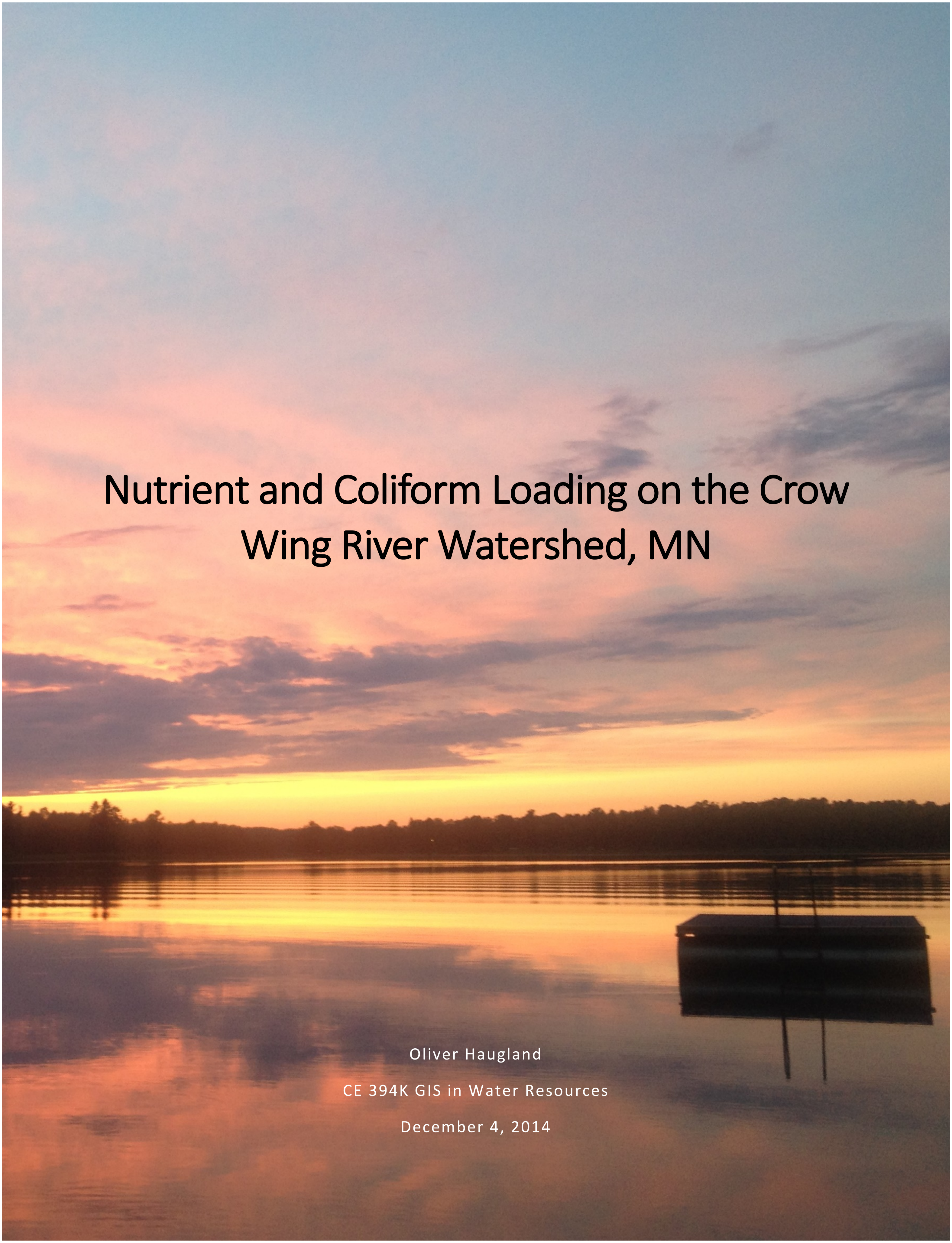

Nutrient and Coliform Loading on the Crow Wing River Watershed, MN

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CE 394K GIS in Water Resources

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1.0 Introduction

Runoff from agricultural farm land is the primary source of surface water pollution in rural areas. Nutrients such as nitrogen and phosphorus are applied as fertilizers and are produced from animal waste. These nutrients and other pollutants like fecal coliforms are discharged from agricultural lands into surface waters in the form of runoff from irrigation and after rain events. Nutrients and fecal coliforms adversely affect water quality. Excess nutrients cause algae and microorganisms to grow faster than ecosystems can handle and increase oxygen demand in a body of water, leading to poor fish health and populations. Increased bacterial growth and fecal coliform contamination can be harmful to human health. It is this imperative to control and monitor pollution from agricultural areas for the protection of water bodies.

Lakes, rivers, and streams define Minnesota. The state motto “Land of 10,000 Lakes” is modest for approximately 12,000 lakes greater than 10 acres. There are more than 104,000 miles of streams and over 9.3 million acres of wetlands. The health of Minnesota’s surface waters is of cultural, economic, and public health significance.

1.1 Objective

The objective of this term project is to investigate the pollution loading on surface waters from agricultural sources. While crops and livestock were both investigated, the primary focus of this study seeks to develop a model for the nutrient and fecal coliform loading on surface waters and discharge to the Mississippi due to livestock. Better understanding of the loading due to this source can aid in the management of livestock and surface water in this area to ensure the high quality of these waters.

1.2 Area of Analysis

The state of Minnesota and the Crow Wing River HUC 8 watershed were chosen as the areas of interest due to personal interest from the author and the high degree of water-recreation in the area. Figure 1 shows the state of Minnesota with the Crow Wing River watershed highlighted.

