Technical Memorandum: Potential Metals Mining and the Voyageurs National Park
Risk Assessment for Upstream Metals Mining

Prepared for: Voyageurs National Park Association, Minneapolis MN
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Table of Contents

Table of Figures

Table of Tables

SUMMARY

This technical memorandum considers the risks to Voyageurs National Park (VNP) from the development of mining leases in the watersheds draining to and through it, including the Rainy Headwaters, Vermilion Lake, and Rainy River-Rainy Lake watersheds. There are copper-nickel and gold leases in the headwaters of the first two watersheds, with those held by Twin Metals near Birch Lake the most advanced. The Northshore Mine and Peter Mitchell Pit currently operate partly in the Rainy Headwaters watershed.

The water flow through the Rainy Lake watershed is primarily northwestward along the International Boundary from headwaters in the United States in the Rainy Headwaters and Vermilion Lake watersheds. The total flow averages 6.75 million acre-feet/year. The Namakan reservoir system, consisting of Kabetogama, Namakan, Sand Point, Crane, and Little Vermilion Lakes, discharges into Rainy Lake through dams at Squirrel Narrows and Kettle Falls, at Bear Portage, and Gold Portage. Rainy Lake receives runoff from 14,900 square miles, with about 54% of the area above Namakan Reservoir and 6% of the area draining to the system below Namakan Reservoir being in Minnesota. The total average flow from the Namakan Reservoir system is 5150 cubic feet per second (cfs), or 51% of the total flow from Rainy Lake. Rainy Lake provides 70% of the flow to Lake of the Woods, although the flow is highly variable. Flows are most variable during early summer due to snowmelt and least variable during late winter when much of the watershed and precipitation is frozen.

Operating rules for the reservoirs, which changed in 2000 to implement a more natural flow regime, increased and decreased high and low flows, respectively. The reservoirs also spilled more during the post-2000 period although the post-2000 climate was more variable, with generally higher average precipitation and temperature.

There are two aquifers over the study area – a crystalline rock bedrock aquifer and glacial till or sand/gravel surficial aquifer. The bedrock type varies from gneiss and granite north of the mineralized areas to more volcanic sources such as basalt further south. The surficial aquifer is less than 100 feet thick over most of the study area and some areas have bedrock outcrops. Glaciation over the past 50,000 years has removed the most weathered rock near the surface, so that the fracture density is low even in the upper portion of the bedrock, except in the Biwabik formation, most conductive formation in the bedrock aquifer. Well yields throughout the Kawishiwi watershed, considered representative of the study area, are less than 10 gpm which reflects the very thin to nonexistent surficial aquifers and the low permeability bedrock, which transmits very little groundwater except in fractures.

Precipitation generally does not infiltrate deeply into the shallow soils of the northern two-thirds of the watersheds but rather becomes interflow or causes the water table to rise and may discharge to the surface becoming overland flow. Surface storage may be important, especially in the areas with substantial wetlands. However, in the headwaters of the watersheds where the mineral deposits are, the soils are deeper and allow deeper infiltration.

Baseflow was estimated for all US Geological Survey gaging stations in the area by determining the recession index and then back calculating a baseflow hydrograph from under the peak of each runoff peak. Assuming baseflow is recharge, the average recharge for the basin above each gage was determined. Total and baseflow yield ranges from 9.5 to 12.3 and from 6.5 to 9.5 in/y, respectively, for gages in the Rainy Headwaters, with gages on smaller watershed having the most extreme values. The total and baseflow yield in the Little Fork and Vermilion River watersheds is less than 9.8 and 7.3 in/y, respectively.

Baseflow as a proportion of total runoff varies from about 0.65 to 0.79, with a few outliers, the lowest of which are for streams with very small watersheds. Baseflow yield is smaller as one moves west from the Rainy Headwaters, along with a decrease in average rainfall. Average recharge for the Little Fork watershed is 5.6 in/y, for the Vermilion River watershed is 7.1 in/y, and for the Rainy Headwaters ranges from 7.5 to 8.2 in/y. These recharge estimates are less by from 0.5 to about 2.5 in/y than the values determined using a common US Geological Survey method.

Low flow conditions occur during baseflow but represent the extreme, and most critical ecologically and economically, lower flows. Groundwater is the primary source of flow, but during low flow is occurring from only a portion of the watershed due to the dry conditions. Low flows can be a very small proportion of baseflow, which reflects that only a small portion of the aquifers in the area are contributing to flow during low flows. Most watersheds in the study area have low flows less than 10% of the baseflow.

The watersheds draining to VNP contain many lakes of many different sizes and morphometric characteristics). Rainy Lake is by far the largest but it is also mostly within and downstream of VNP, lying on the north boundary with a majority within Ontario; contaminants will not flow through it on a pathway to VNP. Contaminants from the Rainy Headwaters would pass through seven lakes while contaminants from the gold deposits in the Vermilion River watershed would pass through the very large Vermilion Lake before reaching VNP. VNP contains 26 interior lakes, although all quite small, with just one of the interior lakes exceeding 247 acres in area.

Groundwater in shallow sand and gravel aquifers is a magnesium bicarbonate type typical of groundwater that has either a short residence time or has been collected in a recharge zone. In till, the groundwater is either calcium magnesium bicarbonate or calcium magnesium sulfate.

Concentrations of copper, cobalt, and nickel can exceed 100 ug/l in surficial material above mineralized areas. This indicates an exchange of groundwater between the surficial and bedrock aquifers or an upward flow gradient. In the bedrock, concentrations are highly variable because they reflect localized concentrations in fracture zones and sometimes increase with depth.

The USGS has commenced a study on two headwaters watersheds, Filson Creek and Keeley Creek near Birch Lake and near the copper-nickel deposits currently being explored by Twin Metals. The surface water is generally very dilute with pH generally mildly acidic, likely due to mineralization as well as the effect of bogs in the watershed. The concentration of Ni and Cu was generally less than 10 ug/l but is highest in watersheds with Cu-Ni deposits. Buffering capacity in the watershed was very low.

Electrical conductivity (EC), a surrogate for total dissolved solids, generally is lower when river flow includes surface runoff, which has less salt because it has less contact time with the surficial aquifer during which salts would be dissolved. Streams and lakes throughout the study area generally have very low EC; the exception is the Ash River which enters VNP from the west. EC is highest during baseflow because most flow is groundwater that has a higher salt content. Rivers entering the Rainy River system from Ontario also have extremely low EC and effectively dilute the already very low salinity in the river system. Carbonate is nondetect at the South Kawishiwi River above White Iron Lake and alkalinity in the Rainy Lake and Namakan Lakes in VNP is very low. Both findings additionally reflect the cumulative lack of buffering.

Mercury contamination is a current issue in all watersheds draining to VNP, with impairment being due to “mercury in fish tissue” rather than in the water column. This reflects the tendency for mercury to be bound in sediment and the tendency for methylation to occur due to bacterial activity. Methyl mercury is soluble in water and it can be incorporated into the body tissues of organisms in the aquatic environment. Mercury works its way up the food chain as larger fish prey on smaller fish and organisms which in turn may have obtained it from the sediments.

The climate has been changing in northern Minnesota. Since 1895, the average temperature increase in the Midwest has been 1.5 degrees F and by mid-century, the temperature in northern Minnesota is projected to increase by up to 5°F. Average precipitation has increased from 5 to 15%. The percent change in very heavy precipitation is 45%. By mid-century, annual precipitation will increase from 1.4 to 1.6 inches, there will be at least one more day with heavy precipitation per year, the wettest annual 5-day total precipitation will increase by up to 0.4 inches, and number of dry days will decrease by up to six days. These observations and projected trends all point to a wetter future with more heavy rainfall which of course means more large floods.

Waste from proposed mining from any of the underground deposits in the Rainy Headwaters could generate acid mine drainage with metals including arsenic, copper, nickel, lead, zinc, and possibly mercury. The low buffering capacity of the rivers could allow contamination to be transported a long distance downstream, including to VNP; the sensitivity to acid precipitation that has been observed in the past exemplifies the problems that would be caused by AMD. Seepage may require decades to transport from the underground sources to the river, but once it reaches the river there would be little chance of preventing it from reaching VNP. AMD seepage over a long time period would likely exacerbate an existing problem in the VNP – methyl mercury contamination because a decrease in pH would increase the methylation rate and concentration in the lakes.

Tailings impoundments could generate AMD or leak other process chemicals. Although they are designed not to leak, liner failures are common. If the leakage is either not detected or not containable, it could reach the surface water system and flow toward VNP. Streams draining toward VNP have high water quality and would be affected by small amounts of contamination for a long time. Once started, a leaky tailings impoundment is very difficult to remediate. The following metals are predicted to be present in the tails at the nearby Polymet Mine: arsenic, boron, calcium, cobalt, copper, iron, magnesium, manganese, mercury, molybdenum, nickel, potassium, and sodium. Other parameters of concern are alkalinity, chloride, fluoride, sulfate and total dissolved solids. Additional mercury reaching the VNP would add to the problems discussed above; in combination with AMD or sulfate loading, the methylmercury problem could be substantially increased.

Increased precipitation due to climate change would increase the moisture accessing the unsaturated zone, including the unsaturated zone in above-ground waste or tailings impoundments.

Immense water resources damage could be caused by a tailings failure. Tailings impoundments fail as a result of a string of incidents, each of which may be trivial and within the bounds of normal events, but when taken together, constitute an event so unusual that it lies outside of the bound of normal occurrence and experience. There have been over 146 tailings impoundment failures (over an unspecified time period), with the majority occurring in the United States. Thirty-six of the failures were due to high rainfall, and the run-out distance for tailings dam failures has been as high as 100 km, with the maximum distance occurring when the failure is into a river system.

The recent failure of the Mt Polley Mine in British Columbia apparently resulted from a failure to manage the tailings impoundment properly. Simply, it appears the mining company stored too much saturated tails waste above the dam and it failed. The failure released more than 10 million cubic meters (350 million cubic feet) of water and 4.5 million cubic meters (150 million cubic feet) of sand into downstream Polley and Quesnel Lake. That is enough water to fill 4,000 Olympic-sized pools. Approximately 2600 tonnes of mercury had been stored in the impoundment since 2009, so the potential contamination is quite large.

The effect of a large spill in a watershed that contains many large lakes is complicated. Water leaving Quesnel Lake, downstream of the Mt Polley spill, was relatively clean for several weeks after the spill. Much sediment was trapped in the lake. It is likely however that the sediment will be a source of heavy metals to the waters flows through the lake for decades. This is similar to the results found for a simulated spill into Birch Lake. A spill in the Vermilion Watershed, if mines are ever developed there, may be more critical. If the waste short circuits through Vermilion Lake rather than mixing, the effects could be much worse at VNP.

The recent occurrence of extreme flooding in northern Minnesota accentuates the concerns raised by the potential for large flooding on tailings impoundments. Global warming and the consequent increase in extreme events will affect mines in many ways, but with increasing flood runoff and climate change, the proximity of any potential tailings impoundment to the river system, the fact that a tailings impoundment must not fail forever, and the connectivity of surface waters in the watershed, development of tailings impoundments presents a large risk to VNP.

