Technical Memorandum: Twin Metals Mining and the Boundary Waters Canoe Area Wilderness, Risk Assessment for Underground Metals Mining

Prepared for: Northeastern Minnesotans for Wilderness, Ely MN

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August 8, 2014

Summary, Conclusion and Recommendations

The study presented herein further develops an earlier conceptual flow and contaminant transport model for ground and surface water flow through the Rainy River Headwaters watershed, including the Kawishiwi River, Isabella River, Birch Lake, and Stony River watersheds, in Northeastern Minnesota. The purpose is to estimate pathways and rates for contaminant transport to reach the Boundary Waters Canoe Area Wilderness (BWCAW) due to the development of mining leases, which could occur within the Birch Lake and Stony River watersheds. The conceptual models are converted into reconnaissance level numerical models to estimate the risk of mine spills and leaks on the BWCAW, and lakes and rivers between the proposed mines and the wilderness.

There are two aquifers in the area- a surficial aquifer and a bedrock aquifer. The surficial aquifer, consisting of either glacial till or sand and gravel, is very thin, averaging about 15 m thick. The hydraulic conductivity is highly variable but generally higher than 1 ft/d. Underlying the surficial aquifer is bedrock generally of the Duluth Complex. Porosity depends on many factors but the summary is that shallow bedrock, except for shale and the Biwabik, should have porosity exceeding 10% and that below 2500 feet (750 m) porosity should be 5% or less. The Biwabik Iron Formation has porosity as high as 50%. The upper 125 m would have higher porosity due to a combination of fracture and matrix porosity. The primary bedrock conductivity is generally low but secondary conductivity is high. This means that groundwater may flow at relatively high rates through bedrock fractures but only in certain areas.

Baseflow, or recharge, varies from 5.66 to 9.52 inches/year (in/y), although for watersheds with more than 100 square miles, the range is from 6.7 to 8.2 in/y. This was based on baseflow recession analysis of the major stream gages within the watersheds. Baseflow is approximately 70% of total streamflow. Stream flow is about 39% of total precipitation across the watershed.

The numerical flow model accurately simulates groundwater flow around the model domain from recharge to discharge to rivers, streams and lakes. Calibration of model parameters was based on matching groundwater levels to observed levels in wells and mining boreholes and on matching discharges to measured baseflows. The wells used for calibration were clustered in a few areas mostly near the mine leases (due to exploration activities). To improve the accuracy of the calibration, additional groundwater levels were added under the ridgelines where it was possible to assume a likely depth to water and by controlling the groundwater level with a connection with surface water.

Horizontal conductivity controlled flows in the numerical model more than vertical conductivity. Each bedrock formation had zones with conductivity varying over at least two and usually three or four orders of magnitude. There is substantial variability, especially in the bedrock as would be expected in a heterogeneous domain with fractures. Conductivity decreases with depth for most formations as expected due to compaction. In some areas, vertical conductivity is higher than horizontal, which establishes a tendency for vertical flow. Birch Lake and the South Kawishiwi River are convergence zones for flow with upward flow from deeper layers reaching these sinks.

The numerical transport model developed herein demonstrates that the time it takes for leaks to reach the BWCAW will depend on where they occur. Particle tracking along the flow paths show that deeper sources have a longer travel time to surface water, however deep sources near the rivers will transport through groundwater discharge to those rivers in times on the order of decades. Shallow leaks and leaks to groundwater from the surface will reach the streams more quickly, in some cases within less than a year but certainly within a few years. This does not account for leaks that travel on the surface to the rivers. These would not disperse through the groundwater and travel time would be immediate. Shallow leaks in the headwaters would reach tributaries and eventually flow into Birch Lake. Particle tracking showed that contaminants from deep sources in the Stony River watershed eventually reach the BWCAW to the northeast in the Kawishiwi watershed. This is an example of groundwater flowing across a topographic divide.

The choice of representative loads from the mines to be added to the systems was based on professional experience and the predicted loads expected at the nearby proposed Polymet Mine. At that mine, it was found that if the engineering design did not operate perfectly, aquatic conditions would be severely degraded[1]. The assumption for developing the deposits in the Stony River or Birch Lake watershed is that strict engineering would apply, but that it would also fail and leaks would occur. Surface leaks were assumed to last for a year and underground sources were assumed to seep for a year, based on a typical scenario in which the deposit would be saturated and oxidation would cease.

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[1] The conclusion regarding the reliance of the Polymet mine plan on engineering is the opinion of this author as detailed in Myers (2014). If any of the design functions less efficiently than modeled by Polymet (2013a), the resulting contamination would be much higher than predicted.

The transport analysis assumes conservative, meaning no geochemical transformations or sorption, transport of sulfate, but it could be any other conservative substance with the load added as described. The concentrations reported herein are entirely dependent on the assumptions made for the load and should not be considered predictions. Rather, they are an example of what could happen in the watershed if the leaks as assumed occur. The concentrations reported in Table 9 are those that could be seen in the streams during baseflow because the flow model simulates the entire baseflow discharge. Tracking them downstream, the entire baseflow can be considered a load. The table shows that the effect on the streams is highly dependent on the location of the source.

The modeling completed herein has shown that substantial contaminant loads can reach streams that drain to the BWCAW due to either deep underground or surface leaks. During much of the year, sufficient flow enters the system to dilute this load before it reaches the BWCAW. However, during baseflow conditions, the load could substantially affect the tributary streams, especially within the Stony River and Birch Lake watersheds. While the watershed is experiencing low flow conditions, the concentration at the Kawishiwi River at Winton, within the BWCAW, could be increased above that at baseflow by five orders of magnitude for the 7Q20[2] flow. This is due to the rivers losing flow in a downstream direction during very low flow periods. In other words, leaks that may have minimal effects much of the year could be devastating at low flow. Once started, leaks will continue to discharge to the rivers for decades due to dispersion during groundwater transport, and will likely coincide with 20-year or longer return period low flows. The potential that leaks will damage the Wilderness is high.

Major spills that could occur within the watersheds would affect the lakes and rivers much differently than the long-term discharge of leaks. Spills can devastate the local area but they mix through the lakes so that the concentration decreases before reaching the BWCAW. Birch Lake would attenuate loads entering it from any of the leases upstream of the lake. Effectively, the load mixes through the effective portion of the lake which in this analysis was assumed to be the eastern half due to freshwater entering the west end. The concentration leaving Birch Lake could be toxic, but will drop two orders of magnitude passing through White Iron Lake. Farm Lake and Garden Lake will further lower the concentration by two orders of magnitude. If the spill occurs downstream of Birch Lake (for instance, at the proposed processing site), White Iron Lake will attenuate the contaminants so that the concentration leaving the lake would be about a quarter that of the same load in Birch Lake. This much higher concentration flows north and continues to attenuate as described previously, but with a much larger chance of damaging the BWCAW. In summary, lakes will attenuate spills by mixing but the effects on the

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[2] A low flow average flow rate Q over 7 days at a 20-year return interval.

lakes and wilderness can be devastating if the substance is highly toxic or if the load is sufficiently large.

These results show that leaks from mines in the watershed leading to the BWCAW could have substantial effects on the wilderness. Catastrophic spills were not considered but the impacts would be much more significant. Spills would not likely transport through the groundwater, so the potential concentrations would simply be the load divided by the flow rate.

This discussion focuses on the peak impact of a spill, but an important point is that leaks, even when stopped within a short time period, will continue discharging to the rivers for many years, sometimes as long as centuries due to dispersion during transport through the groundwater. A leak is not a simple thing to remediate, so it is critical to prevent leaks, which has historically been shown to be almost impossible. If mineral deposits in the Rainy Headwaters are developed, it is not a question of whether, but when a leak will occur that will have major impacts on the water quality of the Boundary Waters Canoe Area Wilderness.

Introduction

Myers (2013c) developed a conceptual flow and transport model for the Birch Lake watershed to assess the potential for contamination from developing mineral leases in the Rainy Headwaters reaching the Boundary Waters Canoe Area Wilderness (BWCAW). The BWCAW is downstream of flows and contaminants originating in the Rainy headwaters. Flow and contaminants pass through BWCAW to flow through Voyageurs National Park to Lake of the Woods. Myers (2013c) found there are seven primary risks to water resources in the BWCAW from the development of mines at the Twin Metals leases. They are risks to water quantity from mine dewatering and production water development; risks to water quality from the development and seepage of acid mine drainage (AMD), seepage of tailings water, tailings impoundment failures, and runoff of sediment from the site due to stormwater; and wetlands disturbance. Failure of pipelines used to slurry ore or tailings from the mines to sites outside of the watershed is an eighth threat.

This technical memorandum builds on the conceptual flow and transport model by expanding it to the entire Rainy Headwaters watershed and creating a reconnaissance level numerical model to assess potential transport of contaminants from the mineral deposits to the BWCAW. The conceptual flow model (CFM) includes groundwater and surface water, including runoff processes, recharge (and seepage of waste), groundwater flow, and discharge to surface water. This technical memorandum develops the quantitative water balance for the area by estimating recharge and actual baseflow by watershed.

The numerical model simulates the pathways and flow times for contaminants discharging from the different deposits at different depths to the streams which transport them to the BWCAW. The modeling utilized the USGS flow and transport codes MODFLOW2000 (Harbaugh et al. 2000) and MT3DMS (Zheng and Wang 1999). Reconnaissance level means the model is designed to detect general trends and order of magnitude time estimates rather than make exact predictions. The model developed herein does provide a base for more detailed modeling as more data becomes available or if more detailed assumptions become justified. The model also provides a base for more detailed simulation of various mining scenarios including contaminant sources emanating from any location or depth within the domain. The model, with estimates of transient parameters for the modeled formations, could also be used to estimate the effects of mine dewatering due to underground or open pit mining.

Conceptual Flow and Transport Model

General Area

The Twin Metals leases lie south of the South Kawishiwi River. The South Kawishiwi River flows west from the BWCAW after splitting from the Kawishiwi River and then rejoins the Kawishiwi and flows back into the BWCA. The Kawishiwi watershed is in the Rainy River Headwaters watershed (http://www.dnr.state.mn.us/watersheds/map.html) (Fig. 1). The river system connects many lakes, some of which are manmade, with more than 40% of the channel length within lakes (Siegel and Ericson 1981). The area lies in two Minnesota groundwater provinces, the Arrowhead and Central Region, and in the fractured igneous or metamorphic bedrock province (http://www.dnr.state.mn.us/groundwater/provinces/index.html). In this area both surficial and bedrock groundwater is considered limited.

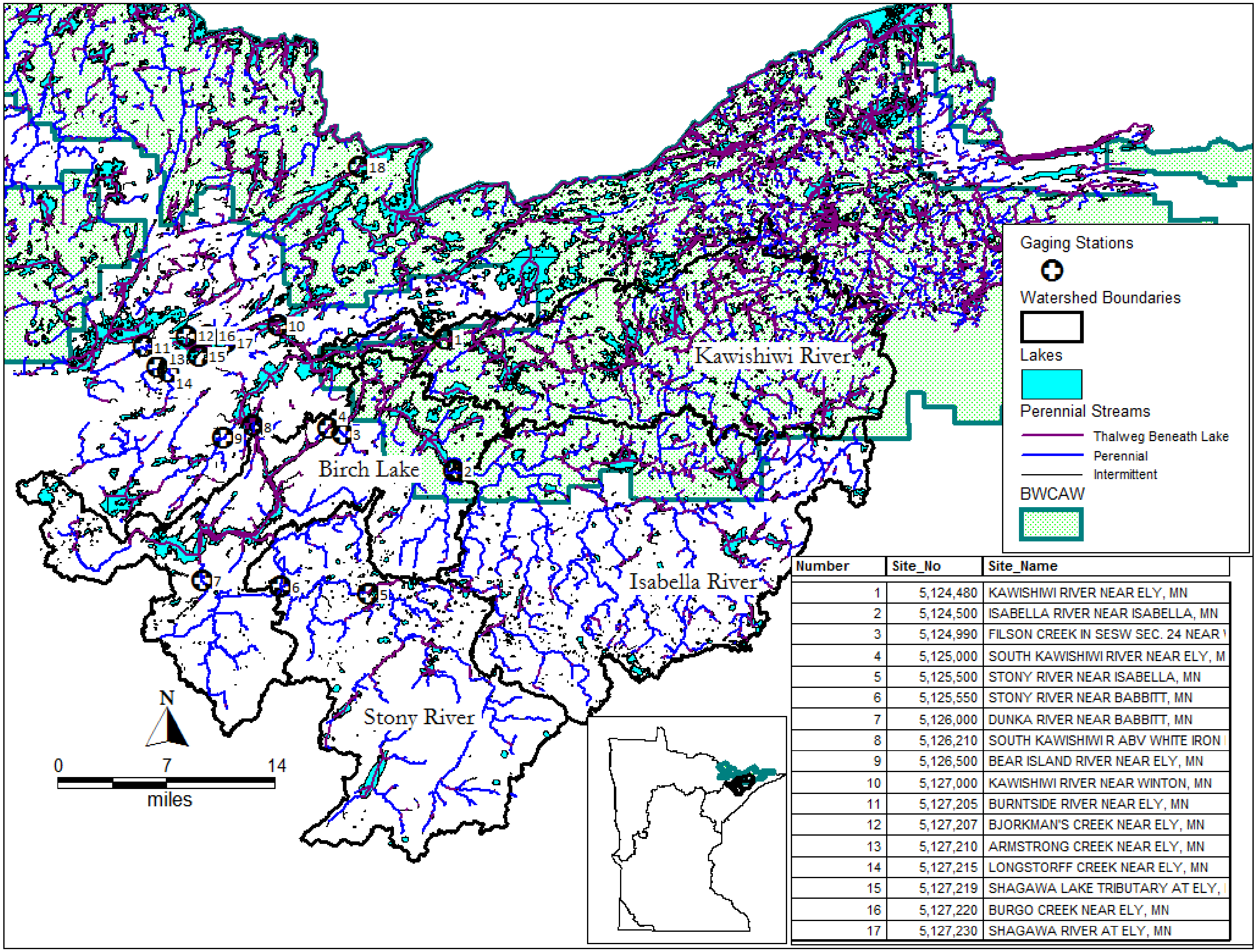
Hydrogeology

The mineral leases are hosted in the Duluth Complex, which is “composed of multiple discrete intrusions of mafic to felsic tholeiitic magmas that were episodically emplaced into the base of a comagmatic volcanic edifice between 1108 and 1098 Ma” (Miller et al. 2002, p 109). The complex dips southeastward with basement rock of Archaen age, which means it becomes deeper in that direction. The Duluth Complex has not been significantly deformed, but displacements due to reactivated basement faults and some cross faults have affected it (Miller et al. 2002). Faults trend north-northeasterly with the maximum offset being 400 feet. Many of the streams may coincide with fault/fracture zones (Stark 1977).

There are two aquifers in the area- a surficial aquifer and a bedrock aquifer. The surficial aquifer, consisting of either glacial till or sand and gravel, is very thin, generally less than 10 feet thick but with some areas especially in the west being 20 feet or slightly more thick (Mast and

Turk 1999). One study found the hydraulic conductivity (K) of the sand gravel ranged from 0.4 to 362 ft/d and for Rainy lobe till from 0.04 to 6.7 ft/d (Stark 1977). Another study found that K for sand gravel ranged from 0.004 to 15.5 ft/d and for Rainy lobe till from 0.000021 to 0.13 ft/d (Siegel and Ericson 1981). These authors (Id.) concluded based on additional data sources that K ranged from 10 to 3500 ft/d for sand and gravel, 0.01 to 30 ft/d for Rainy lobe till, and from 0.00001 to 0.1 ft/ for peat and Des Moines lobe till (Id.). Overall, K ranges from 0.00001 ft/d to 3500 ft/d (0.00000305 to 1067 m/d), or nine orders of magnitude, for the surficial aquifer.

South of the South Kawishiwi River, the bedrock underlying the surficial aquifer is generally of the Duluth Complex (Miller et al. 2002) (Fig. 2, Table 1). Much of the bedrock data is from a study of CO2 sequestration potential (Thorleifson 2008). Hydrogeologically, the Duluth Complex is a low-permeability intrusive formation with a very low K except possibly near some of the infrequent faulting, on which there is available little hydrogeologic data. Porosity depends on many factors but the summary is that shallow bedrock, except for shale and the Biwabik, should have porosity exceeding 10% and below 2500 feet (750 m) porosity should be 5% or less. The Biwabik has porosity as high as 50% and shale is probably less than 5%. Fractures increase the porosity indicating the upper 125 m would have higher porosity due to a combination of fracture and matrix porosity.



Number	Site_No	Site_Name
1	5,124,480	KAWISHIWI RIVER NEAR ELY, MN
2	5,124,500	ISABELLA RIVER NEAR ISABELLA, MN
3	5,124,990	FILSON CREEK IN SESW SEC. 24 NEAR
4	5,125,000	SOUTH KAWISHIWI RIVER NEAR ELY, M
5	5,125,500	STONY RIVER NEAR ISABELLA, MN
6	5,125,550	STONY RIVER NEAR BABBITT, MN
7	5,126,000	DUNKA RIVER NEAR BABBITT, MN
8	5,126,210	SOUTH KAWISHIWI R ABV WHITE IRON
9	5,126,500	BEAR ISLAND RIVER NEAR ELY, MN
10	5,127,000	KAWISHIWI RIVER NEAR WINTON, MN
11	5,127,205	BURNTSIDE RIVER NEAR ELY, MN
12	5,127,207	BJORKMAN'S CREEK NEAR ELY, MN
13	5,127,210	ARMSTRONG CREEK NEAR ELY, MN
14	5,127,215	LONGSTORFF CREEK NEAR ELY, MN
15	5,127,219	SHAGAWA LAKE TRIBUTARY AT ELY,
16	5,127,220	BURGO CREEK NEAR ELY, MN
17	5,127,230	SHAGAWA RIVER AT ELY, MN

Fig. 1: Rainy headwaters watershed and study area, showing subwatersheds, gaging stations (Table 2), and flow arrow for general flow direction through the watershed. Watershed boundaries from Dnr100kwatersheds, www.mngeo.state.mn.us/chouse/metalong.html

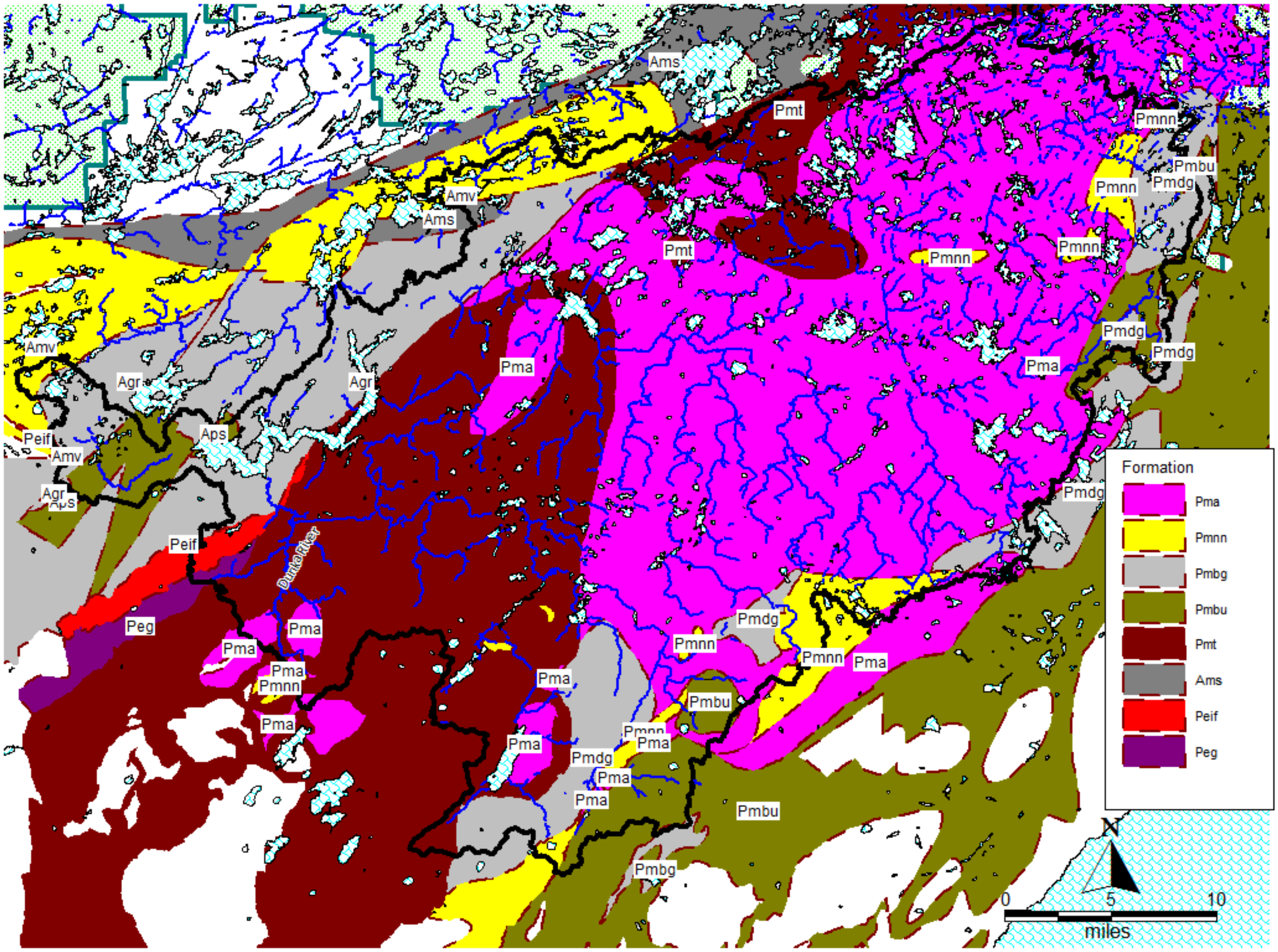


Fig. 2: Bedrock geology of the study area. See Table 1 for a description of the formations.

Table 1: Geologic formations and basic properties.

Label	Primary Rock Type	Secondary Rock types	
Pmt	troctolite	gabbro,	Duluth Complex
Pma	anorthosite	gabrro	Duluth Complex
Pmnn, Amv	basalt	rhyolite, sedimentary rocks	
Agr	granite	granodiorite	Giants Range Granite
Pmbu	gabbro	troctolite	
Peif	iron formation	arenite	Biwabik
Peg	shale	siltstone	

Groundwater in near-surface bedrock is unconfined and hydraulically connected with that in the surficial aquifers, except where the overlying K is extremely low (Siegel and Ericson 1981). Where the surficial aquifer has low K, the bedrock aquifer may be confined. The bedrock tends to be relatively fractured in its upper several hundred feet (Id.). The plutonic rocks have primary porosity up to 3%, but this is not effective and the permeability is very low in the Duluth complex because the pores are isolated (Stark 1977). Weathering and faulting can increase the permeability along fracture zones. The specific capacity of wells in the Duluth Complex ranges from 0.02 to 0.11 gpm/ft, in the Giants Range granite around 0.03 gpm/ft, and in the Biwabik formation from 0.24 to 6.55 gpm/ft.

Well yields throughout the Kawishiwi watershed are less than 10 gpm (Siegel and Ericson 1981) which reflects the very thin to nonexistent surficial aquifers and the low permeability bedrock, which transmits very little groundwater except in fractures. The aquifer along the river is not a target for production water pumping because it is too thin (Siegel and Ericson 1981). The Duluth Formation is relatively fractured for the upper two to three hundred feet, but the well yields range from 5 to 15 gpm, especially in the South Kawishiwi intrusion which hosts the nickel/copper ore body (Cox et al. 2009; Siegel and Ericson 1981). The best bedrock aquifer of the province is the Biwabik formation, in which most of the area iron mines were developed.

Surface Flow Pathways

The primary inflow to the watershed is meteoric water, or precipitation falling as either rain or snow. Precipitation, or snowmelt, becomes evapotranspiration (ET), runoff or infiltration into the soil. Infiltration becomes ET, interflow or shallow groundwater flow, or recharge to the groundwater aquifers. ET includes direct evaporation and transpiration of soil water through the vegetation. River flow includes direct runoff from the surface, interflow, and groundwater discharge of recharge. Interflow is flow through the soils and unsaturated zone above the water table to rivers. Wintertime precipitation is frozen along with the soils so little direct runoff or recharge occurs during that time period. Baseflow consists of groundwater discharge to the rivers (Cherkauer 2004).

Four HU10 watersheds form the study area (Fig. 1). The general conceptual flow model through the study area, shown with arrows in Fig. 1, includes as outlets the Kawishiwi River and the South Kawishiwi River which are gaged at stations shown in Fig. 1 and tabulated in Table 1. Upstream from the mineral deposits, the Kawishiwi River flows from east to west and splits into two branches. The South Kawishiwi was dammed to form Birch Lake, the center of one of the four watersheds. Downstream from the mineral deposits, the main branch of the Kawishiwi River enters the east side of Farm Lake and rejoins the South Kawishiwi waters flowing north from Birch Lake (Fig. 3).

The Stony River and Isabella River watersheds are tributaries to the Birch Lake watershed (Fig. 1 and 3). Much of the Isabella River watershed heads south of and flows north into the BWCAW. The main river, the Isabella, flows from east to west on the northern portion of the watershed from the BWCAW to the west. There are no apparent mining leases in this watershed (Fig. 3). West of the Isabella River watershed is the Stony River watershed which flows into the Birch Lake watershed near the center of Birch Lake (Fig. 3). The Stony River and Birch Lake watersheds are the host watersheds for the contaminant sources considered in this analysis because they contain substantial mining leases (Fig. 3). None of the Stony River watershed lies within or flows directly into the BWCAW, rather flow from that watershed reaches BWCAW by way of the Birch Lake watershed.

The Kawishiwi River downstream of both the Birch Lake and Kawishiwi River watersheds flows into the BWCAW, after flowing through several lakes (Fig. 3 and Table 10). This would be the primary surface pathway for contaminants reaching the Wilderness.

Lakes and wetlands connected by low-gradient rivers cover much of the study area. The boundaries between the watersheds within the study area are topographic divides but have very low relief, with just a couple tens of feet from the top of the divide to lakes and rivers within each watershed. Lakes lie within a few hundred feet of the divides, therefore it cannot be assumed that the groundwater divides between watersheds coincide directly with the topographic divides. The east and northern bounds of the study area generally coincide with topographic divides, but along the southern portion of the study area, the watershed boundary connects high points across wetlands where surface and groundwater could flow in either direction. However, the flux would likely be very low due to the almost flat gradient.

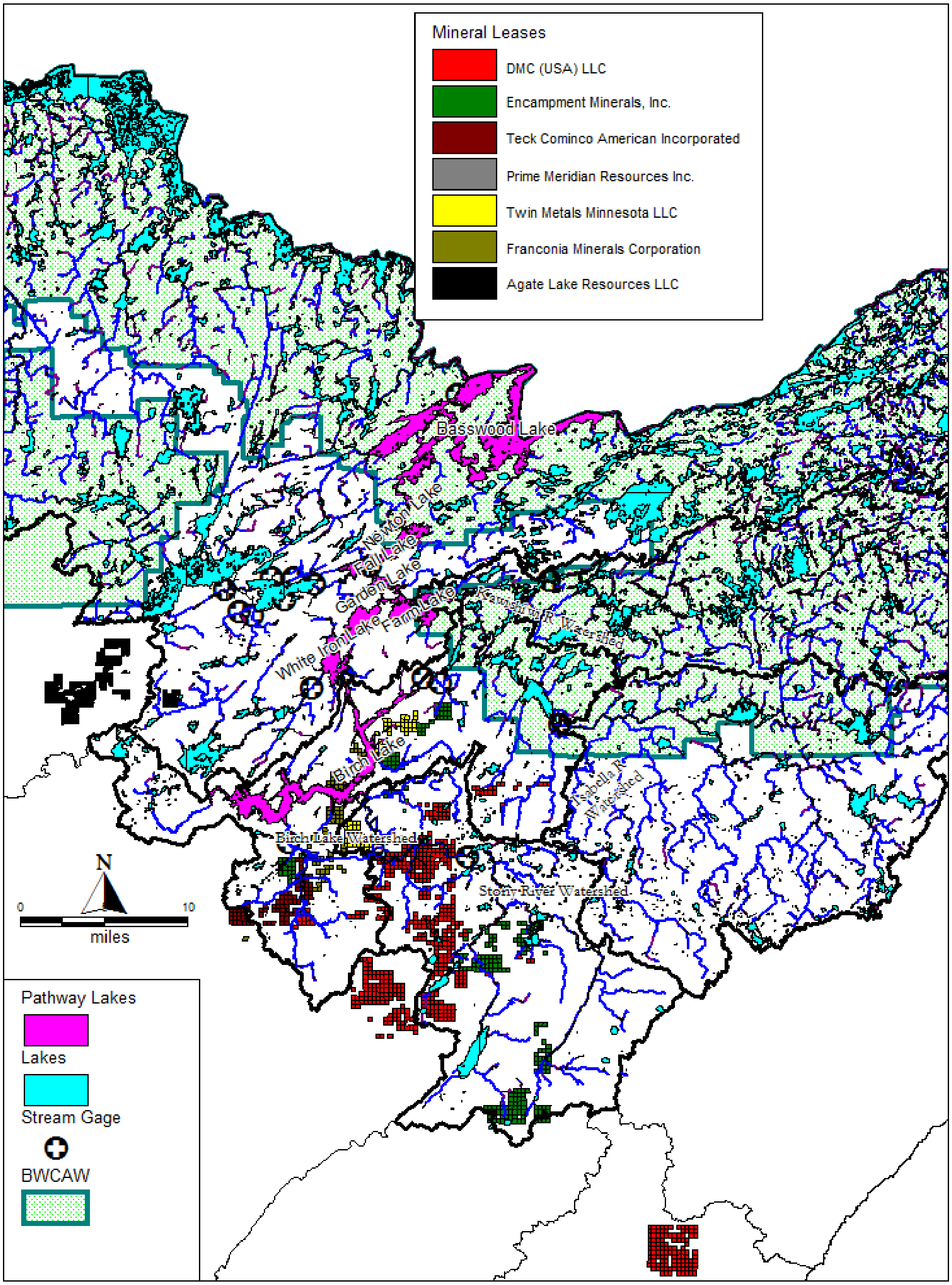


Fig. 3: Surface water pathway to the Boundary Waters Canoe Area Wilderness and the location of mining leases in the Stony River and Birch Lake watersheds.