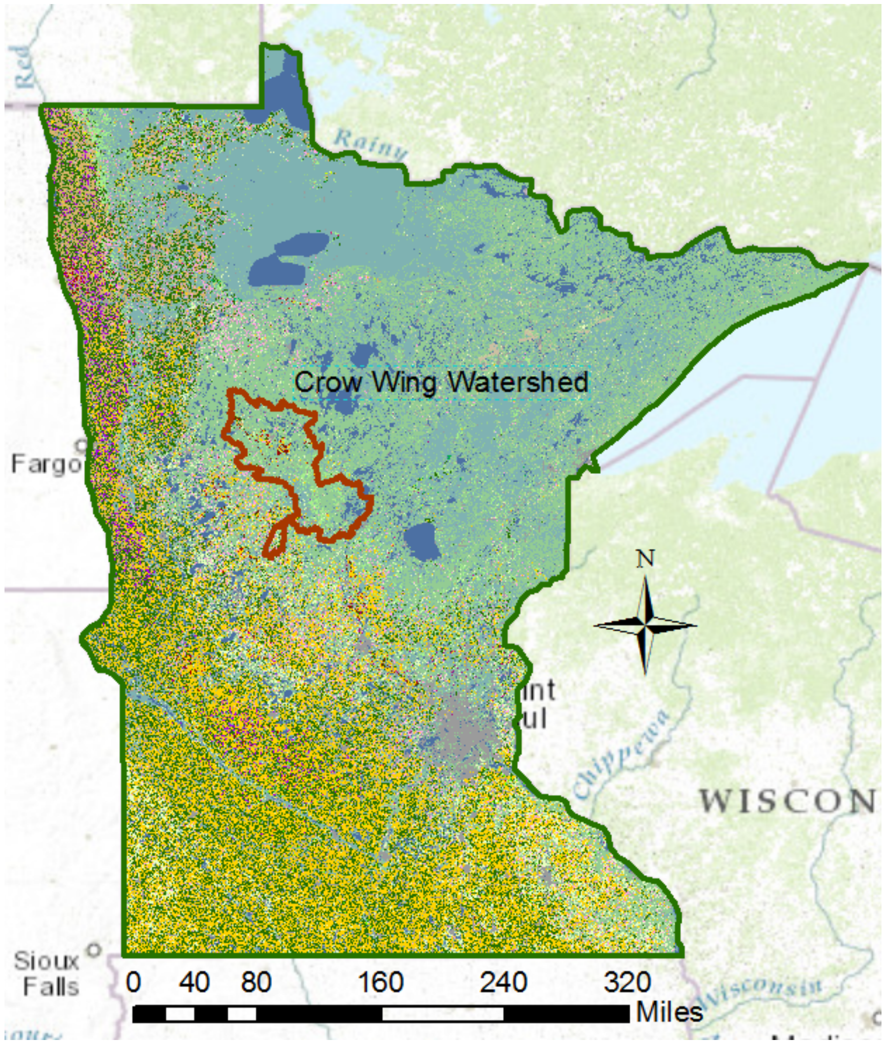


Figure 1 Location of Crow Wing River Watershed

Figure 2 shows the detailed land use in the Crow Wing River watershed as well as all of the livestock farms reported to the Minnesota Department of Agriculture. Table 1 shows the breakdown of land use aggregated into macro-categories from the 2011 National Land Cover Dataset. As Table 1 shows, the majority of this watershed is comprised of forest, agriculture, and water. An analysis that was done on the 2001 NLCD shows that agriculture has increased by 2% in this region in the span of 10 years. Since agriculture is on the rise in this region, it is important that this type of analysis is done.

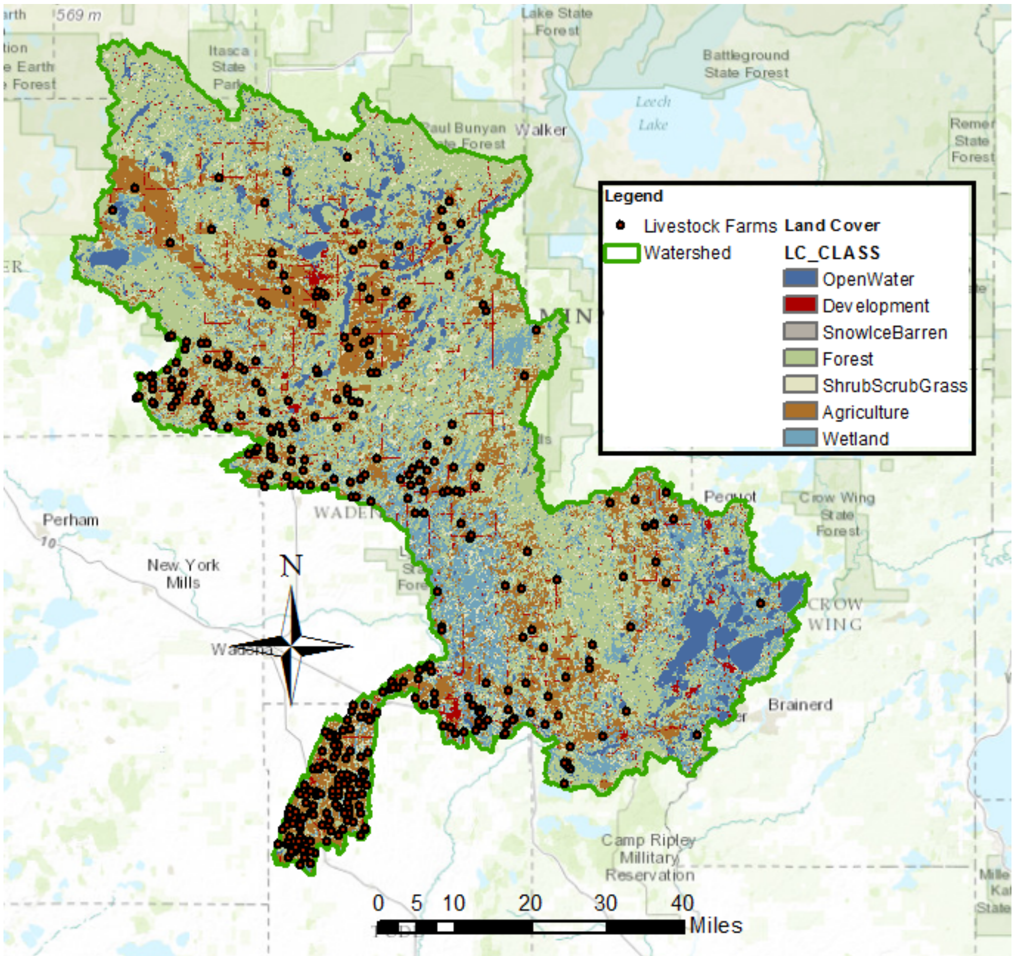


Figure 2 Crow Wing Watershed Land Use

Table 1 Land Cover in Crow Wing River Watershed

Land Cover Class	Percentage
Forest	47%
Agriculture	21%
Wetland	15%
Shrub, Scrub, Grass	7%
Open Water	7%
Development	3%
Total	100%

2.0 Methods and Results

2.1 Data Sources

2.1.1 Minnesota Pollution Control Agency

The Minnesota Pollution Control Agency (MPCA) provides several useful GIS spatial data sets ready for download. A file with all feedlots in the state was particularly useful for this projects. The MN Feedlot data incorporates all registered feedlots in the state and lists the types and quantities of animals in the attribute table. MPCA also gives spatial data of all assessed and impaired waters per Section 303(d) and Section 305(b) of the Clean Water Act. The most recent (2012) assessment was used for this project.

