anoxic conditions can transform phosphorus into an available form and cause an algae bloom.

It would clearly be in the public interest to reduce the loading of phosphorus via erosion and runoff into Lake Mendota. Programs within Dane and Columbia Counties, such as the Yahara Watershed Improvement Network (WIN), seek to reduce phosphorus inputs into local waters. While these programs are a good source of funds and grants to help farmers reduce their phosphorus runoff, they often do not consider what locations would be more effective in reducing phosphorus loading into Lake Mendota. If programs involved with reducing agricultural nutrient runoff could determine which sites, due to their proximity to streams, soil type, and slope, are inherently most likely to send nutrients into streams and lakes, resources could be focused on those locations, making the most efficient use of program dollars.

Methodology

To determine which agricultural sites in the Lake Mendota watershed were most inherently at risk, we decided to make use of the SWAT (Soil and Water Assessment tool) modeling program. This software package, developed by USDA Agricultural Research Service (USDA-ARS) and Texas A&M AgriLife Research department, is open access and public domain. It was developed to assess and simulate water movements within small watersheds. It is commonly used for “assessing soil erosion prevention and control, non-point source pollution control and regional management in watersheds” (“Soil Water and Assessment” 2018). The part of the program we are interested in is its ability to locate areas of non-point agricultural pollution.

While we could have performed our own spatial analysis to locate these “optimal sites” of naturally high risk agricultural areas, we felt SWAT would provide a complete and accurate assessment of the watershed. First, the model would provide us with real numbers of phosphorus loading into Lake Mendota, something that our own fuzzy scoring analysis would not have done. The output of real numbers could eventually be used to compare our analysis with future or high-definition analysis using SWAT. Second, SWAT automatically calculates the two crucial ways of Phosphorus loading into aquatic systems: runoff and sedimentation. These processes are often based on similar variables, such as slope or soil characteristics, making independent spatial evaluations of these two processes difficult. Having SWAT simulate these complex and interrelated processes archives exactly what our project seeks to address. Third, the program utilizes all the factors that we had found to influence p-loading, such as slope, soil hydrologic group, and land cover. Finally, SWAT is a well established and researched program used in watershed analysis around the world. Using this program means that we are using one of the most reputable and accountable watershed models available, much more so than our own project could have ever achieved with our own fuzzy scoring system. We used SWAT 2012 for creating our model.

SWAT Procedures and Considerations

To begin the model, we must define the projection. We utilized *Dane County NAD 1983 (HARN 2011) Meters* projection. Since Lake Mendota's watershed is mostly in Dane County and since Colombia County is very close to Dane Co, this option is a logical choice.

The first operation SWAT simulates is creating the parameters of the watershed itself by establishing stream locations and watershed boundaries. To do this, SWAT calculates watershed divisions from a Digital Elevation Model (DEM). We had initially used obtained county-level 5m DEMs from the Wisconsin Geo-Data portal. The finest resolution available is attractive for our purposes, as Reddy and Reddy found that runoff values in SWAT models varied and sediment yield values decreased for coarser DEM resolutions .Later in the project, we found that the 5m DEM was too fine of detail for us to efficiently run the SWAT simulation. Instead, we utilized a 30m DEM obtained from WI DNR portal. We clipped the DEM to the scale of the Lake Mendota watershed polygon to keep data file size to a minimum. However, the DEM was clipped with a 500m buffer to allow SWAT some wiggle room to evaluate watershed. Since its evaluation may slightly differ from the actual watershed, the extra room is necessary. 500m seemed like a good distance that still minimized data. This watershed polygon was obtained from the Wisconsin DNR's GeoPortal.