Runoff, Baseflow and Recharge

Flow data for all US Geological Survey gaging stations in the area were obtained. Total flow, or total runoff from the watershed above that point, was divided into direct runoff and baseflow using methods of Lim et al. (2005) found at https://engineering.purdue.edu/~what/main.html (accessed 4/29/14) (Table 2). The calculation yields total flow in cfs-days (cubic feet per second x days). This was converted into average flow in cfs and m^3/d (the units used in the numerical groundwater model) (Table 2). The same units apply to direct runoff and base flow. Flow values are totals and averages for the dates and total days shown on Table 2. The baseflow index is the proportion of total flow that is baseflow. Yield is total streamflow per area, so the difference between total precipitation and yield is the average ET from the watershed. Recharge is the baseflow per area, assuming that all recharge becomes baseflow (Cherkauer 2004). However, the area recharge rate is an average of distributed recharge (through the ground surface over the watershed) and recharge of runoff through the bottom of the streams. Also, Table 2 does not account for flow management in the watersheds. Reservoir releases are partially controlled and at least attenuated. The Dunka River receives mine pit dewatering discharges from the Embarrass River watershed (Polymet 2013a) which would affect total flow and could affect baseflow estimates.

Table 2: US Geological Survey gaging stations and station parameters. Flow statistics described in text.

Site No	Site Name	Altitude	Area (sq miles)	Begin Date	End Date	Days	Total Flow (cfs-days)	Avg Flow (cfs)	Flow (m3/d)
5124480	KAWISHIWI RIVER NEAR ELY, MN		254	24259	41758	17470	3290459	188.35	461164
5124500	ISABELLA RIVER NEAR ISABELLA, MN	1453.1	341	27607	41758	3835	1075997	280.57	686970
5124990	FILSON CREEK IN SESW SEC. 24 NEAR WINTON, MN		9.66	27303	31336	4034	30714	7.61	18642
5125000	SOUTH KAWISHIWI RIVER NEAR ELY, MN	1430		18902	41758	8585	3475685	404.86	991271
5125500	STONY RIVER NEAR ISABELLA, MN	1632.45	180	19268	23742	4475	562582	125.72	307811
5126000	DUNKA RIVER NEAR BABBITT, MN	1488.98	53.4	18902	29530	6123	237136	38.73	94826
5126210	SOUTH KAWISHIWI R ABV WHITE IRON LAKE NR ELY, MN		837	27607	41758	5165	3318666	642.53	1573205
5126500	BEAR ISLAND RIVER NEAR ELY, MN	1388.86	68.5	19268	28410	4609	197873	42.93	105117
5127000	KAWISHIWI RIVER NEAR WINTON, MN		1230	2009	41547	35702	35274735	988.03	2419154
5127205	BURNTSIDE RIVER NEAR ELY, MN		69	24601	28763	4163	247431	59.44	145526
5127207	BJORKMAN'S CREEK NEAR ELY, MN		1.36	26481	28763	2283	2449	1.07	2626
5127210	ARMSTRONG CREEK NEAR ELY, MN		5.29	24601	28763	4163	19018	4.57	11186
5127215	LONGSTORFF CREEK NEAR ELY, MN	1360.67	8.84	24601	28763	4163	32278	7.75	18984
5127219	SHAGAWA RIVER Trib AT ELY, MN		0.71	26024	28763	2740	290	0.11	259
5127220	BURGO CREEK NEAR ELY, MN		3.04	24601	28763	4163	13563	3.26	7977
5127230	SHAGAWA RIVER AT ELY, MN		99	24602	28789	4188	375159	89.58	219331
5127500	BASSWOOD RIVER NEAR WINTON, MN	1296.8	1740	11324	41758	30254	40578673	1341.27	3284031

Continued, Site No	Direct Runoff (cfs-days)	Direct Runoff (cfs)	RO (m3/d)	Base Flow (cfs-days)	Base flow (cfs)	Base flow (m3/d)	Base Flow Index (BFI)	Yield (in/y)	Baseflow yield (in/y)	Recharge (m/d)
5124480	772206	44.2	108226	2518252	144.1	352938	0.77	10.1	7.70	0.000536
5124500	401597	104.7	256400	674400	175.9	430571	0.63	11.2	7.00	0.000487
5124990	11881	2.9	7211	18833	4.7	11431	0.61	10.7	6.56	0.000457
5125000	872960	101.7	248969	2602725	303.2	742301	0.75			
5125500	164024	36.7	89744	398558	89.1	218067	0.71	9.5	6.72	0.000468
5126000	85393	13.9	34147	151744	24.8	60679	0.64	9.8	6.30	0.000439
5126210	936426	181.3	443911	2382240	461.2	1129295	0.72	10.4	7.48	0.000521
5126500	53557	11.6	28451	144317	31.3	76666	0.73	8.5	6.20	0.000432
5127000	10880914	304.8	746217	24393822	683.3	1672937	0.69	10.9	7.54	0.000525
5127205	57817	13.9	34005	189613	45.5	111521	0.77	11.7	8.96	0.000624
5127207	1155	0.5	1239	1294	0.6	1388	0.53	10.7	5.66	0.000394
5127210	7678	1.8	4516	11340	2.7	6670	0.60	11.7	6.99	0.000487
5127215	12586	3.0	7403	19691	4.7	11581	0.61	11.9	7.26	0.000506
5127219	174	0.1	155	116	0.0	103	0.40	2.0	0.81	0.000056
5127220	5912	1.4	3477	7650	1.8	4499	0.56	14.5	8.21	0.000571
5127230	84337	20.1	49307	290821	69.4	170025	0.78	12.3	9.52	0.000663
5127500	8949944	295.8	724319	31628729	1045.4	2559712	0.78	10.5	8.16	0.000568

Yield is relatively unvarying near and around the study area; if the high and low outliers are removed, the yield ranges from 8.5 to 12.3 inches/year (in/y). The outliers are small tributaries with small watersheds (Table 2), so small scale geologic factors could control the yield (and also the recharge).

Baseflow, or recharge, varies from 5.66 to 9.52 in/y, although for watersheds with more than 100 square miles, the range is from 6.7 to 8.2 in/y. Assuming the Kawishiwi River near Winton gage is representative, the average recharge is 7.54 in/y, or 0.00052 m/d for the study area. For the subwatersheds, Birch Lake, Stony River, Isabella River, and Kawishiwi River, the S Kawishiwi River above White Iron Lake near Ely, the Stony River near Isabella, the Isabella River near Isabella, and the Kawishiwi River near Ely gages provide the most representative data and yield recharge equal to 0.00052, 0.00047, 0.00049, and 0.00054 m/d, respectively. The low rates for the Dunka River near Babbitt and Filson Creek gages, 0.00044 and 0.00046 m/d, respectively, suggest the overall rates for the Birch Lake watershed could be high because these small watersheds are embedded within the Birch Lake watershed. Filson Creek is a 25.2 km^2 tributary to the S Kawishiwi River described by Siegel (1981) as having two substantial lakes and being 60% covered by upland forest, 30% covered by wetlands and lakes, and the remainder by stands of pine. The watershed has less than one meter of drift covering the bedrock which outcrops over about 10% of the watershed (Id.). Under the wetlands, there is a layer of peat with thickness up to 15 meters (Id.). Peat generally has very low permeability (Siegel et al. 1995) and wetlands underlain by peat are usually perched, so that little recharge through the wetlands occurs.

The several gages for small watersheds near Ely (Table 2), but outside the study area, show more variability which probably reflects small scale heterogeneity. The rates also represent different time periods (Table 2) but there is little reason to expect substantial changes due to land use due to the relatively undeveloped nature of the watershed. Climate change may eventually affect (or may have already affected) the recharge rates (IPCC 2007). Spatial heterogeneity is discussed below.

Climate, geomorphology and land cover are the primary factors to consider when estimating recharge (Scanlon et al. 2002). Lorenz and Delin (2007) derived a regression equation to estimate regional scale recharge for all areas of Minnesota based on precipitation, growing degree days, specific yield based on Rawls et al. (1982) and baseflow recession indices, similar to the method used to estimate recharge herein. Specific yield is a landscape characteristic estimated as the moisture difference between field capacity and the wilting point over the basin. Growing degree days, a surrogate for ET, was used because estimates are widely available. They estimated recharge as baseflow from a set of basins with an upper size limit of 5000 km^2. They did not consider recharge variability with drainage area. Their method yielded a recharge estimate for the Kawishiwi watershed equaling 20 to 30 cm (8 to 11 in/y). This estimated recharge is similar to the yield for study area watersheds estimated herein and exceeds the recharge estimates by approximately 20 to 30 %. This suggests the equation (Delin et al 2007) is not accurate for northeast Minnesota, although gaging stations from that area were part of the data base used to develop it.

Long-term drainage from surface storage in areas with numerous lakes supports long-term baseflow which complicates the estimate of recharge (Sophocleous 2002) and could have caused the overestimates for this area discussed above. The watershed is a system of connected local flow systems defined by microscale topography embedded within a larger flow system (Winter 1998). Water storage in the Kawishiwi River basin includes surface storage in wetlands and small lakes and subsurface storage in the unsaturated zone and groundwater.

Interflow is both unsaturated and saturated flow just below ground surface to streams that occurs during and just after a storm, with saturation causing temporary perched zones (Sophocleous 2002). Because of the shallowness and flatness of the groundwater table in this watershed, especially in wetland areas, interflow should be limited and should soon discharge to the ground surface and become overland flow among the wetlands. Short-term shallow groundwater discharge to the rivers may be caused by groundwater ridging, which would rapidly increase the groundwater head and substantially increase the gradient for flow to surface drainages (Sophocleous 2002). Interflow may therefore resemble groundwater recharge and be difficult to separate from the runoff hydrograph which may cause recharge estimates to be erroneous.

Spatial Heterogeneity

Many factors control the heterogeneity of the surficial aquifer including recharge and K. Wetlands, soil types, and soil landforms control recharge. That includes whether the soil is well drained, whether the soils contain substantial peat, and whether the bedrock is shallow. Minnesota has several well-developed GIS databases describing soils at a statewide level with accuracy to a 40 acre scale. All are described in Land Management Information Center (1996) and associated GIS databases and briefly in the following paragraphs with maps for the study area (Fig. 4 through 8).

Wetlands cover just 7.6% of the 1103 square mile study area, with most of the wetlands being in the southern portion (Fig. 4). If the wetlands are perched, these could be areas with little recharge. If they are connected to the groundwater, they could be alternately recharge and discharge areas. Based on the small area included and their overlap with lower permeability soils (discussed below), the area of wetlands is of less importance in the spatial distribution of recharge. Perennial streams draining perched wetland areas however could convey runoff and focus recharge along the streams.

The hydrologic soil classification shows that almost half of the study area (mostly over the northern portion (Fig. 5)), is mostly slow draining, being rated C, D (Table 4). The A group is the second largest area (Table 3) and covers the central portion just south of the C, D area (Fig. 5); these soils have high infiltration (Table 3). The remaining areas along the southern boundary of the study area have infiltration rates intermediate to the C, D and A groups.

Soil type is a soil landscape unit based on four characteristics, each with a letter description (Table 5), although some soils, such as PEAT, are self explanatory and not represented in Table 5 because their characteristics do not break down easily into the categories. Most of the soils are relatively free-draining based on soil type, although a substantial amount has bedrock for a sublayer (Fig. 6 and Table 5). Type RLWL covers the largest area and mostly coincides with the C, D hydrologic soil classification (Fig. 5). This type is free draining but underlain with bedrock (Table 5). Loamy is similar to the fine-grained description for hydrologic soil classification C. SSWL, the second largest landscape unit area, has sand throughout and is free draining, so its correspondence with hydrologic soil classification A, fast infiltration, is expected. Groups south of SSWL are LLWL and SLWL, which have slower infiltration than those discussed above.

Maps of surface permeability (Fig. 7) and subsurface permeability (Fig. 8) show that the central region of the study area has the highest infiltration rates through the soil profile. The northern region has much lower infiltration rates, less than 0.8 inches/hour. Much of the southern portion of the study area is unclassified or a mixture of the rates from the northern and central region.

The descriptions of soils resulting from Figs 4 through 8 indicate the study area has three different basic classifications which can be used to understand surficial layer conductivity. The northern portion, encompassing much of the Kawishiwi and Birch Lake watershed, has free-draining surface soil underlain by bedrock. Meteoric water would enter the soil but the bedrock would restrict its downward movement. The majority of the higher recharge in this area may quickly reach the stream discharge points without circulating deeply. The K zone for this area should have a high vertical anisotropy, near 100. In contrast, a larger proportion of recharge in the central portion should reach deeply into the groundwater. The vertical anisotropy for layer one through this zone should be lower, no higher than 10. The southern portion of the area is mixed and should have K intermediate to the other zones.

Table 3: Area (square miles) of soils groupings by category. Hydrologic soil group is the NRCS soil classification (see Table 4). Sub perm is permeability (in/h) of the layer 5 feet below ground surface. Surface perm is permeability (in/h) of the top 5 feet of soil. The total study area is 1103 sq miles. Categories do not add to 1103 sq miles because the area of unclassified and water ratings do not have areas listed for Sub or Surface Perm.

Hydrologic Soil Group	Area	Sub perm	Area	Surface perm	Area
C,D	548.9	Greater than or equal to .8	587.3	.8 - 5	3.2
A	245.1	Greater than or equal to 5	288.4	.2 - 5	5.7
A/D	155.1	Greater than or equal to 2.5	45.1	Greater than or equal to 5	16.0
C	47.2	Less than or equal to .8	5.7	Greater than or equal to 2.5	278.9
C,B/D	44.5	.8 - 5	3.2	Greater than or equal to .8	630.0
No Rating	31.2				
B	21.4				
Water	7.9				
Total	1101.3		929.8		933.9

Table 4: Description of soil properties with respect to infiltration by hydrologic soil group (NRCS 2007).

Hydrologic soil group	Description
A	Soils having high infiltration rates even when thoroughly wetted, consisting chiefly of deep, well to excessively drained sands and or gravel. These soils have a high rate of water transmission and would result in a low runoff potential.
B	Soils having moderate infiltration rates when thoroughly wetted, consisting chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.
C	Soils having slow infiltration rates when thoroughly wetted, consisting chiefly of (1) soils with a layer that impedes the downward movement of water, or (2) soils with moderately fine to fine texture and slow infiltration rate. These soils have a slow rate of water transmission.
D	Soils having very slow infiltration rates when thoroughly wetted, consisting chiefly of (1) clay soils with a high swelling potential, (2) soils with a high permanent water table, (3) soils with claypan or clay layer at or near the surface, and (4) shallow soils over nearly impervious materials. These soils have a very slow rate of water transmission.

Table 5: Description of soil type.

Factor number	Description
1	Texture of the soil material below 5 feet of the surface, with "S" designating sandy; "L" for loamy or silty; "C" for clayey "X" for mixed sandy and loamy; "Y" for mixed silty and clayey; and "R" for bedrock.
2	Texture of the material in the first 5 feet below the surface, or a significant part of it, with "S" for sandy; "L" for loamy, and "C" for clayey.
3	Drainage of the unit, where "W" means well-drained (water table commonly below the rooting zone), and "P" means poorly-drained (water table within the rooting zone).
4	Color of the surface horizon with "D" for dark-colored and "L" for light colored (Darker colors associated with higher organic matter content).
For example, RLWL means bedrock below 5 feet below the surface, loamy for the top 5 feet, well-drained below the root zone, and light colored.	

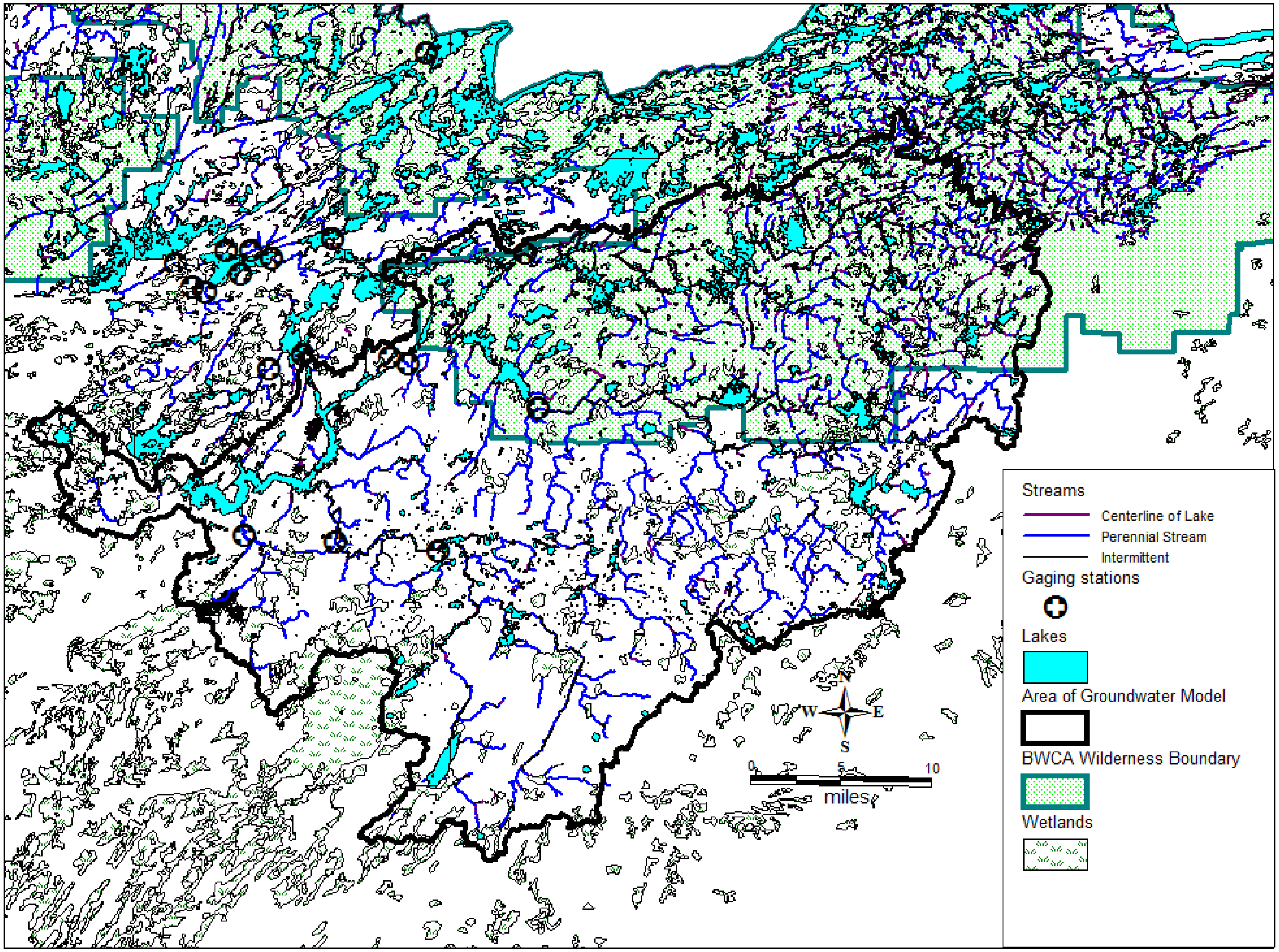


Fig. 4: Distribution of wetlands and lakes across the study area. Stream file Strm_baseln3, lakes and wetlands from Dnr100khydrography, from www.mngeo.state.mn.us/chouse/metalong.html

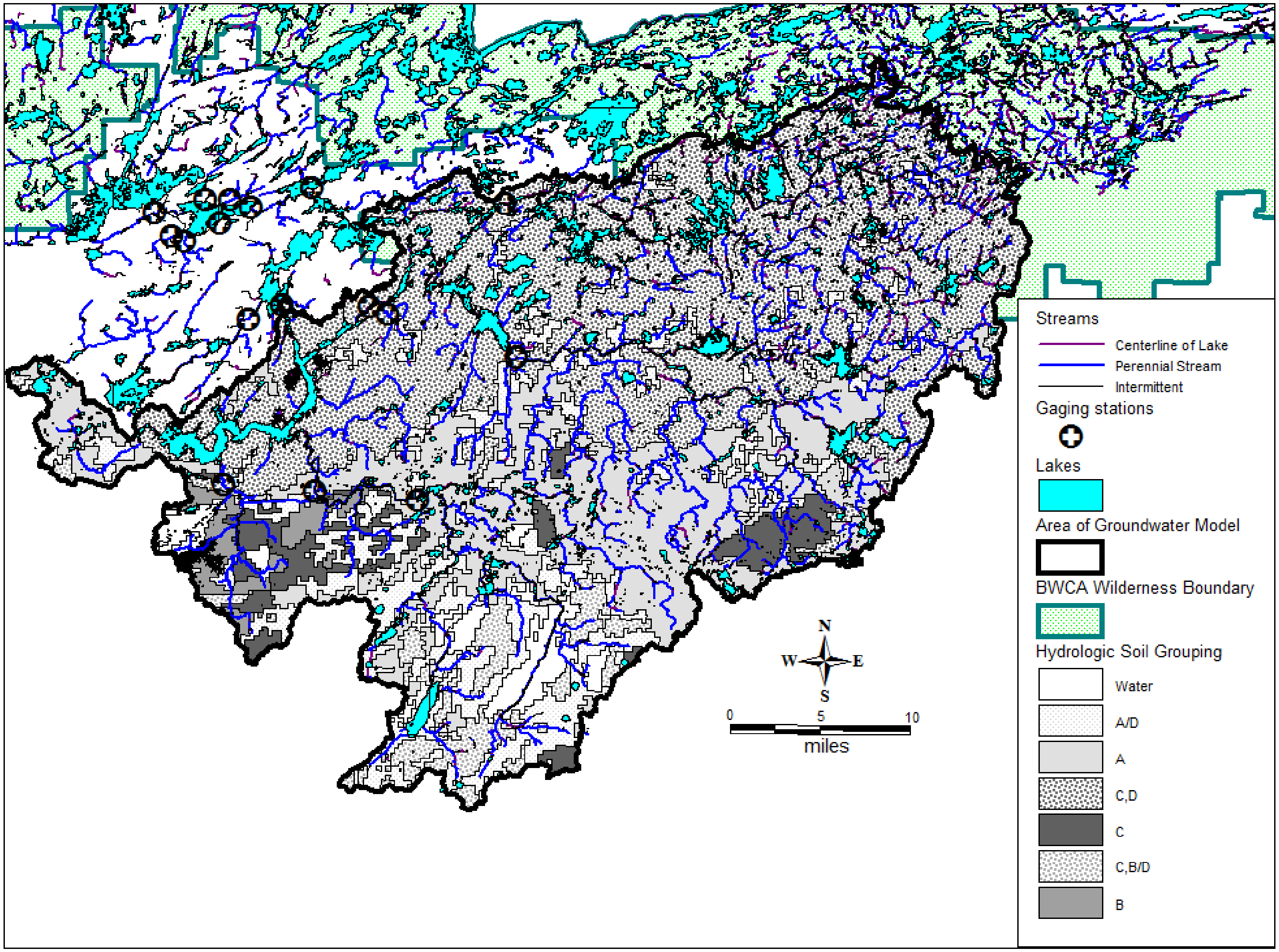


Fig. 5: Distribution of hydrologic soil grouping (NRCS 2007) across the study area. See Table 3 for a description of soil grouping. From Minnesota soil atlas: http://www.mngeo.state.mn.us/chouse/metadata/soil_atlas.html

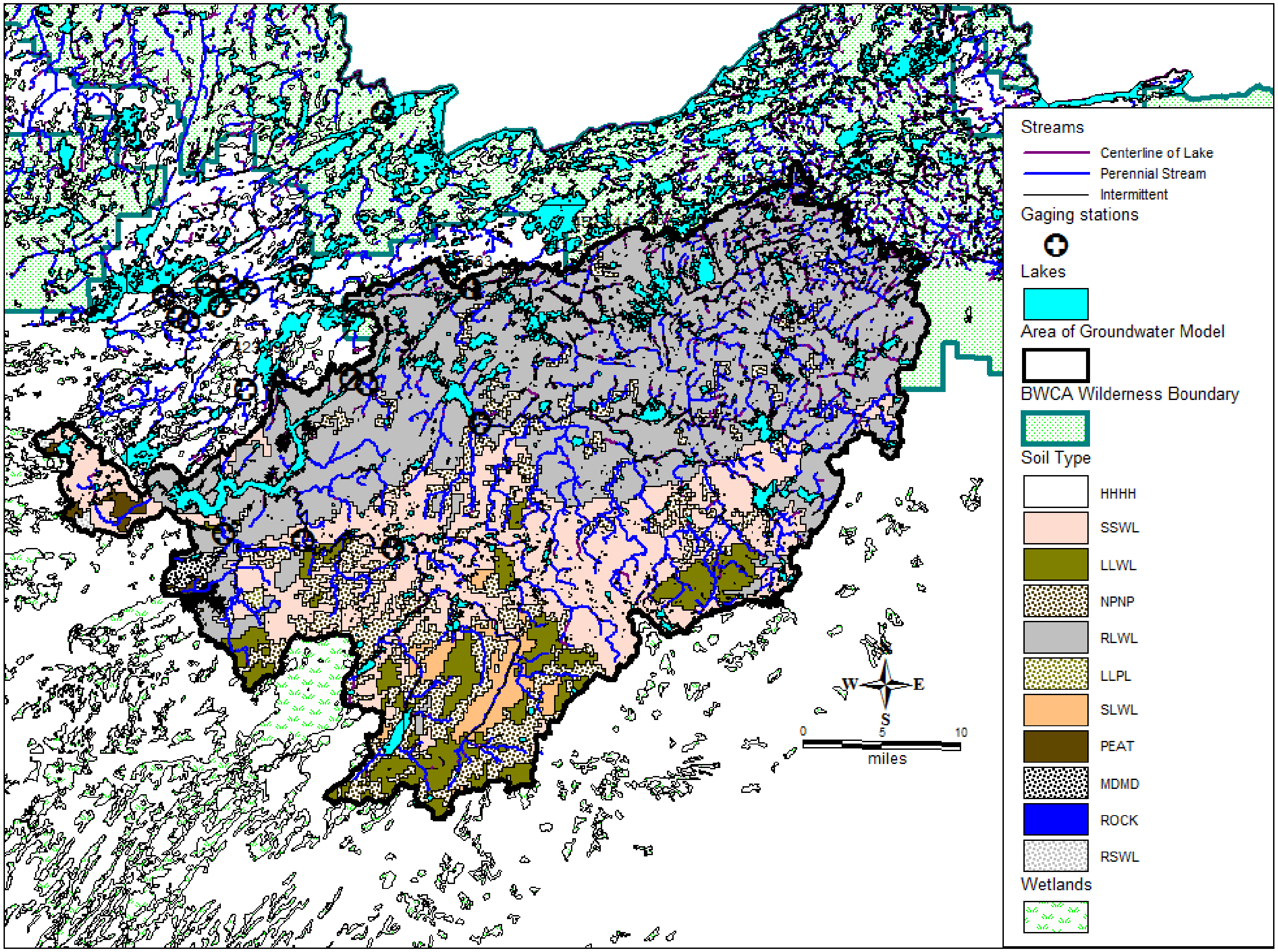


Fig. 6: Distribution of soil landscape units over the study area. See Table 5 for a description of the units. From Minnesota soil atlas: http://www.mngeo.state.mn.us/chouse/metadata/soil_atlas.html