2.1.2 National Land Cover Data

The National Land Cover Database (NLCD) operated by USGS provided the data for some of the land cover. This dataset gives a detailed multi-class breakdown of land use over the United States. The spatial resolution of the data is 30 meters and is mapped in the Albers Conic Equal Area Projection. Data was downloaded for 2001, 2006, and 2011.

2.1.3 University of Minnesota and Minnesota Department of Agriculture

Minnesota has 39 agroecoregions. Each agroecoregion is associated with a specific combination of soil types, landscape and climatic features, and land use. Agroecoregions are units having relatively homogeneous climate, soil and landscapes, and land use/land cover. A file geodatabase was acquired from the Minnesota Department of Agriculture. The resolution of the data is 30m.

2.1.4 NHDPlusV2

The National Hydrography Dataset is a digital vector dataset that contains hydrographic features including lakes, ponds, streams, and rivers. NHD flowlines provided valuable information for this project, including flows, velocities, and lengths for the streams and rivers analyzed in this project.

2.1.5 National Elevation Dataset

Elevation data was obtained through the National Elevation Dataset (NED). A 30m resolution digital elevation model (DEM) was created for the area of interest in order to derive a flow network using spatial analysis tools. The DEM was obtained through the GIS server.

2.1.6 Pollution Loading Data

Nutrient and coliform production and loading data came from several sources as the result of literature search. Oregon State University in conjunction with the EPA has a report entitled *Evaluating Coliform Concentrations in Runoff from Various Animal Waste Management Systems* (1998) which compiled many useful manure and coliform production and runoff data.

Nutrient runoff data from livestock was acquired from Edwards, et al. (2000) and NRCS (1995).

Crop Nutrient Runoff was obtained from a report compiled by the Food and Agriculture Organization of the United Nations[3]. It should be noted that the values for nutrient runoff vary greatly among farms depending on how much fertilizer is applied. Data was taken from that collected in Ontario, Canada, which was the most similar geographical location to the site of interest. For a more accurate model, specific data from the farms in the area of interest is necessary.

Surface water pollution data was obtained from the EPA Storet data warehouse. It is a collection of all water quality data collected and used by state, federal, university, and tribal agencies.

2.2 Results and Discussion

2.2.1 Nutrient Loading from Crops

Estimated yearly Nitrogen and Phosphorous loss data was taken from Edwards, et al. (2000) for several crop types. This paper gives estimated yearly N and P losses from a range of crop types in a similar climate to that of the Crow Wing River watershed. The USDA agroecoregions data was used to generate the distribution of crop types for the Crow Wing River watershed. The area associated with each crop type was multiplied by the estimated N and P losses to get an estimated yearly N and P loss due to runoff. The breakdown for each crop is given in Table A1 in the Appendix. The yearly N loss was determined to be 708,251 kg/yr for the watershed. The total yearly P loss was determined to be 41,548 kg/yr.

According to NHD, the average gauge adjusted flow for this watershed is 1396 cubic feet per second. The average concentration of each pollutant in the discharge of this watershed can be estimated as the yearly mass discharge divided by the yearly volume of water that passes through this watershed. This was determined to be 0.44 mg/l for N and 0.026 mg/l for P.

The average phosphorous level for the discharge of this watershed from the past 10 years according the Minnesota Pollution Control Agency is 0.06 mg/L with a standard deviation of 0.034. The average inorganic nitrogen level of this watershed from the past 10 years according to the MPCA is 0.30 mg/L as N with a standard deviation of 0.28. From these values it shows that the estimates for runoff are in the correct order of magnitude, but that the N runoff estimates are too great. These loadings are estimates for runoff from crops only. Livestock will contribute to the loading and will be considered subsequently.

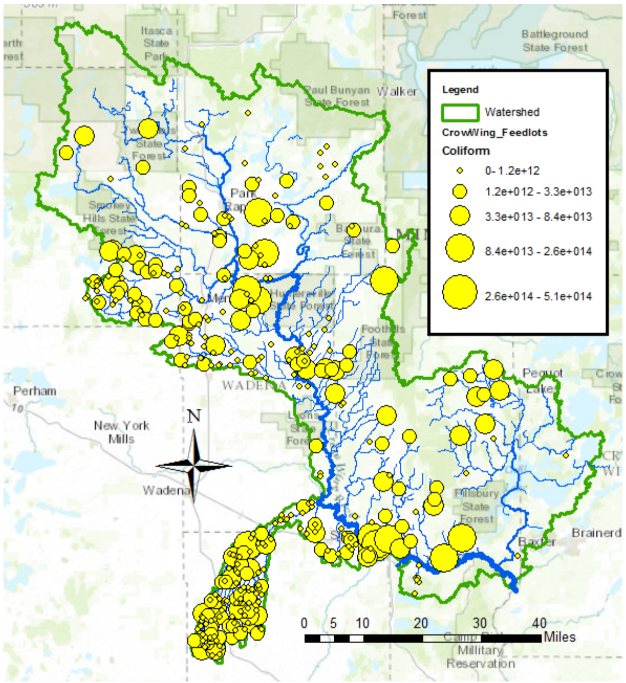
2.2.2 Livestock Pollution Production

The Minnesota feedlots dataset was extracted for the Crow Wing River watershed. The three types of livestock animals that comprise the majority of feedlot populations are bovines, pigs, and poultry. The National Resources Conservation Service (1995) nutrient loading data for various types of animals and the Oregon State coliform runoff report data was manipulated to estimate fecal coliform, nitrogen, and phosphorous production for each animal and thus for each farm. Estimating this production per animal is considered to be a fairly accurate and reasonable estimate. Unfortunately estimating the runoff from the feedlots into surface water and this the discharge for the watershed is a far more arbitrary evaluation as the amount of runoff will vary greatly depending on the management practices of each farm, the overland distance the runoff must travel to the nearest body of water, and the type of land over which the runoff will be routed. Based on the Oregon State review, a coefficient of 0.2 will be used to estimate the runoff from the production of each pollutant. A summary of this data is given in Table 2. Average weights for each animal were collected from NRCS (1995).