With this data, SWAT proceeds with stream delineation, where the program calculate where streams would be in watershed. We had the option of either loading in our own locations of streams or having SWAT estimate locations of stream location based from the DEM. We chose to have SWAT determine these stream locations for two reasons. First, since proximity to a stream or intermittent streams is listed as an important factor determining phosphorus runoff (Larson and Sharara, 2016, p 28), we needed to ensure that SWAT would be calculating these streams. Shapefiles readily available only contain permanent navigable streams, this would not let SWAT calculate the most accurate location of P-loading. We felt the paths SWAT would calculate would likely include these intermittent streams located in low areas of the landscape. Second, since we were also using a courser DEM resolution of 30m, the calculated streams would be slightly different from the real-world streams we would have imported. If we had used a shapefile of real stream locations, there would could cause a discrepancy in areas where, in the simulation, the stream shapefile would be flowing over the higher-elevation pixels of the relatively course DEM. We let SWAT calculate stream locations to avoid this disparity within the simulation.

After SWAT delineates streams within the watershed, the program creates boundaries of sub watersheds. We had the option to specify the size of the subwatersheds, but proceed with the recommended size SWAT calculates. We were satisfied with the number of sub basins it creates, and for the goal of our project (of locating specific plots of phosphorus loading), this step was irrelevant, making the default sub-basin size acceptable. SWAT also proved the option of manually adjusting the locations of these sub watersheds. We stayed with the calculated sub-watersheds (which are created where two streams join together) because, again, this part of the project was irrelevant to the goals of our project, and it is best to err on the default options SWAT provides.

The model can also incorporate data about point source pollution into its model, which we excluded. Our design goal of creating a "natural" simulation of the Lake Mendota watershed means that point sources of phosphorus, which largely do not exist in pre-settlement conditions, are not a necessary input. Additionally, our goal is specifically seeking to locate *non-point* agricultural sources of phosphorus, making any addition of point-source of pollution a source of bias in our results.

We did manually command SWAT to model the watershed ending at our "output location", or the spot where water within our watershed exits at a single point. Since we are calculating outputs for lake Mendota, we set this as the current water output from the lake – the Tenney Park Locks.

After creating watershed parameters for its simulation, SWAT then uses inputs about land cover to calculate the amount of phosphorus inputs into the watershed system. These inputs include land use, soil, and slope. The input of land use was based off the original vegetation vector polygons of the Mendota area, obtained from the Wisconsin DNR. However, we had to adjust the original vegetation types to the pre-listed land use codes that SWAT uses. We chose the options most ecologically similar to one another. Some land uses were a perfect match and no conversion was necessary. Others, such as prairie, did not have an input code for SWAT, forcing us to re-list the land use as a similar type, such as grassy rangeland.

Original Vegetation Listing	**SWAT Code**	**Code Explanation**
Open Water	WATR	Water
Sugar Maple, basswood, red oak, white oak, black oak	FRSD	Forest - Deciduous
Oak	OAK	Oak Forest
Oak Openings	RNGB	Range - Brush
Prairie	RGNE	Range - Grasses
Marsh & Sedge Meadow, wet prairie, lowland shrubs	WETL	Wetland

Table 1: Original Vegetation Codes to SWAT Land Use Codes

SWAT requires fine-scale polygons of soil data, which we obtained with county-level soil shapefile from USDA NRCS. These polygons of soil series within the watershed are with joined with the exhaustive SSURGO database of soil qualities. SWAT reads the information within SSURGO, such as soil hydrologic group and soil phosphorus content, to make calculations of phosphorus loading. While SWAT would accept either data via the SSURGO or STATSGO database, we determined SSURGO would be acceptable since it provides the most detailed level of information and was designed primarily for local efforts; SSURGO serves as an outstanding source for determining erodible and chemical fate assessment, while, STATSGO is generalized and intended for regional-scale site analysis, which is too generalized for our project goals. Other recent projects of our scale have utilized SSURGO as well (Almendinger 2017). The NRCS shapefiles contained several erroneous soil types, specifically containing incorrect

Map Unit Key (MUKEY) code, which is used to join the shapefiles with the SSURGO database. Thus, we had to incorporate soil attribute data from the City of Madison (obtained from the Robinson Map Library) and manually correct these erroneous MUKEY codes within the NRCS polygon attribute table to allow the two datasets to join

Last of the land input, SWAT creates a raster file of similar slope polygons across the watershed using the DEM. To do this, slope steepness must be classified into groups, which the operator must manually specify.. We chose the maximum number of classifications allowed in SWAT (5 classes) to provide the finest groupings of slopes. Since the greatest runoff and sedimentation takes place at the higher slopes, we specified that the steeper slopes are finer in scale than lower slopes (e.g. 1-3% vs 6-8%) (D’Souza 1975).