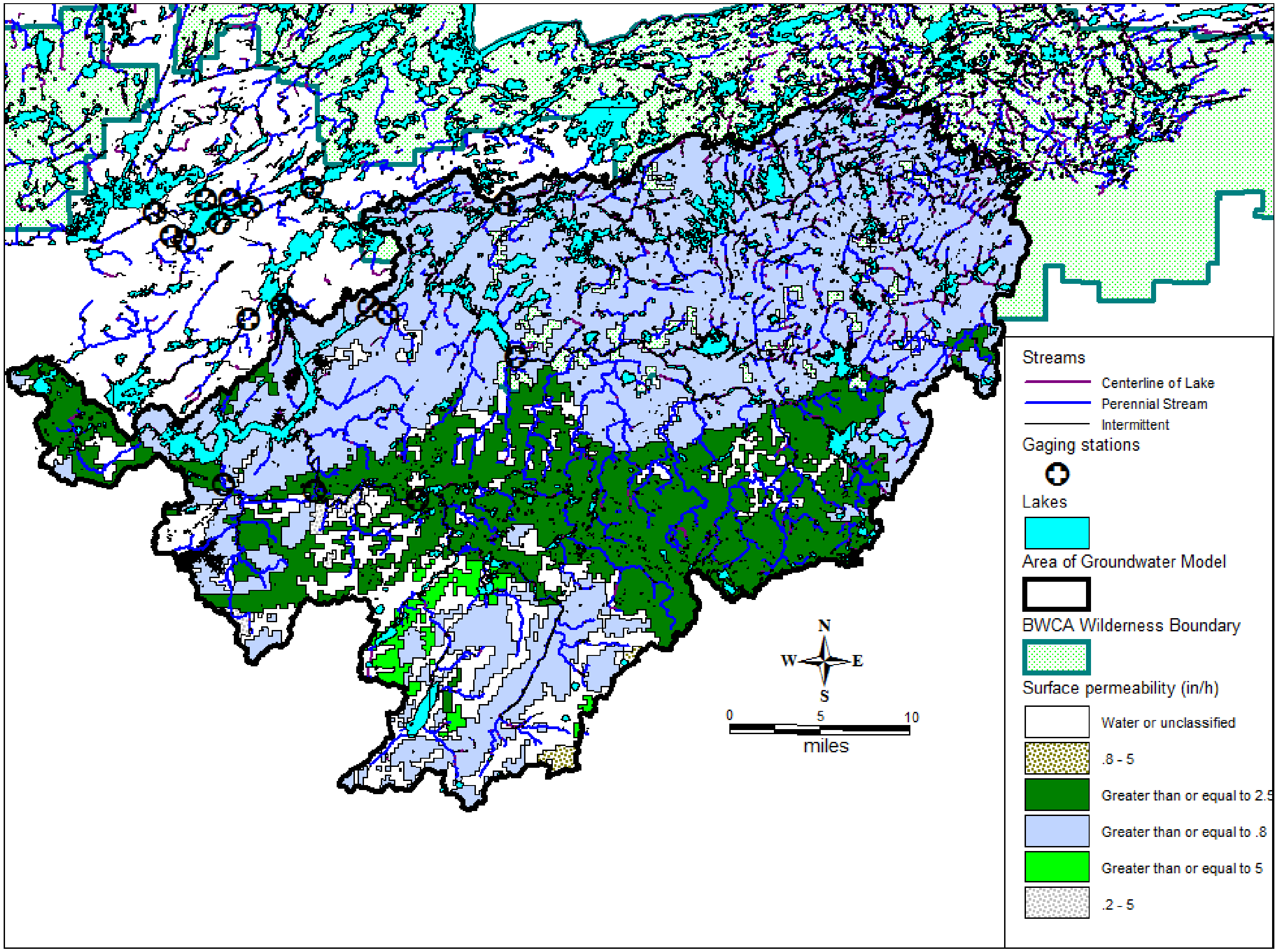


Fig. 7: Distribution of surface soil permeability across the study area. From Minnesota soil atlas: http://www.mngeo.state.mn.us/chouse/metadata/soil_atlas.html

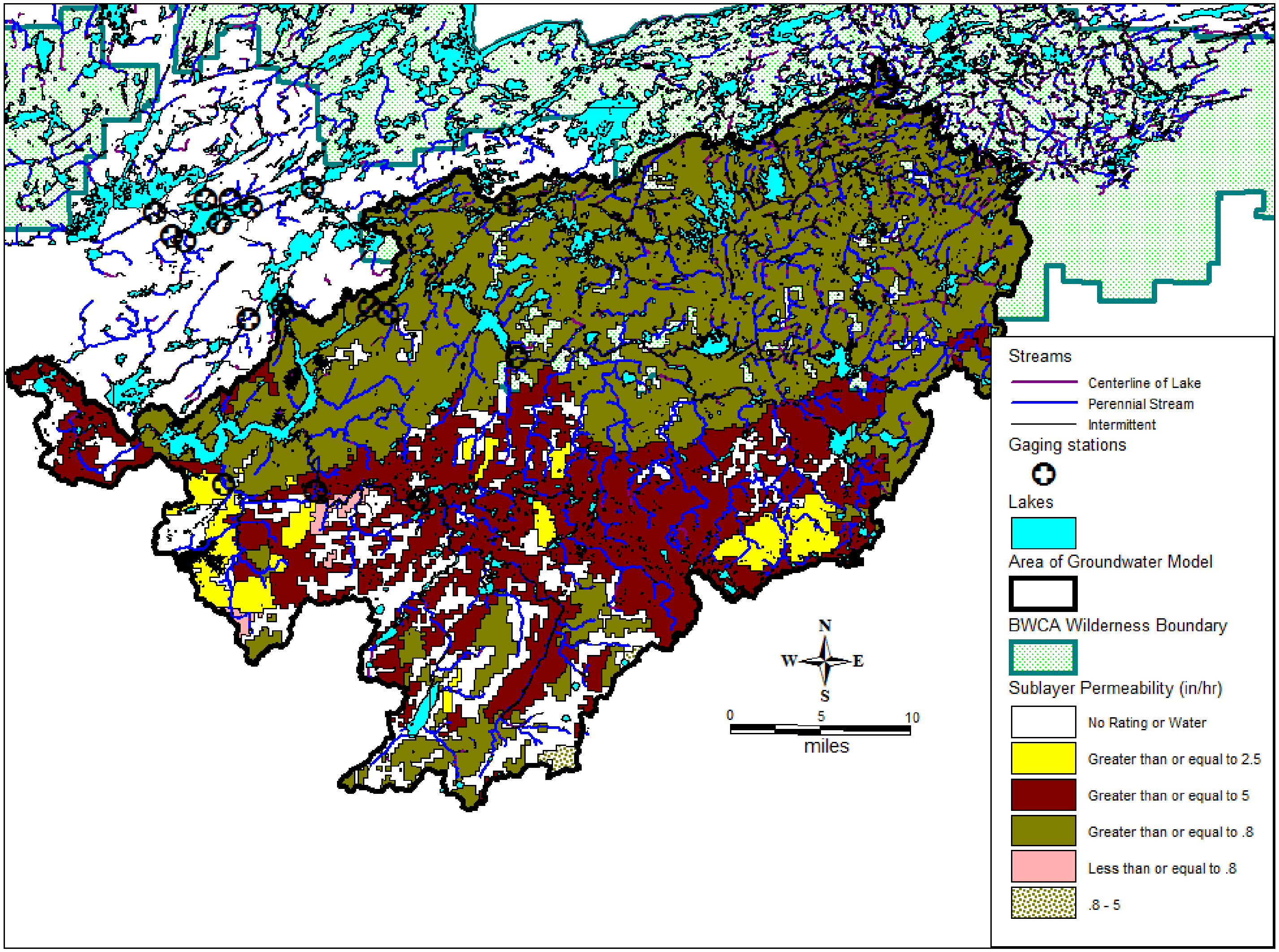


Fig. 8: Distribution of subsurface soil permeability across the study area. From Minnesota soil atlas: http://www.mngeo.state.mn.us/chouse/metadata/soil_atlas.html

Seasonal Variability

During the spring snowmelt, flow from the watershed reaches a peak and there is a substantial wetting of the aquifers due to recharge. Average monthly river flow at the Kawishiwi River near Ely gage peaks at more than 30 in/y during May just two months after the low flow of less than 3 in/y recorded in March (Fig. 9). Much recharge would likely occur during this snowmelt freshet flood because there is water running on the ground surface and river and stream levels are higher than the water levels in the streambanks. Siegel and Ericson (1981) noted that 60 percent of runoff occurs during snowmelt from April through June and less than 11 percent occurs from December through March. Climate change could affect this distribution, but trends for northern Minnesota are unclear; higher precipitation could be offset by higher evapotranspiration so that the net change in recharge could be negligible (IPCC 2007). No groundwater level data is published by the US Geological Survey for this area, but studies in support of mining in the Partridge River watershed just west of the Kawishiwi River include data showing that groundwater levels fluctuate up to six feet during the spring (Polymet 2013b).

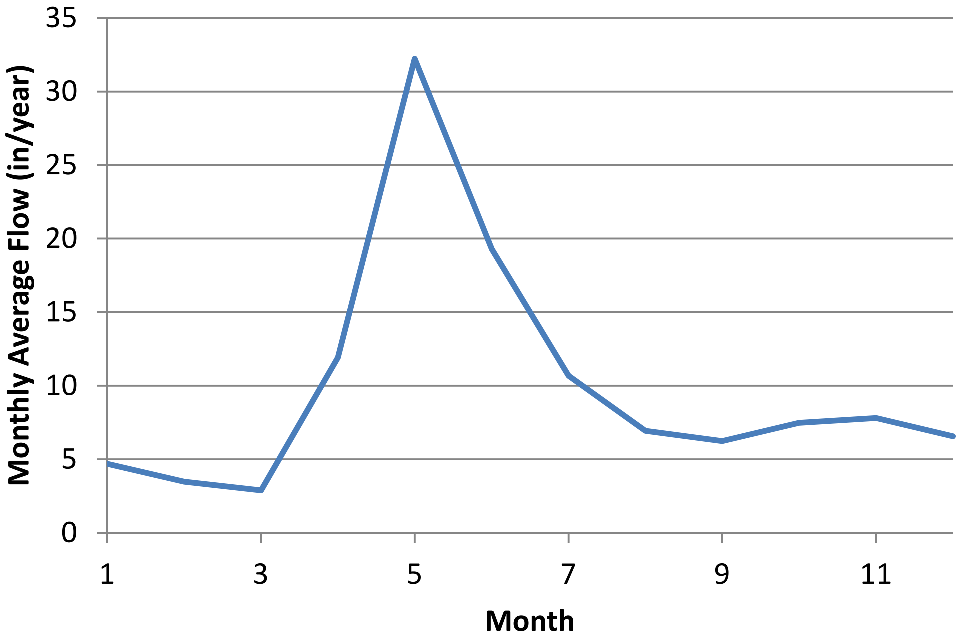


Fig. 9: Average flow by month (1=January, 12=December) in inches per year for the Kawishiwi River near Ely, MN.

It is common to assume that the 30-day low flow rate equals groundwater recharge over the basin (Cherkauer 2004; Scanlon et al. 2002), but in the Partridge River basin, just west of the Laurentian Divide, Myers (2013a) found that this is not possible because the long time period since recharge would have occurred (recharge cannot occur while precipitaton is frozen and the watershed is ice-in) is much longer than the travel time through the aquifers due to the high K and thin surficial aquifers. In other words, during the winter when the watershed is frozen, groundwater is draining to the streams but not being replenished by recharge so the baseflow rates are much lower than they are when the watershed groundwater is fully recharged. Spring baseflow represents recharge that occurs more than a 5-month travel time from the stream because recharge cannot occur when the precipitation and soils are frozen.

Transport

Contaminant transport is the process whereby a contaminant moves from a source (here, a spill or leak at a potential mine) to a sink, or receptor (here, the water resources of the BWCAW). Three processes control contaminant movement - advection, dispersion, and sorption (Fetter 1999). Advection, the movement of the contaminant along with the flow of the water, is controlled by the properties of the formation rather than the contaminant. Dispersion occurs because the particles in a plume move at different rates due to the different sizes and connectivity of pores in the formations; contaminants move slower following a tortuous route or when flowing through larger pores, and faster when being squeezed through small pores (Fetter 1999; Anderson and Woessner 1992). Sorption, the process of a constituent becoming bound on soil particles, is a function of the particular constituent and the geochemistry of the formation. Myers (2013c) reviewed the groundwater and surface water chemistry of the area and found basically that the water quality is very good but has poor buffering capacity, so that little attenuation of contaminants would occur.

If there is no sorption, the constituent discharged from a source will eventually reach a sink. Such transport is considered conservative, meaning the contaminant is not transformed chemically or sorbed to aquifer materials during transport. The seepage rate affects how quickly a certain concentration reaches a point, such as a well or the river. At a sink, the concentration will eventually approach a steady state concentration lower than the source concentration if the source rate and concentration remain constant. The steady state concentration depends on advection and dispersivity. Higher vertical and lateral dispersivity will cause the contaminant to spread more so that the concentration along the primary flow path is lessened. Sorption, if it occurs, slows the transport because the constituent adsorbs to sites along the pathway and decreases the total load eventually reaching the sink.

In surface water, transport follows the river and river turbulence causes dispersion. As the flow in the river increases in a downstream direction, dispersion will cause the contaminants to spread through the increased flow and be diluted. Sorption may also attenuate the concentration. For example, mercury often binds to river sediments and only moves through the river system during high flows (Wershaw 1970; Jenne 1970).

Contaminants emanating from underground mines in the Birch Lake or Stony River watersheds will move laterally and vertically through the groundwater until they reach a river, if there is an upward vertical gradient. If no vertical gradient exists, the contaminants may never reach the surface within the watershed; the present numerical analysis estimates whether and where vertical gradients exist that would cause groundwater to flow from depth to the surface. Discharge to the surface could occur to any of the tributaries, wetlands, or lakes being modeled in the study area. Contaminants in that discharge would flow through downstream lakes and rivers to the BWCAW.

Contaminant transport through groundwater and discharge to surface waters would occur at a relatively constant rate, although short-term recharge events could prevent discharge to surface water at certain times. During high flow periods, dispersion and dilution are substantial. The critical period for surface transport occurs during dry periods, when the streams are limited to baseflow. As seen in Table 2, the baseflow does not increase substantially in a downstream direction. Low frequency low flows such as the 7Q10 flow (the seven-day annual low flow with ten-year return interval), actually decrease in a downstream direction, meaning that the river loses flow rather than receiving sufficient tributary or groundwater discharge to maintain its normally gaining river flow character. During low flows, it is unlikely that the river discharges into groundwater (Sophocleous 2002), so flow reductions would be due to evaporation which would concentrate the contaminant in the downstream direction. At low flows, the load remains the same in the downstream direction, but the flow decreases and concentration increases.

Most of the aquifer and streamside soils are poorly buffered which means that acid leaving a mine or reaching a stream would not be neutralized (Siegel 1981). Acid precipitation has depleted the soils of neutralizing capability in some areas (DeSallas et al. 2014), although portions of the Duluth Complex have neutralizing capability due to silicate mineralization (Lapakko 1988). Acid-dependent transport would not be attenuated under these conditions. It is even possible some elements, such as cadmium, iron, or selenium, could be dissolved along the flow path downgradient from the mine source. Consideration of this potential dissolution is beyond the scope of this project.

Waste stored on the ground surface is subject to seepage by meteoric waters and leaching of contaminants. This water can either infiltrate to shallow groundwater through which it can move to streams through the interflow, or, it can flow across the ground surface to the streams. In either case the flow path is much shorter than for waste deposited underground. Because such seepage may depend on there being wet antecedent conditions, the seepage may reach the stream at a time when river flows are not critically low. This would be most likely for seeps that flow on the surface. Seeps that enter the surficial aquifer may lag several months before discharging to streams, possibly at their most critical flow periods.

Development of Numerical Model

The conceptual model of groundwater flow developed above is the basis for a numerical groundwater and transport model using MODFLOW-2000 (Harbaugh et al. 2000) and MT3DMS (Zheng and Wang 1999). Additionally, flowpaths were determined from MODFLOW-2000 using the MODPATH code (Pollock 1994). The purpose of this modeling is to simulate the potential for contaminants released due to mining the various deposits in the Birch Lake and Stony River watershed to reach surface water and the BWCAW. The strategy is to develop a numerical model that accurately represents the flow and transport through the system at a reconnaissance level of accuracy. The first section below describes the development and calibration of the flow model, the second section briefly describes how the mineral deposits would be developed based on descriptions in mining company documents and web pages, the third section describes particle tracking through the domain, and the fourth section describes contaminant transport modeling and how the seepage or leaks from the potential mining were simulated. Following the modeling, a simple discussion of transport through the surface waters to the BWCAW provides relative sulfate concentrations for the simulated loads.

Model Domain and Discretization

The study area described above is the model domain (Fig. 1). The general cell size is 500 m square which approximates the 40 acre lease size and would be appropriate for adding loads to the transport model. The cells expand to 1000 m square on the fringes in the upper Kawishiwi and Isabella River watersheds (Fig. 10). The model domain has three layers, with layer 1 being the surficial till and sand/gravel layer and layers 2 and 3 being bedrock. The top of layer 1 was set based on 30 m and 10 m digital elevation models (DEMs) (Fig. 11). Layer 1 was set to be 15 m thick, based on the median and mean depth to bedrock for the well database being 14 and 17.4 m. However, thickness can be variable, with the maximum depth being 75 m and in a few locations the bedrock outcrops, which means the calibrated K may vary to reflect the differences in transmissivity due to thickness. Layer 2 thickness was set so that the total thickness of layers 1 and 2 equaled 140 m. The bottom of layer 3 was set at elevation -1000 m, so layer 3 was near 1200 m thick.

Head-controlled flux boundaries: MODFLOW DRAIN boundaries, were specified for larger lakes (reach numbers less than 50) and rivers (reach number greater than 70) (Table 7 in the water balance identifies reach numbers) because they should be discharge points or sinks for the groundwater (Fig. 12). Lakes have a lower conductance due to fine sediments on their bottom. The conductance of larger rivers would be higher than lakes due to the sorting of sediments and higher than that of smaller streams because the area in contact with the groundwater is larger. The head of the lakes was set to less than a meter below the top elevation of the cells represented by the boundary. Therefore, lakes received groundwater inflow only when the groundwater level is close to the ground surface. In areas with lower groundwater levels, the model does not simulate a connection. The head of rivers was set 5 m below the average top elevation of each model cell containing a stream. This allowed for more consistent discharge to rivers which tend to have eroded channels of several meters below the surrounding ground surface. The conductance for lakes was set according to a 400x400 m cell area, K=0.001 m/d, and thickness equal to 0.3 m. The conductance for rivers was set as for lakes, but with area being 400x10 m and K=1.0 m/d. DRAIN reaches which flow to a gaging station for which the baseflow is known were given separate reach numbers for calibration, as follows.

- Reach 71 – Dunka R
- Reach 72 – Stony R between Babbitt and Isabella (upstream)
- Reach 73 – Stony R above Isabella
- Reach 74 – Isabella R above Isabella
- Reach 75 – Filson Creek nr Ely
- Reach 76 – S Kawishiwi R between Iron Lake gage (DS end of reach) and S Kawishiwi R nr Ely, Dunka R, and Stony R nr Babbitt gages, this section includes Reach 1, Birch Lake. The reach gains the difference in flow between the DS gage and the three upstream gages. Reach 75, Filson Creek, enters above the S Kawishiwi R nr Ely gage
- Reach 77 – river and tributaries above the Kawishiwi R nr Ely gage
- Reach 78 – S Kawishiwi R between split and S Kawishiwi R nr Ely
- Reach 79 – Kawishiwi R between split and flow from watershed – not gaged.

Recharge: Four recharge zones were specified based on subwatershed (Fig. 13), with rates set so that recharge equals the measured baseflow in the primary rivers. The total distributed recharge equals approximately 1,425,000 m^3/d. This rate was based on the average baseflow for the four subwatersheds and equals about 0.000504 m/d over the study area. The Kawishiwi River at Winton gage drains all of the study area plus about 130 square miles and has an average recharge rate of 0.00052 m/d. Recharge rates were not adjusted during calibration.

Hydrogeologic Parameter Zones: The initial parameter zones were based on the bedrock geology (Fig. 2) for layers 2 and 3, and on the soils maps (Figs. 5 through 8) for layer 1. Zones with few or no targets were not sensitive to parameter changes so the final values were selected on formation type and on values necessary to generate reasonable head and flux values. Zones with many targets would be sensitive to changes, and the final values for these zones were chosen based on automated calibration. Sensitive zones were also split once or twice to improve the fit for various areas. The final parameter zones are show in Figs. 14 through 16.

Calibration Targets: Minnesota does not maintain any groundwater level data in the study area (http://www.dnr.state.mn.us/waters/groundwater_section/obwell/locations.html, accessed 4/30/14). The USGS database contains just ten wells. The county wells index prepared by the MN Geological Survey and MN Department of Health includes data from drill holes completed for mining industry exploration; some of them include groundwater levels (http://www.mngeo.state.mn.us/chouse/metadata/wells.html, accessed 4/30/14). Within the four watersheds that define this study area, there were 1238 wells in the database. The wells from this data base with depth to water and water level elevation were selected as targets. They were segregated by model layer based on depth and digitized into the groundwater model. The target wells cluster near the deposits because much of the well level data is from exploration wells. Other information in the database includes well depth and depth to bedrock, which was used to select the model layer to match the measured groundwater level and to calculate the thickness of the surficial aquifer. (Fig. 17). Some of the exploration wells were clustered within tens of meters and were impossible to distinguish at the model scale, hence Fig. 17 does not show their names.

The problem with the observed water levels is that the wells are so close together they represent essentially the same information. There was variability in the heads for clustered wells at depth but there was no trend with well depth. Head would differ as much as 10 m for wells within a 100 m square, but there was no consistent trend with depth. This finding suggests the different wells tap different fracture zones at a scale much finer than the detail used for the modeling. The head targets were thinned, first by keeping just one well per layer within 200 m of each other, and second by keeping just one well per model cell. This was done because the MODFLOW-2000 parameter estimation routine would not converge due to the correlation among residuals. Additionally, as noted, there were few measurements in parts of the domain, particularly in the Isabella River and Kawishiwi River watershed. For these areas, artificial targets were created based on the ground surface. At nine locations, a target was set in the three model layers at ground surface elevation minus 4 m , but with a weight of 0.3 to limit the effect of these artificial targets on the calibration. This was similar to the strategy used by Halford and Plume (2011), who set points 1 m below ground surface in wetland areas.

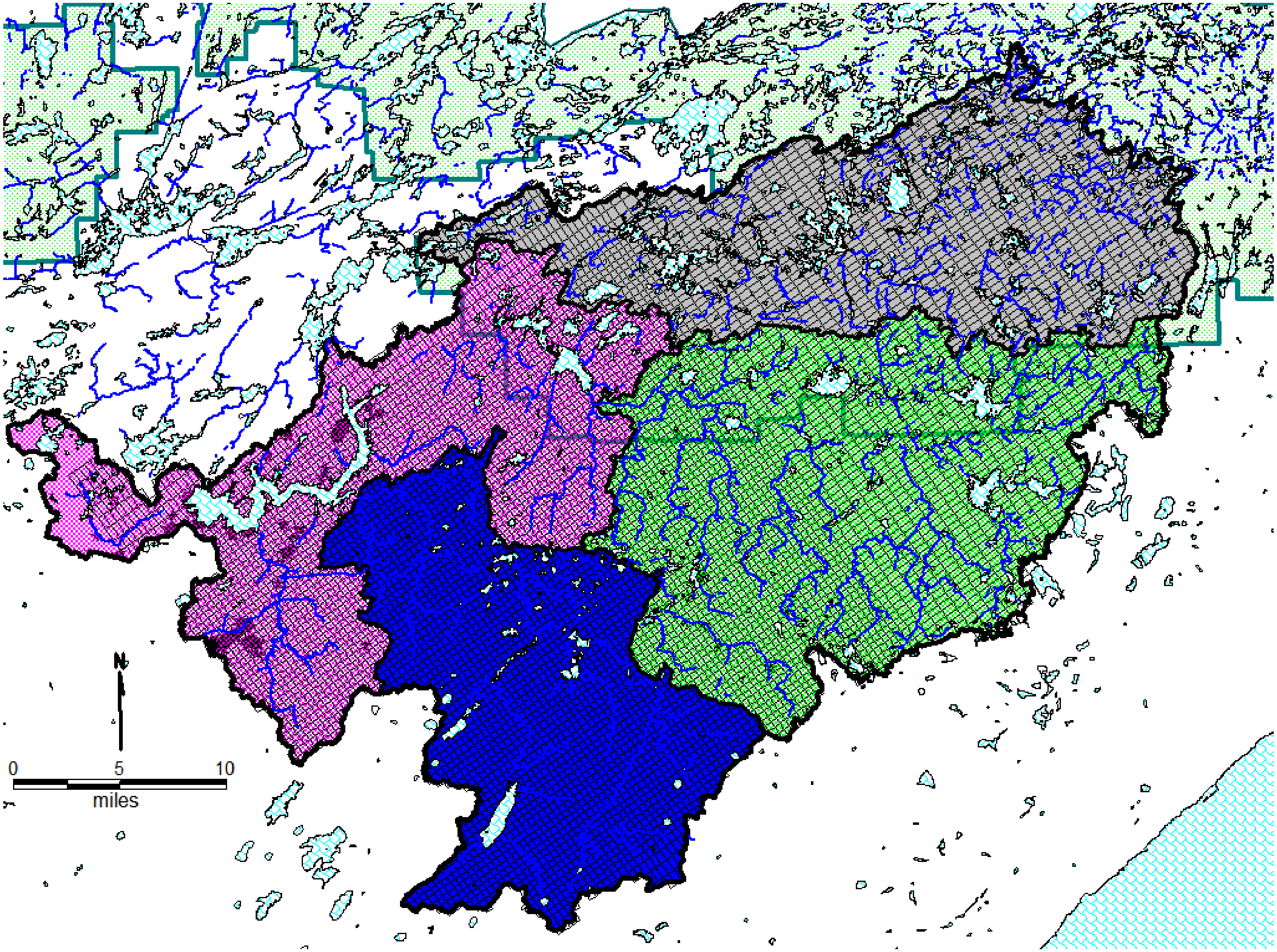


Fig. 10: Model grid over the domain, showing watersheds and recharge zones. See Fig. 1 for watershed labels.

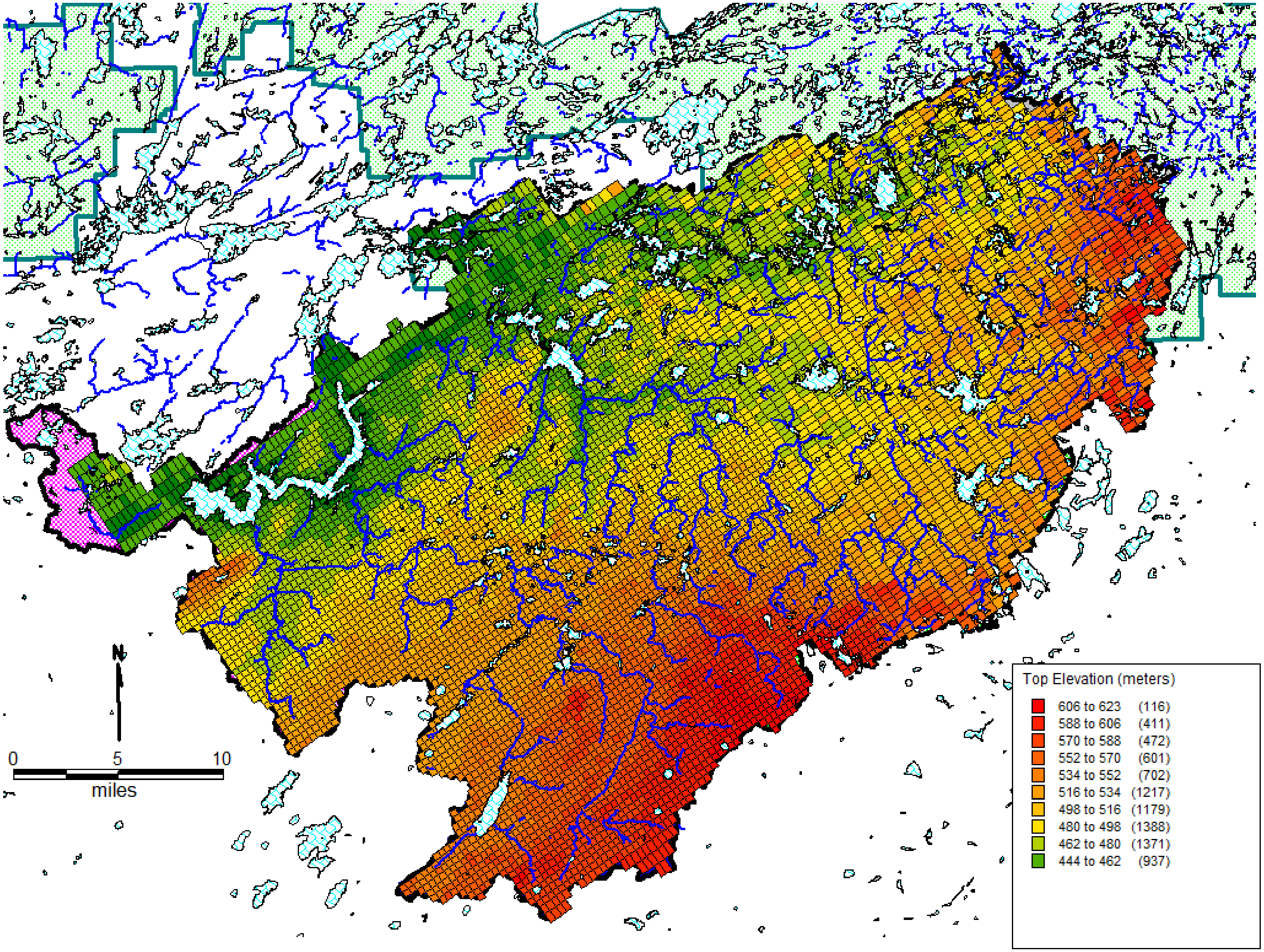


Fig. 11: Layer 1 top elevation by cell in meters.