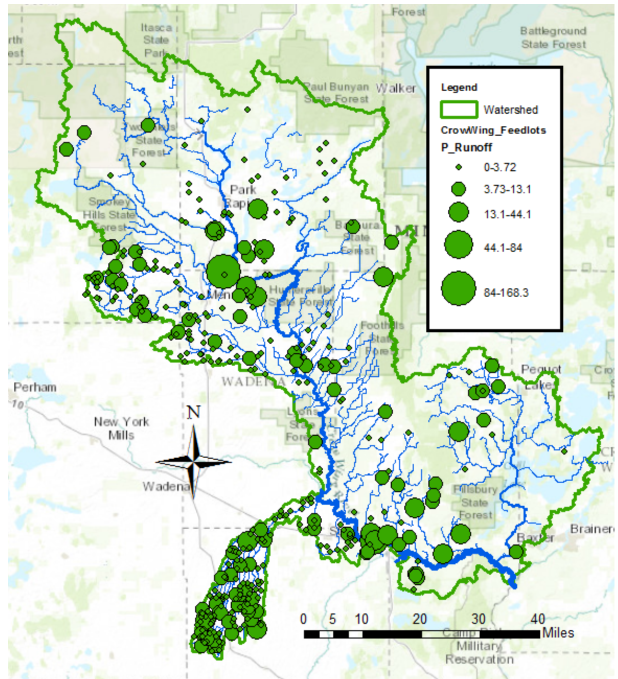
Table 2 Pollutant Production and Runoff from Livestock

	Livestock	Cattle	Pig	Poultry
	Wt (lb)	1200	200	4
	Manure Production (lbs/day)	80	12	0.21
	% Water	88%	91%	75%
Fecal Coliforms	Fecal Coliforms (coliforms/g manure)	2.00E+07	6.50E+05	1.30E+06
	Fecal Coliforms/ animal head/ day	7.27E+11	3.55E+09	1.24E+08
	Estimated Runoff (col./head/day)	1.45E+11	7.09E+08	2.48E+07
Total N	Total Nitrogen (lb/animal head)	0.48	0.084	0.0036
	Estimate Runoff (lb/head/day)	0.10	0.02	0.0007
Total P	Total P (lb/animal head/day)	0.12	0.032	0.00124
	Estimated P Runoff (lb/head/day)	0.024	0.0064	0.000248

Three fields were added to the feedlots attribute table. The field calculator was used to multiply the number of animal heads for each animal by the associated estimated coliform, nitrogen, and phosphorus loadings. The estimated pollutant runoff for each feedlot is represented in Figure 3 with graduated symbols. The NADPlus V2 flowlines are also shown for reference. The coliform data was spatially joined with the sub-watersheds and a coliform loading density was calculated as coliform runoff loading per sub-watershed surface area and is shown in Figure 4. The Coliform Densities were stratified qualitatively to show the relative level per sub-watershed. Several spatial interpolation techniques were ran on the data to generate images for spatial loading and runoff. Kriging, Empirical Bayesian Kriging, Spline, Thiessen, and Natural Neighbors methods were all ran. Many produced interpolated values outside of the reasonable range, often negative. The Natural Neighbor and Empirical Bayesian Kriging interpolations appeared to be the most reasonable in this regard and is shown in Figure 5. Note that these figure are purely to get an idea of macro-scale loading in this watershed, and the values do not indicate the actual loading at any given point. The average estimated runoff loading can be used to estimate the average discharges for the watershed into the Mississippi River. For the purposes of this report, N and P will be treated as inert and fully suspended or dissolved in the water. In reality, algae and other microorganisms would be consuming these nutrients. Using the average flow, and daily runoff loadings, the average N and P concentrations at the outlet of the watershed were estimated to be 0.57 and 0.15 mg/L respectively. This is higher than the measured 0.3 and 0.06 mg/L N and P respectively that is seen at the outlet gage, however, many conservative assumptions went into the model and it is comforting that they hypothesized and observed values are roughly on the same order of magnitude.



(a.)



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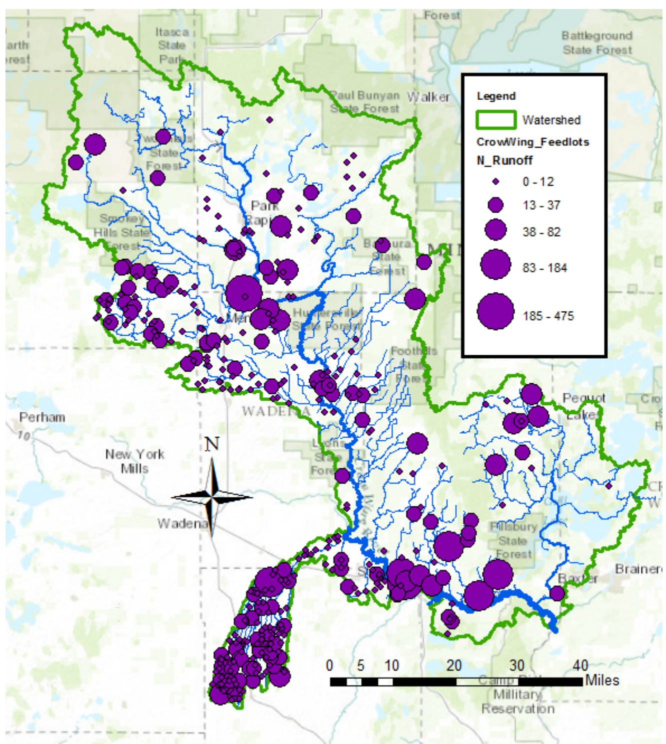


(c.)

Figure 3 Estimated Average Runoff per Farm (a.) Coliforms, (b.) Phosphorus (lb. /day), (c.) Nitrogen.