A third long-term water quality threat of mining in the study area is the discharge of high sulfate pit water or high salinity dewatering water. Deep groundwater has been shown to have very high, almost brine level, salt concentrations. If this were leaked or discharged during mine dewatering to surface water, the current dilute concentrations in the study area streams would be ruined. Additionally, the expected overflow of pits at the Steep Rock Mine on the Seine River in Ontario will cause very high sulfate inflows to Rainy Lake and VNP.

Voyageurs National Park is in a unique position with regard to the threat of mining development. There are substantial mineral deposits and mining leases in the headwaters of the watersheds that drain toward VNP. Contaminants could be diluted by flow or removed in the lakes between the mines and VNP. However, the watershed has very poor buffering capacity meaning that AMD which reaches surface water draining to the park will make it to the park. Acid could increase the methylation of mercury. Mine seepage could exacerbate the high metals content of some VNP lakes and the general mercury problem throughout the watershed. Large scale spills could flow directly through to the park under the proper hydrologic conditions. Development of mining leases in Rainy River watershed presents a significant long-term risk to VNP.

INTRODUCTION

This technical memorandum analyzes and discusses the risks to Voyageurs National Park (VNP) from the development of mining leases in its watershed. VNP lies in the middle of the Rainy River watershed, which eventually flows to the Lake of the Woods and beyond. Water and contaminants originating in the Rainy Headwaters, Rainy River-Rainy Lakes, or Vermilion River watersheds drain into the Rainy River and through VNP (Figure 1). VNP contains three major reservoirs, Rainy, Namakan, and Kabetogama Lakes, the operation of which are the "most significant" natural resource management issue at VNP (http://www.nature.nps.gov/water/homepage/WorldWaterDay_VOYA.cfm, site visited 7/24/14). Changing the operating rules has sparked several research papers on the effect of water levels on stream and lake chemistry and biota (Luce and Metcalfe 2014, Christensen et al 2013, 2004). The Little Fork River watershed lies to the west of the Vermilion River watershed and drains through the Little Fork River into Rainy River downstream from VNP (Figure 1). The study area watersheds are part of the greater Winnipeg River watershed, a general outline of which is Attachment 1. The Winnipeg River watershed ultimately drains to Hudson Bay. Seventy percent of the basin draining to VNP is in Canada (Kallemeyn et al 2003), but this assessment does not account for Canadian mining operations.

There are leases for potential mines at ore deposits in both the Rainy Headwaters and Vermilion River watersheds (Figure 1). The deposits most likely to be developed first are those held by Twin Metals, Inc., which includes Duluth Metals, Franconia, and Beaver Bay (Barber et al. 2014). Contaminants originating from the mining of any of these ore bodies would flow through VNP.

This technical memorandum qualitatively assesses the risks of developing a sulfide nickel/copper (Ni-CU) mine or a gold mine within the watersheds draining toward VNP. It describes a conceptual model of flow and transport in the watershed, the likely potential mining of the ore deposits, and describes the risks to be expected from that mining. The focus herein is on contaminants that either leak from conceptual tailings or waste impoundments or transport due to spills. Leaks are generally considered long-term problems because they may not be detected for a long time and they require years to be remediated. A spill is a short-term event in which a contaminant load reaches a water source in a few days or weeks. For the purposes of this report, long- and short-term generally refers to more than a year and less than a few weeks, respectively. The transport pathways to and through VNP are qualitatively outlined herein.

A conceptual flow model (CFM) describes the flow paths through a watershed from precipitation to runoff, and from recharge to discharge in the aquifer. The CFM developed herein includes groundwater and surface water, including runoff processes, recharge (and seepage of waste), groundwater flow, and discharge to surface water. It discusses the relative magnitudes of flow and estimates baseflow and recharge, but does not develop a detailed water budget. The CFM then imposes the potential mining into the flow model to consider the risks to the watershed.

There is no plan of operations for any potential new mining, so the description of the probable mining would be based on information from relevant reports (Parker and Eggleston 2014). Twin Metals is moving forward with pre-feasibility plans, filing various technical reports on reserves and financial aspects of their potential mine plans (Barber et al. 2014). Other mine plans are less well developed so discussions are based strictly on online or geologic literature sources. Part of the Northshore Mine and Peter Mitchell Pit also lie within the Vermilion watershed. Other sources are hydrology studies completed by the US Geological Survey (USGS) and State of Minnesota.

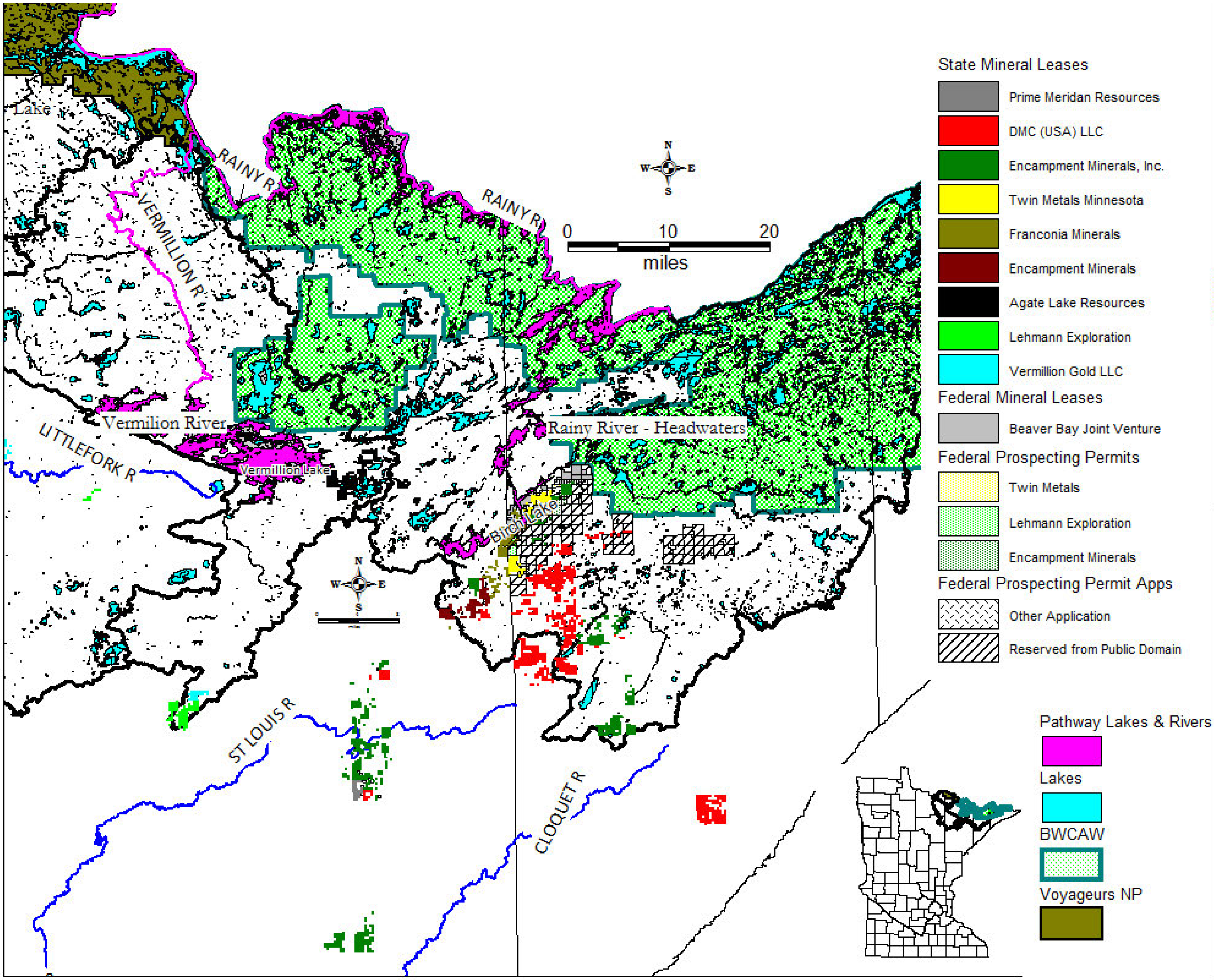

Figure 1: Map of Study Area, including major watersheds, mine Leases and primary surface water pathways from the leases to Voyageurs National Park (VNP). Pathways from the Rainy River Headwaters and from the Vermilion River watershed to VNP are shown. See Figure 2 for an expanded view of the leases in the Rainy Headwaters. Watersheds, lakes, streams from http://www.mngeo.state.mn.us/chouse/metalong.html, leases from http://mcc.mn.gov/gis.html

Summary of Mining and Mining Leases in the Watershed

Minnesota Department of Natural Resources (MDNR) publishes GIS map layers for active mining leases issued by the state and the U.S. Forest Service published GIS maps for federal mining leases, prospecting permits, and prospecting applications. Figure 1 shows the leases for the entire study area, with leases in the Rainy Headwaters and Vermilion Lake watershed. Leases further west in the Little Fork River watersheds would drain to the Rainy River downstream of VNP. Figure 2 shows the leases in Rainy Headwaters watershed, in both the Birch Lake and Stony River watersheds. The leases in the Vermilion River watershed are for gold and the others are for Ni-Cu.

MDNR lists three projects in the Rainy Headwaters in their Index for Advanced Projects for Metallic Minerals – Twin Metals Minnesota Maturi Deposit, Encampment Minerals Serpentine Deposit, and the Tech American Inc Mesabi Deposit (http://files.dnr.state.mn.us/lands_minerals/mpes_projects/minnesota_mine_sites_and_advanced_minerals_projects_winter2014.pdf). The index includes projects considered to be at the advanced stage, including active mines. Twin Metals current plans are also found at http://www.duluthmetals.com/s/NewsReleases.asp?ReportID=677352&_Type=News-Releases&_Title=Duluth-Metals-Files-NI-43-101-Pre-feasibility-Study-Technical-Report-on-the. The list includes the PolyMet NorthMet Deposit, which is west of the divide in the St Louis River basin and the Cliffs Natural Resources Northshore Mine, which is located in the middle of the Rainy Headwaters near the Encampment Minerals deposits (Id.). The Northshore Iron Mine also lies in the northeast end of the Mesabi Range on the divide between the St. Louis and Rainy Headwaters watershed (Northshore Mining Company 2014). Current mine dewatering discharge is to either of the two watersheds. After the Northshore Mine closes, the entire Peter Mitchell Pit will lie within the Rainy Headwaters, and any pit discharge will be to the Dunka River (Id.).

Lehman Exploration Management has leases in the Vermilion and Little Fork watershed, but they have not been very active. The last active drilling occurred in 2010 (http://www.dnr.state.mn.us/lands_minerals/exploration.html#2, site visited 7/24/14), although their leases remain up to date (Figure 1). The location of the leases appears to be in Ely Greenstone, north of the Giants Range granite (Morey et al 1970). The MinnTac taconite mine also lies in the Little Fork watershed.