Slope (%)	Classification group in SWAT
0-3%	Very low slope
3-6%	Low Slope
6-8%	Slope
8-10%	High slope
>10%	Very high slope

Table 2: Slope Classifications

After all of the land inputs are processed, SWAT overlays all land layers via union processing to create polygons of unique combinations of land type, soil type, and slope classification called a Hydrologic Response Unit.(HRU). To save processing time, SWAT allows the user to set minimum size thresholds for HRUs. Any HRU below a certain size percentage of of its respective sub-basin would be excluded in the simulation.Since our project is interested in calculating Phosphorus amounts for all agricultural plots, some of them very small, we cannot make use of this processing time-saver, and set the minimum threshold to 0%, meaning that all HRUs, no matter how small, would be included in the simulation.

SWAT uses historical weather data to run the simulation. Texas A&M University maintains a website with weather station data specifically for SWAT simulations. With a single weather station within the watershed, we chose to use the De Forest weather station data. This is acceptable; interpolation from outside weather stations because the scale and midwestern location of our project means that variations in climate across the watershed are negligible (Kyle 2015).

Our simulation ran and created an annual report for the 35-year simulation. While SWAT allows for daily and monthly outputs from its simulation, we are unconcerned with temporal scale of the simulation and are only looking at aggregated measurements of HRUs over the simulation. Annual reports satisfy our needs.

We did not calibrate the SWAT analysis with ground truth data. We did not have access to ground truth data, and if anything, we were not concerned with precise values for the watershed as a whole; we are interested in the relative values of HRUs across the watershed, so the lack of calibration should be a minimal source of potential error in our analysis.

SWAT Output and Post-processing

The SWAT simulation produces an output file of calculated runoff and sediment outputs of phosphorus over the entire 35-year simulation (kg/ha) for each HRU, which we joined with the HRU shapefile SWAT produced with the union overlay of all input vector layers.The HRU values were then classified according to the amount of output phosphorus calculated for both runoff and sediment. We classified the HRUs according to the Jenk's Natural Break method, which puts data into inherent classes of similar data groups. We produced 10 classes for both phosphorus outputs, and selected only those HRUs within the top three classes to be our areas of primary focus. The top two were labeled as "very high" phosphorus output, and the 3rd highest grouping was labeled as "high output. This created an exclusive but extensive list of all the high output HRUs within the watershed. Finally, the selected and classified HRUs were overlaid via union with Columbia and Dane county parcel data. These post-processing steps created exactly what our project goals seeked; a map of potentially high phosphorus output agricultural locations as well as a datatable of each land property containing a phosphorus-susceptible spot, complete with owner identification and mailing address

Results, Analysis and Discussion

The creation of the map and data table can be seen in images 1 and 2.

We believe these results are consistent with what we expected to see. In looking at the output results, it appears that slope steepness and soil characteristics are the determining factors in organic/sedimentation loading, which is consistent with the real-world studies, but are two correlated factors (Shabani 2014). Runoff is heavily influenced by stream proximity and soil characteristics, both of which is displayed in our output. Similar phosphorus estimations place heavy emphasis on nearness to stream bank and soil qualities, thus explaining our output (Czymmek 2003).