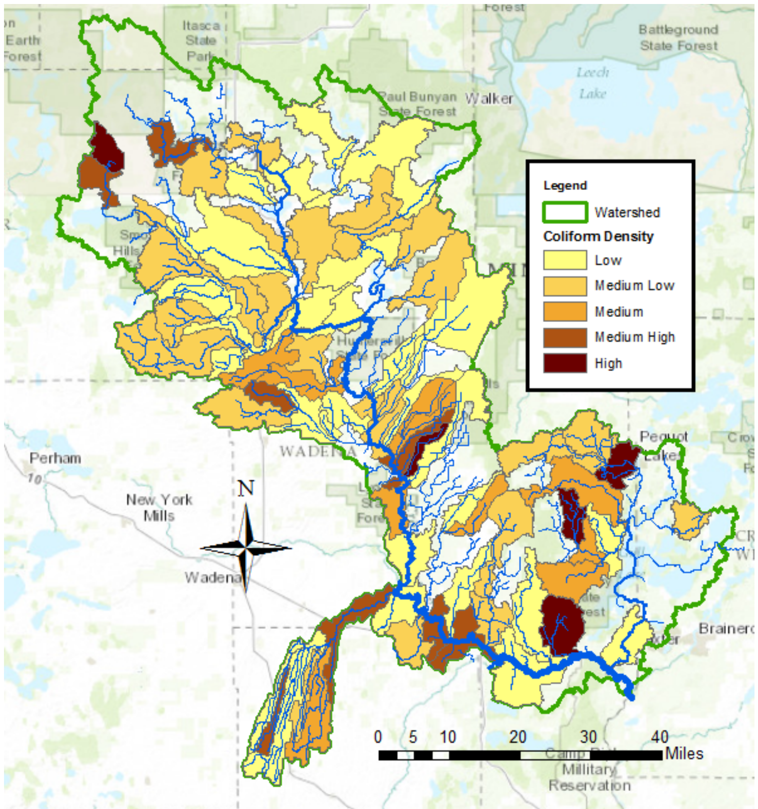
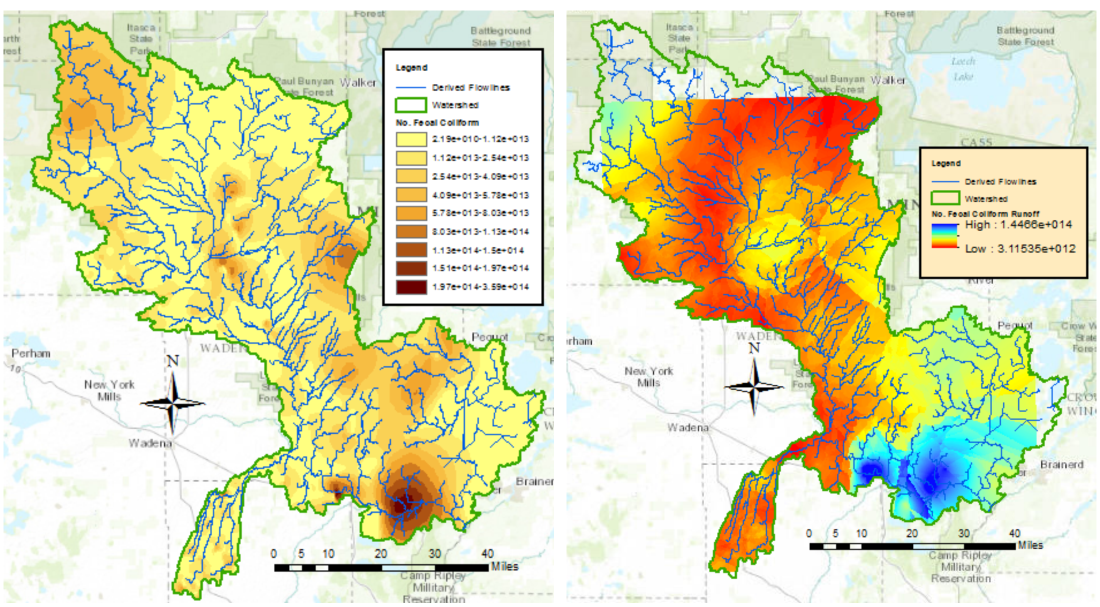


Figure 4 Coliform Runoff Density per Subwatershed



(a) (b)

Figure 5 (a) Natural Neighbor and (b) Empirical Bayesian Kriging Interpolation of Produced Coliform Runoff

For the fecal coliform discharge of the watershed, a more complex analysis is required. Fecal coliforms are living organisms that thrive in the digestive tracks of animals, but do not survive particularly well outside of these tightly controlled anaerobic environments. Therefore, after being excreted by animals and diluted by runoff and streams, the bacteria begin to die at an exponential rate. In modeling the discharge fecal coliforms from the watershed, the die off of the bacteria must be considered. The number of active coliforms at a given time from leaving an animal is given by the following equation:

$$N_t = N_o e^{-kt}$$

Where N_t is the active number at a given time, N_o is the initial number, k is a die-off constant, and t is time. The OSU coliform report (1998) references a study by McFeters and Stuart (1972) that found a k values of 2-3.1 $days^{-1}$ for natural waters at pH=8.1 for a range of temperatures of 4-6 ^oC. For this report, a value of 3 $days^{-1}$ is chosen. For further analysis, the travel time from a feedlot to the output of the watershed is needed. The average travel time (hydraulic residence time) of a given stretch of stream can be found by dividing the length of the stretch by the velocity. A travel time feature was added NHDPlus V2 calculated from the gage adjusted flows and velocities for each stream segment. For each farm a travel time to the outlet can be found using network analysis to trace downstream and sum the travel time for the selected stretch.

Network analysis could not be performed on the NHDPlus V2 flow lines, so flowlines were derived from the DEM using spatial analysis tools. A DEM for the watershed was extracted from the NED. Sinks in the DEM were filled using the fill tool available through the spatial analyst extension. A flow direction raster was generated from the filled raster, then a flow accumulation raster. Streams were defined via map algebra as grid cells with an accumulation greater than 5000. Stream links were generated for the stream raster, and then converted into vector format. The watershed discharge gage was added and snapped to the derived flowlines. The derived flowline vectors and the discharge gage were used to create a geometric network so that network analysis could be performed. The derived flowlines did not have the flows, velocities, or travel times attributed to them, so the Transfer Attributes tool was used to transfer the needed NHD attributes to the derived flowlines using a selection distance of 200 meters. The result was a network of flow lines with the travel times assigned to each segment of stream so an accurate flow path travel time could be found for any point in the watershed (given a close proximity to the streams) via network analysis. Figure 6 shows the derived network of flowlines.