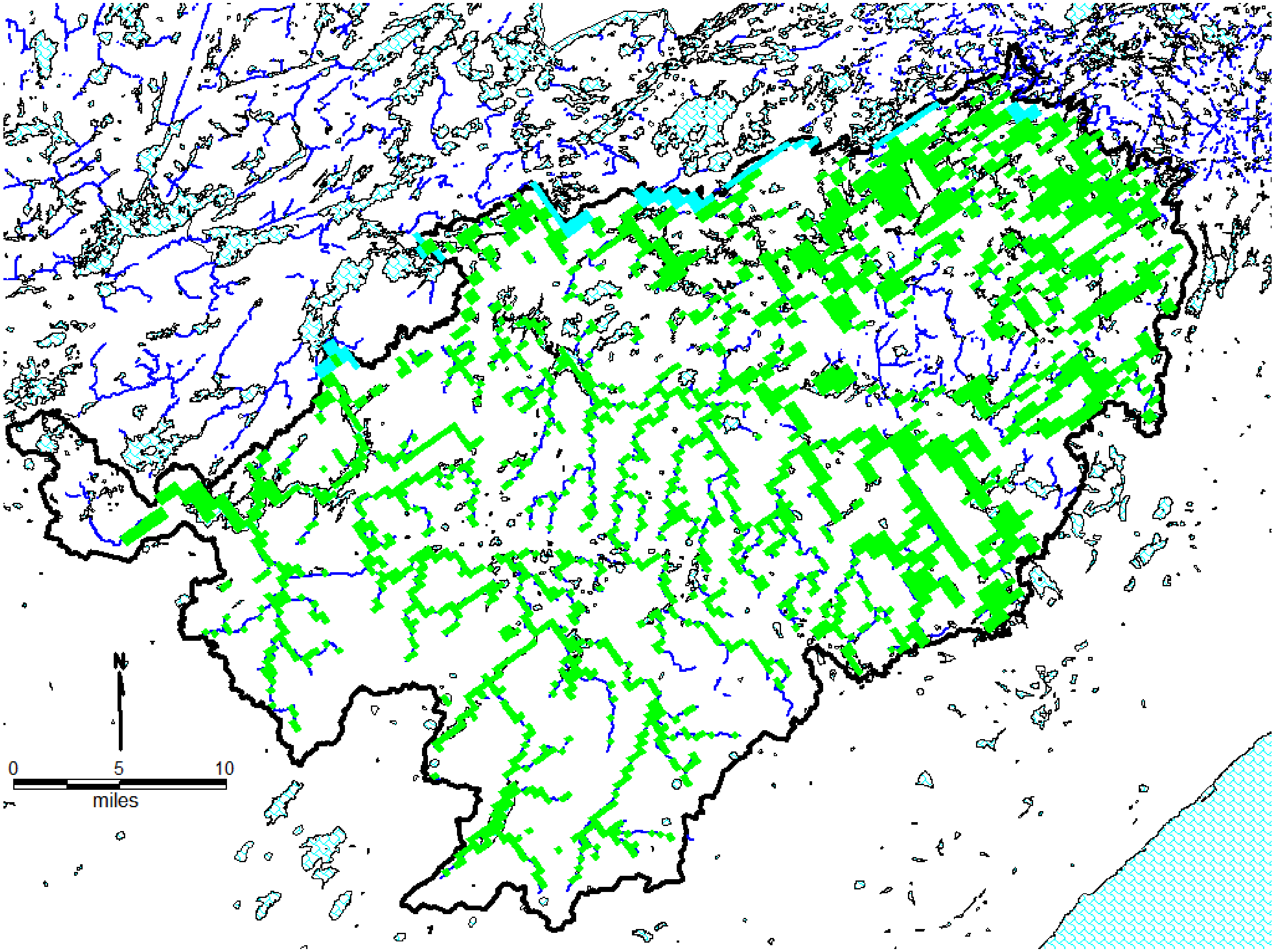


Fig. 12: Location of DRAIN boundaries in green, layer 1, and general head boundaries (GHBs) in blue, layer 2. Lakes with blue thatching were used to set distance and head values in the GHBs.

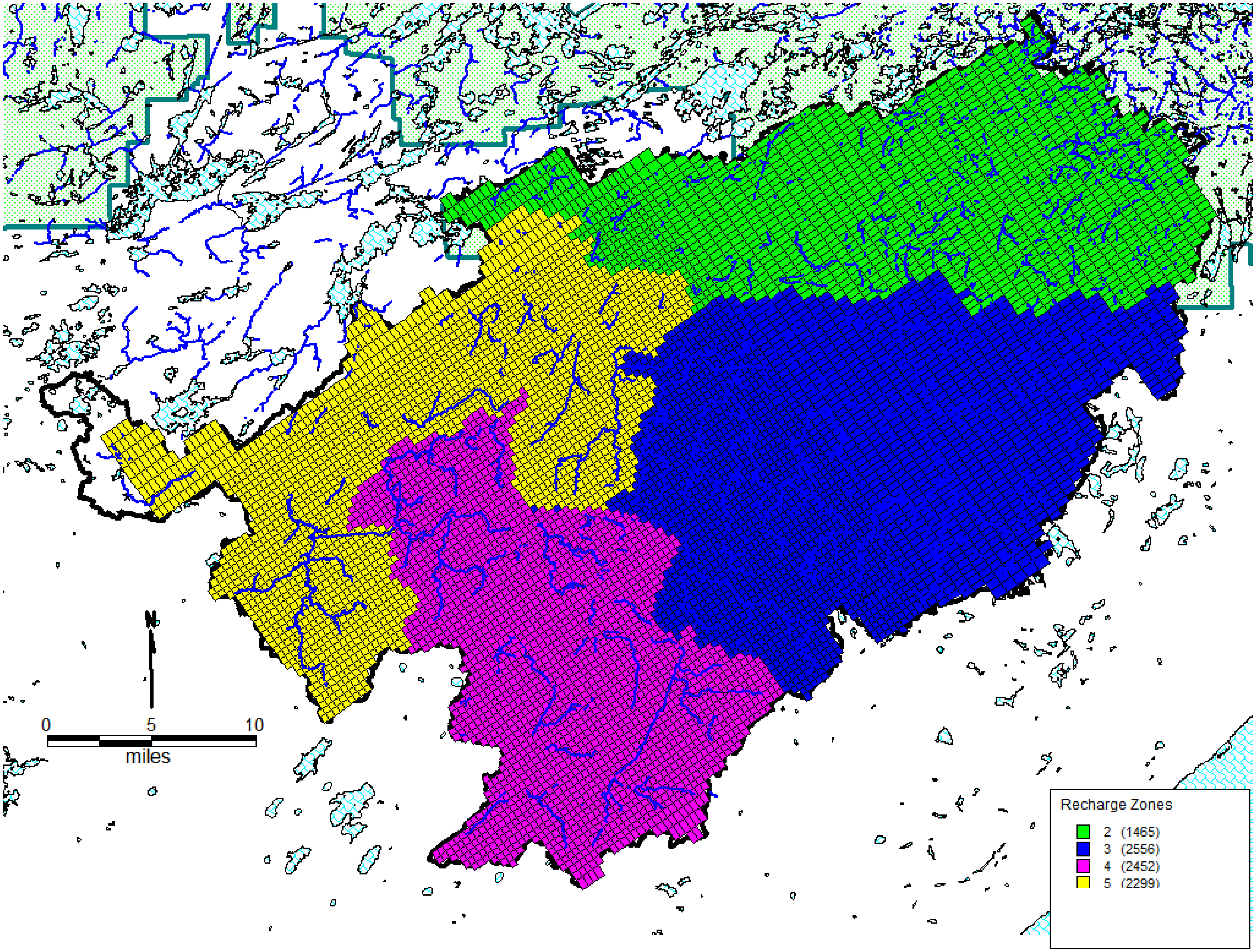


Fig. 13: Model recharge zones. Final recharge rates equal 0.00054, 0.00049, 0.00047, and 0.00052 m/d for zones 2 through 5, respectively.

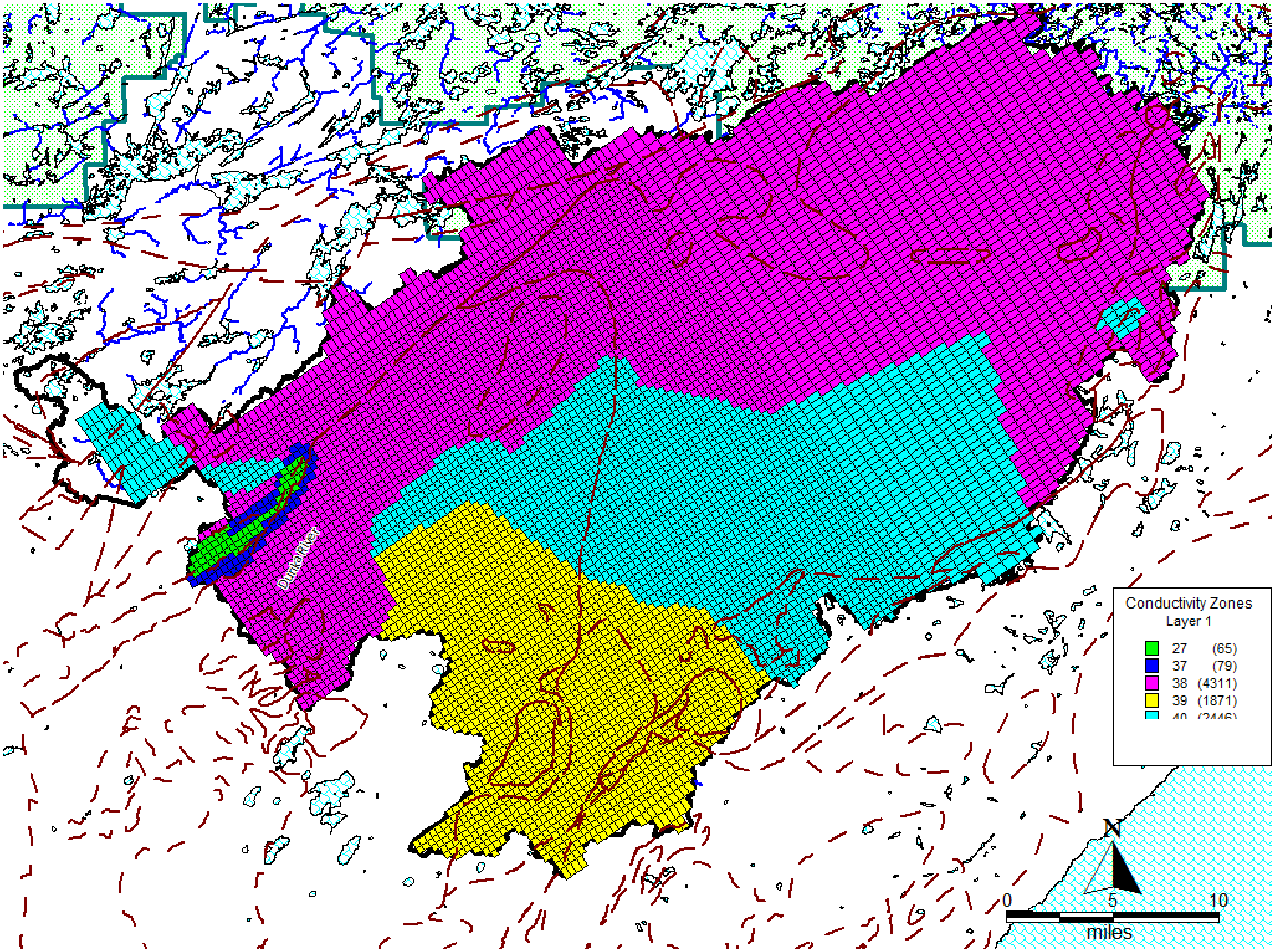


Fig. 14: Layer 1 hydrogeology zones. See Table 7 for final values. The outlines of geologic formations, which are mapped in Fig. 2, are included on this map.

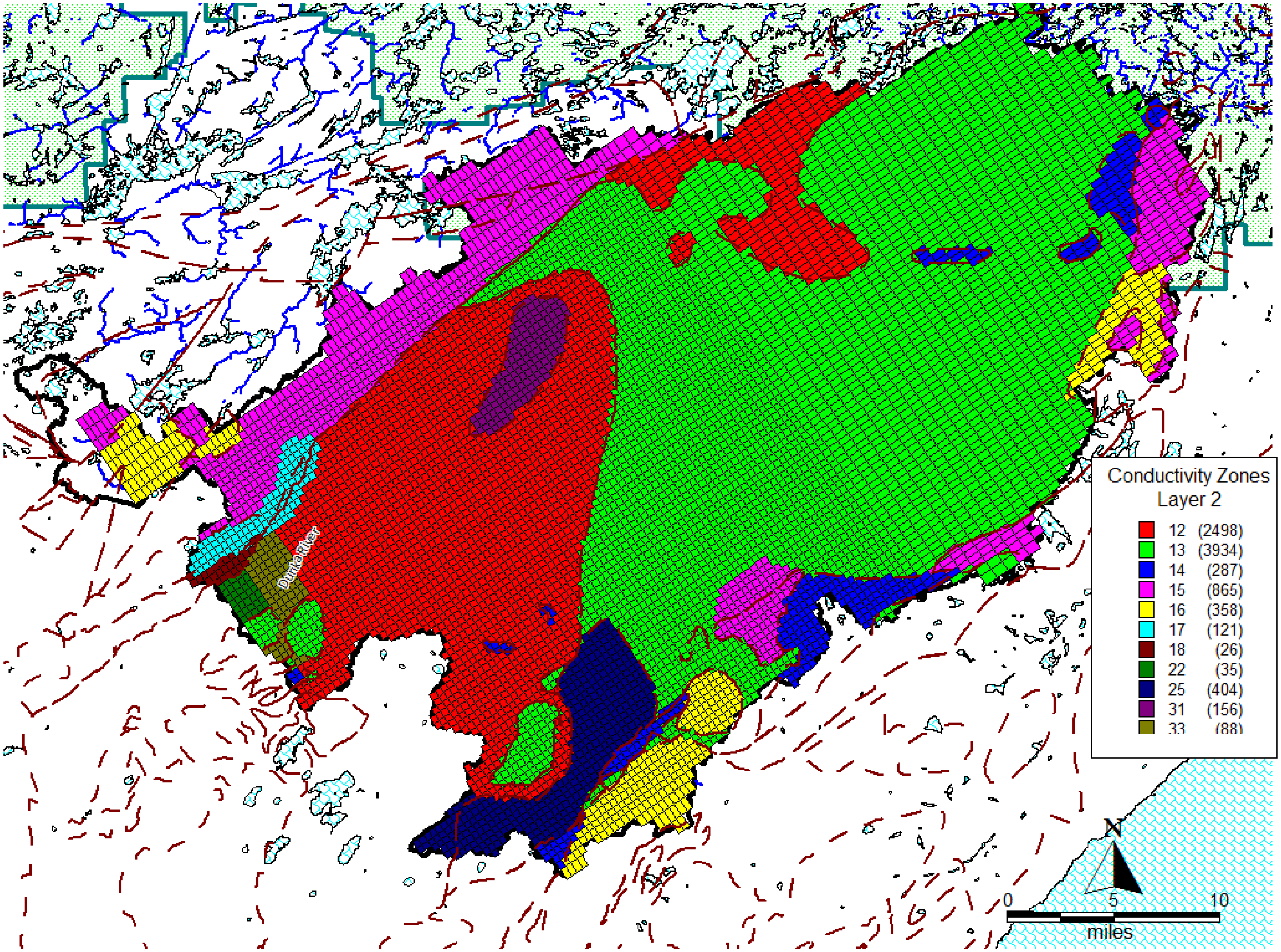


Fig. 15: Layer 2 hydrogeology zones. See Table 7 for final values. Geologic formation outlines, which are mapped in Fig. 2, are included on this map.

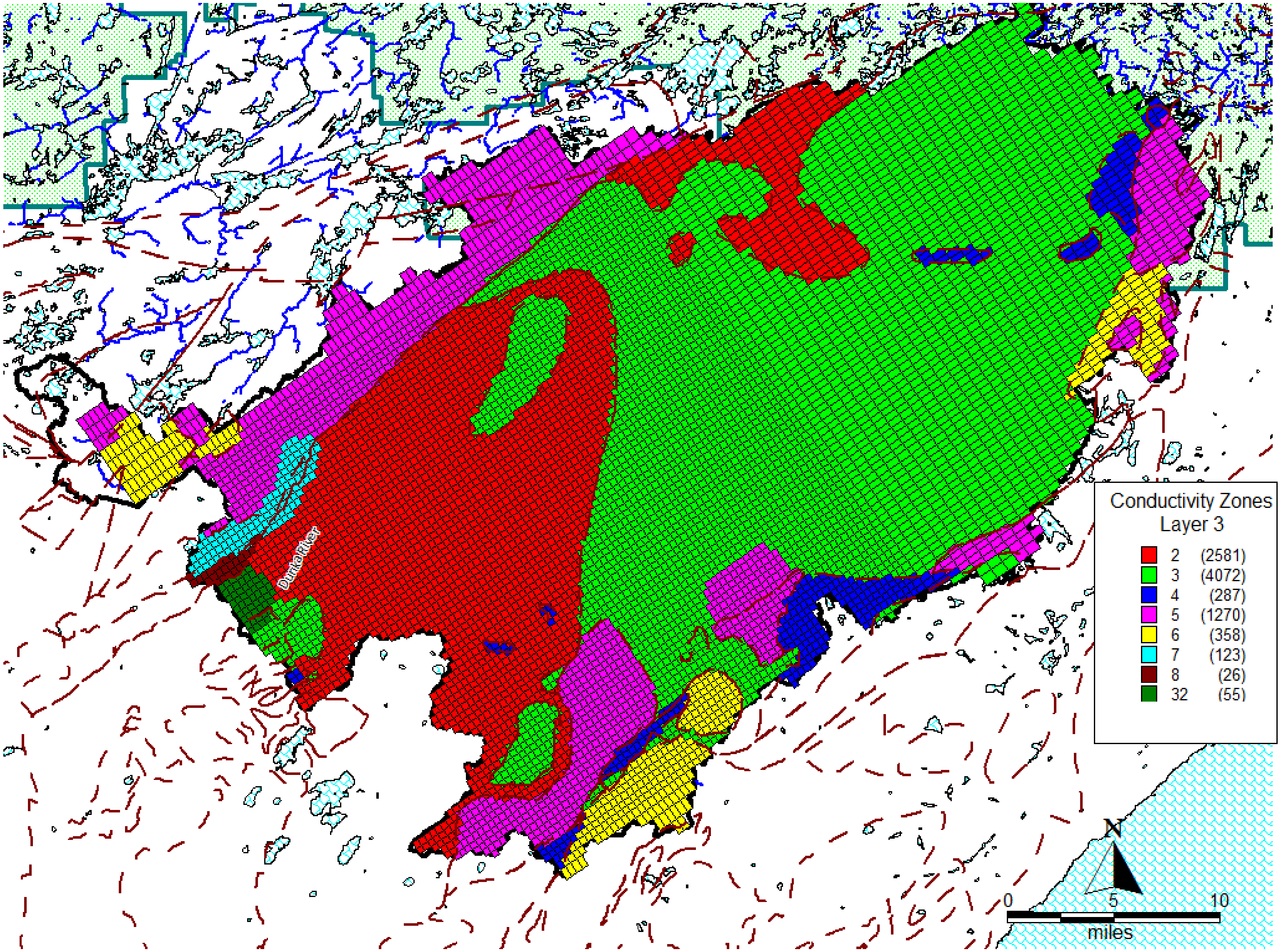


Fig. 16: Layer 3 hydrogeology zones. See Table 7 for final values. Geologic formation outlines, which are mapped in Fig. 2, are included on this map.

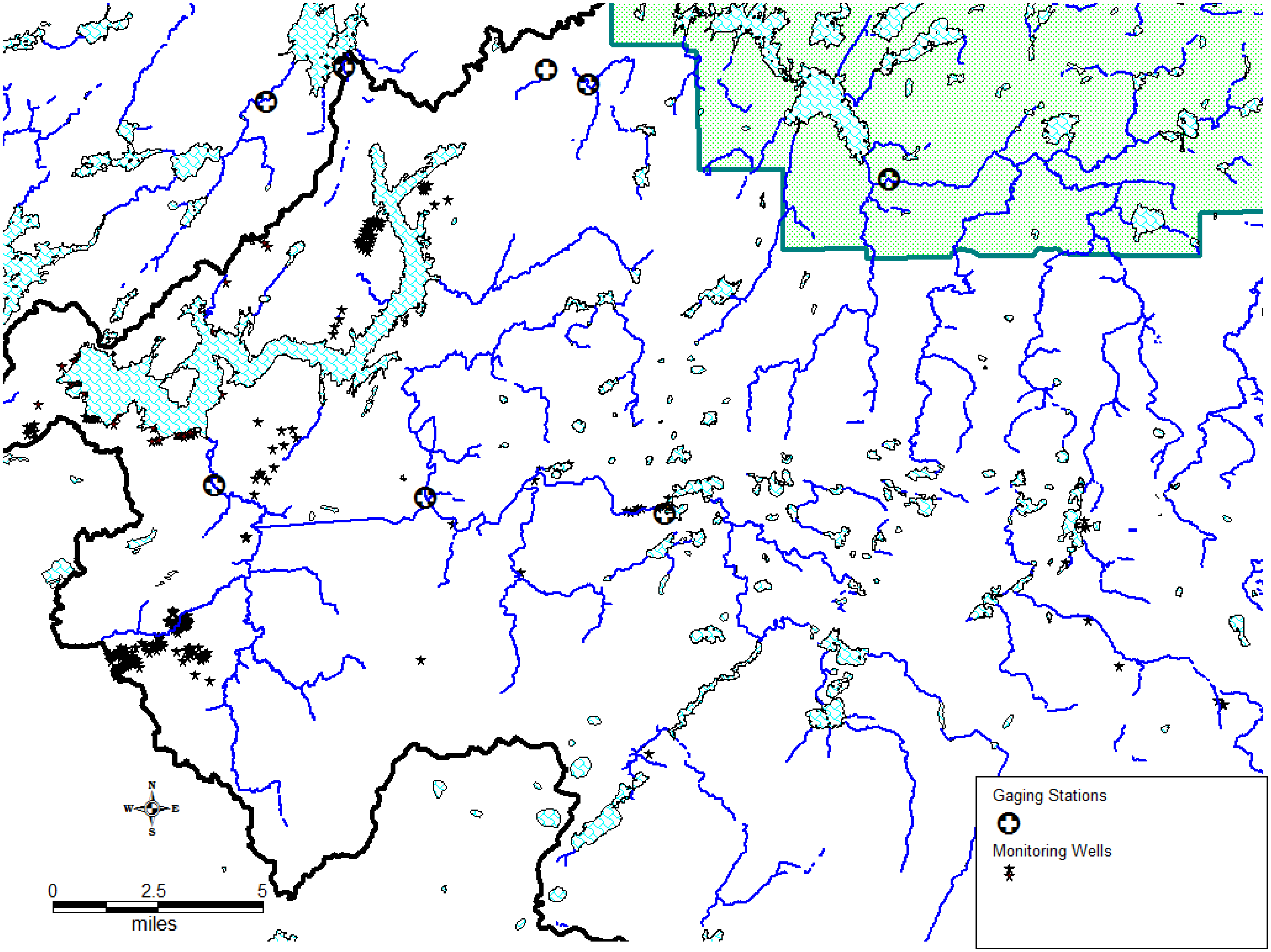


Fig. 17: Location of target wells in the study area.

Calibration

Calibration was completed in steady state mode because of the lack of transient data and because pumping stress is not simulated. Calibration is the process of adjusting K and boundary reach conductance to minimize certain test statistics, most specifically sum of squared residuals (SSR) and the actual mean (which should approach 0.0). A residual is the difference between the simulated and observed value so squaring the residuals and summing them provided an objective function which when minimized provides the best fit of the model to the observed data. Initial K values were 1 and 0.1 for bedrock layers 2 and 3, respectively. The high value for layer 2 was based on fractures and scale effects.

Initial calibration was completed using trial and error. Then, sensitivity analyses were conducted wherein the K value was multiplied by multipliers ranging from 0.5 to 2.0 times, to find the value which minimized SSR. Sometimes the analysis would yield local minimums, wherein the SSR is lower than for parameters values both higher and lower, but the calibration would continue until a global minimum SSR was found (if possible). Also analyzed in this way were various boundary conductance values. Finally, the automated MODFLOW-2000 parameter estimation routine was used to estimate composite sensitivities and to fine-tune the final parameter values.

Initial head for the steady state analysis for all layers was the ground surface, so simulated drawdown equals depth to water.

During calibration there was a tendency for groundwater to flow to and be prevented from crossing the no flow boundary on the north. The topographic divide along this border is less than 10 m above the surrounding areas in some locations and may not be a groundwater divide, at least not in all model layers. Because the simulated water level in all three layers was close to the observed values and they suggest a potential for cross-divide flow at depth, a general head boundary (GHB) was established in layers 2 and 3 to allow groundwater to cross the boundary in controlled locations. The GHB head and distance to the head was based on the water level in the lakes nearest the boundary (Fig. 12). Reaches were chosen based on low points in the topography and the location of lakes on both sides of the divide. The location of the GHBs influence flow paths through the domain, mostly through the Kawishiwi watershed. Adding the GHBs increased the SSR by just 400 (from 7900), so they did not have a huge effect on the simulated head values.

Calibration was deemed complete at a point where continued parameter estimation yielded composite scaled sensitivity (CSS) values within a few orders of magnitude for all parameters, the parameter estimates ceased changing, and the SSR was at a minimum. CSS is a dimensionless number that allows a comparative assessment of how sensitive a parameter is to the observations available (Hill et al. 2000). If changing a parameter's value has little effect on the test statistics, the parameter is not sensitive. Correlation among parameters is also important. The relative size of the CSS can be used to consider whether to create additional parameter zones by splitting existing zones or, alternatively, whether to combine zones (which would occur if the CSS for a value is substantially lower than for other parameters).

Table 6 shows the unweighted and weighted test statistics. The SSR was 4405 and 2173 for unweighted and weighted targets, respectively. The standard deviation is 4.2 and 3.0% of the range in observations, from the lowest to highest groundwater elevation, which was 150 meters. The most interesting difference between the weighted and unweighted statistics was that the unweighted mean was slightly negative and the weighted skew was 0.82 which reflects that many of the ground surface targets had positive residuals because the simulated head was lower than the assumed observed depth below ground surface, which were near watershed divides in recharge zones.

Table 6: Steady state calibration test statistics for weighted and unweighted residuals. RMS is sum of root mean squared error.

	Residual	Weighted residual
Residual mean	-0.70	0.22
Median	-0.12	-0.08
Abs Res Mean	4.95	3.51
Res Std Dev	6.35	4.48
SSR	4404.94	2173.06
RMS error	6.39	4.49
Standard Deviation	6.38	4.50
Sample Variance	40.67	20.26
Kurtosis	0.27	1.23
Skewness	-0.09	0.82
Min Residual	-17.18	-8.96
Max Residual	14.97	14.97
Minimum	-17.18	-8.96
Maximum	14.97	14.97
Number	108	108
Range	150	150
Scaled Std Dev	0.0423	0.0299
Scaled Abs Mean	0.0330	0.0234
Scaled RMS	0.0426	0.0299

The relation of simulated to observed groundwater elevations scatters around a 1:1 line as it should (Fig. 18). There is no detectable trend with observed groundwater elevation and simulations should yield no bias. The trend of residuals with observed groundwater elevation also shows a nice scatter around the zero value. However, there is a slight tendency for residuals to slope up and to the right in a couple clusters on the graph. Each cluster corresponds to the clusters of observation wells (Fig. 19). The apparent trend could reflect a slope in the water table that is not simulated exactly in this model, or could indicate horizontal anisotropy (Kx differs from Ky) which would cause groundwater to flow preferentially in one direction. The slope of observed heads is steepest to the northeast, which suggests that K is highest in southeast to northwest direction. However, this is not conclusive because the wells are laid out in that general direction (along the string of mineral deposits) which also intersects at right angles with lakes. Birch Lake provides a sink which could draw the flow from higher points near the divides. This is more obvious in layer 2 in which the groundwater is more obviously connected to rivers and lakes. If the observations regarding K and the slope of observed heads just discussed are accurate, there would be a tendency for more flow and transport from the Stony River watershed toward Birch Lake and the BWCAW.

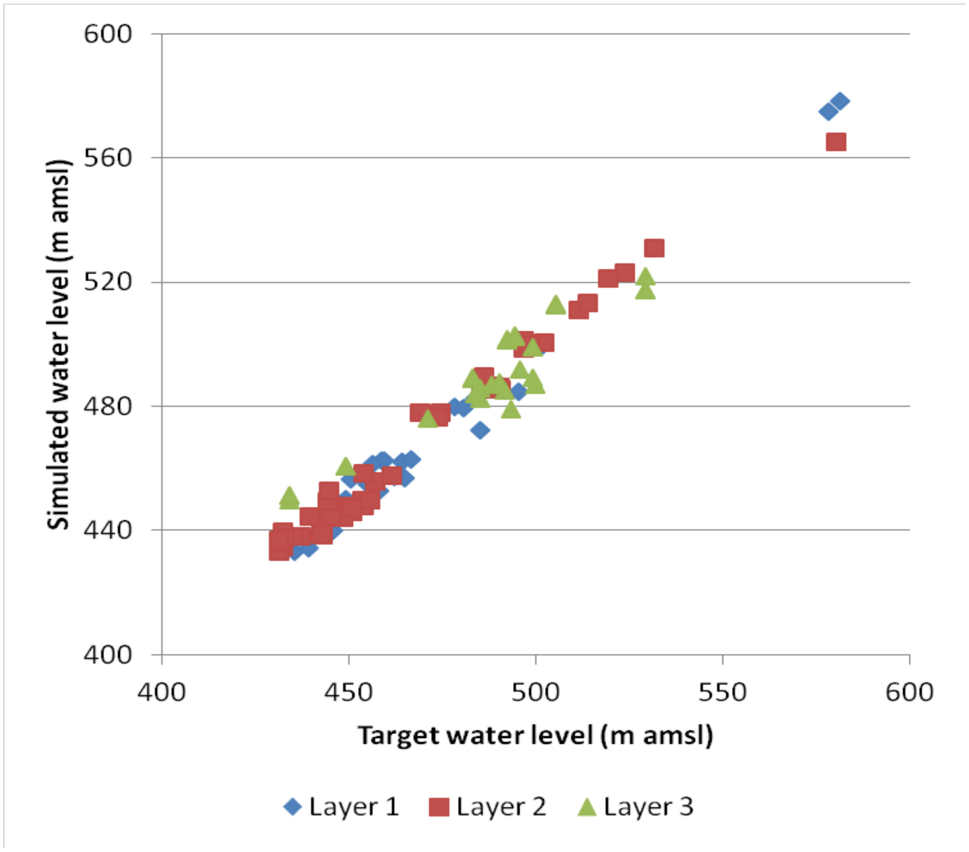


Fig. 18: Relation of simulated to observed water level, by model layer.