The Vermilion River watershed contains one of four areas with active exploration for gold in the LOW watershed, including International Falls, Bigfork West, Bigfork East, Linden Grove, and

Vermilion (http://files.dnr.state.mn.us/lands_minerals/mpes_projects/ mn_min_goldexplore_map_0214.pdf). The Vermilion River watershed drains to VNP although the leases are above Vermilion Lake (Figure 1). This is the site of the first gold rush in Minnesota (Walker 1974). Vermilion Gold (2014) has leases in greenstone deposits in either free gold or arsenopyrite minerals, which does contain sulfide. They consider the deposits to be high grade at open pit mining depths (Id.). They project spending $2,000,000 during 2014 on exploration activities (Id.).

The most active mining copper-nickel proposal appears to be that of Twin Metals at four mineral deposits – Nokomis, Maturi, Spruce Road, and Birch Lake - located 10 miles east of Babbitt, MN and 15 miles southeast of Ely MN in the Birch Lake watershed, in the headwaters of the Rainy Headwaters watershed (Figure 2) (Barber et al. 2014). These deposits are 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. Each deposit would be accessed with underground methods (Parker and Eggleston 2014) and Twin Metals suggests that some tailings could be deposited underground and has also stated that tailings would be stored south of the divide out of the Rainy Headwaters watershed.

The Maturi deposit extends 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 to about 4000 feet below ground surface[1]. The Birch Lake deposit contains up to eight possible significant faults, which are identified as significant issues which will potentially affect the underground mining operations and the location of high grades of mineralization.

[1] The source for this information is Figure 7-7 in Parker and Eggleston (2012) which does not have units specified on the vertical axis. The ground surface shows at a little less than 500 which if meters would be near 1500 feet, the ground surface elevation. The depth ranges to about 900 below ground surface, which if meters would be near 3000 feet.

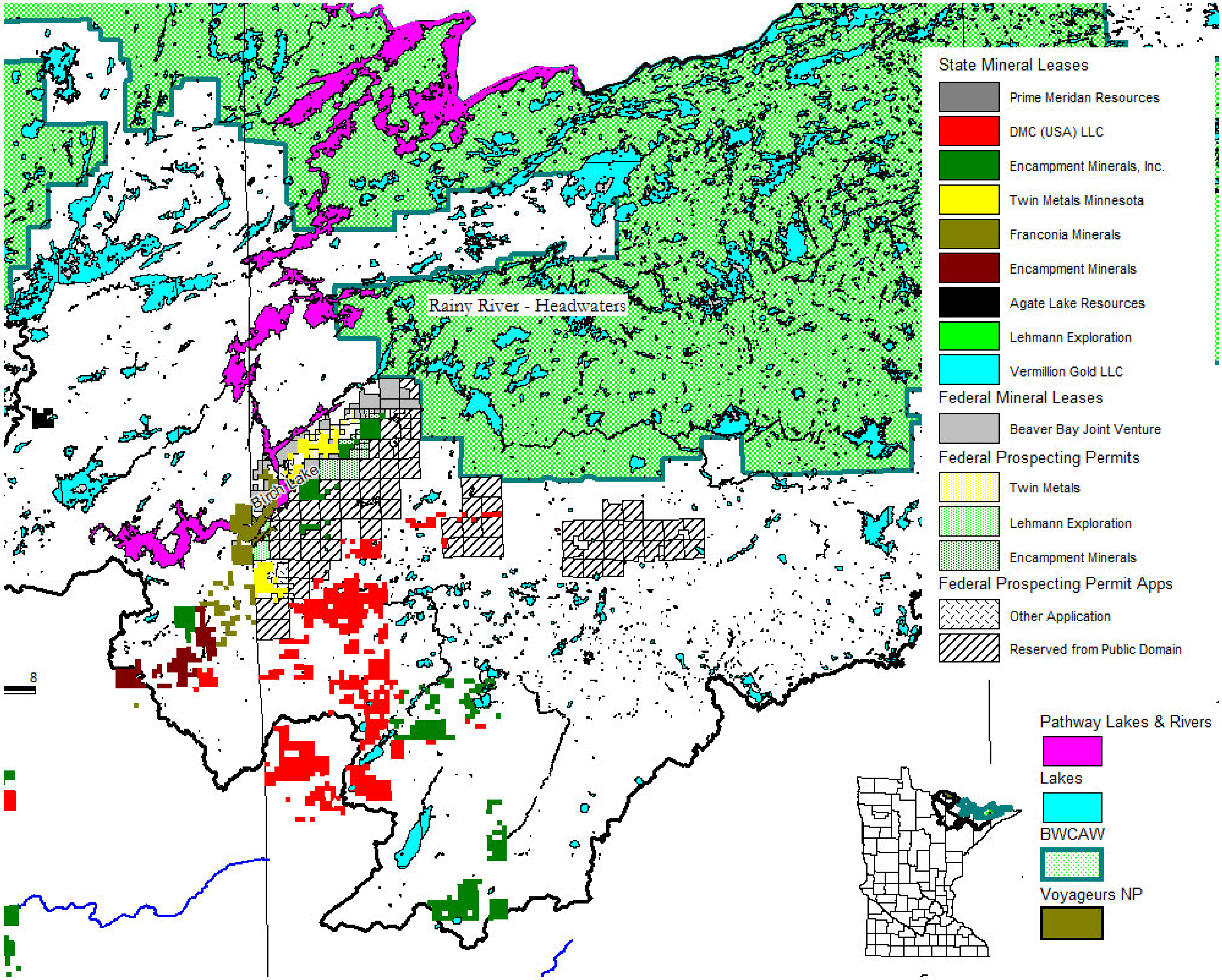

Figure 2: Expanded view of Figure 1 showing more detail around the mining leases in the headwaters of the Rainy River Headwaters watersheds. Watersheds, lakes, streams from http://www.mngeo.state.mn.us/chouse/metalong.htm; leases from http://mcc.mn.gov/gis.html

Conceptual Flow Model

The study area includes the watershed draining to VNP, as shown in Figure 1 for the portion of the watershed in the United States; Attachment 1 shows an outline of the entire Winnipeg River watershed of which the study area is part. A conceptual flow model (CFM) is a description of the flows through a watershed and/or aquifer. The CFM includes a description of the flow from precipitation through recharge to discharge, a description of the geologic formations through which the groundwater flows and from which runoff commences, the soils and other surface conditions, and in this area the lakes. Baseflow and recharge rates are estimated. The large-scale river and lake system upstream of VNP originates and controls the flows to and through the park. This section begins with a summary of the large-scale flows from throughout the watershed, based primarily on Kallemeyn et al. (2003), and then discusses the details controlling runoff, such as hydrogeology, soils, recharge, and baseflow. The lakes are discussed after the general CFM because they play a particular role in contaminant transport.

Rainy Lake Flow System

The water flow through the Rainy Lake watershed is primarily northwestward along the International Boundary (Attachment 1), with headwaters in the United States being in the Rainy Headwaters and Vermilion Lake watersheds (Figure 1). Water commencing in the headwaters drops about 443 feet in 21 days before it reaches the outlet of Rainy Lake; the total flow is about 2.2trillion gallons per year, or about 6.75 million acre-feet/year (af/y). The Namakan Reservoir system consists of five lakes, Kabetogama, Namakan, Sand Point, Crane, and Little Vermilion (Christenson et al. 2013). The Namakan reservoir system discharges into Rainy Lake through three outlets: (1) through dams at Squirrel Narrows and Kettle Falls at the northwest end of Namakan Lake, (2) at Bear Portage on the north-central side of Namakan Lake and (3) Gold Portage at the west end of Kabetogama Lake.

Namakan Reservoir controls a drainage area of 7440 square miles (mi^2) and an additional 7460 mi^2 drain directly into Rainy Lake. About 54% of the area above Namakan Reservoir is in Minnesota, but below Kettle Falls only about 6% of the Rainy Lake drainage is in Minnesota. The total average flow from the Namakan Reservoir system is 5150 cubic feet per second (cfs), or 51% of the total flow from Rainy Lake. Most of the additional flow from Rainy originates in Canada, including the Turtle River (1310 cfs) and Seine River (1700 cfs). Rainy Lake then is 70% of the flow to Lake of the Woods. The flow from the Rainy Lake watershed had been highly variable with coefficient of variation of 33%. Figure 7 in Kallemeyn et al. (2003) shows that discharge from Rainy Lake has varied from less than 100 to greater than 600 cms since 1923[2].

Attachments 2 and 3 show the average and extreme inflows and outflows from and water levels for Namakan and Rainy Lakes, respectively. Flows are most variable during early summer because they are affected by snowmelt and least variable during late winter when much of the watershed and precipitation is frozen. The lake levels fluctuate by just a few feet. The large volumes of Namakan and Rainy Lakes (see Table 5 below) help even out the flows.

Operating rules for the major reservoirs in VNP (and the system above Lake of the Woods) were changed in 2000 to instill more natural level fluctuations to rivers and reservoirs (Luce and Metcalfe 2014; Kallemeyn et al. 2003). Operating rules are basically upper and lower reservoir water level limits for each reservoir. The limits, targets the operators strive for, vary seasonally. Generally the targets are higher in the summer than at the end of the winter, which correspond to the observed flows discussed in the previous paragraph. The maximum and minimum levels changed very little but the rules allowed the reservoir levels to rise and fall more gradually through the runoff period. Luce and Metcalfe (2014) found that the rule change led to levels in the Lake of the Woods being an average one meter higher.

Luce and Metcalfe (2014) compared reservoir levels and river flows for the pre- and post-rule change periods. They found that high and low flows during the post-rule period are higher and lower than during the pre-rule period, but the reservoirs still fluctuate less than they would in a natural system. The reservoirs likely spilled more during the post-period although the post-2000 climate was more variable, with generally higher average precipitation and temperature.

The next sections focus on the processes that lead to surface and groundwater flow from the headwaters watersheds. The discussion is limited to the Minnesota portions of the watershed.

Hydrogeology

Precambrian rocks underlie most of the study area, the three major watersheds that drain to VNP. The oldest rocks, of early Precambrian, or Archaen age, outcrop in the northwestern portion of the area (Ojakangas and Matsch 1982). VNP mostly consists of granite, biotite schist, and migmatite (Agm) with a belt of greenstone (volcanic-sedimentary rock) in the northwest portion of VNP (AMV, Figure 3). The greenstone hosts the potential gold deposits. Except for the greenstone, this is part of the Vermilion Granitic Complex. The granitic complex covers much of the southern portion of the Rainy Lake Rainy River watershed and the northern two-thirds of the Vermilion River watershed. Further south lies the iron ranges of Middle

[2] The figure would be added to this report except the pdf version secure which disables the snapshot function in Adobe Acrobat.