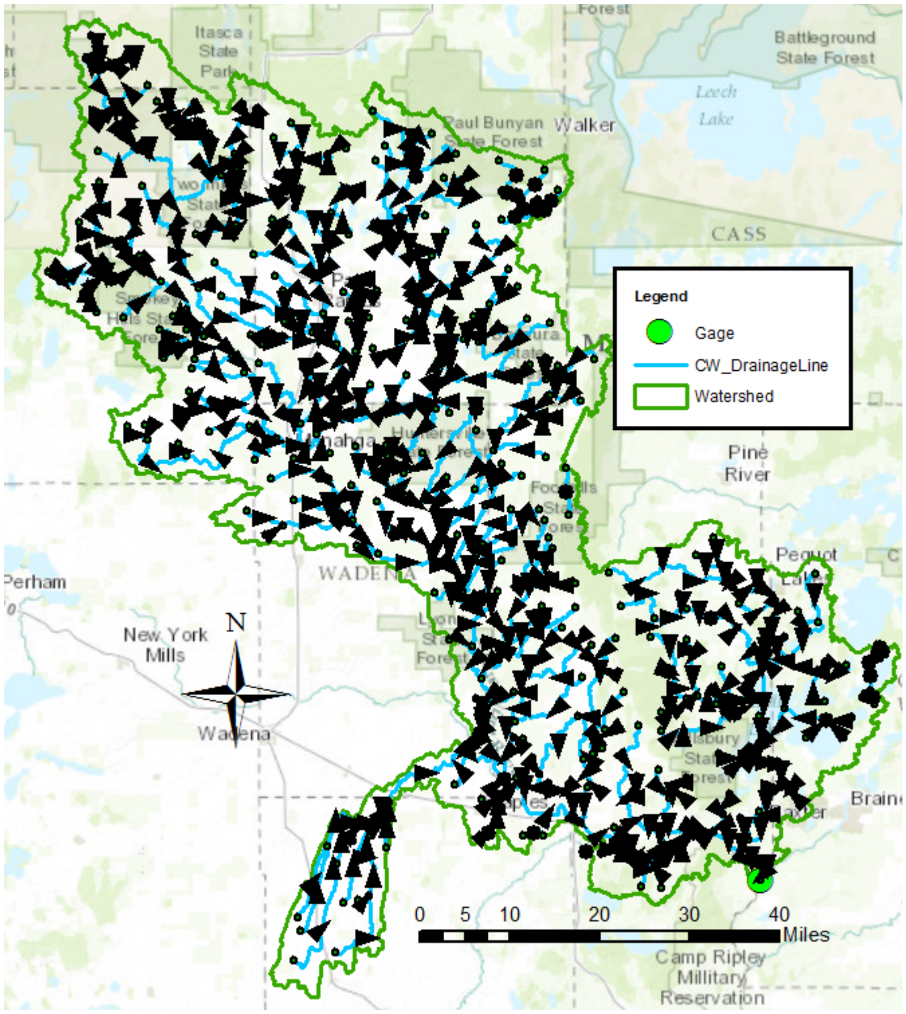


Figure 6 Derived Drainage Network

Three farms were chosen to demonstrate the fecal coliform model. These farms were chosen based on their proximity to streams and their spatial variability within the watershed. The farms and their selected downstream flowlines are shown in Figure 7. The calculated fecal production and contribution to the discharge of the watershed for each of these farms is given in Table 3. The average fecal coliform discharge at this watershed, per MPCA measurements from the past ten years, is 21.4 most probable number per 100mL, or 214 per liter. It is promising that the modeled results are of a magnitude which could be considered reasonable for the contribution of one farm. With appropriate coding, one could develop a program to calculate the predicted fecal coliform contribution of each of the 372 farms in the watershed to the discharge of the watershed in the Mississippi by this method.

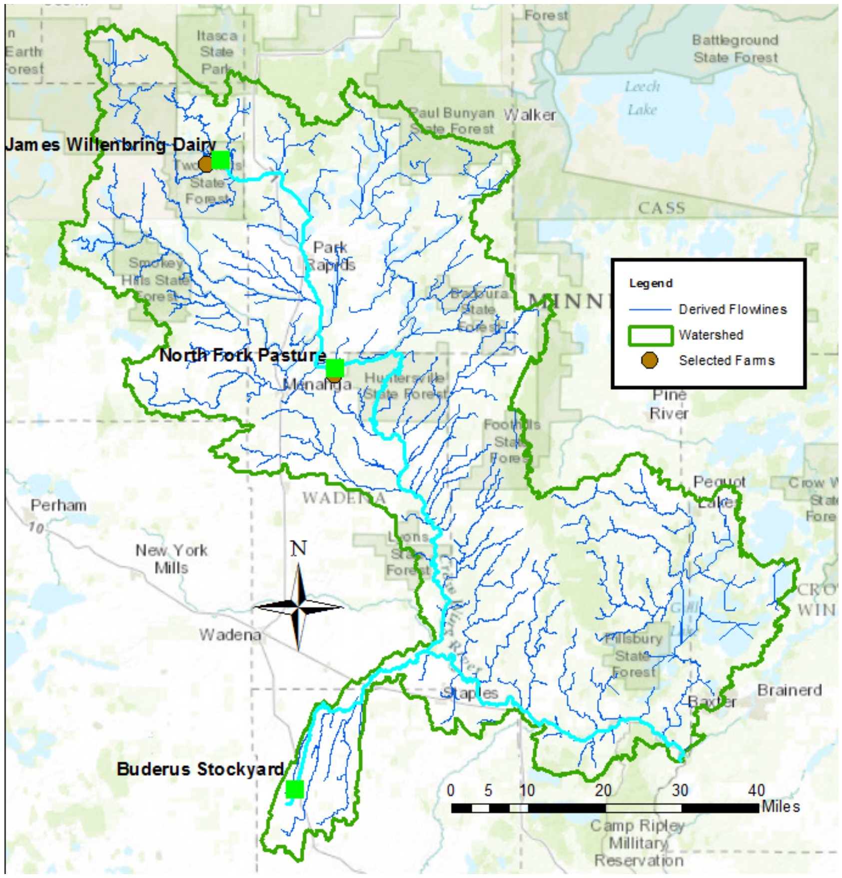


Figure 7 Selected Farms and Downstream Flow Path

Table 3 Summary of Fecal Coliform Production and Contribution to Watershed for 3 Selected Farms

Farm	Primary Animal	Number	Distance to stream (m)	Distance Downstream (km)	Travel Time (days)	Initial Fecal Coliform (#)	Coliforms at outlet (#)	Concentration at outlet (#/L)
North Fork Pasture	Bovine	712	1500	105.9	3.12	3.625E+13	3.11E+09	0.71
Buderus Stockyard	Bovine	356	60	107.1	3.37	5.162E+13	2.09E+09	0.48
James Willenbring Dairy	Bovine	250	100	138.3	4.29	1.03E+14	2.68E+08	0.06

2.2.3 Investigation of Impaired Water Bodies

The Minnesota Pollution Control Agency is responsible for assessing surface water bodies and compiling a list of impaired water bodies every year per Clean Water Act 303(d). The impaired water bodies for this region are overlaid with the flowlines and the interpolated coliform runoff loading in Figure 8. The vast majority of the impairments are for mercury contamination, which is a historical problem from the mining in northern Minnesota and the burning of coal for power. There are several nutrient impairments in lakes towards the outlet of the watershed which is expected. There are no bodies of water with coliform impairments. This model could be used to ensure that livestock farming growth remains in check to prevent these impairments.