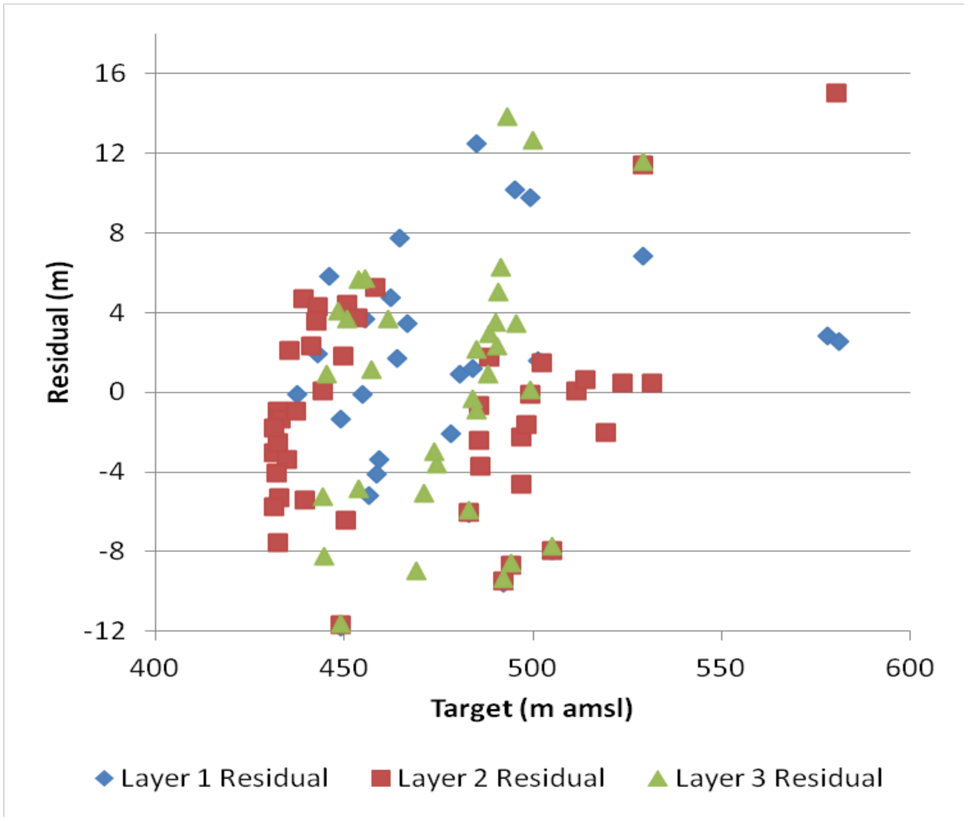


Fig. 19: Relation of residual to target groundwater elevation, by layer.

Final K zone values are shown in Table 7. The values for Kh in the surficial aquifer in layer 1 are high but well within the observed values discussed above while the Kv values reflect highly stratified till. Zone 37 has a high Kh but is an outcrop of Biwabik iron formation which has high measured values (Siegel and Ericson 1981).

Each bedrock formation has zones with K varying over at least two and usually three or four orders of magnitude. The parameter values show substantial variability, especially in the bedrock as would be expected in a heterogeneous domain with fractures. The simulated values may show additional variability because calibration was based on clusters of observations.

K decreases with depth for most formations, meaning that values in layer 3 are less than in layer 2, as expected due to the compaction occurring due to more weight and less weathering with depth. In zones 32 and 3, Kh was much less than Kv (Table 7). This demonstrates a tendency for vertical flow, and should be expected considering the zones are near the domain boundaries. The zones were adjacent and both are Duluth Complex, thus it is reasonable that the layers have upthrust so that the bedding has become vertical (Miller et al. 2002), which causes the observed high vertical anisotropy.

Table 7: Final calibrated conductivity values. Kh is horizontal K; Kv is vertical K.

Formation/lithology	Zone	Kh	Kv	Layer
Duluth Complex, troctolite/gabbro	2	0.307	0.01008	3
	12	0.342	0.137	2
	22	0.102	0.114	2
	32	0.00014	0.0182	3
	33	0.035	0.0145	2
Duluth Complex, anotrhosite/gabbro	3	0.025	0.2	3
	13	2.9	0.4	2
	31	0.26	0.002	2
basalt/rhyolite	4	0.05	0.025	3
	14	0.1	0.06	2
Giants Range granite	5	0.0015	0.0015	3
	15	0.214	0.2	2
	25	0.8	0.5	2
gabbrow/ troctolite	6	0.27	0.01	3
	16	2	0.09	2
Biwabik iron formation	7	0.16	0.001	3
	17	0.36	0.0075	2
	27	0.3	0.001	1
	37	26	0.02	1
shale/siltstone	8	0.1	0.01	3
	18	2	0.1	2
Surficial aquifer	38	7.4	0.16	1
	39	1	0.05	1
	40	5.2	0.1	1

Layer 1 started out as just one zone, not the five shown in Fig. 14, but simulations were unstable, which caused SSR to vary both higher and lower with the parameter value multiplier. Varying K lowered residuals in one area while increasing them in other areas. Therefore, layer 1 was split into zones 38, 39, and 40 according to the soil maps as described above and zones 27 and 37 were added to reflect an outcrop. At one point during calibration it appeared that zones 27 and 37 were not sensitive, but combining them caused a several percent increase in SSR so the split was retained. Zones 39 and 40 were not sensitive while zone 38, which extends across much of the Kawishiwi and Birch Lake watershed, was sensitive, especially in the horizontal direction (Fig. 20, Layer 1). This zone affects the water table slope over much of the area that has observation wells. The outcrops, zones 27 and 37, also influenced the water table slope near Birch Lake.

Zones 12 and 13 are sensitive in layer 2 (Fig. 20, Layer 2). Zone 13 is especially sensitive because it controls the water levels near the watershed divide where the artificial targets based on ground surface were added. Even with adjusting Kx13, these observations added the most to the SSR because they were among the highest residuals. Presumably this was because the zone was near topographic highs as described above. The weights are 0.3 which lessens their influence on K, but Fig. 20 does not account for weight. These areas are east of the mineral leases so the high residuals have little effect on the simulated transport. The only effect could be in the flux rate to the west across the study area.

Zones which cover larger areas also are more sensitive in layer 3 (Fig. 20, Layer 3). Varying the parameter multiplier from 0.5 to 2.0 added up to 300 to the SSR. Lowering or raising the value of a couple parameters, most notably Kv32, actually decreased the SSR by up to 100. However, doing so renders other parameters less than optimal.

CSS varied from 0.011 to 10.1, three orders of magnitude, although only five parameters had values greater than 1.0 (Fig. 21). Eleven of the lowest fourteen, and the lowest four, CSS were for vertical K. Fourteen of the highest seventeen CSS values were for horizontal K. This result indicates that Kh controls head values much more than Kv. The highest CSS is for zone 13, which controls the head values near the ground surface level observations, which were shown above to affect the model SSR more than other observations. In general, the CSS range is acceptable for final model calibrations.

The higher values for zones 38 and 40 indicate that the model accuracy could be improved substantially with more shallow wells throughout the domain. The DRAIN heads helped to control the head in these areas, which indicates that at least the water table elevation should be accurate. Without observations it does not affect SSR.

None of the eight lowest CSS values are in layer 3, which suggests that deep parameter zones have substantial influence over the head in upper layers. This indicates that additional deep wells spread throughout the domain would be useful to improve modeling and predictions should hydrology studies ever be undertaken to develop these deposits.

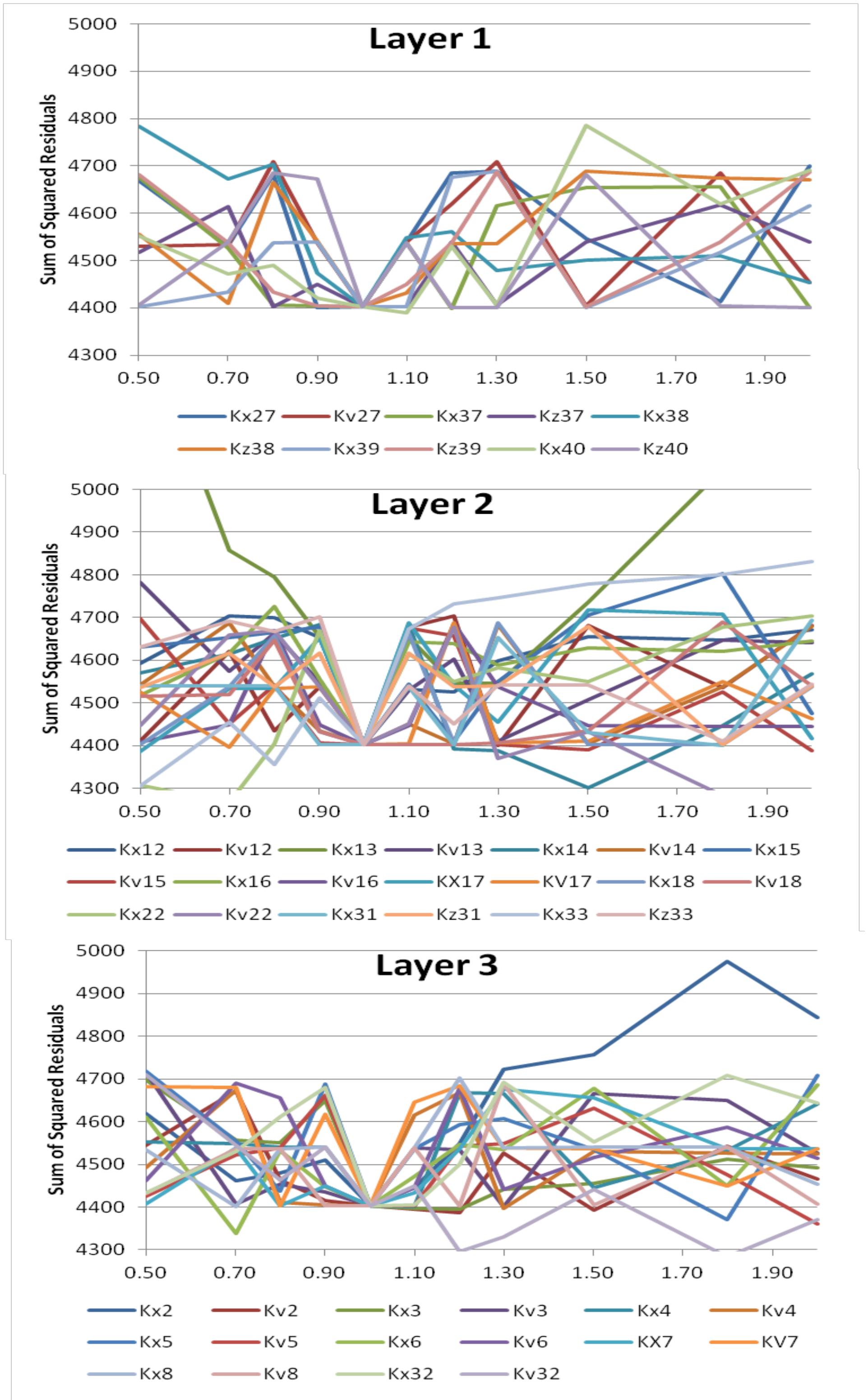


Fig. 20: Sensitivity of individual conductivity parameters, by layer. Note the different vertical axis scales.

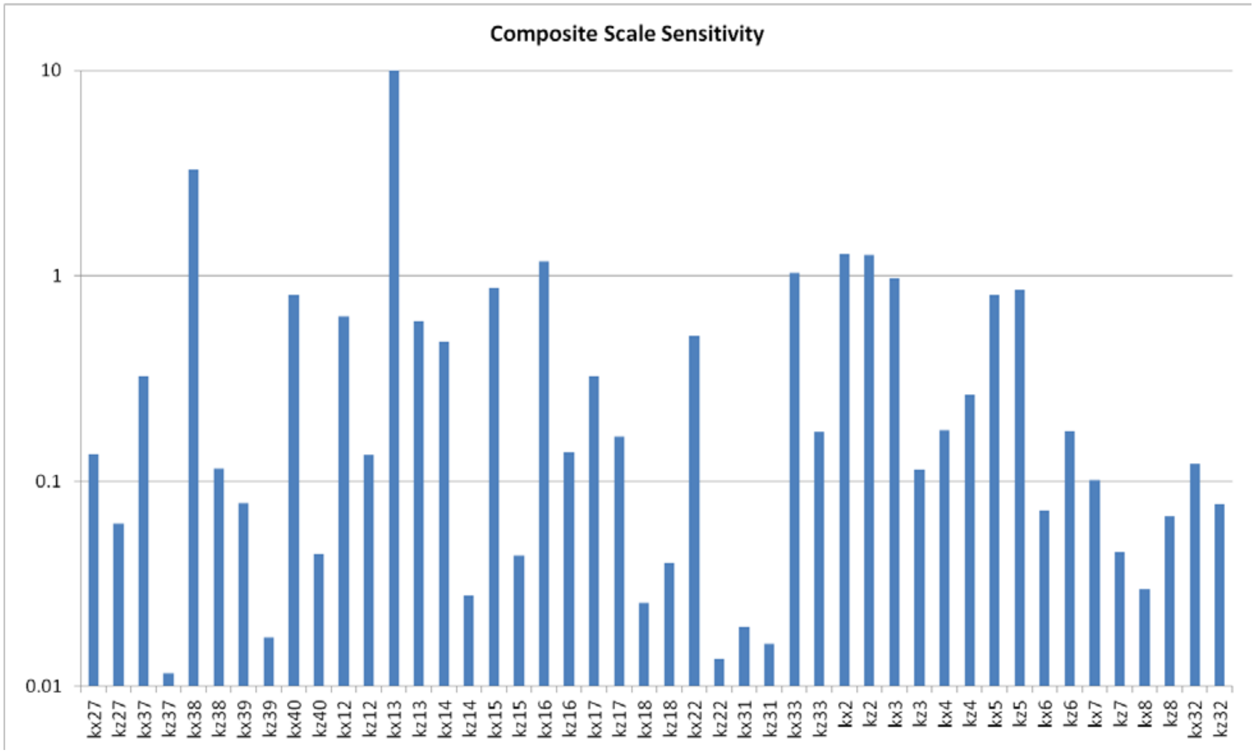


Fig. 21: Composite sensitivity for most hydraulic conductivity parameters. Note the logarithmic vertical scale.

Simulated head values generally show groundwater movement from southeast to the north and northwest, as discussed above with respect to the GHBs (Figs. 22 through 24). The water table in layer 1 follows the irregular topography (Fig. 22) with higher points being dry. The contours in deeper layers reflect a more consistent slope to the northwest (Fig. 23 and 24).

Nuances in the head contours reflect heterogeneities in and variations in the values of the calibrated K zones. The most obvious area is above zone 31 (most obviously in layer 2) about five to seven miles east of Birch Lake (Fig. 23).

The depth to water in layer 1 primarily ranges from zero to about 10 m, although a few areas in the west and south have head levels above ground surface, reflected as a negative depth to water (Fig. 25). These areas reflect an upward gradient with the very low Kv. Areas in all layers that have substantial positive depth to water occur under the small ridges where the water table slope is less than ground surface slope (Figs. 25 through 27). Negative values in layer 3 demonstrate an upward gradient to Birch Lake (Fig. 27).

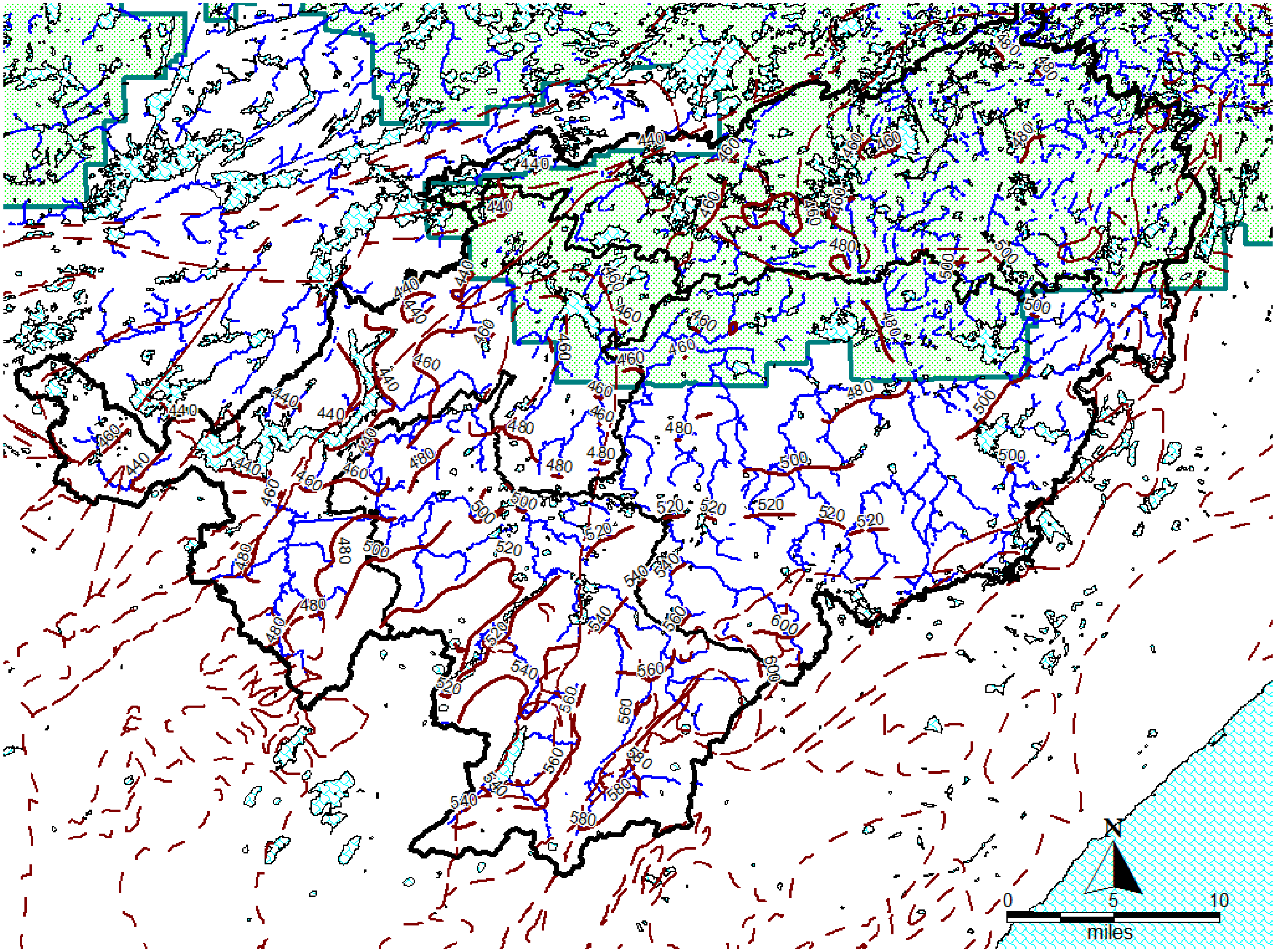


Fig. 22: Steady state head contours, layer 1. Areas without contours are dry.

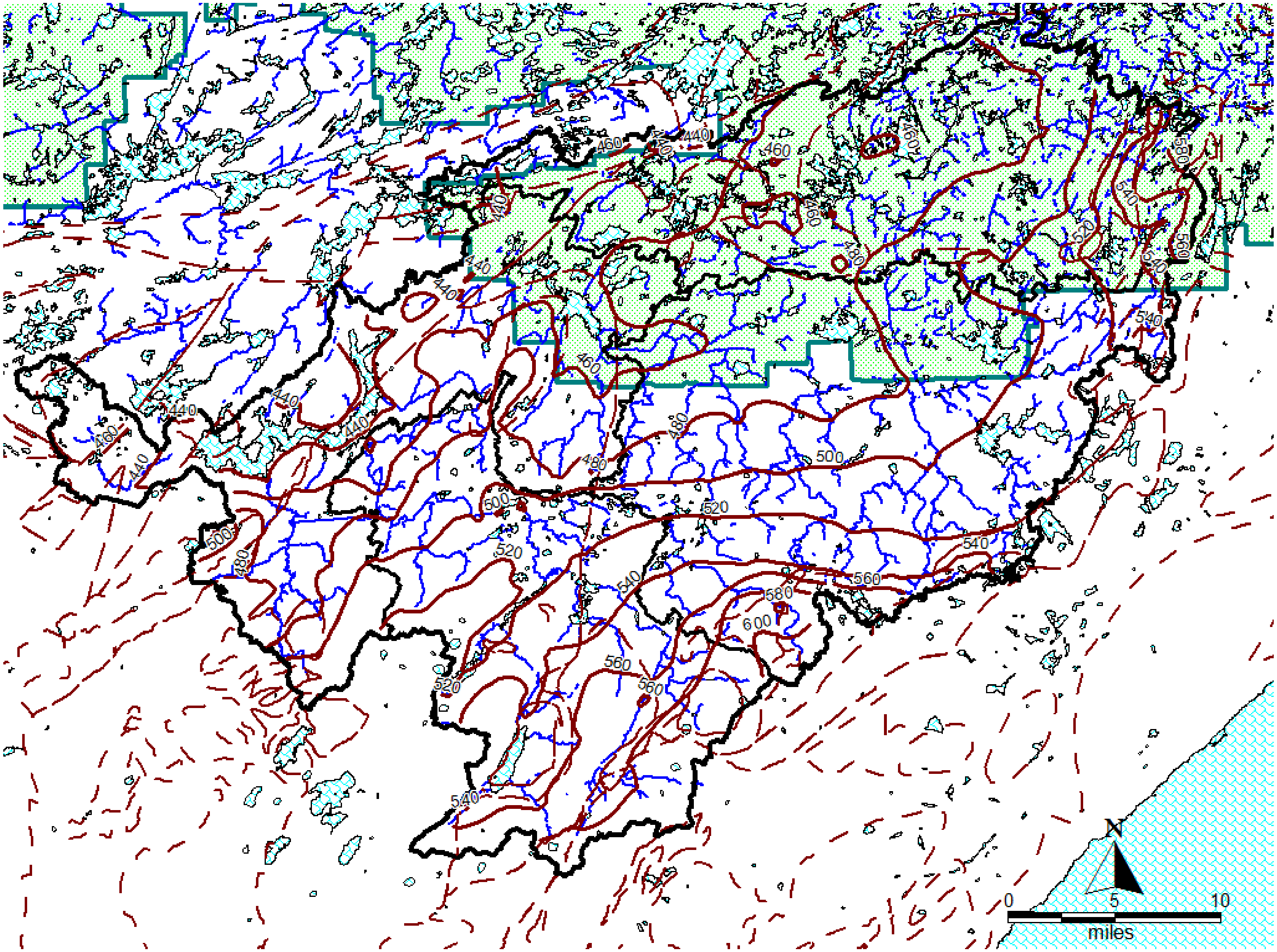


Fig. 23: Steady state head contours, layer 2.

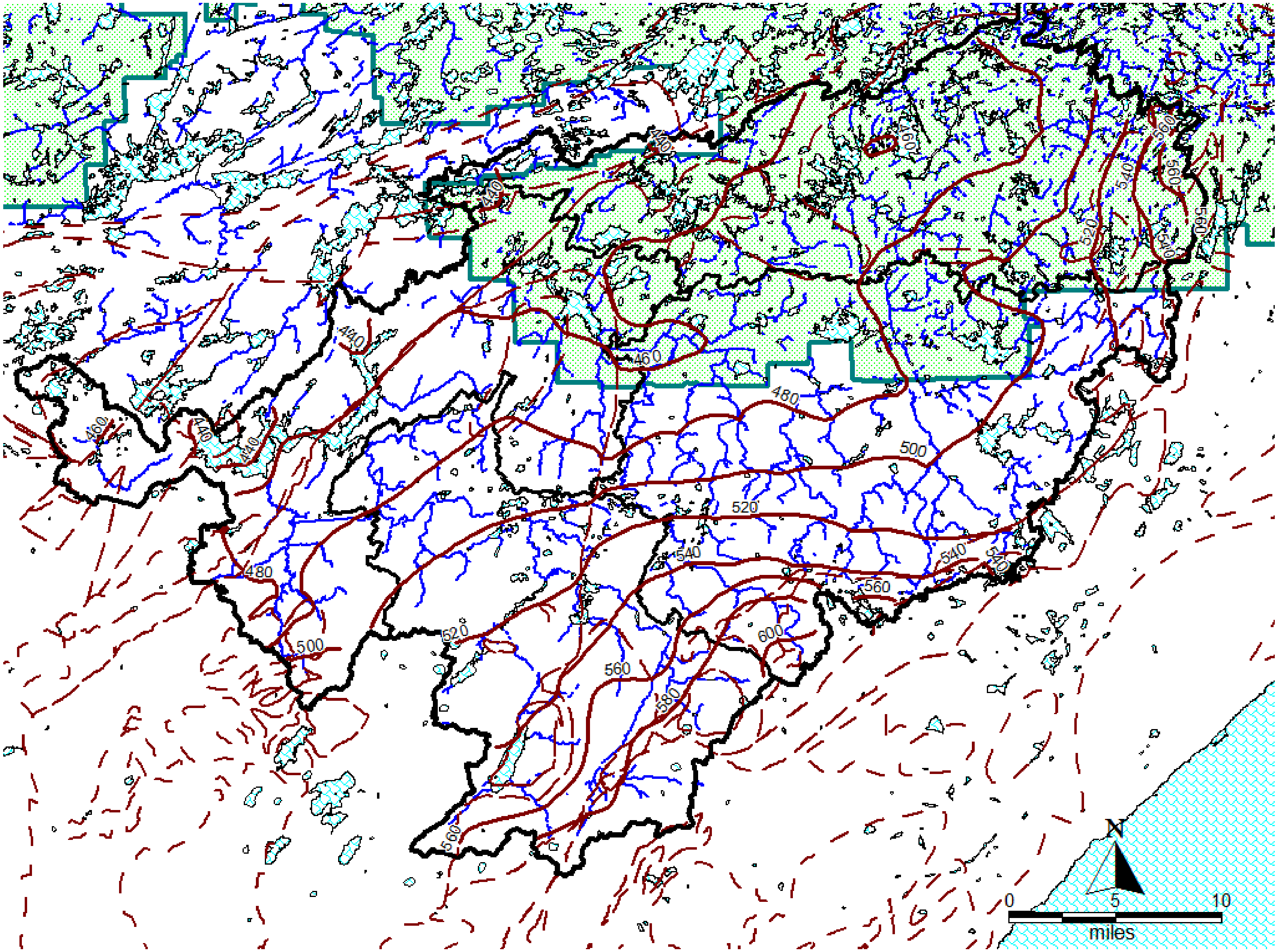


Fig. 24: Steady state head contours, layer 3.

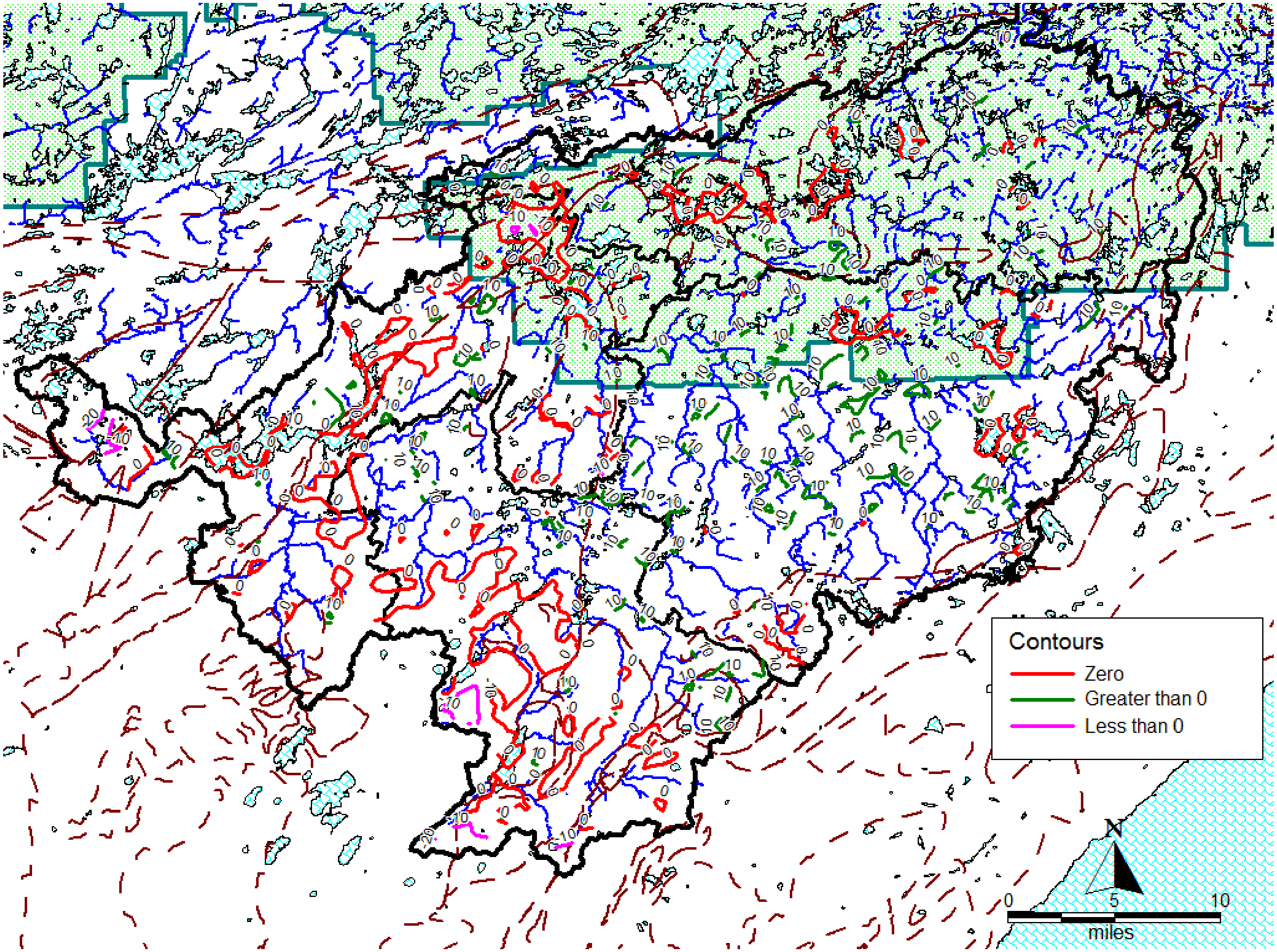


Fig. 25: Steady state difference from ground surface contours, layer 1.