Precambrian age, including the Vermilion Range and the Mesabi Range (Figure 3, Peif, the iron formation (Figure 4, Table 1)), which is just south of the Vermilion River watershed boundary. Forming the headwaters of the Vermilion River watershed is Giants Range granite (Agr). North of the Agr the geology is complex with a number of intrusions (Agd).

East of the Vermilion River watershed lies the Rainy Headwaters and the bedrock geology is an eastern continuation of the bedrock in the Vermilion River watershed. The southern two-fifths of the watershed is the Duluth Complex which hosts most of the Cu-Ni deposits. The Duluth Complex 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. 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. Hydrogeologically, the Duluth Complex is a low-permeability intrusive formation with a very low conductivity except possibly near some of the infrequent faults. There is little data available concerning the hydrogeology of the faults.

There are two aquifers over the study area – a crystalline rock bedrock aquifer and glacial till or sand/gravel surficial aquifer (Mast and Turk 1999; Olcott 1992). The bedrock type varies from gneiss and granite north of the mineralized areas to more volcanic sources such as basalt further south (Figure 4). The surficial aquifer is less than 100 feet thick over most of the study area and some areas have bedrock outcrops.

The Rainy River watershed including VNP was glaciated from 10,000 to 50,000 years ago, scouring from which formed most of the natural lakes in northern Minnesota (Kallemeyn et al 2003). This removed the most weathered rock near the surface, so that there is not a high density of fractures in the upper portion of the bedrock. The transition from the surficial to bedrock aquifer often is a zone of rapid decrease in conductivity.

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 most conductive bedrock aquifer, because of fracturing, of the province is the Biwabik formation, in which most of the area iron mines were developed.

Table 1: Description of map units in Figure 3. Adapted from Morey and Meintz (2000)

Adg	Gabbro, diorite, peridotite, and associated komatiitic flows of the the upper part of the Newton Lake Formation in Lake and St. Louis counties
Agd	Multiphase intrusions of hornblende-pyroxene-bearing and biotite-bearing monzonite, monzodiorite, diorite, syenite, and granodiorite—Typically postdates regional metamorphism and deformation associated with the Algoman orogen
Agm	Granite-rich migmatite—Granitic gneiss, paragneiss, schist, and migmatite in the Vermilion Granitic Complex and other parts of extreme northern Minnesota. Grades into granitoid rocks.
Agr	Syntectonic to pretectonic granitoid rocks—Granite and granodiorite of the Vermilion Granitic Complex, the Giants Range and Bemidji batholiths, as well as smaller intrusions of tonalite and monzonite of the Algoman orogen in northern Minnesota.
Amm	Mixed metavolcanic rocks—Mafic to felsic volcanic sequences that have variable amounts of felsic volcanogenic and volcaniclastic rocks and lean iron-formation. Includes parts of the Ely Greenstone and the Soudan Iron Formation (shown in red) in northeastern Minnesota
Amv	Mafic metavolcanic rocks—Dominantly basalt that contains thin sedimentary units, including iron-formation (shown in red). Includes parts of the Ely Greenstone and the Newton Lake Formation in northeastern Minnesota
Aps	Paragneiss, schist, and amphibolite—Amphibolite-facies equivalent of units Amv and Ams; locally includes abundant intrusions of unit Agr.
Asm	Paragneiss and schist-rich migmatite—Grades into undivided metasedimentary rocks (unit Ams).
Ast	Saganaga Tonalite of northeastern Minnesota—Emplaced more-or-less contemporaneously with deposition of metasedimentary and metavolcanic rocks
Kc	Coleraine Formation—Jasper-pebble conglomerate, sandstone, and shale of diverse origin on the Mesabi range of northern Minnesota
Peg	Shale, siltstone, feldspathic graywacke, and associated volcaniclastic rocks—Includes the Virginia Formation in St Louis, Itasca, and Lake counties
Peif	Iron-formation—Includes the Biwabik Iron Formation and subjacent units of arenite and conglomerate assigned to the Pokegama Quartzite in Itasca, St. Louis, and Lake Counties.
Pma	Anorthositic series—Plagioclase-rich gabbroic cumulates and related rocks
Pmbg	Selected granophyric and leuco-granitic phases of troctolitic-gabbroic intrusions in the Beaver Bay Complex.
Pmbu	Beaver Bay Complex and other named and unnamed gabbroic-troctolitic intrusions—Includes a number of other intrusions in a variety of dikes and sills such as the Endion sill and the Pigeon River Intrusions
Pmdg	Felsic series—Granophyric granite and related felsic rocks.
Pmg	Early gabbros—Gabbro and related rocks in northeastern Minnesota that have petrologic affinities to the Logan Intrusions
Pml	Logan Intrusions—Diabase, porphyritic diabase, gabbro, and related felsic sills and dikes
Pmnn	Normally polarized volcanic rocks, undivided—Basalt, andesitic basalt, rhyolite, and related volcanogenic interflow sedimentary rocks along and inland from the North Shore of Lake Superior
Pmnr	Reversely polarized volcanic rocks, undivided—Mixed tholeiitic diabasic and porphyritic basalt, trachybasalt, and rhyolite in far northeastern Minnesota
Pmt	Troctolitic and gabbroic cumulate rocks—Constitute at least nine named and several unnamed intrusions

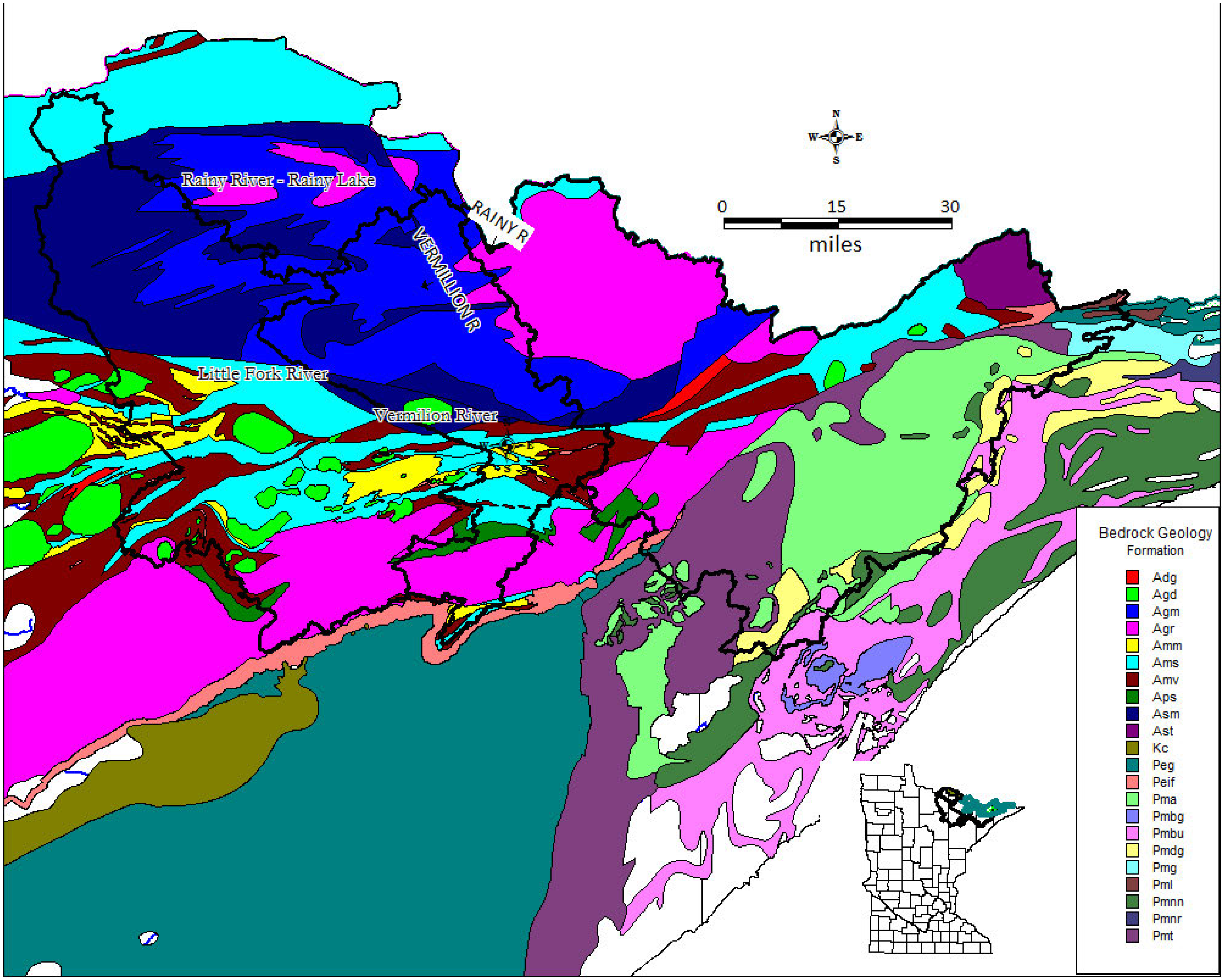

Figure 3: Geology type for the watersheds draining to Voyageurs National Park.