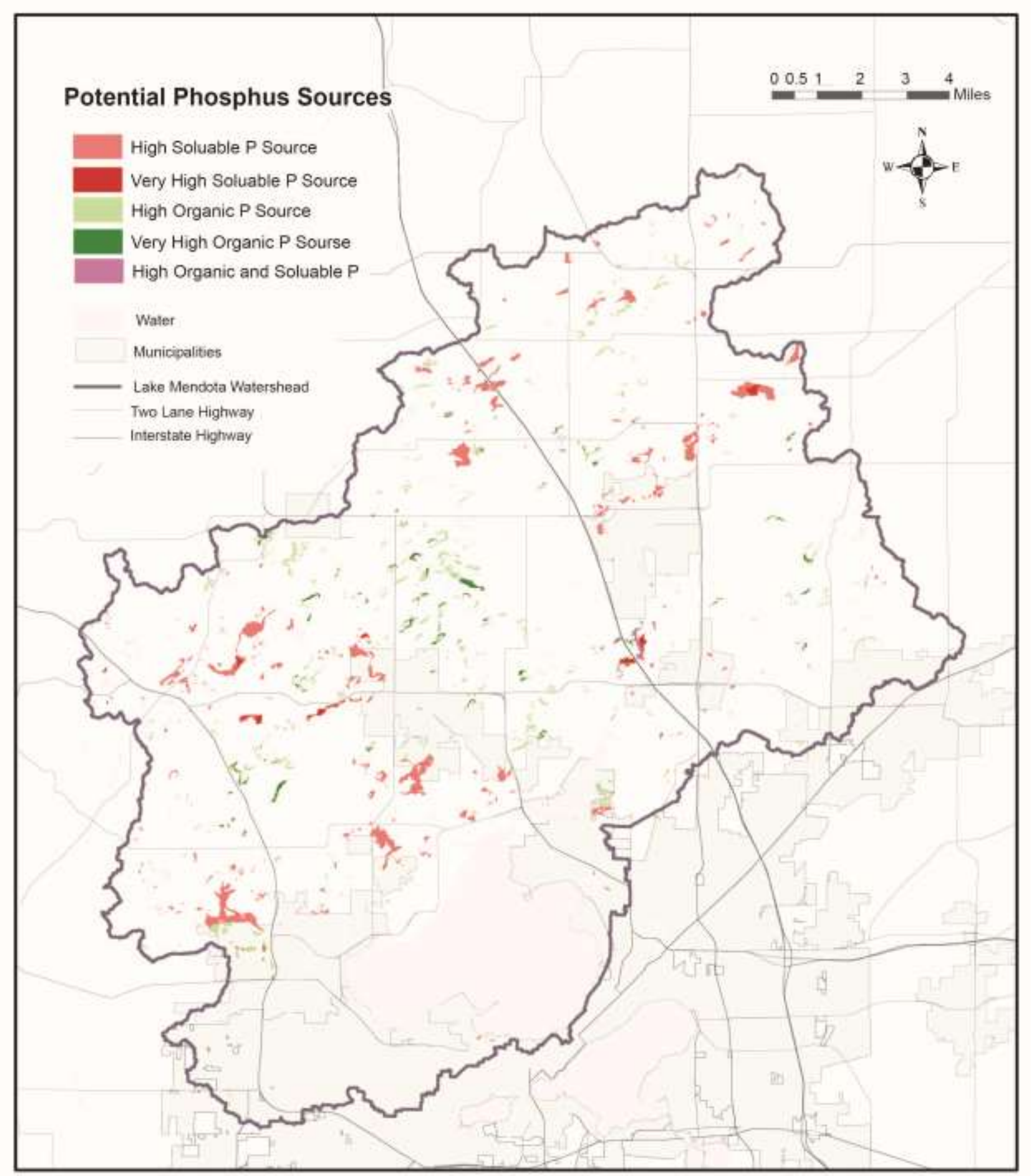


Image 1- Final map of Lake Mendota watershed, with potentially high areas of soluble