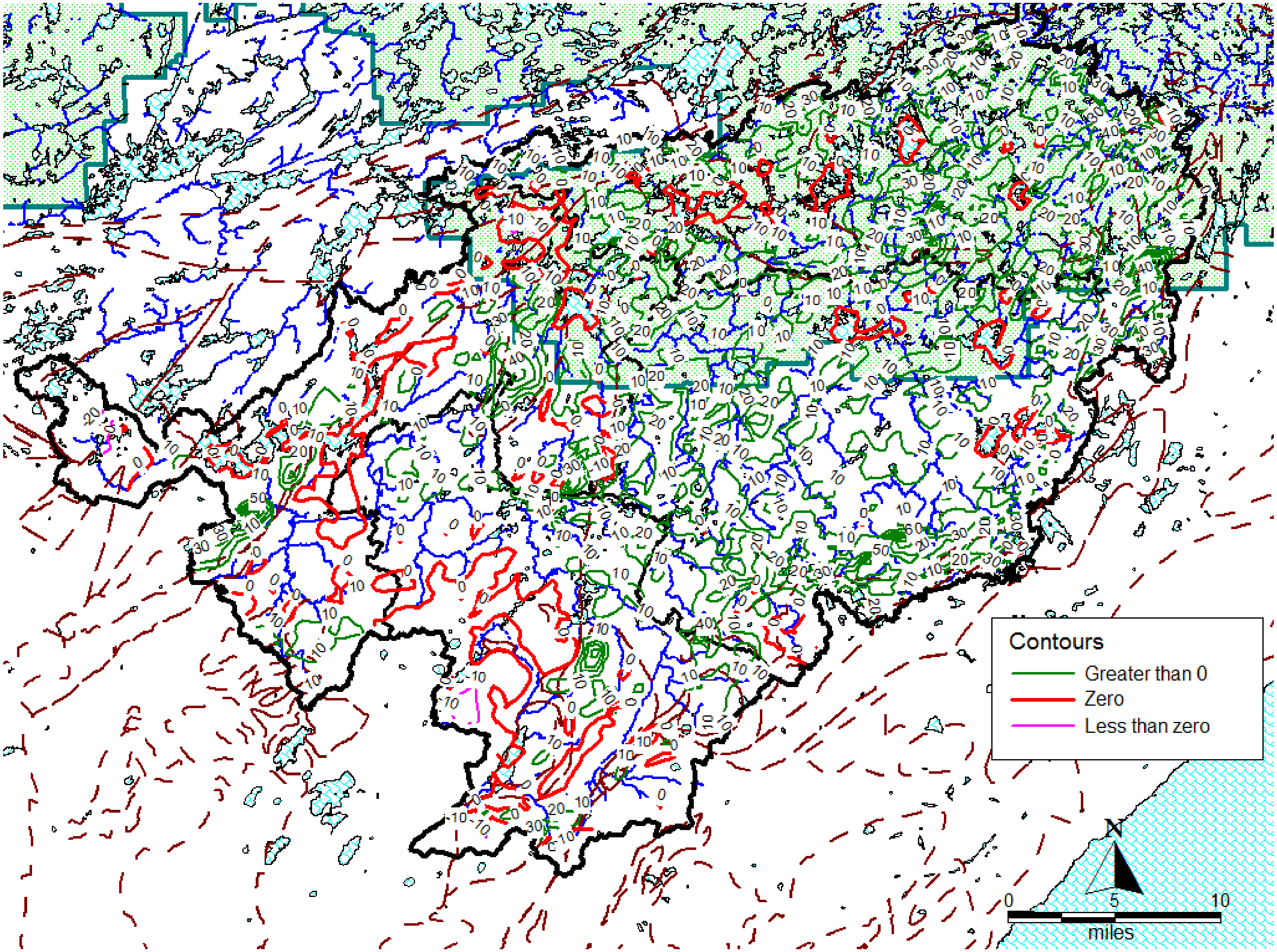


Fig. 26: Steady state difference from ground surface contours, layer 2.

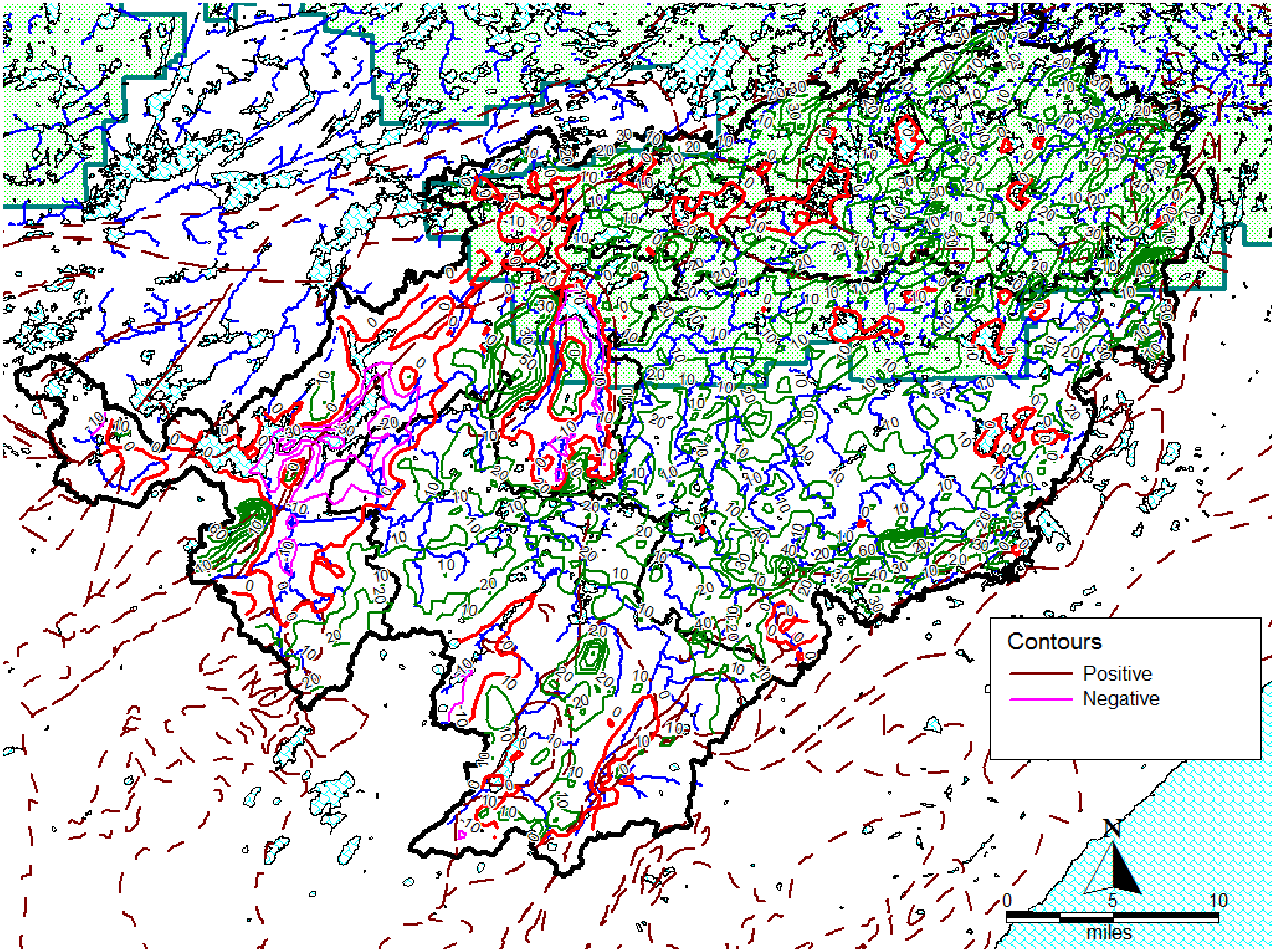


Fig. 27: Steady state difference from ground surface contours, layer 3.

Water Balance and Flux to the Rivers

The water balance table (Table 8) shows that total flux from the model is within about 12 m^3/d of the total recharge, as it must be if the model converges. Total recharge in zones 2 through 5 was set equal to the estimated baseflow from the watershed that ultimately discharges to the rivers and lakes (which are assumed to be hydraulically connected to the rivers)[3]. Recharge was close to discharge in the Isabella and Stony River watersheds but varied by from 10 to 20% in the other watersheds (Table 8). The Kawishiwi River watershed is somewhat lower and the general groundwater flow direction was toward that watershed (Figs. 22 through 24). Groundwater was allowed to flow northeast through GHBs, which account for much of the additional discharge from that watershed. Net discharge from the model through GHBs was about 28,000 m^3/d. The Birch Lake watershed has less discharge than recharge. However, the percent differences between watersheds are small and show that the distribution of recharge and discharge through the model domain is accurate.

All ten river reaches gain flow more slowly in their headwaters (more horizontal cumulative flux line) and gain more rapidly toward the outlet from the watershed (Fig. 28). Ten of the simulated lakes received zero discharge because they were in the upper portions of the watersheds. Both reflect that the headwaters are primarily recharge rather than discharge zones in the watersheds, as may also be seen on the depth-to-water maps showing areas near higher points having a much deeper water table (and dry areas in model layer 1) (Figs. 25 through 27).

The GHBs prevented the head contours from extending above the ground surface near the model boundary. The GHB discharge is a very small proportion of the recharge so little transport across the boundary would occur.

Birch Lake is a large lake near the outlet from the study area. The model simulated discharge into the lake (reach 1) is almost 75,000 m^3/d. Head contours and velocity vectors (not shown) demonstrate converging flow at the lake, so it would be a natural sink for contaminants. Especially in layer 3, the difference from ground surface contours are negative, demonstrating an upward gradient from that layer toward the lake. The boundaries for the S Kawishiwi and the Kawishiwi River also show converging flow due to the discharge to the river.

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[3] These boundaries were originally set to be RIVER boundaries to allow water to flow in and out of the surficial aquifer. It became difficult during calibration to balance distributed recharge with river recharge and the RIVER boundaries kept the groundwater level too high. Using DRAIN boundaries may lose some of the surface/groundwater interaction, but this primarily would be in areas that are perched, or above the actual water table.

Table 8: Water balance (m^3/d) from groundwater model, including DRAIN, general head boundary (GHB), and recharge fluxes, by watershed (BL-Birch Lake, IR- Isabella R, SR- Stoney R, KR - Kawishiwi R.) See Fig. 12 for GHBs.

Name		Reach or Zone	Watershed	Flux	Sum GHB and DRAIN by Watershed	
	Recharge	2	KR	373302	-409668	
	Recharge	3	IR	432989	-439274	
	Recharge	4	SR	291247	-288608	
	Recharge	5	BL	327444	-287444	
Total				1424982	-1424994	
	GHB	1	BL	-1549		
Birch Lake	DRAIN (lake)	1	BL	-74868		
Argo	DRAIN (lake)	2	BL	0		
Bruin	DRAIN (lake)	3	BL	-7064		
Clear	DRAIN (lake)	4	BL	-646		
Bald Eagle	DRAIN (lake)	36	BL	-21722		
August	DRAIN (lake)	37	BL	-1687		
Filson Cr	DRAIN	75	BL	-11230		
S Kawishiwi R, Keeley Cr	DRAIN	76	BL	-60906		
Snake R, Robin Cr, Bald Eagle Cr, August Cr	DRAIN	78	BL	-107772		
Hog	DRAIN (lake)	22	IR	0		
Clear	DRAIN (lake)	23	IR	0		
Perent	DRAIN (lake)	25	IR	-8821		
Silver Island	DRAIN (lake)	26	IR	-4425		
Harriet	DRAIN (lake)	27	IR	-1979		
Dumbbell	DRAIN (lake)	28	IR	0		
Isabella Lake	DRAIN (lake)	41	IR	-3657		
Isabella River, tributaries	DRAIN	74	IR	-420392		
	GHB	2	KR	-904		
	GHB	3	KR	261		
	GHB	4	KR	-13427		
	GHB	5	KR	-8866		
Pickeral	DRAIN (lake)	5	KR	-4415		
	GHB	6	KR	-1905		
Greenstone	DRAIN (lake)	6	KR	-285		
	GHB	7	KR	-1787		
	DRAIN (lake)	7	KR	-4496		
	GHB	8	KR	3781		
One Lake	DRAIN (lake)	8	KR	-2143		

Table 8: Continued						
Three, Four Lake	DRAIN (lake)	9	KR	-13081		
Hudson	DRAIN (lake)	10	KR	-510		
Insula	DRAIN (lake)	11	KR	-12912		
Alice Lake	DRAIN (lake)	12	KR	-8851		
Bow Lake	DRAIN (lake)	13	KR	0		
Boulder Lake	DRAIN (lake)	14	KR	0		
	DRAIN (lake)	15	KR	-1182		
	DRAIN (lake)	16	KR	0		
Koma	DRAIN (lake)	17	KR	-802		
Polly	DRAIN (lake)	18	KR	-3157		
Phoebe	DRAIN (lake)	19	KR	0		
Grace	DRAIN (lake)	20	KR	0		
Beth	DRAIN (lake)	21	KR	-647		
Kawishiwi Lake	DRAIN (lake)	24	KR	-1214		
Headwaters, Kawishiwi R	DRAIN	77	KR	-280643		
Kawishiwi R nr outlet	DRAIN	79	KR	-11417		
Denley, Nira, & Harris Cr	DRAIN	80	KR	-41067		
Greenwood	DRAIN (lake)	29	SR	-3036		
Sand	DRAIN (lake)	30	SR	-3684		
McDougal	DRAIN (lake)	31	SR	-1004		
Bongaa	DRAIN (lake)	32	SR	-1364		
Wampus	DRAIN (lake)	33	SR	-1411		
West Chub	DRAIN (lake)	38	SR	0		
Slate	DRAIN (lake)	39	SR	-342		
Stony Lake	DRAIN (lake)	40	SR	-5758		
Dunka R and tribs	DRAIN	71	SR	-73129		
Nip Creek	DRAIN	72	SR	-31066		
Stony R, Greenwood R, Stockade Cr, Homestead Cr, Mary Ann Cr, Spur End Cr, Wilbur Cr	DRAIN	73	SR	-167814		

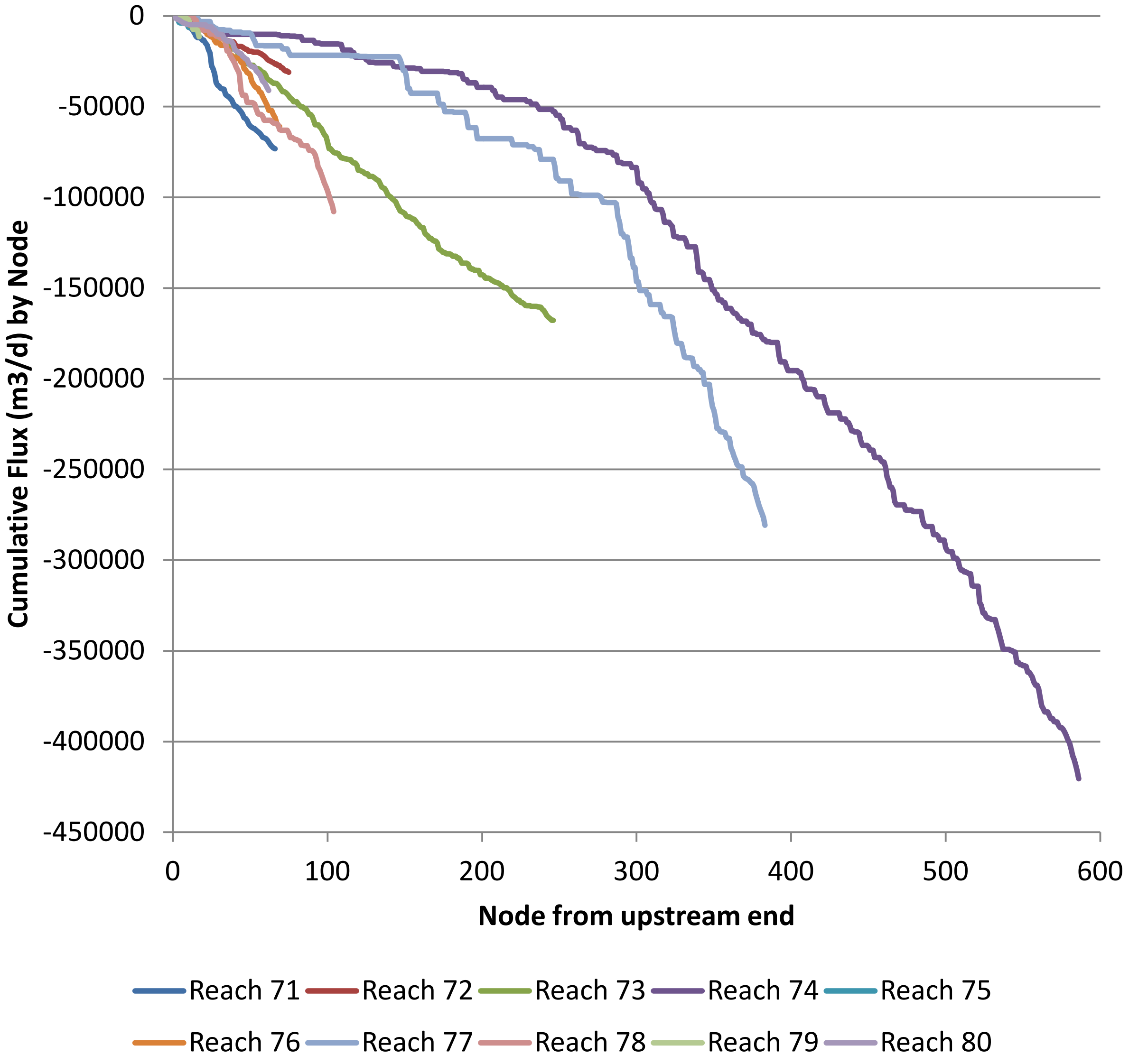

Fig. 28: Cumulative flux from upstream to downstream, by model node.

Potential Twin Metals Copper Mining

There are mineral leases throughout the Stony River and Birch Lake Watersheds (Fig. 29), which are the contaminant sources simulated below. Myers (2013c) reported on the leases held by Twin Metals, although they are just a portion of the potential mineral leases in the area. Twin Metals is a joint venture between Duluth Metals Corporation and Antofagasto Minerals (http://www.miningminnesota.com/who_companies.php, accessed 6/16/14). Duluth Metals has acquired Franconia Minerals (Id.).

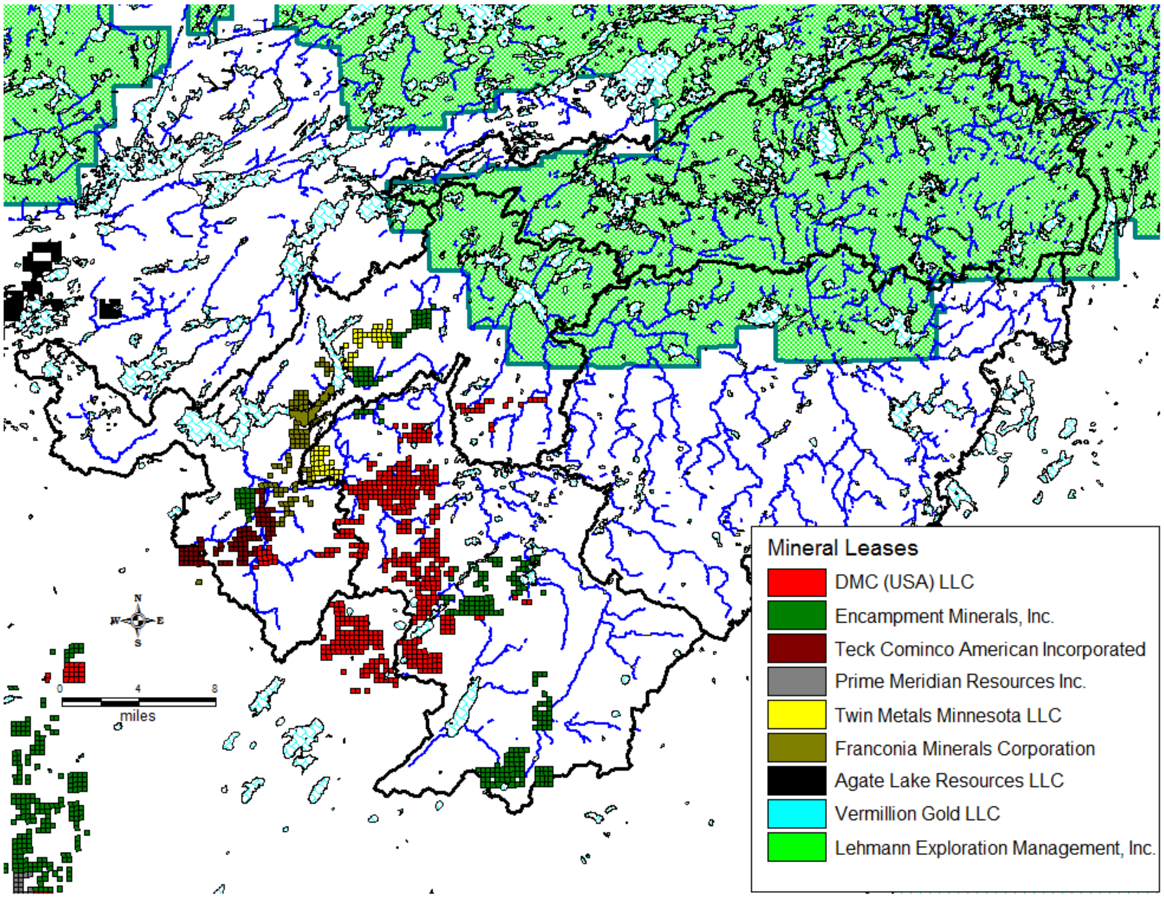

Fig. 29: Location of mineral leases in the study area. See Fig. 1 to identify the watersheds. Many leases in the Birch Lake watershed lie next to the lake.

Twin Metals proposes mining at four mineral deposits – Maturi, Maturi Southwest, Spruce Road, and Birch Lake - located 10 miles east of Babbitt, MN and 15 miles southeast of Ely MN. All four deposits are in the Birch Lake watershed and lie south of the South Kawishiwi River or adjacent to the west end of Birch Lake (Fig. 30). Each deposit would likely be accessed with underground methods (Parker and Eggleston 2014; Cox et al 2009). The reserve calculations were based on underground mining methods but some deposits, including Maturi Southwest, reach close to the surface which could lead to some surface mining. Twin Metals (2014) suggests that 55% of the tailings could be deposited underground. A tailings impoundment may be constructed at the Dunka Mine site, with some tailings backfilled into the abandoned open pit (Cox et al 2009); this is not simulated herein.

The deposits are all hosted in the Duluth Complex, a composite intrusion, in the basal portion of the South Kawishiwi intrusion. The mineralized zone is as much as 1000 feet thick in locations. All deposits are magmatic nickel-copper-platinum group element deposits which are mostly considered sulfide deposits (Parker and Eggleston 2014). They occur in localized areas along the basal zone of the South Kawishiwi at the contact (Miller et al. 2002, p 167). The sulfide content of the Spruce Road deposit is 2 to 5% by volume and 3 to 4% by weight, with chalcopyrite being the primary copper sulfide; it is the only deposit with sulfide content specified. This exceeds the sulfide concentration at the proposed Polymet mine (Polymet 2013a).

The Maturi deposit extends from near ground surface to as much as 4500 feet below the ground surface. The depth of the Spruce Road deposit ranges from the ground surface to about 1500 feet bgs. The Birch Lake deposit ranges 700 to 2200 feet below ground surface. The Birch Lake deposit contains up to eight possible significant faults (Parker and Eggleston 2014), which are identified as substantial issues which will potentially affect the underground mining operations and the location of high grades of mineralization. Faults can also affect groundwater flows, but there is little evidence available to determine whether they are conduits or blockages to flow.

Based on the head contours, showing a southeast to northwest trend, developed in the numerical modeling above (Figs. 22 through 24), contaminants released from these leases will move toward rivers that flow into the BWCAW. Most will flow through the Birch Lake watershed. Surface waters from both Stony River and Birch Lake watersheds drain through Birch Lake and the S Kawishiwi River to the Kawishiwi River and into the BWCAW.

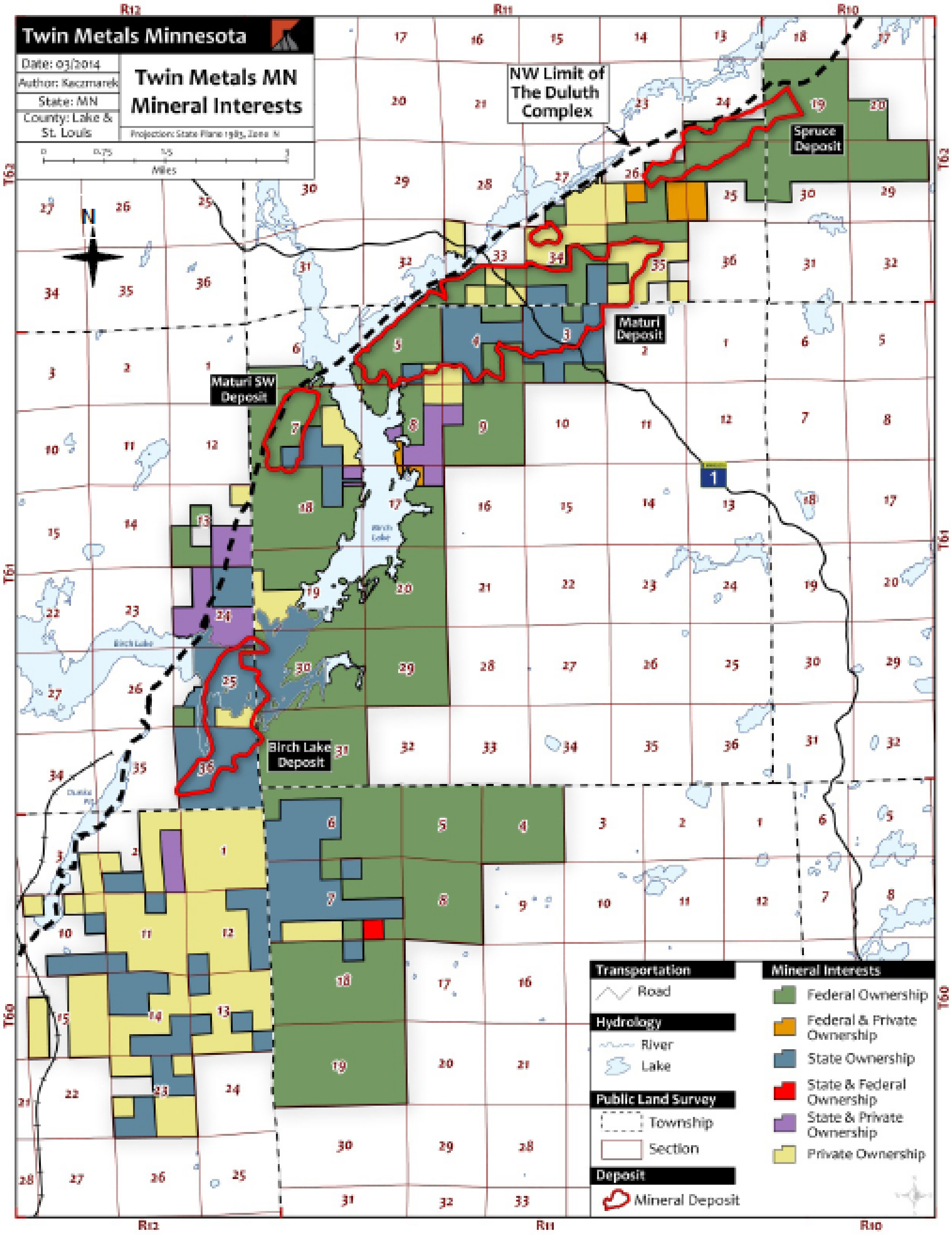

Fig. 30: Snapshot from Figure 4-3 in Parker and Eggleston (2014) showing the location of the Birch Lake, Maturi, Maturi Southwest, and Spruce Road deposits. Scale is provided by the squares which are approximate townships.

Particle Tracking

A particle tracking analysis of the flow model developed above determines the advective pathway for contaminants introduced at any given point to their final sink, or discharge point. Advective pathway means simply the path that a particle will follow if not subject to dispersion or attenuation. Particle tracking was completed using the final steady state flow model using the program MODPATH (Pollock 1994).

Contaminants were placed in approximately 630 model cells coincident with mineral leases (Fig. 29) at five different levels - the middle and top of layer 3, the middle and top of layer 2, and the top of layer 1, or the water table. The first four placements would represent a contaminant leaching from an underground mine facility. The middle of layer 3 is approximately 750 m (c 2460 ft) below ground surface (bgs), although it is variable. The top of layer 3 and middle and top of layer 2 are 140, 77.5, and 15 m bgs, respectively (460, 254, and 49 ft). The water table entry point would represent the point of a surface leak or spill seeping through the vadose zone to the water table. This analysis tracks the path a particle would take and the time for it to travel from source to sink. Neither the load nor concentration is important in this analysis.

All analyses were completed in the forward mode, meaning that particles were released at time zero and tracked forward in time until they reach a sink, which in all cases was a DRAIN boundary. MODPATH utilizes the head and cell-by-cell flow solution from MODFLOW. It does not directly use aquifer properties beyond the solution other than porosity, which controls the rate that a particle advects along with the groundwater flow.