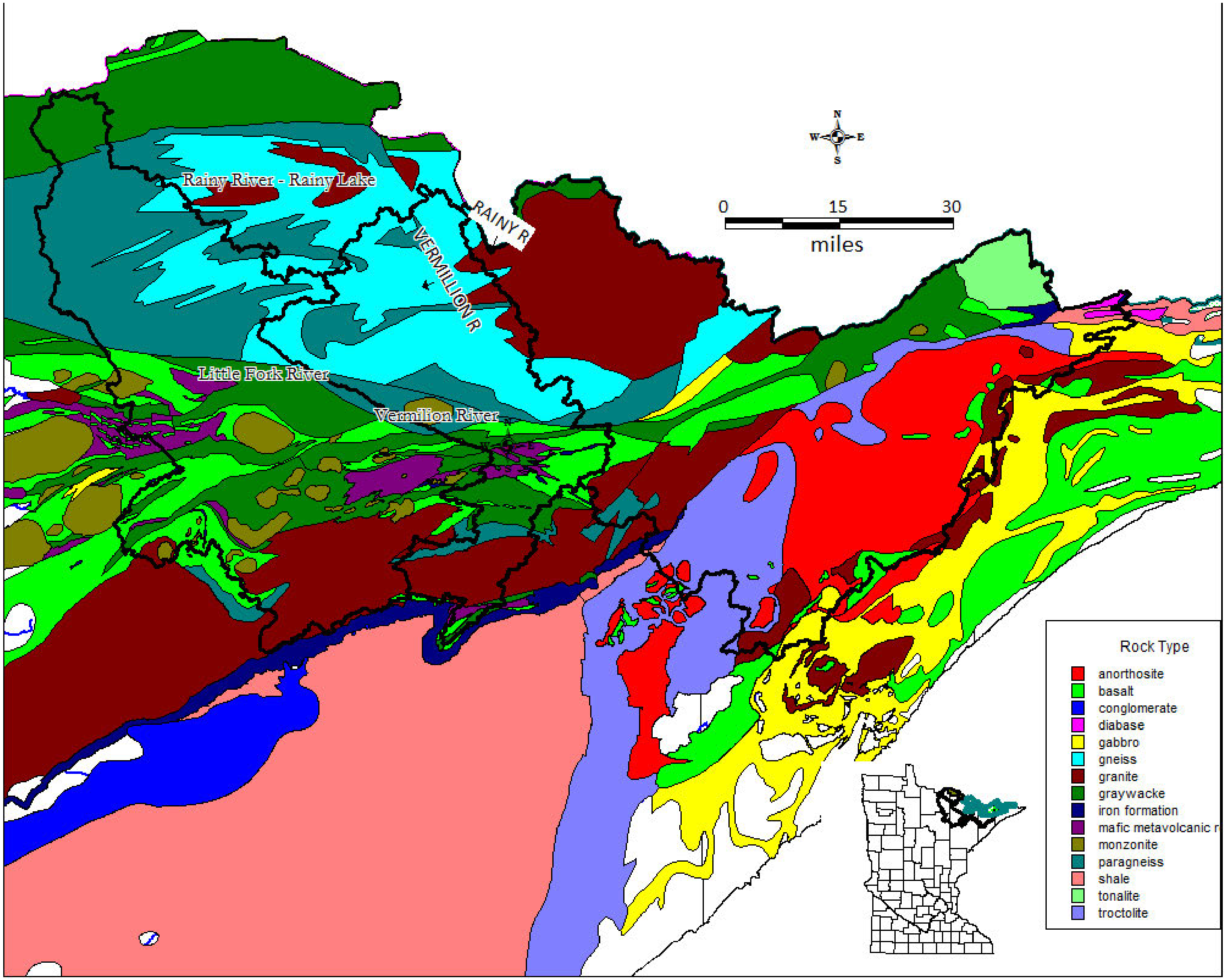

Figure 4: Bedrock type for the watersheds draining to Voyageurs National Park

Soils and wetlands control where recharge occurs and the location of most pathways as well as affecting the groundwater chemistry. Minnesota has several well-developed GIS databases describing soils at a statewide level with accuracy to a 40 acre scale, as described in Land Management Information Center (1996) and associated GIS databases.

Figure 5 shows the larger wetlands in the area. The density and areal coverage is higher in the Vermilion River, Little Fork River, and Rainy River Rainy Lake watersheds than in the Rainy headwaters. If the wetlands are perched, meaning no connection with groundwater, these areas could have little recharge (Sophocleus 2002, Winter 1998). Otherwise, wetlands could be alternately recharge and discharge areas.

Tower Ely glacial drift and bedrock covers most of the north and eastern portions of the study area (Figure 6). Agassiz Lacustrine Plain covers much of the western part of the Vermilion River watershed and most of the Little Fork River watershed. This material differs from glacial drift in that it is lake-bed sediment so the soils are probably much finer and the flow characteristics would differ. Lake beds would be more homogeneous with low conductivity.

Soil type is a soil landscape unit based on four characteristics, each with a letter description (Table 2), describing texture and drainage. Some soils, such as PEAT, are not included because their characteristics do not break down easily into the categories. Most of the study area soils are relatively free-draining (Figure 7). Type RLWL covers the northern two-thirds of the study area. This means light-colored, well-drained loam above shallow bedrock, which suggests there should be substantial interflow through the soils and recharge to the surficial aquifer but not a lot of connection to deeper layers. RSWL differs because sand occurs in place of the loam and covers much of the upstream half of the Vermilion River watershed. The headwaters of the Vermilion River and Rainy River Headwaters are SSWL which means that sand extends below the upper five feet.

The soil type just described mostly coincides with the hydrologic soil classification (Figure 8). The area described as RLWL and RSWL is mostly hydrologic type C or D meaning there is substantial runoff (Table 3); in this case the runoff would be due to shallow bedrock. Just south is an area with a large amount of A group soil, which would have high infiltration. This is the area in which sand replaces bedrock under the upper five feet of soil. Infiltration would occur much deeper here. The remaining areas along the southern boundary of the study area have infiltration rates intermediate to the C, D and A groups.

Maps of surface permeability (Figure 9) and subsurface permeability (Figure 10) shows that much of the northern part of the study area has both surface and subsurface permeability greater than 0.8 inches/hour (in/h). The south-central portion has much higher permeability with surface rates exceeding 2.5 in/y and subsurface rates exceeding 5 in/h. The least permeable areas for both surface and subsurface permeability are in the far northwest portion near VNP.

Finally, Figure 11 shows that almost all soils in the study area are acidic, with the exception being in the far northwest where they are neutral. This probably corresponds with the poor buffering capacity in surface waters discussed below.

A general description of the soils and wetlands in the area is that precipitation generally does not infiltrate deeply in the northern two-thirds of the watersheds but rather becomes interflow or causes the water table to rise and may discharge to the surface becoming overland flow. Surface storage may be important, especially in the areas with substantial wetlands. However, in the headwaters of the watersheds where the mineral deposits are, the soils are deeper and allow deeper infiltration. More water contacts the underlying bedrock, which corresponds to the results found modeling the watersheds draining to Birch Lake (Myers 2014b; Siegel 1981).

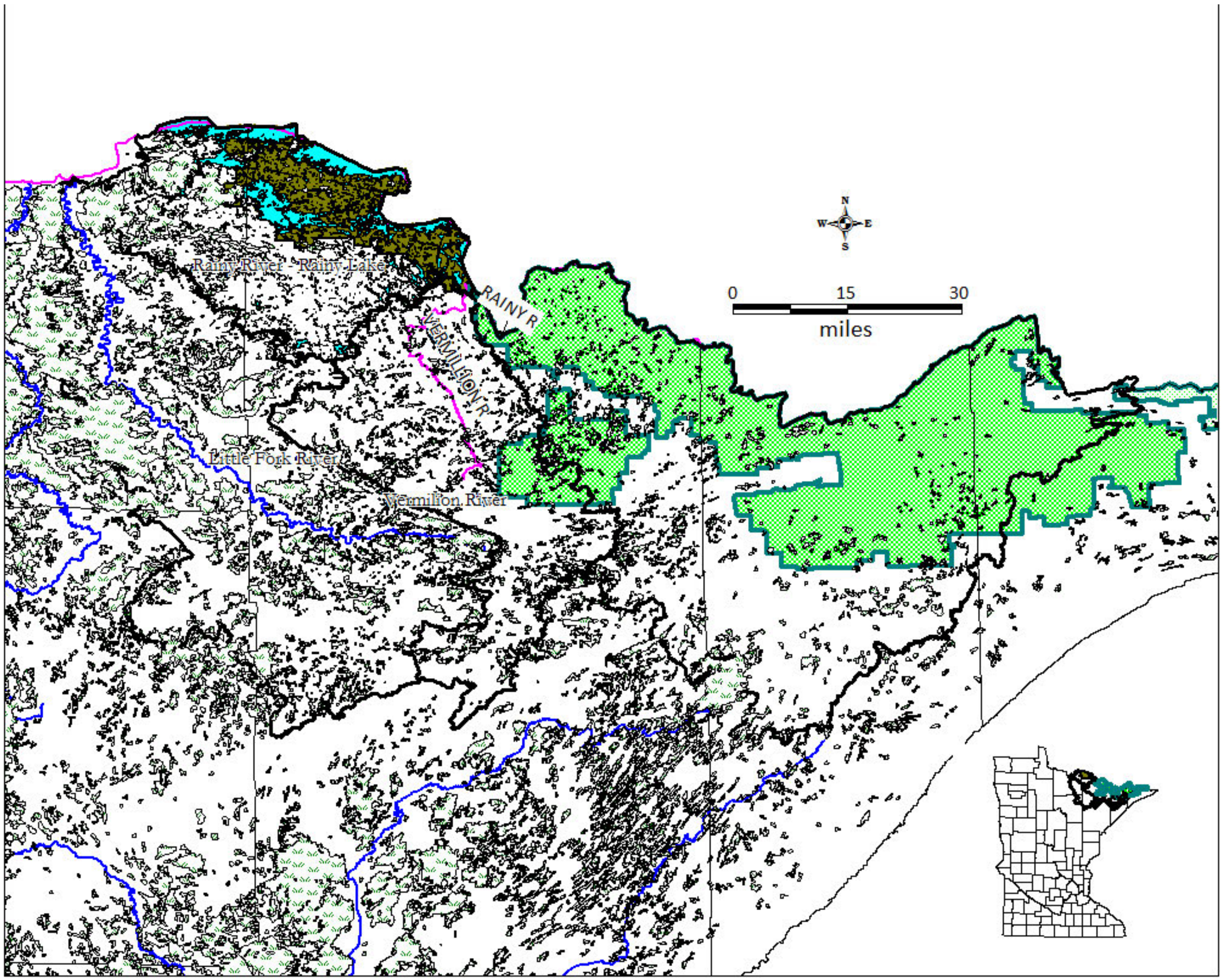

Figure 5: Location of wetlands in the watersheds draining to Voyageurs National Park. Wetlands GIS file from Dnr100khydrography, from www.mngeo.state.mn.us/chouse/metalong.html