(from runoff) and organic (from sedimentation) loading listed

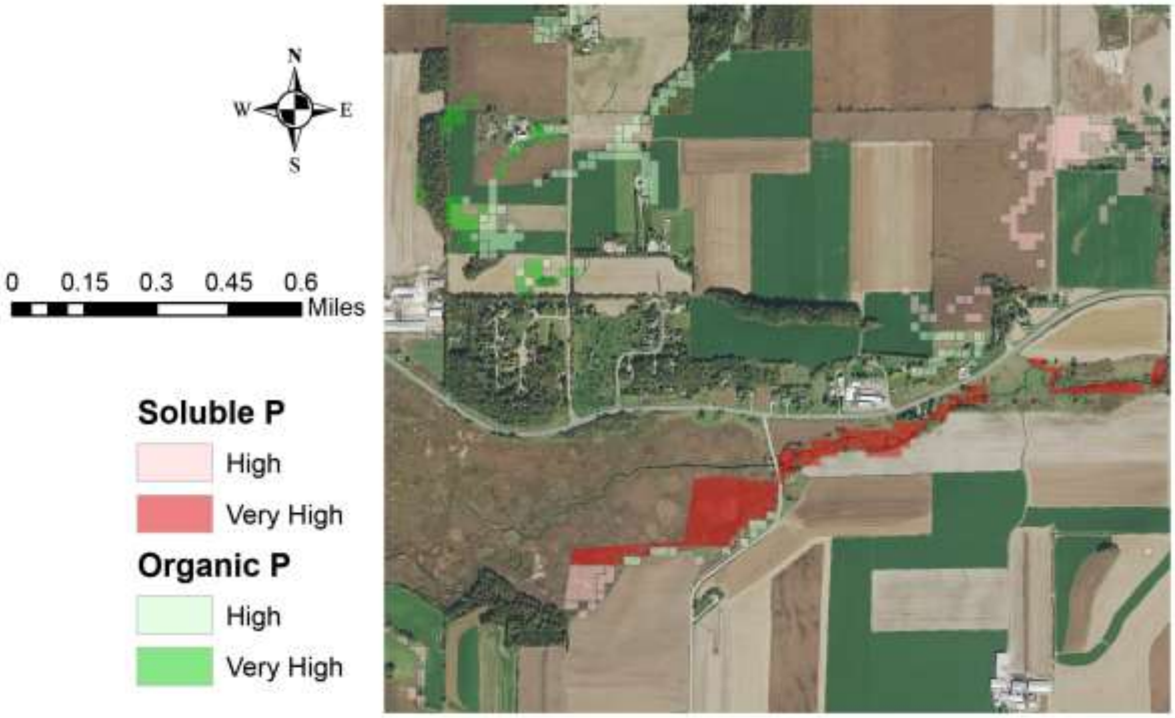


Image 2- Zoom in of potion of watershed with orthophoto overlay. The highway running east-west is Hwy 19.