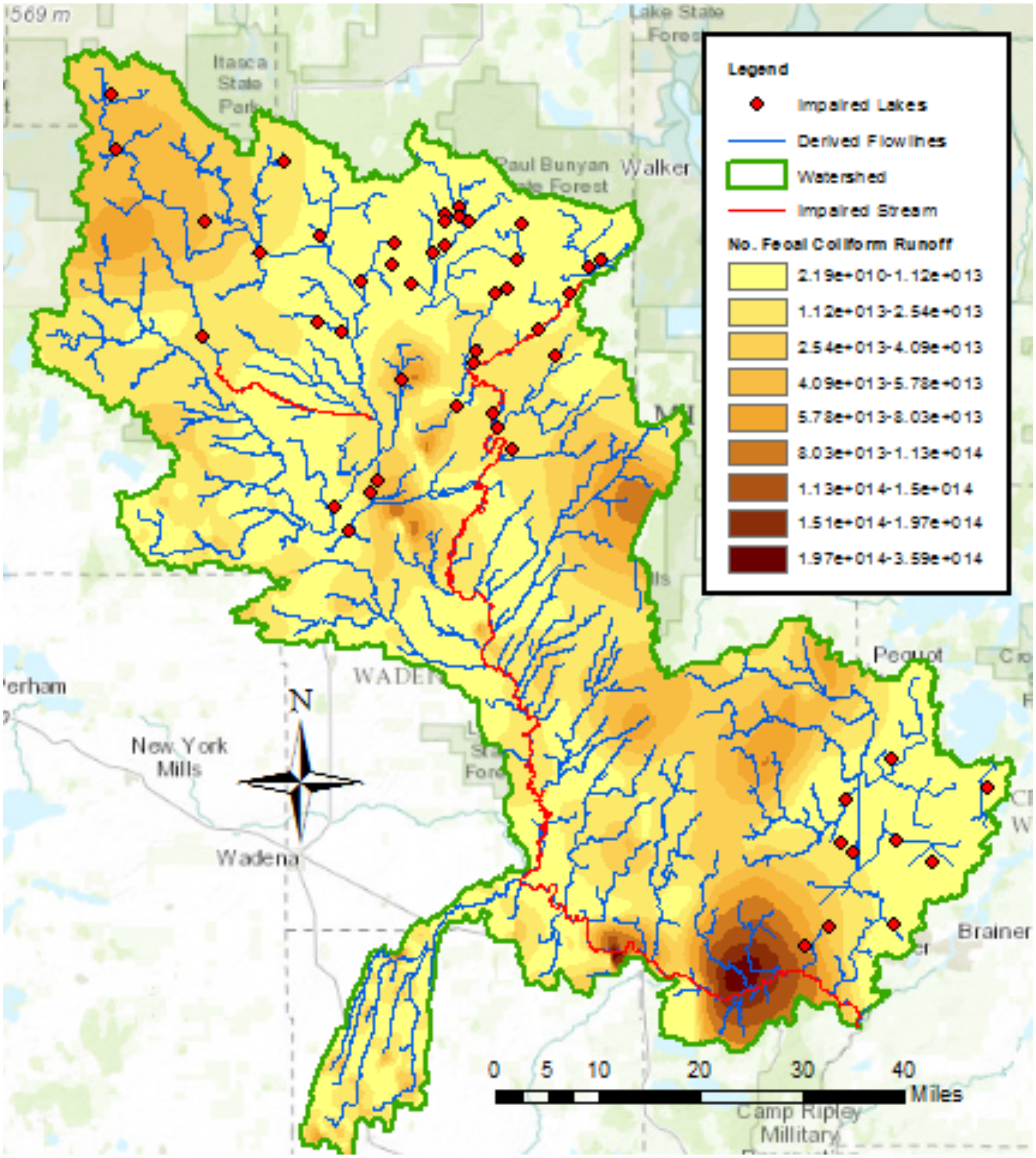


Figure 8 Impaired Water Bodies

2.2.4 Composite Analysis

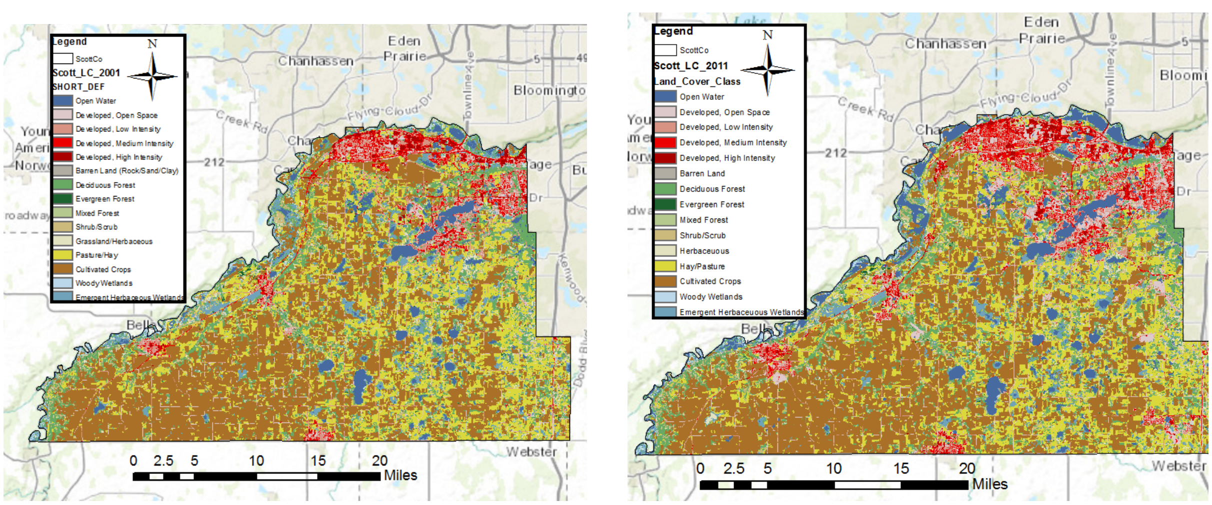
Total Pollutant discharges from the Crow Wing River watershed for both crop and livestock sources are compiled in Table 4. As previously stated, the predicted fecal coliform level could be computed using a program. Examples were given in Section 2.2.2 on how this is done for each farm. The nitrogen and phosphorus concentrations estimated at the outlet are about a factor of ten greater than those observed. This is likely due to the conservative estimates made on the loading. With a greater understanding of nutrient transport in the watershed a more accurate prediction could be made. The livestock loadings seem to be the source of the over prediction, particularly with the phosphorus loading. 20% of manure was assumed to runoff from each farm, which is certainly on the high side. Knowledge of each farm's runoff management practices would allow for a more accurate estimate.