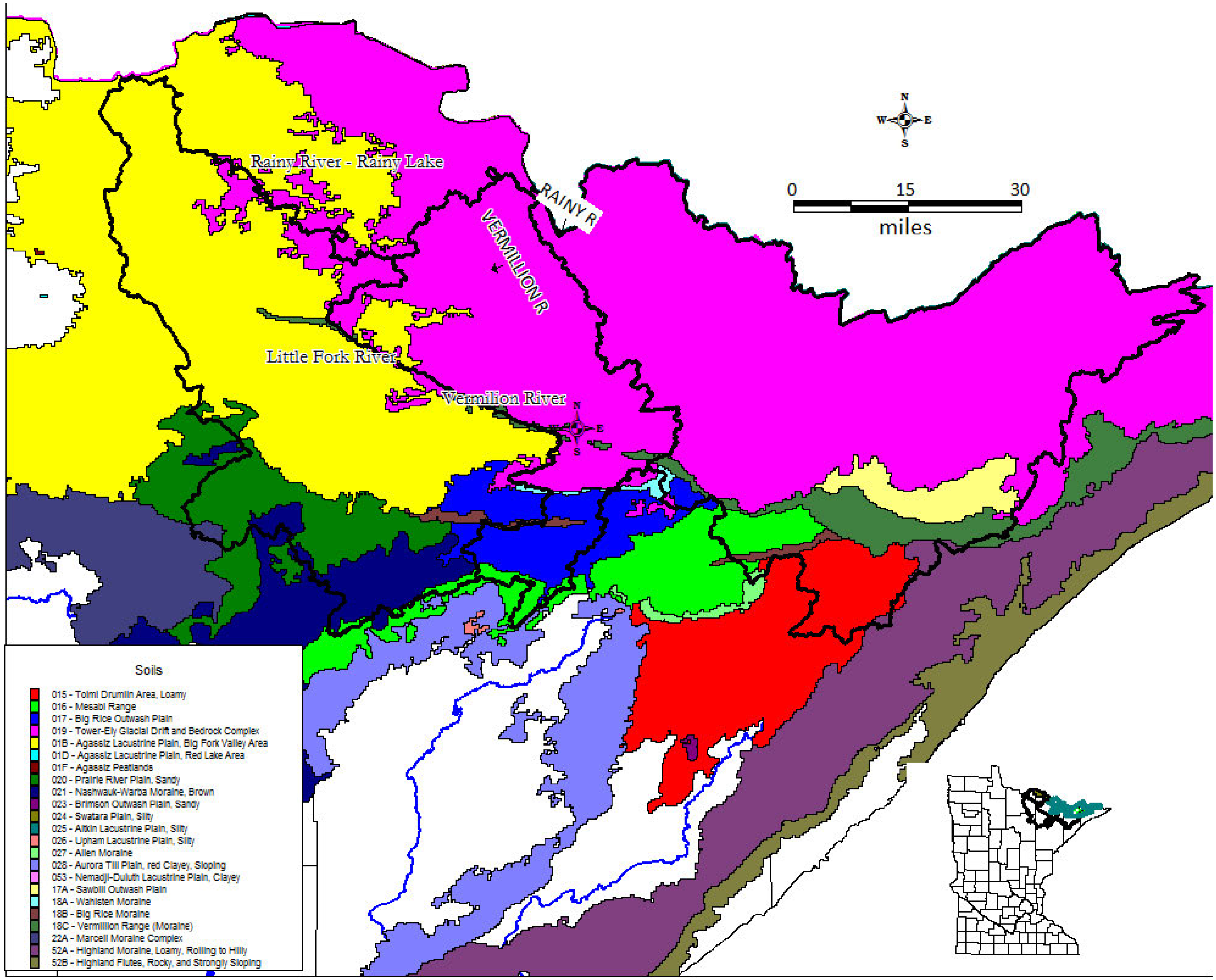

Figure 6: Soil type for the watersheds draining to Voyageurs National Park. From Minnesota soil atlas: http://www.mngeo.state.mn.us/chouse/metadata/soil_atlas.html

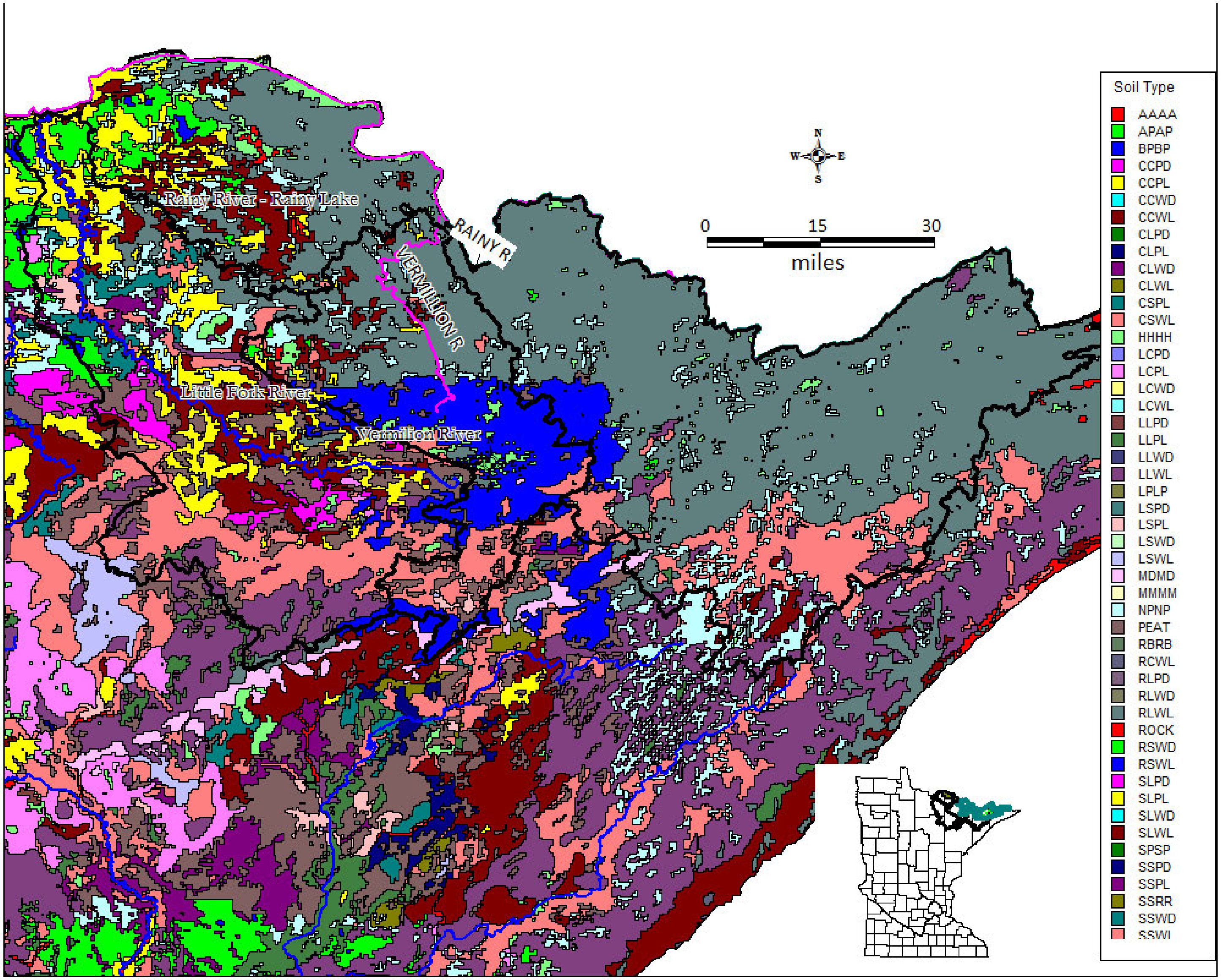

Figure 7: Soil type (Table 2) for watersheds draining to Voyageurs National Park. From Minnesota soil atlas: http://www.mngeo.state.mn.us/chouse/metadata/soil_atlas.html

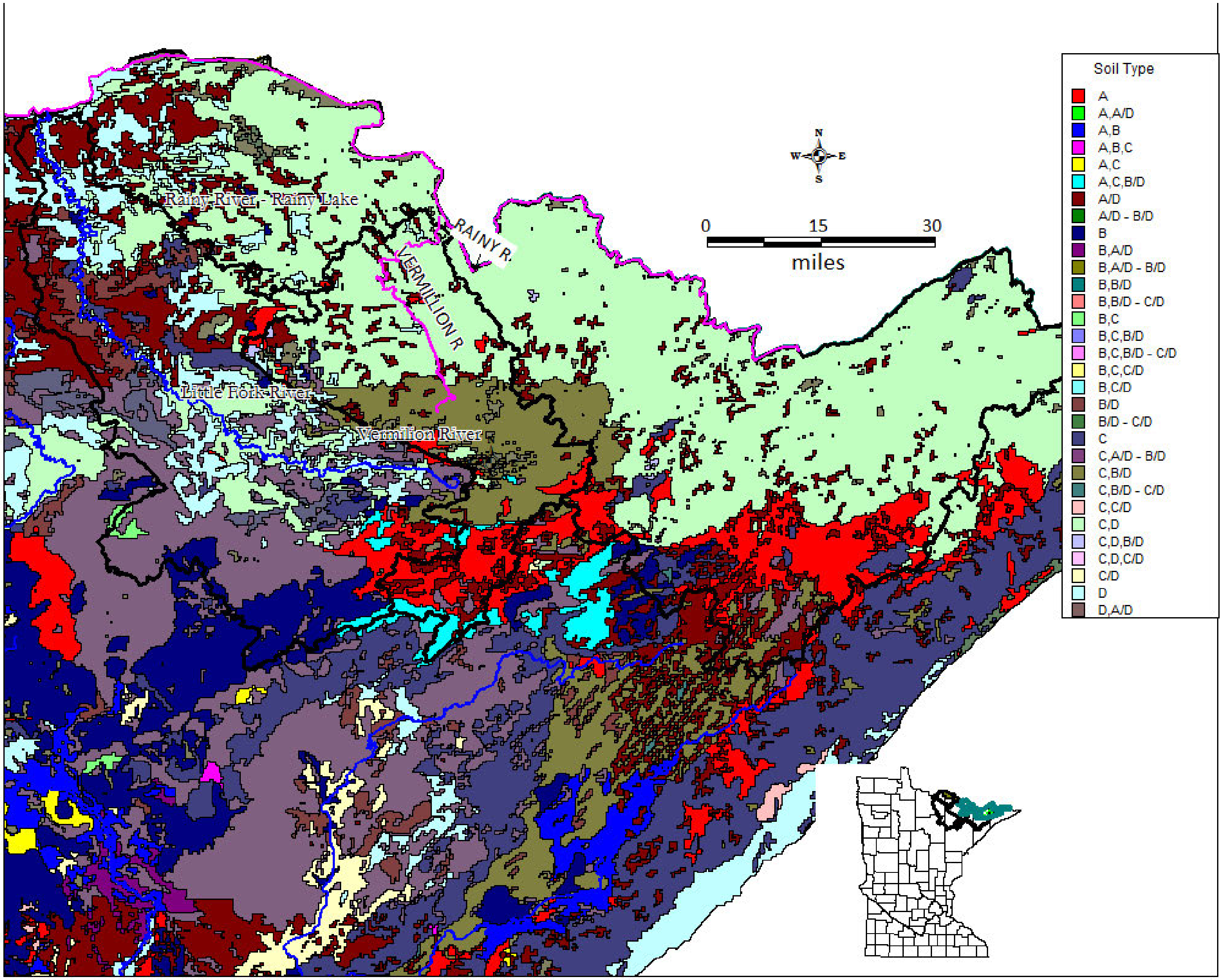

Figure 8: Hydrologic soil type (NRCS 2007) for watersheds draining to Voyageurs National Park. From Minnesota soil atlas: http://www.mngeo.state.mn.us/chouse/metadata/soil_atlas.html. See Table 3 for a description of the hydrologic soil type.