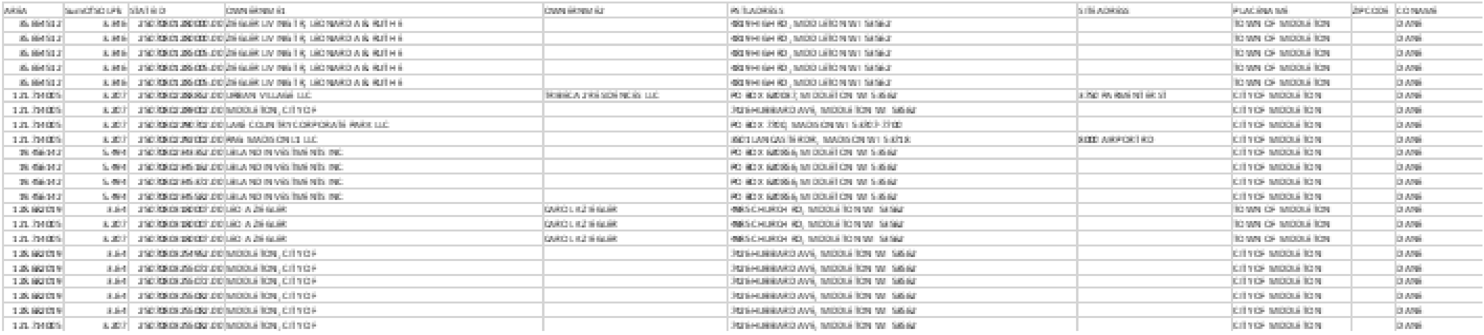
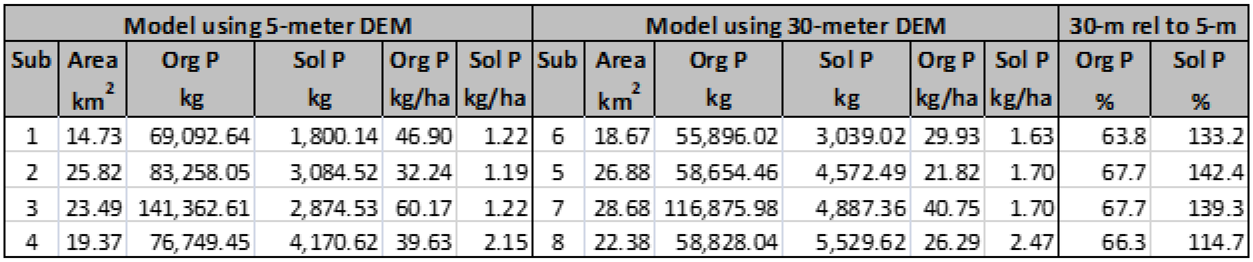


Table 3- Example of Soluble Phosphorus Parsel Table

After completion of the SWAT model based on the 30-meter DEM we wanted to determine the difference in the results we got from those of a model based on the 5-m DEM. We created a model based on the 5-m DEM for a subset of the entire Lake Mendota watershed – four of the twenty one sub basins in the full model. This is a comparison of the P production for the four sub basins in the two different models.



Model using 5-meter DEM						Model using 30-meter DEM						30-m rel to 5-m	
Sub	Area km^2	Org P kg	Sol P kg	Org P kg/ha	Sol P kg/ha	Sub	Area km^2	Org P kg	Sol P kg	Org P kg/ha	Sol P kg/ha	Org P %	Sol P %
1	14.73	69,092.64	1,800.14	46.90	1.22	6	18.67	55,896.02	3,039.02	29.93	1.63	63.8	133.2
2	25.82	83,258.05	3,084.52	32.24	1.19	5	26.88	58,654.46	4,572.49	21.82	1.70	67.7	142.4
3	23.49	141,362.61	2,874.53	60.17	1.22	7	28.68	116,875.98	4,887.36	40.75	1.70	67.7	139.3
4	19.37	76,749.45	4,170.62	39.63	2.15	8	22.38	58,828.04	5,529.62	26.29	2.47	66.3	114.7

Table 4: Comparison of 5-meter and 30-meter DEM models of four sub basins within Lake Mendota Watershed

This shows a very consistent underrepresentation of the organic/erosion P numbers for the sub watersheds, and a mostly consistent overrepresentation of the soluble/runoff P numbers. This can be explained due to our course 30m DEM. The courser DEM will mask and smooth out fine features on the landscape. Image 3 demonstrates this. The “smoothing” of the landscape results in small depressions and potential pooling sites for surface runoff. These depressions contribute to the prevention of a substantial volume of potentially phosphorus-loaded water from running to the stream (Dunne, 1978). Thus, without this detail, SWAT calculates a direct flow into streams without these infiltrating depressions. Additionally, the course DEM smooths out very steep slopes in the landscape, resulting in an under-calculation of erosion. Since soil erosion is influenced by slope and is exponentially more erodible as the slope increases, the smoothing out of the topography and the loss of the highly erodible steep slopes results in an underestimate by SWAT with the 30m DEM compared to the 5m DEM (Reddy 2015). The under and over-estimations of the phosphorus outputs are consistently skewed, meaning that while the raw numbers are off, we believe our pinpointing of phosphorus sources in the landscape should still be reliable.