Table 4 Total Pollutant Loading and Concentrations at Watershed Outlet

Criteria	Fecal Coliforms	Nitrogen	Phosphorus
Crip Runoff Loading (kg/yr)	--	708,252	41,549
Livestock Runoff Loading (kg/yr)	5.33E+18 (MPN)	4,451,832	1,148,290
Total Runoff Loading (kg/yr)	5.33E+18 (MPN)	5,160,084	1,189,839
Predicted Concentration at Watershed Outlet (mg/l)	Requires Program Development	3.22	0.74
Measured Concentration at Watershed Outlet (mg/l)	214 (MPN/L)	0.3	0.06

2.2.5 Other Investigations

An initial goal of this project was to look at how land use changes affect types of pollution over time. The NLCD was used for Scott County which has seen a high level of development in the past 15 years. Land cover was compared for 2001 and 2011 and is shown in Figure 9. Scott County saw a 35% increase in development and a 6% decrease in farmland during this time period. Upon investigating the impaired waterbodies during this time period, 18 new impairments were found, but further investigation showed that this was because more waterbodies were assessed during this period. EPA Storet data was investigated as well for this area, but many of the gages were only active in a single location for one or two years. The gages which were consistent showed very little changes in pollution profiles during this time period. Due to a lack of noticeable patterns, this thrust of the project was abandoned.



(a) 2001 (b) 2011

Figure 9 Scott County Land Use Change

3.0 Conclusion and Future Work

Agriculture runoff loadings for nutrients and coliforms were estimated based on literature and the hydrography of the Crow Wing River watershed. ArcGIS was a valuable tool for manipulating and analyzing this spatial data. The Crow Wing River watershed is currently healthy with respect to its water bodies. As agriculture industry in the region increases, it is important to monitor pollution runoff to ensure the water quality in the region. The model predicted nutrient values greater than that which was measured via MPCA gages. The coliform loading was considered to be roughly of the correct order of magnitude. With further development and more accurate data inputs, this model could be used to help insure that growth is managed responsibly.

Many simplifying assumptions were made in the development of this model. Future work could include decompressing these assumptions and simplification to provide a more accurate model. Currently, only the average yearly discharge and runoff levels were considered. It would be particularly valuable to look at runoff loading based on daily precipitation levels, since real runoff would cause peaks of pollutant discharge much greater than that of the yearly average. Seasonality also plays a role in this story, since most of the surface water in the region is covered by ice for about 3-4 months of the year. Runoff loading from the livestock manure was also a very rough estimate since it greatly depends on the management practices of the farm. Deposition of any manure runoff into the soil during transport to the nearest body of water would be valuable to look into, since it is likely that there is a high level of adsorption to the soil. If a program were developed to find the network downstream segments for each farm in succession, the total fecal coliform discharge into the Mississippi could be estimated. Ideally, I would like to use the coliform model in conjunction with the USGS Sparrow model which is able to consider pollutant fate. Overall GIS has been a valuable tool for analyzing water resources through the lens of water pollution.

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Appendix

Table A1: Nutrient loss per crop type

CLASS_NAME	COUNT	Area m^2	Area km^2	Hectares	Estimated Yearly N Losses (kg/ha/yr)	N Loss (kg/yr)	P Loss(kg/yr)
Corn	155439	139895100	139.8951	13989.51	26	363727.26	5805.64665
Sorghum	10	9000	0.009	0.9	4	3.6	0.3735
Soybeans	57268	51541200	51.5412	5154.12	4	20616.48	2138.9598
Sunflower	874	786600	0.7866	78.66	4	314.64	32.6439
Sweet Corn	6	5400	0.0054	0.54	26	14.04	0.2241
Barley	858	772200	0.7722	77.22	4	308.88	32.0463
Spring Wheat	45859	41273100	41.2731	4127.31	4	16509.24	1712.83365
Winter Wheat	61	54900	0.0549	5.49	4	21.96	2.27835
Rye	1615	1453500	1.4535	145.35	4	581.4	60.32025
Oats	9853	8867700	8.8677	886.77	4	3547.08	368.00955
Millet	163	146700	0.1467	14.67	4	58.68	6.08805
Canola	53	47700	0.0477	4.77	4	19.08	1.97955
Flaxseed	14	12600	0.0126	1.26	4	5.04	0.5229
Alfalfa	104811	94329900	94.3299	9432.99	4	37731.96	3914.69085
Other Hay/Non Alfalfa	449242	404317800	404.3178	40431.78	4	161727.12	16779.1887
Sugarbeets	40	36000	0.036	3.6	4	14.4	1.494
Dry Beans	54976	49478400	49.4784	4947.84	4	19791.36	2053.3536
Potatoes	47479	42731100	42.7311	4273.11	4	17092.44	1773.34065
Other Crops	272	244800	0.2448	24.48	4	97.92	10.1592
Peas	26	23400	0.0234	2.34	4	9.36	0.9711
Herbs	18	16200	0.0162	1.62	4	6.48	0.6723
Clover/Wildflowers	1412	1270800	1.2708	127.08	4	508.32	52.7382
Sod/Grass Seed	7	6300	0.0063	0.63	4	2.52	0.26145
Fallow/Idle Cropland	4239	3815100	3.8151	381.51	4	1526.04	158.32665
Developed/Low Intensity	12750	11475000	11.475	1147.5	4	4590	476.2125
Grass/Pasture	165072	148564800	148.5648	14856.48	4	59425.92	6165.4392
Cranberries	2	1800	0.0018	0.18	4	0.72	0.0747
					Total:	708251.94	41548.84965