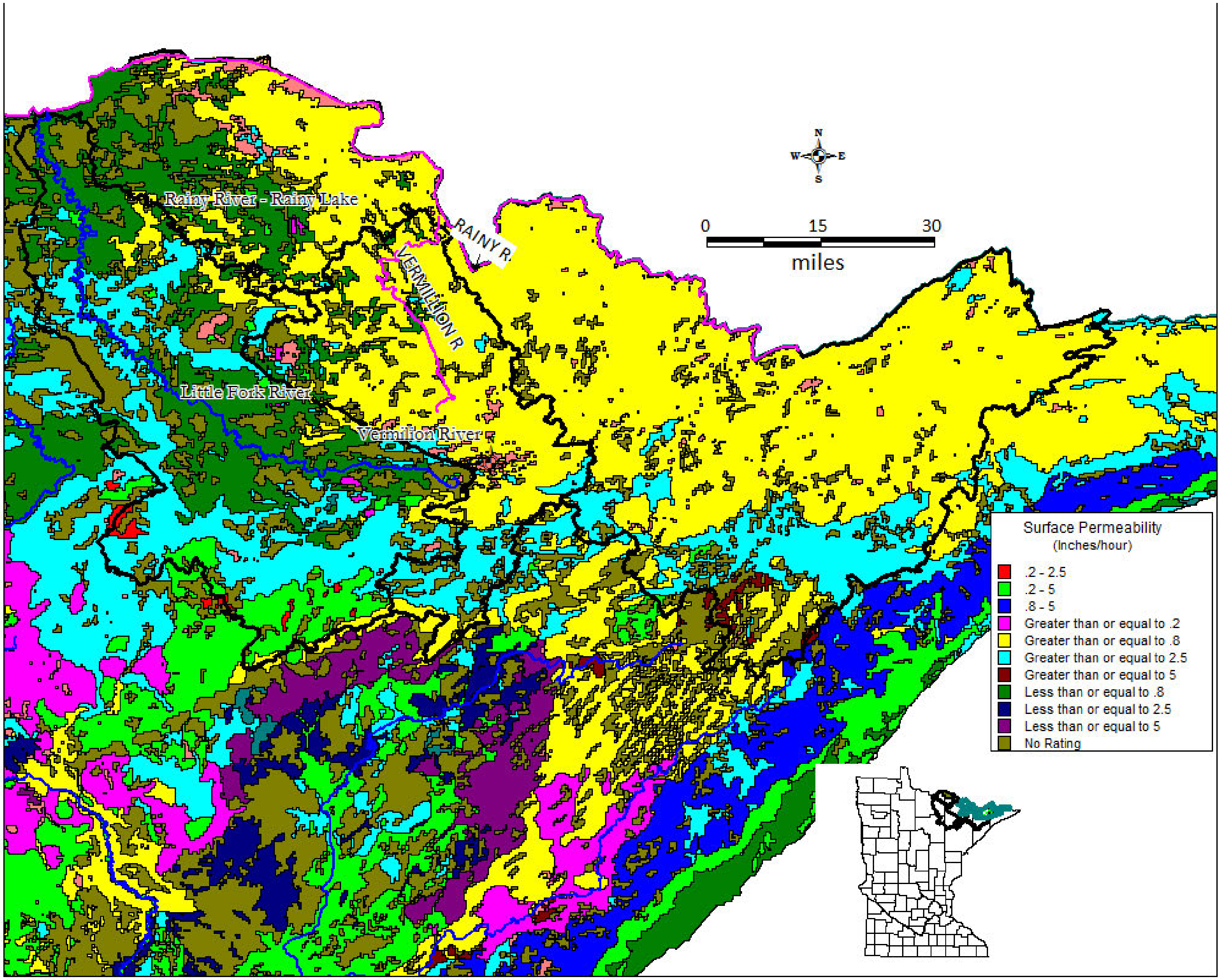

Figure 9: Surface permeability for watersheds draining to Voyageurs National Park. From Minnesota soil atlas: http://www.mngeo.state.mn.us/chouse/metadata/soil_atlas.html

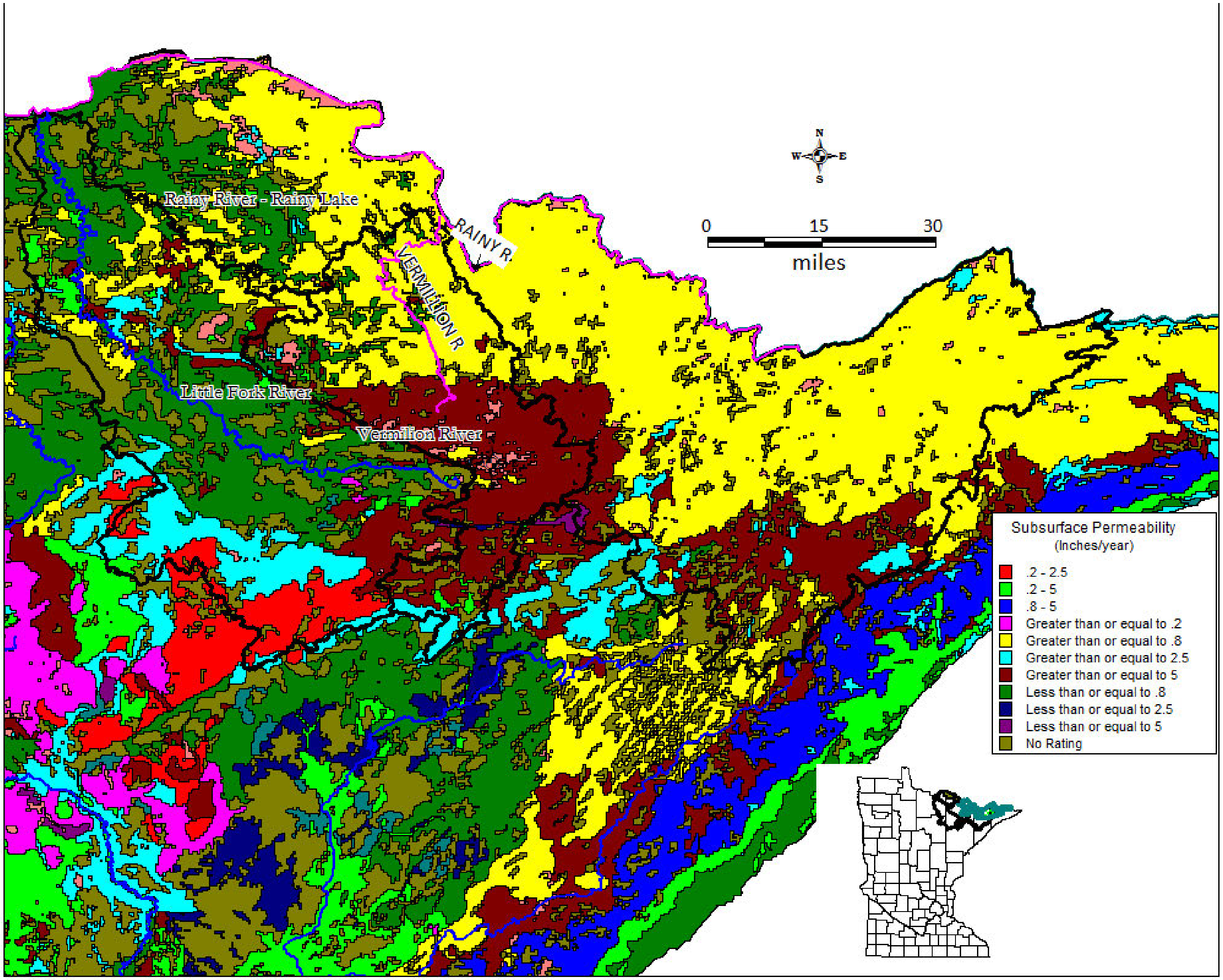

Figure 10: Soil subsurface permeability for watersheds draining to Voyageurs National Park. From Minnesota soil atlas: http://www.mngeo.state.mn.us/chouse/metadata/soil_atlas.html

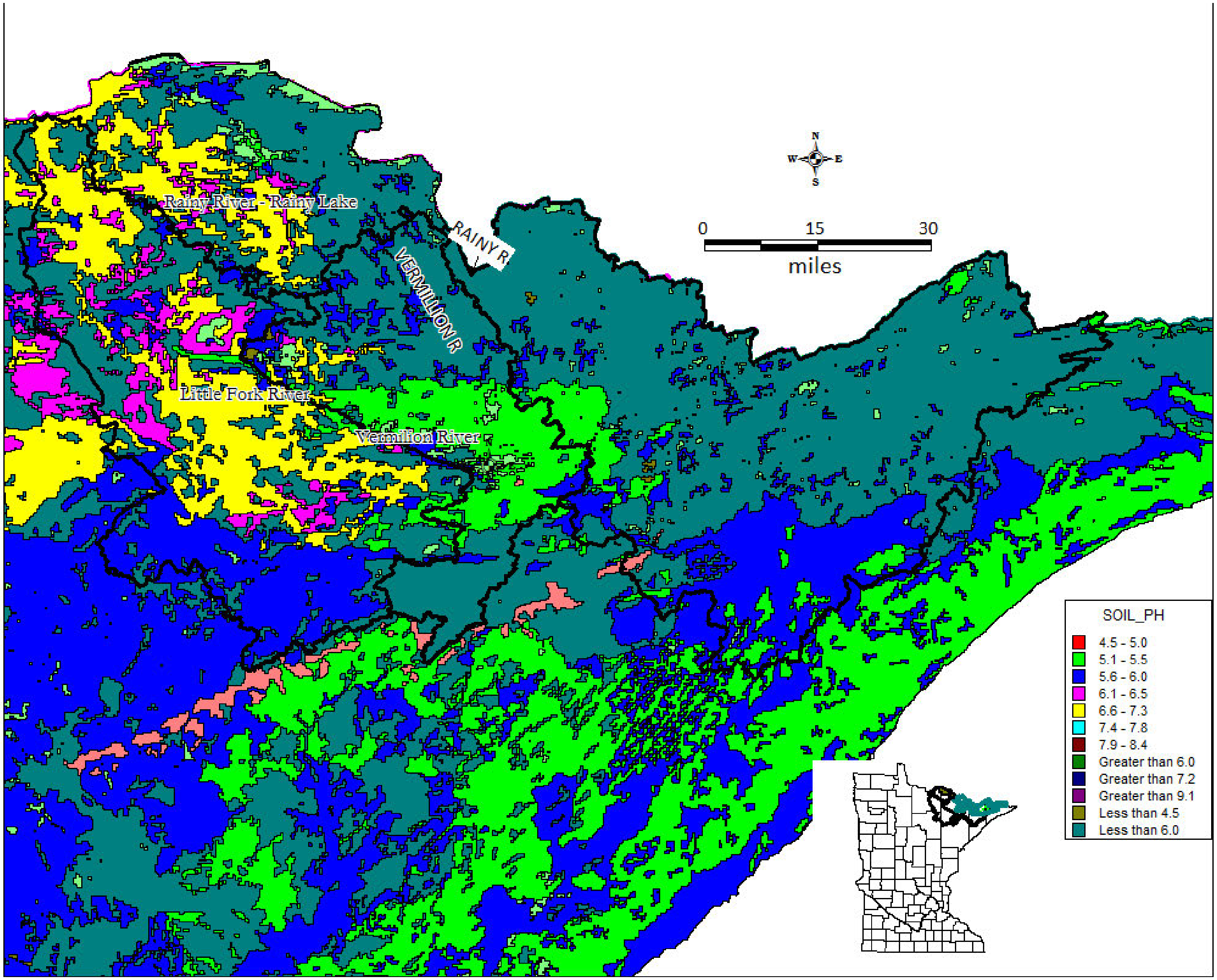

Figure 11: Soil pH for watersheds draining to Voyageurs National Park. From Minnesota soil atlas: http://www.mngeo.state.mn.us/chouse/metadata/soil_atlas.html

Table 2: 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.	