In bedrock, fractures control permeability and secondary porosity, and also flow paths. In the Biwabik formation, porosity is as high as 50% due to leaching. This is zone 17 and 7, for which porosity was set to 0.4 and 0.3, reflecting the compaction with depth. Zones 18 and 8 are shale in layers 2 and 3 with porosity set at 0.05 and 0.03, reflecting little-fractured shale and compaction. Zones 15 and 5 are Giants Range granite, which typically has very low porosity; here zone 15 is set at 0.05 and zone 5 at 0.03, for layers 2 and 3 respectively. These values are slightly elevated because the calibrated K suggests some fracturing. The remaining formations are Duluth complex including some intrusions (Fig. 2). They are a combination of sedimentary and volcanic rock. The upper portions would have porosity exceeding 0.1; porosity in deep portions, below 750 m, would be less than 0.05. Zones 12 and 13 would have porosity equal to 0.12, and zones 2 and 3, layer 3, were set to 0.07 (they are not as deep as Thorfeison 2008, Fig. 38). Zones 16 and 6 are mafic intrusive rock, which likely has slightly higher porosity, so are set to 0.14 and 0.08, respectively. Zone 4 and 32 were combined with zones 2, 3, 12, and 13, based on being adjacent. See Figs. 14 through 16 for maps of parameter zones.

Results of Particle Tracking

Each contaminant introduction into a cell starts a transport pathway to a sink, so the useful results are a determination of which areas would drain contaminants to a river through which they can reach the BWCAW, and how long it takes for a particle to reach a river. The longer the transport time, the more dilution and attenuation that could occur to a contaminant plume. The analysis tends to overestimate the shorter times, however, because actual bedrock fractures could be much tighter in certain areas which would concentrate more flow in a smaller area than considered in individual model cells.

Particles introduced at the middle level of layer 3, or about 750 m bgs, required the longest time of any of the particle introductions to reach surface water (Fig. 31). The minimum time was 26 years, and approximately 5.7% of the locations reached sinks in less than 100 years, with travel times extending to greater than 10,000 years for many pathways. About 2.8 and 23.5% of the particles released at the top of layer 3 and middle of layer 2 reached the surface in less than 50 years, respectively (Fig. 31). The risk clearly increases as the source becomes closer to the surface.

The primary factor controlling transport time, other than distance from the sink, is whether the particle sinks deeper into the bedrock. As seen above and in Figs. 32 and 33, groundwater travels downward in certain areas. Contaminants released in such an area would not present substantial risk to the BWCAW at least for a short-term period after mine construction. However, the transport through fractures could speed the travel time more than indicated herein. Also, longer pathways could result in contamination reaching the BWCAW after mining has ceased.

Most particles released at the water table reach surface water quickly, with 21% of particles reaching surface water within 10 years and 62.9 % in 50 years. Transport of some particles was only a year or two. The short layer 1 pathways demonstrate this (Fig. 32). Short pathways from the water table source were generally those located closer to larger rivers. Interestingly, some of the longer transport times occurred because particles were transported deeply into layer 2 or even layer 3 (Fig. 33). These pathways originate in the west-central portion of the Stony River watershed and flow northwest toward tributaries to Birch Lake. These sites are distant from sinks, in locations where recharge dominates the vertical flow in layer 1.

Certain particles released at the top of layer 2 exhibited different behavior than those at other release levels (Fig. 31). Particles simulated to be released into a cell with upward flow into a DRAIN cell in layer 1 reached surface water in less than a year, and in some cases in just a few days. In some instances the bottom of a DRAIN cell intersected the top of layer 2. These extremely short times did not occur for releases in layer 1 because the water table in those cells was several meters above the river level. These very short transport time estimates are likely unreliable.

Between less than 0.2 and 0.5 proportion (Fig. 31), particles released at the top of layer 2 appeared to transition from resembling layer 1 to middle of layer 2 releases (Fig. 31). This indicates that some of the particles that were not quickly captured by the DRAINs were transported deeper into the layer.

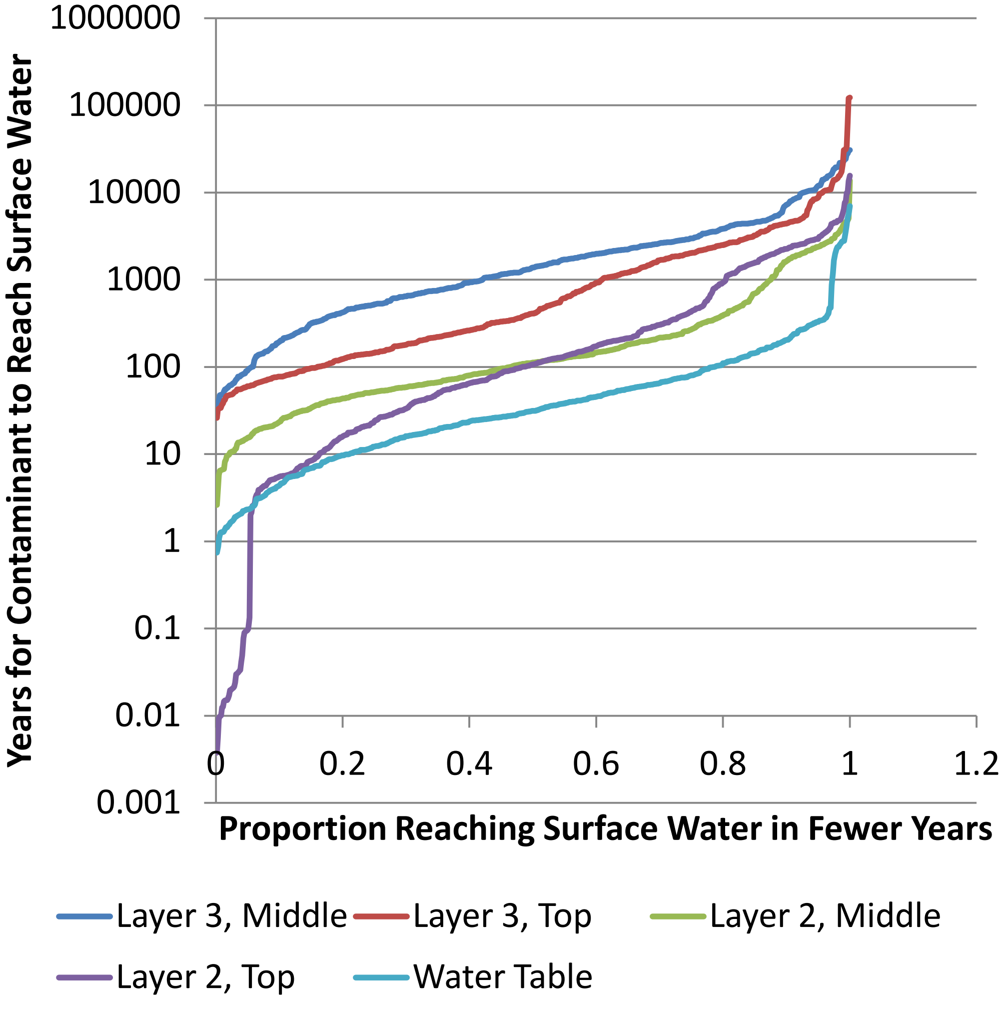

Fig. 31: Proportion of particles reaching surface water sources in a number of years. Note that years are on a logarithmic scale.

Adding the particles at the top of layer 3 resulted in generally much longer pathways, primarily through layer 3 (Fig. 33). Some of the pathways originate in the Stony River watershed and flow into the BWCAW. Pathways through layer 2 are much shorter in each direction (Figs. 32

and 33). This reflects the higher vertical anisotropy through that layer and generally higher vertical K. The longer flow paths through layer 3 reflect the layer's thickness and the variable vertical flow direction. Short pathways result from particle introduction in layer 3 where a river boundary is close; in these areas the flow is upward toward the sink and the particles advect along with the flow. The flow pathways for particle introduction in the middle of layers 2 and 3 are similar to that for the particles introduced at the top of layer 3 (Fig. 33).

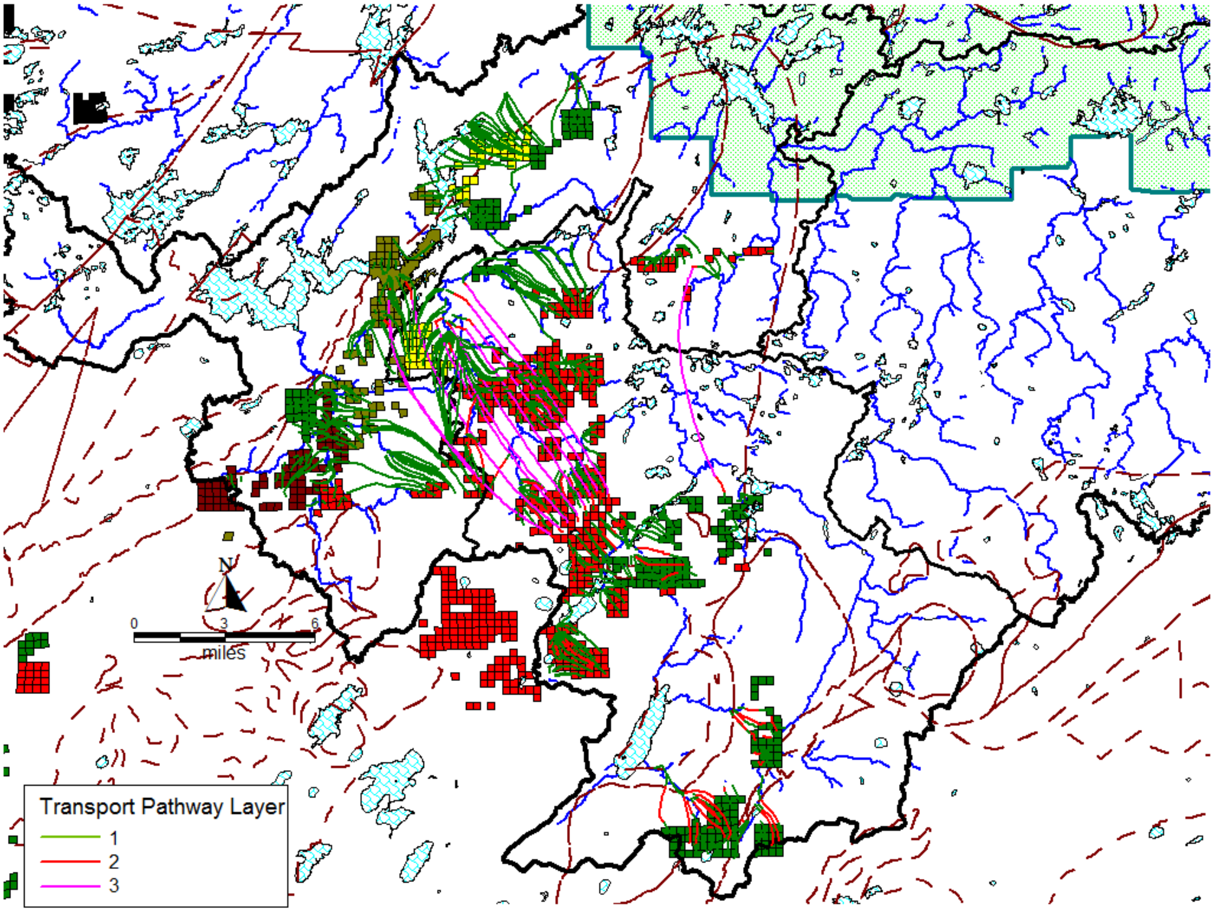

Fig. 32: Particle tracking for particles introduced at the water table at model cells near all of the mineral leases.

The particle pathways generally indicate that leases trending southwest to northeast within the Birch Lake watershed will discharge to surface water relatively quickly, after which they transport north toward the BWCAW as described below. These include leases held by Franconia, Twin Metals, and Teck Cominco (Fig. 29). Leases held by Encampment in the headwaters of the Stony River watershed would discharge to surface water relatively nearby. The large cluster of leases primarily held by DMC in the west-central portion of the Stony River watershed generally followed a longer pathway into the Birch Lake watershed and discharge directly to the South Kawishiwi River or Birch Lake. However, for placement of the contaminant at the water table some pathways end at the Stony River. As noted, particles originating at depth in the middle of the Stony River watershed flow northeast into the BWCAW, below a surface water divide.

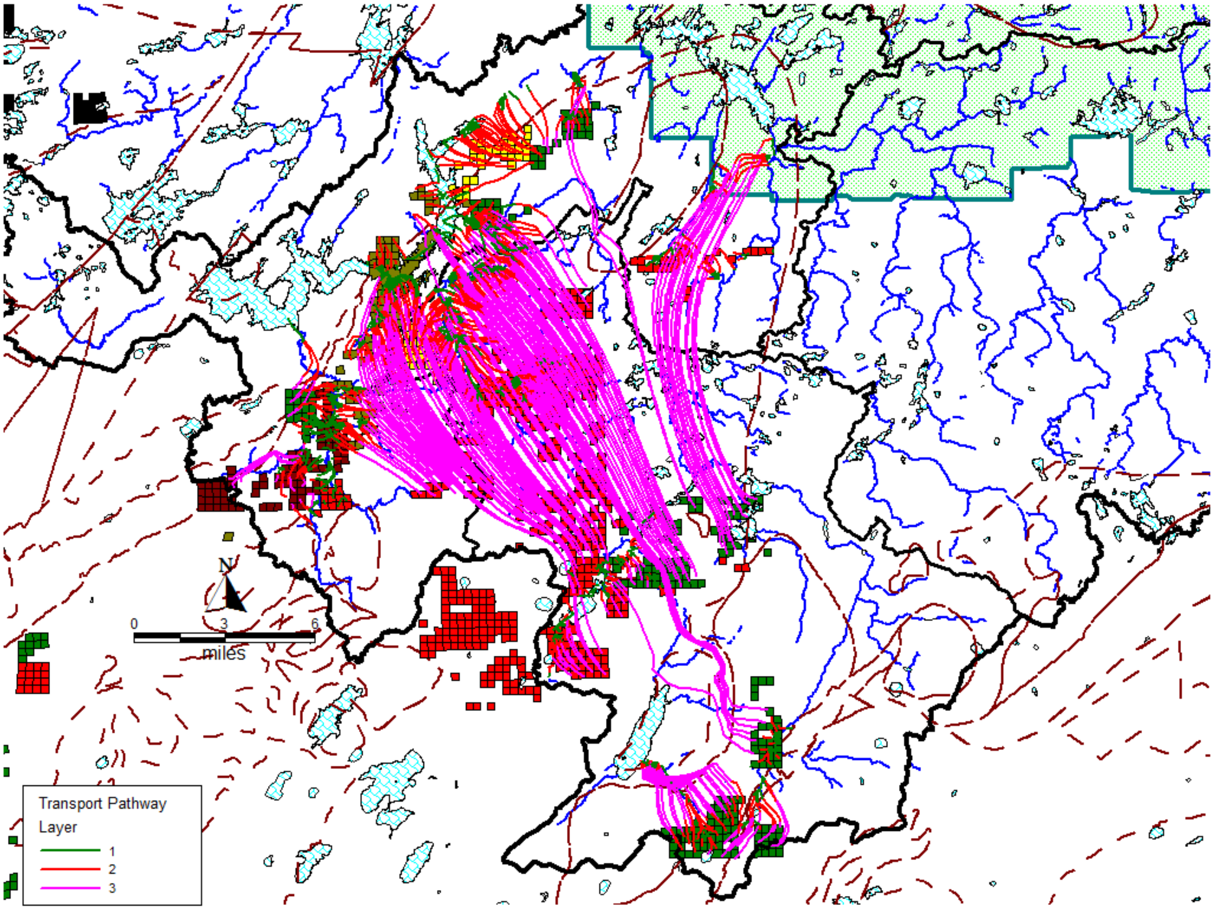

Fig. 33: Particle tracking for particles introduced at the top of layer 3 at model cells near all of the mineral leases.

Contaminant Transport Analysis

The second step of risk analysis is to consider the potential concentration of contaminants entering rivers moving to the BWCAW. Transport analysis translates the concentration at the source to a monitoring point or a sink according to the processes of advection, dispersion, and sorption (Fetter 1999). Contaminant transport analysis was completed with the MT3DMS model (Zheng and Wang 1999)

Dispersion coefficient, the new parameter required for transport analysis, depends on the flowpath length through the aquifer (Fetter 1999; Xu and Eckstein 1995). Sorption, the process of a constituent becoming bound on soil particles, is a function of the particular constituent and the geochemistry of the formation. Sorption is not considered herein.

Dispersivity is a function of length of the flow path from source to sink (Fetter 2002, Xu and Eckstein 1995). In this model, the longest paths are those that emanate from particle placement at mid level in layer 3, and are approximately 33,000 m. This length is much longer than the length at which Xu and Eckstein (1995) found that further increases in dispersivity with length became negligible, 1000 m. Because the flow paths from different sources in this model domain vary from less than 100 m to as much as 33,000 m, using dispersivity for 1000 m is reasonable and avoids changing D for each source. The apparent longitudinal dispersivity therefore is 11.8 m. As noted by Fetter (1999), transverse dispersion is usually given as a fraction of the longitudinal dispersion. For this analysis, the transverse and vertical dispersivity equals 0.2 and 0.1 times the longitudinal dispersivity (Schulz-Makuch et al. 1999, as used by Myers 2013b). The initial longitudinal, transverse, and vertical dispersivity for the analysis is thus 11.8, 2.4, and 1.2 m respectively.

Two contaminant sources are considered for the transport model – underground and surface. This discussion uses sulfate as a contaminant, but the contaminant could be of any conservative substance. There are an infinite number of potential waste simulations, but those chosen are representative of mining in a sensitive area with substantial oversight. The sources analyzed, both in location and load, are representative of average leaks that will occur from mining in any relatively well-regulated area. The regulatory environment would at least require mines to attempt to contain their wastes, therefore the scenarios chosen herein are not the worst imaginable. However, simple scaling or summing the results for additional years could give representative results for higher annual loads or longer durations of a leak.

An underground source would result from waste being backfilled into underground workings and from oxidation of the rock walls. The waste oxidizes while the rock is being backfilled, but oxidation decreases manyfold after the water level recovers. A waste load was simulated as discharge from three different points within layers 2 and 3, coincident with the mineral leases discussed above. Five representative locations centered in the mineral leases were chosen as underground sources (Fig. 34). The waste load is added to the flow stream with a high concentration but low discharge injection well boundary over six cells in the middle of lease clusters for a period of one year, the first transient model stress period. Six cells cover 1.5 million square meters which is representative of the likely extent of a mine. The simulation is of the natural flow leaching through the waste, so there is no new flow added to the system. For that reason, injection into each of the cells is done at the rate of 60 m^3/d. Concentration is

10,000,000 ug/l, a reasonable estimate and of the same order of magnitude as expected concentrations from sources at the proposed Polymet mine (Myers 2013a, 2014; Polymet 2013a). Total load from each source is 2,628,000 kg/y. This load is about half of the total load projected to be discharged into the West Pit at the Polymet Mine in 13 years or about 5% of the load to be dumped as backfill into the East Pit in three years at the proposed Polymet Mine (Myers 2013a; Polymet 2013a). Thus, the contaminant load introduced into the simulation is on the higher side of discharges expected at Polymet, except for the huge load they would introduce as high sulfide backfill into the pit. The short time frame for seepage, one year, represents the fact that rising groundwater levels would submerge the waste and decrease oxidation.

Above-ground sources result from meteoric water leaching contaminants from waste stored on the ground surface. For comparison with the underground source, these are simulated as a 10,000,000 ug/l concentration added to the natural recharge in layer 1 of the same cells analyzed for the underground sources. The contaminated recharge occurs for just one year to compare with the deep sources described in the previous paragraph (Fig. 34). This would be the equivalent of the operator developing a waste rock storage area and covering it after discovering a leak, completing reclamation over a one-year time period, or moving the waste to a different location that removes the contaminant source. Total load considered for a source in the Birch Lake watershed is 2,847,000 kg and for the Stony River watershed 2,573,250 kg. It is possible that the seepage could continue for much longer than this, but this analysis assumes that mines would be required to cover, monitor, and ultimately remediate waste piles.

The model was run in transient mode for two time periods, or stress periods – for a one-year period as explained for contaminant injection to the model and then for a 1000-year period to simulate long term movement of the contaminant. The waste injection during the first period was the only flow change implemented to the model. The first, one-year stress period had 20 time steps with a 1.2 time step multiplier and the second 1000-year stress period had 60 time steps with a 1.1 time step multiplier. The time steps increase in length through the time period based on the following time step being longer than the previous time step by a multiple of the time step multiplier.

Ten simulated wells monitoring concentrations in all three layers were added to the model (Fig.34). Five (MW-1 through MW-5) were added near the center of the waste sources and five (MW-1d through MW-5d) were added downgradient of the sources, near the middle of the thousand year concentration contours. Loads to various simulated DRAIN reaches were monitored to determine peak loading, which would correlate with highest load to the BWCAW.

Dispersion from the five sources was not so great as to cause substantial overlap in the contaminant plumes from two sources, at least until far into the simulation well beyond the peaks. For this reason, the model simulated all five sources in one run. The concentration contours show the dispersion and concentration contours emanating from each source.

Results of Contaminant Transport Modeling

After ten years, the plume shapes extend lengthwise in the direction expected from the particle tracking (Fig. 35). Sources 1 and 2 in the Stony River watershed disperse along a lengthwise line toward the northeast. The 1 ug/l contour is about 4000 m from those sources. The contours also expand southeast due to lateral dispersion. Concentration contours do not expand as far around sources 3 through 5 in the Birch Lake watershed because there is a greater vertical flow component in those areas. The contours expand a bit more in layer 3 than 2 (not shown because it mirrors layer 3) due to lower porosity and specific storage. After 1000 years, the contours have expanded much more and there is overlap among sources for the 1 and 10 ug/l contour (Fig. 36). It clearly affects a much larger area over time, although with a smaller concentration.

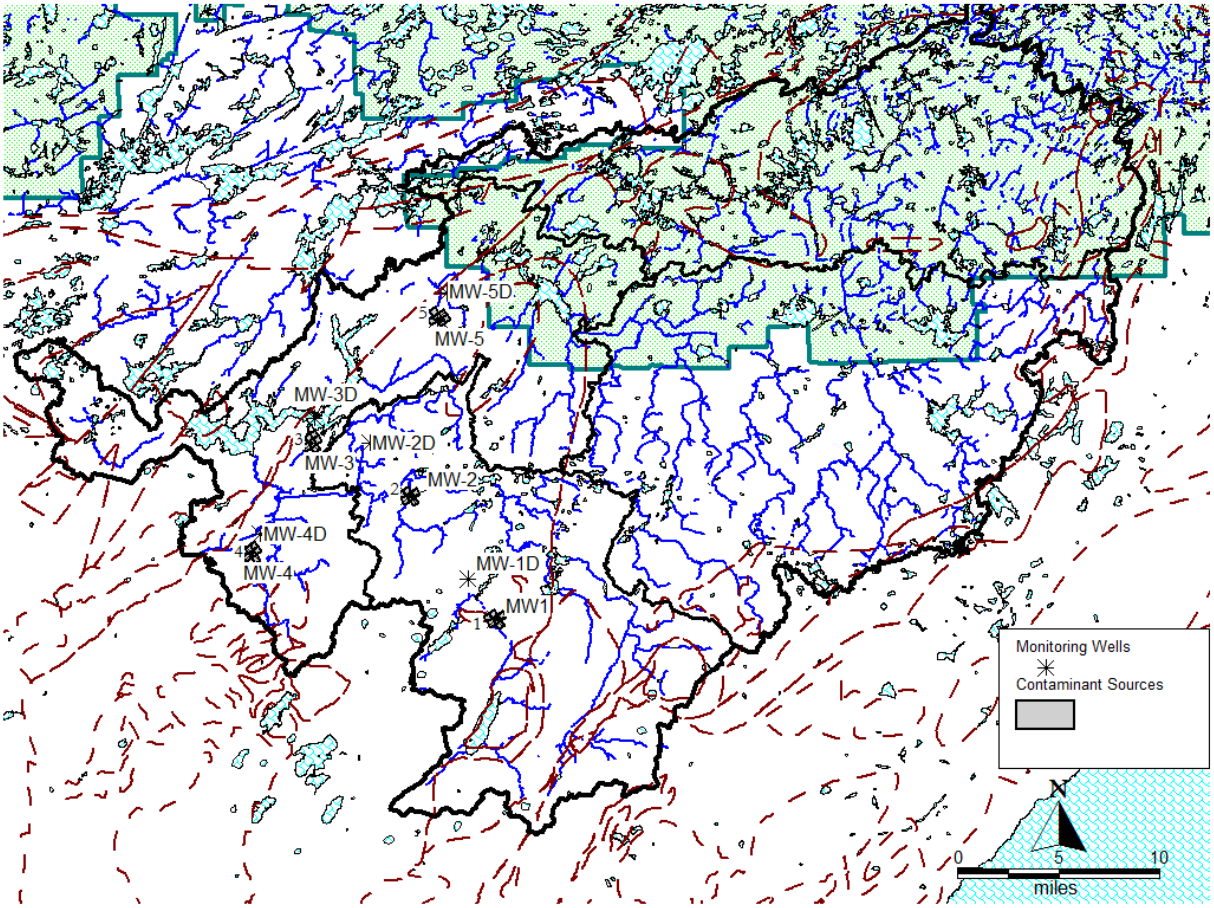

Fig. 34: Location of simulated contaminant sources and monitoring wells. Underground contaminant sources are in layers 2 and 3. Sources in Layer 1 leach to recharge zones. Monitoring wells measure contaminant concentrations in all three layers, and are located at the center of the contaminant sources and downgradient of those sources near the center of the 1000-year concentration contours.

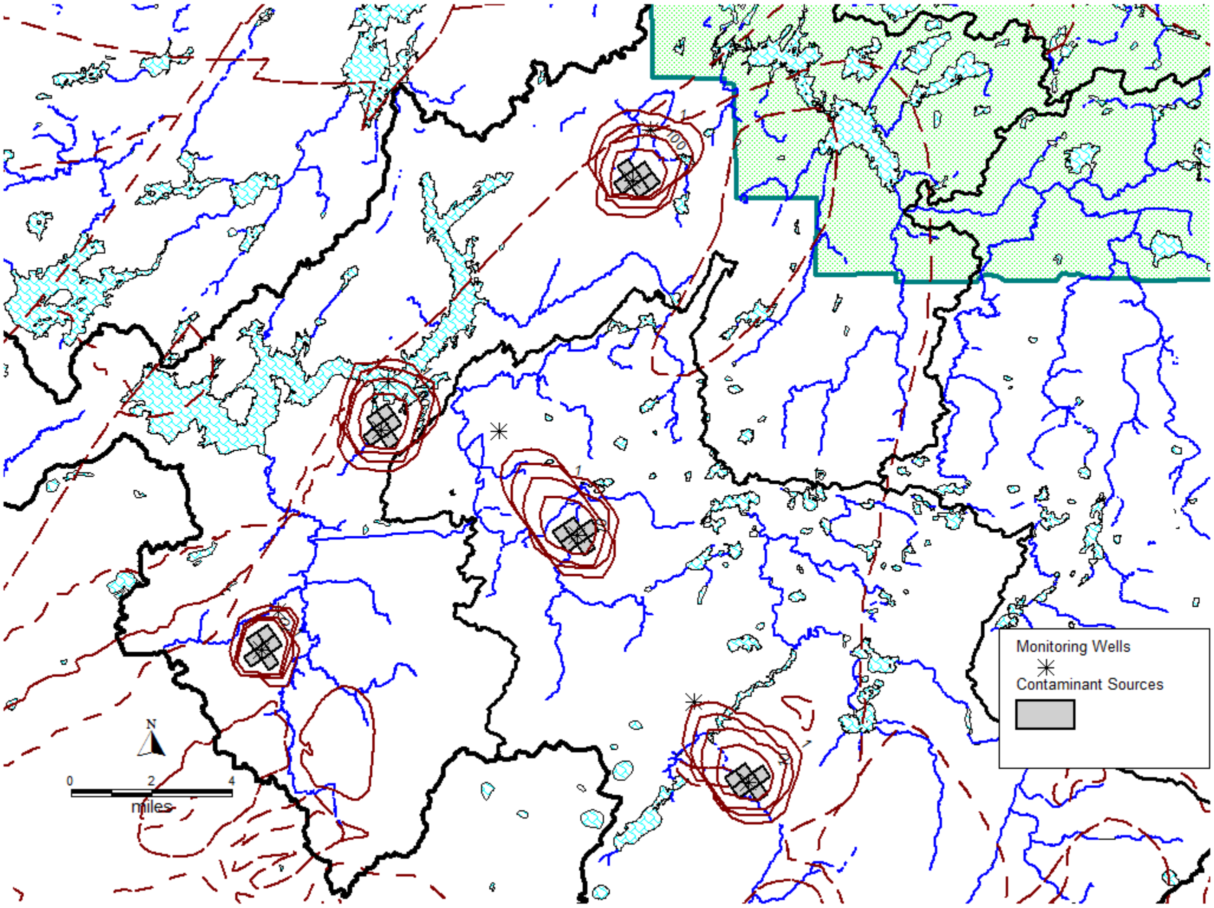

Fig. 35: Concentration contours, layer 3 after 10 years, for underground sources. The contours range from 1 to 10,000 ug/l from outer to inner.