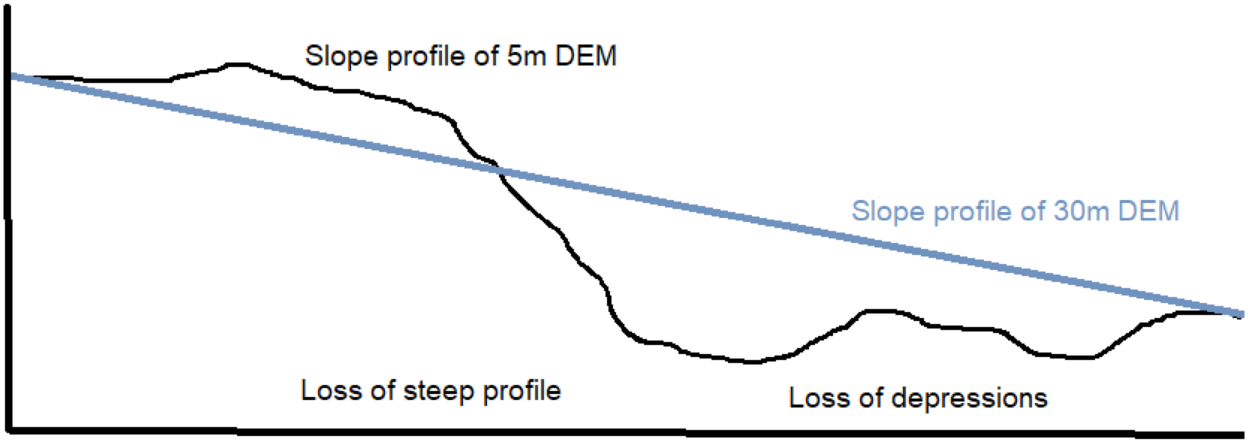


Image 3- Diagram showing loss of topographic detail with a course DEM. Note the loss of the erosion-causing steep profile and the runoff-preventing depressions

As was mentioned in the section on our methodology, we did not gather ground truth from sites in the watershed to calibrate the model. Our expectation is this has a minimal impact on determining the highest P potential sites in the watershed, relative to the other sites. A more intensive project, with ground truth gathering, could prove or disprove this expectation.

Another possible source of error in our model is the use of the 30-meter DEM as the foundation. Our analysis of the four sub basins showed that the differences between the two models were consistent for both forms of phosphorus. A full study of the entire watershed may indicate differences in the results of the two models.

Perhaps the largest source of error is the inaccuracy of WISCLAND2, which was used to display high-output HRUs in agricultural areas. As can be seen in Image 2, there are inaccuracies with this; lands immediately bordering croplands and grassy wetlands are sometimes misidentified as agricultural areas. What results is an identification of potential phosphorus-loading agricultural areas that are, in fact, not agricultural. This can be addressed through manual discretion of these selected sites with a high-resolution aerial photograph overlaid with the HRU layer, such as what is done in Image 2.

Conclusions

Armed with the names of the owners and the addresses of the farms that are situated on the highest P potential sites in the watershed, funding organizations can make informed decisions about subsidizing the construction and maintenance of detention ponds and hauling manure to offsite processing centers. Funding these sites entirely will be much more effective than dividing up available funding among every farm in the watershed, which will often result in providing insufficient funding to all.

Future Research

Analysis of the annual data shows that the organic P production was greatly elevated for the years 1979 and 1986. Further research may be able to show why the watershed sent so much P to the reaches feeding Lake Mendota during these years, which could provide avenues for research into determining ways to minimize P production during similar years in the future.

There is no reason why this procedure must be limited to the Lake Mendota watershed. A similar model could be created for the watershed of any phosphorus-limited, eutrophicated water body. The Wisconsin DNR has announced a plan to dramatically reduce phosphorus in the flowages of the Wisconsin River (Bergquist, 2018). While significant computing power and/or time would need to be committed to the project, our methodology would apply to a project of this scale.

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