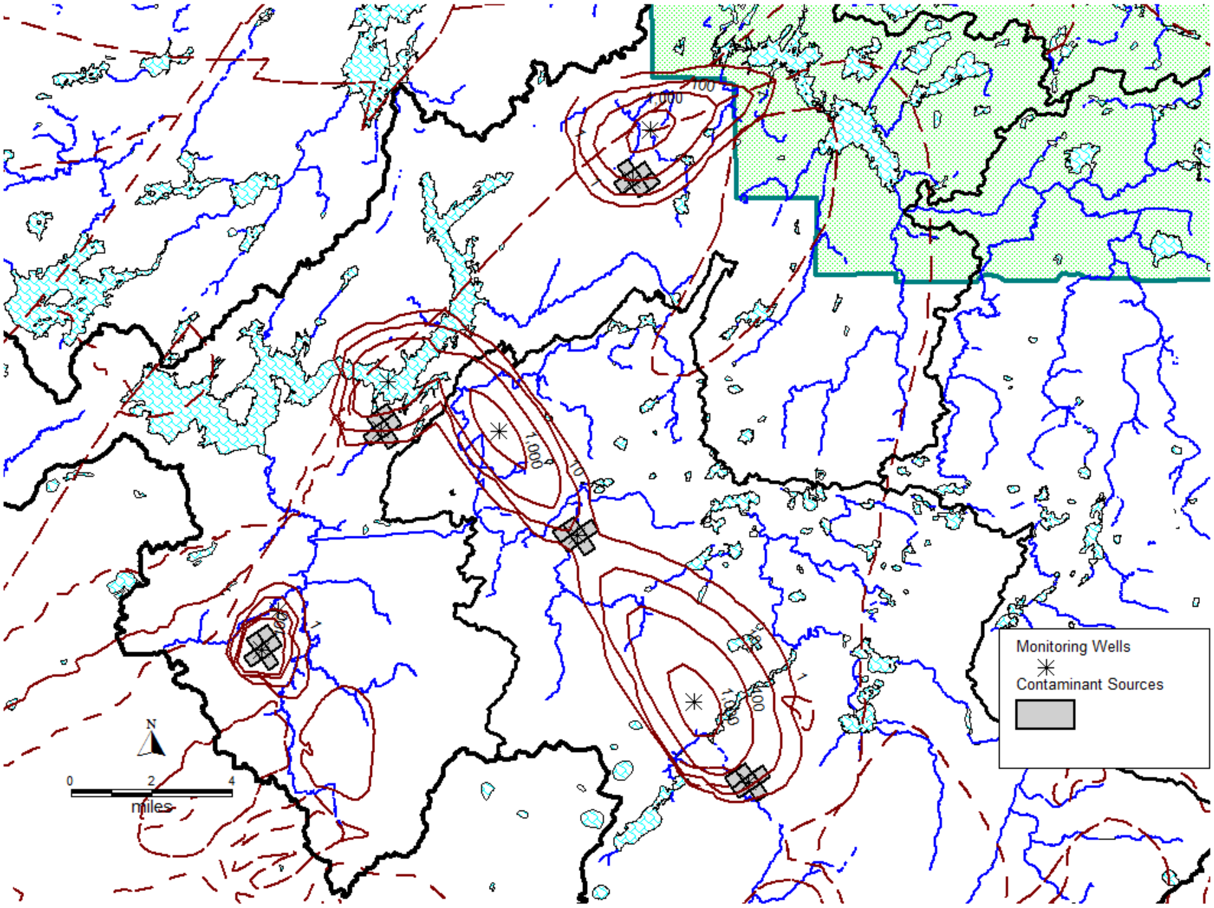

Fig. 36: Concentration contours, layer 3 after 1000 years, for underground sources. The contours range from 1 to 10,000 ug/l from outer to inner.

The surface sources primarily affect the surface layer, although vertical dispersion and advection causes some to move into layers 2 and 3. After just one year, at the end of the contaminant seepage, concentrations are highest around the sources (Fig. 37). Layer 1 concentrations exceed 100,000 ug/l and contours extend up to 2000 m from the source. After 100 years, concentrations at the source still are near 10,000 ug/l and the 1 ug/l contours extend up to 10,000 m from the Stony River sources. The trend due to flow direction is less obvious for surface sources in layer 1, in part because of dry cells and irregular topography. Concentrations in deeper layers are substantially lower than in layer 1, although contaminants plunge deeply into layer 3 from the surface for the Stony River sources; this reflects some of the longer particle transport times discussed above.

The contaminant contours in summary show that mining sources could affect substantial areas of groundwater. All groundwater eventually reaches surface water, but the travel time can vary greatly, as seen above. Surface sources will clearly reach the rivers more quickly, as discussed in the following paragraphs.

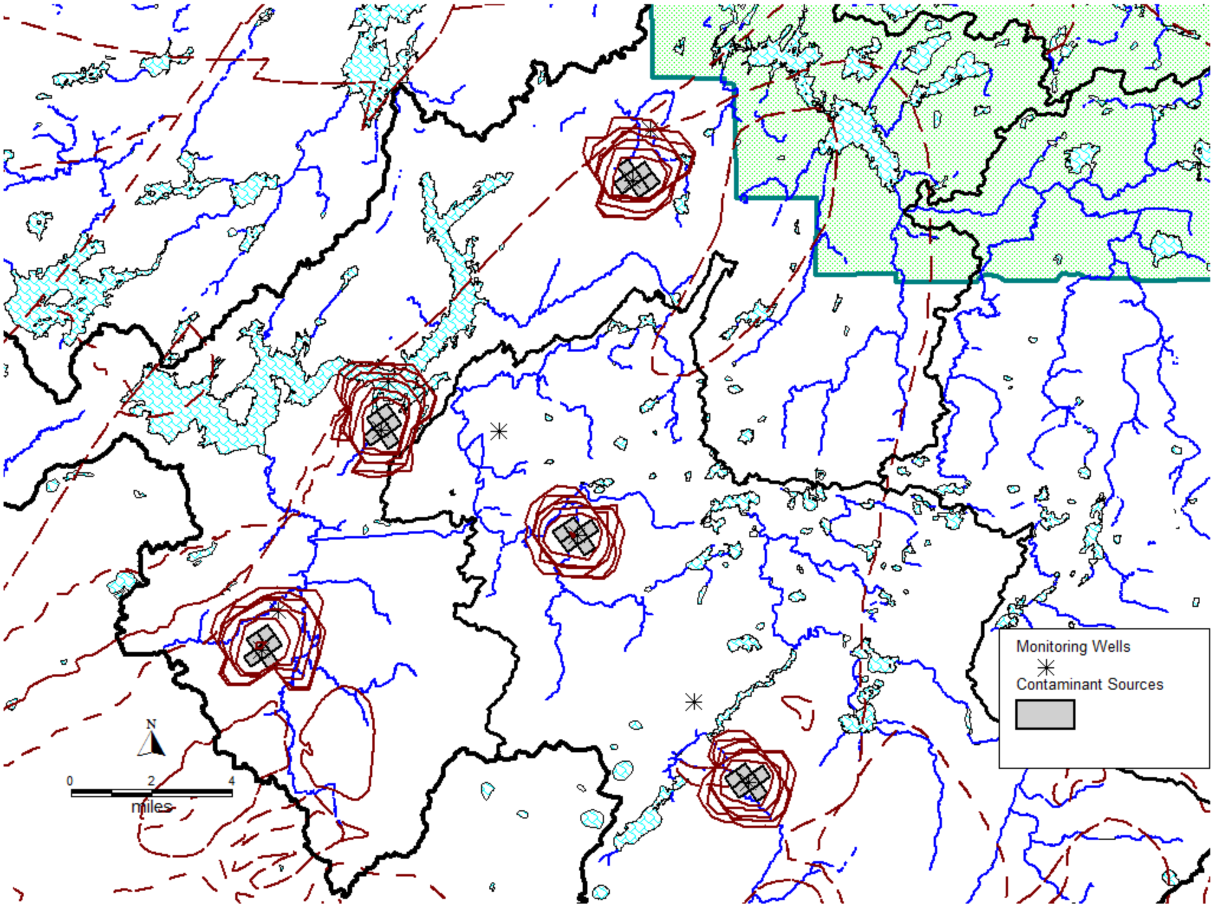

Fig. 37: Concentration contours, layer 1 after 1 year, for surface sources. The contours range from 1 to 100,000 ug/l from outer to inner.

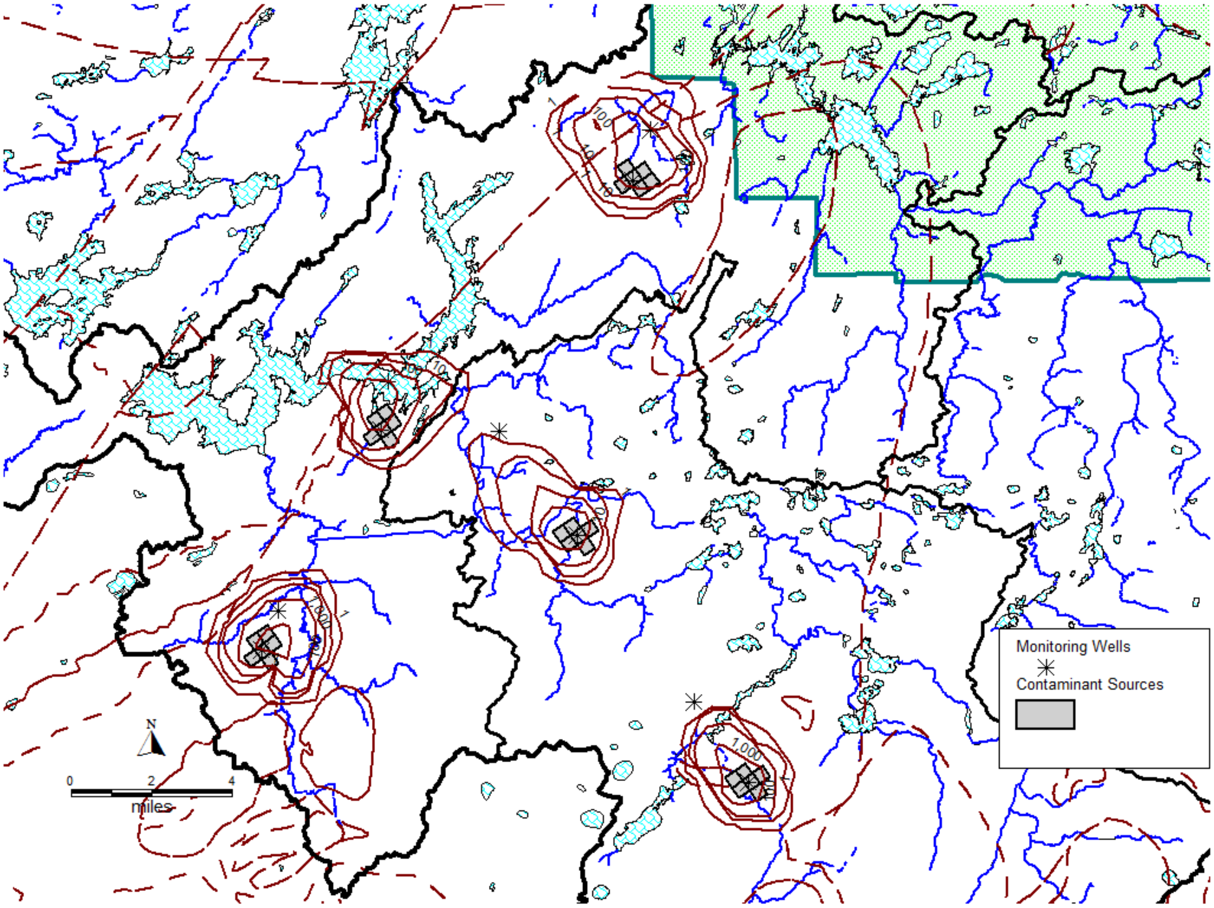

Fig. 38: Concentration contours, layer 1 after 100 years, for surface sources. The contours range from 1 to 10,000 ug/l from outer to inner.

Peak concentrations reach various river reaches at times depending on whether the source is underground or on the surface and on the distance the source is from the river (Table 9). Except for Filson Creek, the peak concentration reaching a river from an underground source is 1232 ug/l, reaching the Stony River after ten years. Filson Creek received almost 4000 ug/l at a point about ten years after the contaminant release. The peaks from underground sources all require from ten to forty years to reach a river, although fracture flow could decrease that time. The times reflect the particle travel times above.

The peak concentrations for the surface sources in the Stony River watershed reach the river at the end of the first year. This reflects the close proximity of the sources to the sinks. Contaminants reaching the Stony River peak at almost 33,000 ug/l. Also, the source near Filson Creek reaches that creek at the end of the first year, and ranges as high as 120,000 ug/l. These routings do not account for surface flows to the rivers which could either add load or dilute it, depending on the source. Contaminants reach Birch Lake and Dunka River after two to five years, but the peak concentrations are lower than those to Stony River and Filson Creek, due to longer distance from the sources allowing more dilution. It is apparent that the magnitude, duration and time until effects begin depend on the exact location and depth of the leak and the geology between the leak and the streams. Leaks from the surface reach the streams quicker and with less attenuation due to shorter flow paths.

Leaks through groundwater commence a long-term process in which contaminants travel to surface waters for a long time after the leaks have been discovered and plugged. Impacts from such leaks can continue for decades, with substantial concentrations still reaching the rivers up to 100 years after the leaks cease.

Table 9: Concentrations (ug/l) discharging to reaches 1, 71, 72, 73, and 75 at various times corresponding to stress periods (1 or 2) and time step (number in parentheses). Steady state discharge to reach 1, 71, 72, 73, and 75 is -74,916, -73,295, -31,383, -168,050, and -11,439 m^3/d, respectively. The discharges are stated as a negative because they represent a loss from the groundwater domain. Reach 1 is Birch Lake, Reach 71 is Dunka River, Reach 72 is Stony River between Babbitt and Isabella, Reach 73 is Stony River above Isabella, Reach 75 is Filson Creek nr Ely. Other reaches did not receive substantial load.

Deep Sources		Reach				
Stress period	Years	1	71	72	73	75
1(20)	1.0	1.64	3.71	334.04	112.22	2512.98
2(14)	10.0	166.56	203.85	1232.08	256.04	3989.01
2(21)	21.8	223.47	242.32	1149.71	220.85	3172.49
2(24)	30.2	233.54	247.74	1043.41	196.92	2738.44
2(27)	40.9	230.76	249.63	903.37	169.44	2308.54
2(36)	99.4	132.55	209.85	389.83	74.32	1037.91
2(60)	1000.0	18.05	4.51	0.32	0.95	190.01
Surface Source						
1(20)	1.0	383.2	775.1	32931.9	6654.5	120482.6
2(1)	1.3	726.7	1382.4	30431.2	5409.8	81234.8
2(3)	2.1	1538.2	2513.6	24938.2	3507.8	45849.5
2(5)	3.0	2127.6	3037.2	19507.2	2323.1	32963.3
2(9)	5.5	2158.2	2630.2	9977.2	1117.3	18451.0
2(11)	7.1	1759.4	2066.7	6482.5	809.8	13179.9
2(14)	10.0	1160.8	1287.9	3346.0	537.5	8207.6
2(21)	21.8	496.0	544.5	971.2	241.2	3998.0
2(36)	99.4	110.0	347.9	322.4	89.0	1327.0
2(60)	1000.0	0.2	0.1	0.1	0.0	1.2

The analysis herein shows that even relatively small leaks could cause substantial loads to reach the rivers and drain to the BWCAW. These could be long-term sources of contamination. Underground sources maintain higher concentrations longer, but surface sources could be much more damaging to the resource.

Surface Water Transport Analysis

Contaminant transport through rivers and lakes is substantially different than through groundwater. In rivers, advection controls the average rate of movement downstream and dispersion caused by turbulence spreads the contaminants throughout the river cross-section. Turbulence causes some of the contaminant to flow faster downstream than the river and some to flow more slowly. A slug of contaminant causes a high concentration peak after mixing below the point of entry to the river, which decreases with distance downstream as the contaminant disperses. The contaminant is observed at downstream locations for a longer timeframe than the length of the actual discharge, but the peak concentration decreases. Longitudinal dispersion is much less important for steady state discharges into the river, and the stream concentration will equal the discharge concentration adjusted for dilution by streamflow. As streamflow decreases, the concentration will increase if the discharge load remains constant. The following sections detail the surface water routing of groundwater contaminant discharges estimated herein.

Surface Water Transport of Groundwater Discharges

The primary sources of contaminants would be located in the Stony River and Birch Lake watersheds. Depending on the location within the source watersheds, contaminants will reach one of the streams that drain to Birch Lake or discharge directly to the lake (Figs. 32 & 33). This applies to underground sources and to spills on the surface, as simulated herein. Contaminants would reach the BWCAW by way of Birch Lake and then transport through a series of lakes into the Wilderness and eventually into the border-spanning Basswood Lake (Fig. 3). The lakes include White Iron, Farm, Garden, Fall, Newton, and then Basswood Lake (Fig. 3 and Table 10).

Table 10: Morphometric characteristics for lakes along the flow path. Volume is calculated by assuming the average depth of the littoral area is 7.5 feet and the average depth of remainder is the average of 15 and the max depth.

Lake	Area (ac)	Littoral area (ac)	Max Depth (ft)	Volume (af)	Flushing time per lake	source: http://www.dnr.state.mn.us/lakefind/
Birch	1267	754.9	45	28715	0.06	showreport.html?downum=11041200
White Iron	3238	1603	47	87251	0.19	showreport.html?downum=69000400
Farm	1292	459	56	45505	0.10	showreport.html?downum=38077900
Garden	653	239	55	22509	0.03	showreport.html?downum=38078200
Fall	2258	1178	32	50433	0.07	showreport.html?downum=38081100
Newton	516	358	47	9964	0.01	showreport.html?downum=38078400
Basswood Lake	22722	7034	111	1276419		showreport.html?downum=38064500

The Kawishiwi River and Isabella River watersheds discharge into the river system and would dilute contaminant concentrations, as discussed above. Because of decreasing low flows in a downstream direction (Table 2 and associated text), dilution was shown to be effective only during normal base flows, not during low flows. Groundwater contaminant discharges reach close to steady state so the contaminants will mix through the lakes and eventually reach a concentration at the downstream end that depends on the discharge concentration adjusted by dilution. During dry periods, dilution is minimal and the stream concentration becomes close to that at the point of discharge. During the driest periods, the dilution is based on the flow at the point of interest.

The Kawishiwi River at Winton gage is representative of the flows leaving the study area and reaching the wilderness. It monitors flow leaving the Rainy Headwaters watershed, including the Kawishiwi River watershed and some area north of the Rainy Headwaters (Fig. 1), so the flow is higher than observed discharging from the Birch Lake or Stony River watershed (Tables 2 and 9), except during low flows at which time the river is a losing system. Baseflow at the Winton gage is 1,672,937 m^3/d, or 683 cfs. This is substantially higher than the cumulative flows simulated for the tributary reaches by the model (Table 9). However, this gage occasionally has much lower flows. The critical 7-day low flow statistics for a 2-, 5-, 10-, 20-, 50- and 100-year return interval are 182, 84.1, 42.9, 4.6, 0.0, and 0.0 cfs, respectively at this gage (Winterstein et al. 2007).

Leaks that coincide with these low flows could have substantial impacts on the river system and BWCAW. As shown above, once a leak commences it will flow through groundwater and discharge to surface water for years, so the chance that it will coincide with low flow conditions is high. Table 11 shows the concentrations that will reach the BWCAW based on groundwater load discharges to specific reaches and the assumption that the simulated groundwater discharges continue during low flows.

Table 11: Concentration in ug/L at the Kawishiwi River at Winton gage for various loads generated by leaks from potential mines reaching various tributaries. The load would be diluted according to the flows at this gage. The values are for loads from individual reaches, assuming no overlap among discharges. This table shows the potential concentration reaching the wilderness for conditions simulated herein. Low flows from Winterstein et al. (2007).

	Reach	Load (m3/d x ug/l)	Baseflow	7Q2	7Q5	7Q10	7Q20
Underground	1	-17495785	7	39	85	167	1555
	71	-18296353	8	41	89	174	1626
	72	-38666385	16	87	188	368	3436
	73	-43027269	18	97	209	410	3823
	75	-45630324	19	102	222	435	4054
Surface Sources							
	1	-161683995	67	363	786	1540	14366
	71	-222608665	92	500	1082	2121	19780
	72	-1033502013	427	2321	5023	9847	91832
	73	-1118290617	462	2511	5435	10655	99366
	75	-1378200404	570	3095	6698	13131	122460

The modeling completed herein has shown that substantial contaminant loads can reach streams that drain to the BWCAW due to either deep underground or surface leaks. During much of the year, sufficient flow enters the system to dilute this load before it reaches the BWCAW. However, during baseflow conditions, the load could substantially affect the tributary streams, especially within the Stony River and Birch Lake watersheds, although dilution occurs before the load reaches the wilderness. When the watershed is experiencing low flow conditions (Winterstein et al. 2007), the concentration at the Kawishiwi River at Winton (immediately upstream of entry to the BWCAW) would be increased above that at baseflow by five orders of magnitude for the 7Q20 flow. In other words, leaks that may have minimal effects much of the year could be devastating at low flow. Because once started, leaks will continue for decades and likely coincide with 20-year or longer return period low flows, the potential that leaks will impact the Wilderness is high.

Surface Water Transport of Spills

A large spill that causes a rapid flow of contaminants into the surface water system could be very damaging. Many of the potential mines are on or near Birch Lake, so a spill quickly reaching that lake is possible. Treating a spill as a single impulse to the lake that quickly mixes through the applicable volume, the concentration within and exiting the lake decreases with time according to the following equation (Thomann and Mueller 1987):

$$\boldsymbol{s(t) = \frac{M}{V} e^{\left(\frac{K' t}{V}\right)}}$$

Here, s is concentration at time t, M is the total impulse load, and V is the lake volume (Table 10). K' is Q+KV where Q is flow through the lake (assumed to be the flow at the S Kawishiwi River above the White Iron Lake gage) and K is the reaction coefficient, which is 1 for a conservative substance. A standard assumption for transport analysis is that the load fully mixes into the lake, but that clearly would not occur in Birch Lake due to its large area and large littoral zone (Table 9) and significant flows entering the lake from different directions. Based on the location of the leases (Figs. 29 &30), the load would enter the lake somewhere in its east half. River flow entering the west end would prevent the load from dispersing in that direction. For this simplified analysis, Birch Lake's volume was assumed to be half its actual volume.

Continuing downstream to subsequent lakes, the outflow from one lake becomes the inflow to the next. The response in subsequent lakes can be analyzed using a response equation due to a step load (Thomann and Mueller 1987):

$$\boldsymbol{s = \frac{W}{Q + KV}\left\{1 - e^{-\left(\frac{Q}{V}+K\right)t}\right\} + s_0 e^{\left[-\left(\frac{Q}{V}+K\right)t\right]}}$$

All variables are described above except that s_0 is the initial concentration, or that occurring at the end of the previous calculation period. If the analysis time step is 0.01 years, the concentration at year = 0.01 is the initial concentration for the calculation for time step year 0.01 to 0.02.

Spills were simulated with an instantaneous input of 3,000,000 kg of a conservative substance. The mass was chosen for comparison with the loads simulated as leaking into groundwater. It is 10% of the amount of sulfate proposed to be added to the East Pit at the proposed Polymet Mine during the eleventh year, when the category 4 temporary waste rock is dumped into the pit. Total category 4 rock mass at Polymet is 6.2 mil tons. For input directly into Birch Lake, the concentration in Birch Lake initially exceeded 120 mg/l and dropped to less than 1 mg/l within 0.16 years (Fig. 39). Flow from Birch Lake with the simulated concentration becomes inflow to White Iron Lake which sees concentrations exceed 3 mg/l in about 0.02 years. Continuing downstream the concentration peaks at 0.16 mg/l in 0.03 years at Farm Lake. Although not shown in Fig. 39, the concentration continues to decrease with distance downstream from Birch Lake.

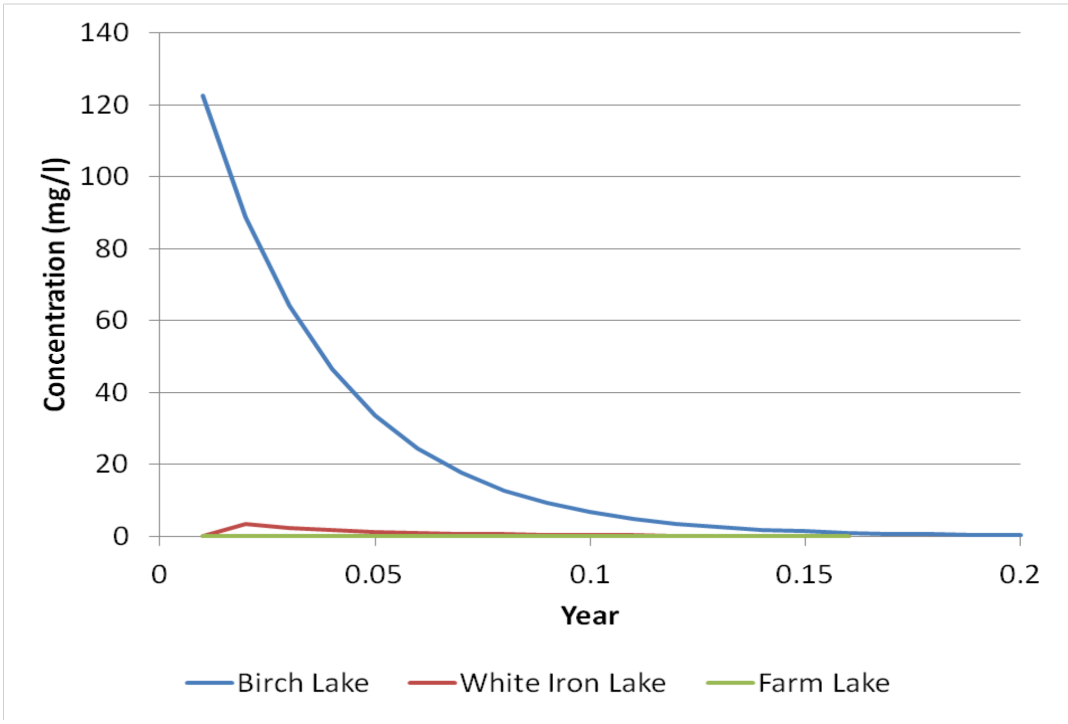

Fig. 39: Concentration hydrographs for three lakes with an initial load of 3,000,000 kg input to Birch Lake.

A second scenario is a spill occurring downstream of Birch Lake in the potential vicinity of an ore processing plan. In this scenario, the spilled contaminant would initially mix through White Iron Lake. Concentrations would peak at 26 mg/l in that lake and at 1.3 and 0.13 mg/l in Farm Lake and Garden Lake, respectively. The Garden Lake concentration would be the concentration effectively reaching the BWCAW. Depending on the substance, this concentration could have substantial effects on the wilderness, although lakes just upstream of the wilderness would experience the most extreme effects.

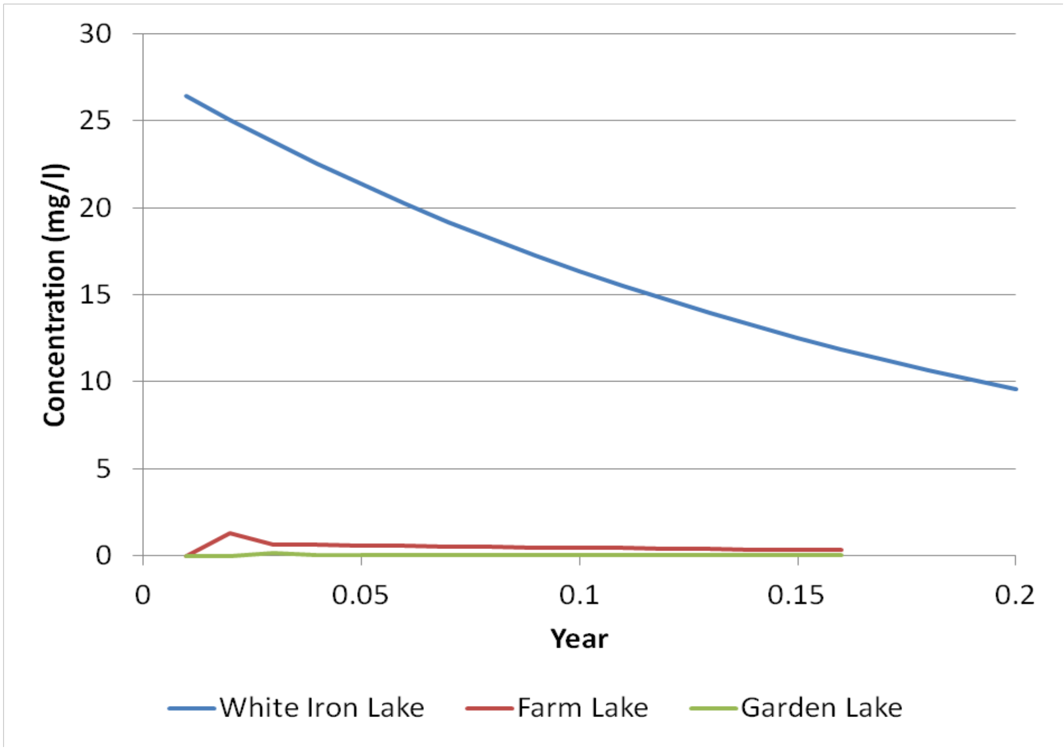

Fig. 40: Concentration hydrographs for three lakes with an initial load of 3,000,000 kg input to White Iron Lake.

The times to peak concentrations within the lakes are less than the retention times (Table 10). This could result in the concentrations being overestimated because it ignores a small amount of dilution. However, the assumption of complete mixing in the lakes inherent in the equations used for analysis causes the method to underestimate the concentration.

An upper end analysis was tested using the same amount of conservative waste as input into a hypothetical stream with dimensions, flows, and dispersivity based on the water volume within the lakes (Thormann and Meuller 1987). The estimated stream dispersivity is very low because the effective stream is very wide (to account for lake volume). Because the analysis treated transport almost as a plug flow, due to limited dispersivity, concentrations were unrealistic. For this reason, this upper end analysis is not shown in this paper.

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