Table 3: 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.

Estimate of Surface and Groundwater Flows

Precipitation segregates into evapotranspiration (ET), runoff or infiltration into the ground. ET includes direct evaporation of surface water and precipitation intercepted by vegetation and transpiration of soil water through the vegetation. River flow is either direct runoff from the surface, interflow, or groundwater discharge of recharge. Infiltration either becomes interflow, recharge to groundwater, or transpiration back to the atmosphere.

Interflow is flow through the soils and vadose zone above the water table to rivers, and includes both unsaturated and saturated flow to streams that occurs during and just after storms, with saturation causing temporary perched zones (Sophocleous 2002). Because of the shallowness and flatness of the groundwater table in this study area, especially in wetland areas, interflow is limited. Because of the variable thickness of the soil layer between the water table and ground surface, interflow likely encounters areas that are too thin to fully transmit the flow causing some to discharge to the ground surface and become overland flow. Another possible short-term shallow groundwater discharge to the rivers may be caused by groundwater ridging which causes a rapid conversion of the capillary zone to atmospheric pressure which would rapidly increase the groundwater head and significantly increase the gradient for flow to surface drainages over the short-term (Sophocleous 2002).

Groundwater discharge to rivers is baseflow, which is assumed to equal recharge (Cherkauer 2004; Scanlon et al 2002). Wintertime precipitation is frozen along with the soils so little direct runoff or recharge occurs during winter. Sixty percent of the runoff at the Kawishiwi River near Ely gage occurs during snowmelt from April through June whereas less than 11 percent occurs from December through March for the 1955 to 1976 time period (Siegel and Ericson 1981). 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 (Figure 12). This seasonal runoff causes stream levels to rise which causes a gradient for water to flow from streams into streambanks, increasing the recharge during spring snowmelt. Groundwater levels just outside of the study area have been shown to fluctuate up to six feet during the spring (Polymet 2013a), in response to the spring snowmelt, which Myers (2013a and b) found represented about 8 to 11 in/y recharge.

Seasonal groundwater level fluctuates up to six feet at two wells within the study area (Figures 13 and 14). The well in Figure 13 is more than 30 feet deep and that in Figure 14 is less than 10 feet, but the seasonal fluctuations are similar. Close examination of the low point reached in 1977 suggests that the fluctuations in the deeper well lagged a bit, but that may be an artifact of the frequency the water level was measured. These figures show the substantial variation both seasonally and among dry and wet years.

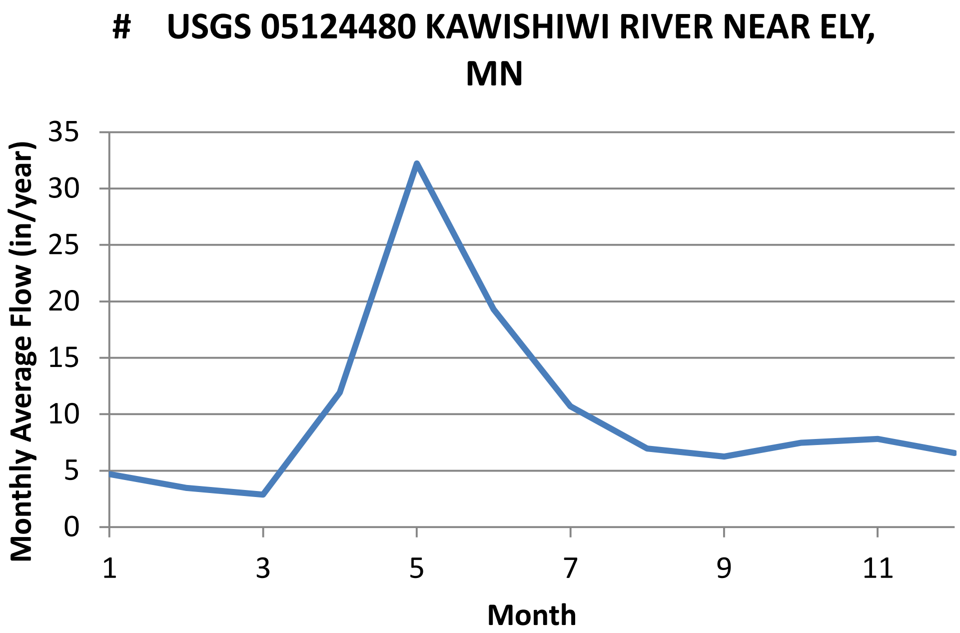

Figure 12: Average flow by month (1=January, 12=December) in inches per year for the Kawishiwi River near Ely, MN. Source: http://waterdata.usgs.gov/mn/nwis/sw/

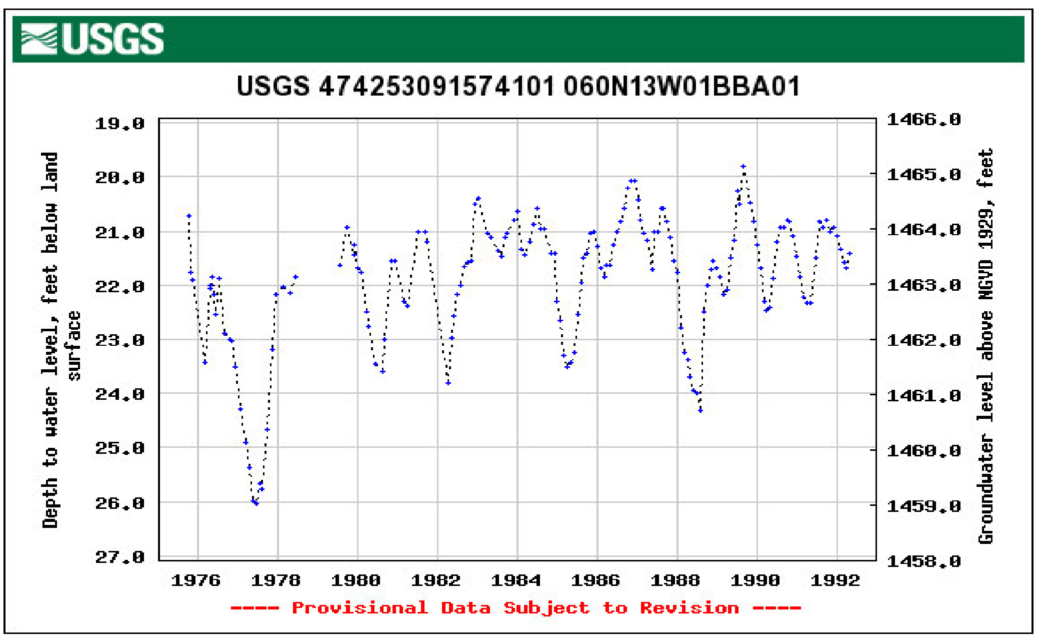

Figure 13: St Louis County, MN, HU 09030001, Latitude 47°42'53", Longitude 91°57'41", Land-surface elevation 1,485.00 feet above NGVD29, Depth of well 30.0 feet below land surface, depth of is 42.0 feet below land surface. This well is completed in the Wisconsin Stage (112WSCS) local aquifer. Source: http://nwis.waterdata.usgs.gov/mn/nwis/gwlevels

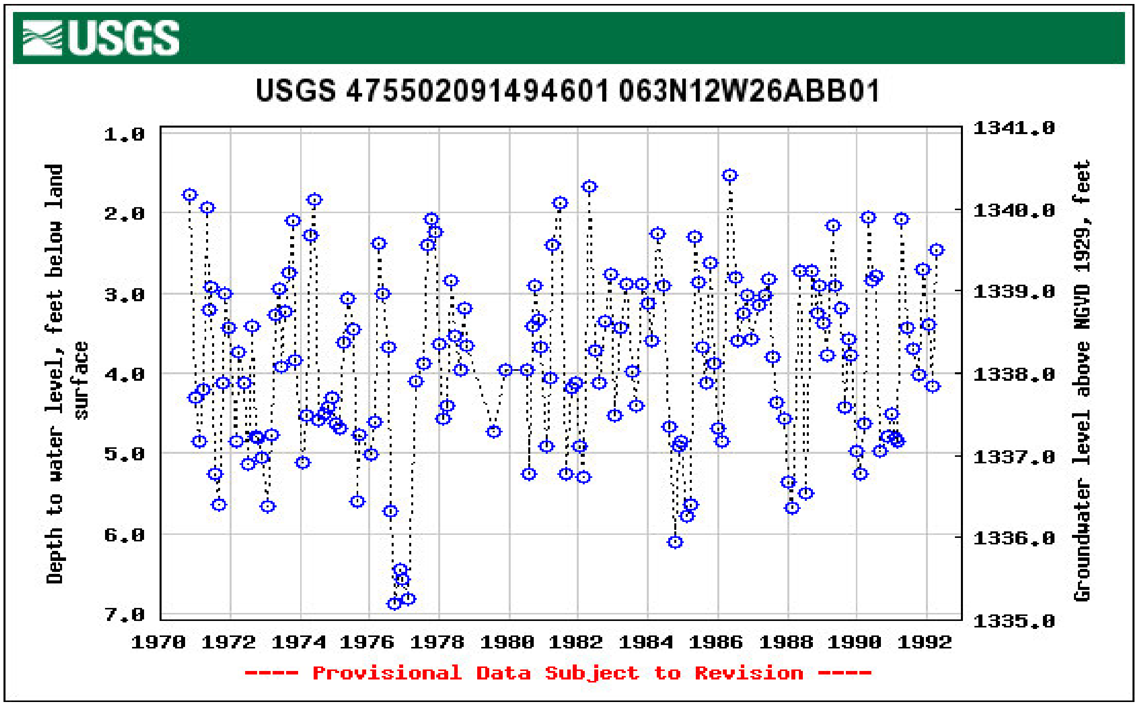

Figure 14: St Louis County, Minnesota, Hydrologic Unit Code 09030001, Latitude 47°55'02", Longitude 91°49'46" NAD27, Land-surface elevation 1,342.00 feet above NGVD29, The depth of the well is 9.0 feet below land surface. The depth of the hole is 9.0 feet below land surface, near Ely, MN. Source: http://nwis.waterdata.usgs.gov/mn/nwis/gwlevels

Setting baseflow equal to groundwater recharge over the basin (Scanlon et al. 2002) does not mean that the lowest observed flows on a river equals an average recharge rate distributed evenly across the basin. Peak recharge coincides with the snowmelt because more water is available for infiltration and seepage from stream channels. Except during a low snowmelt year, most of the watersheds would initially be contributing recharge at the peak snowmelt. With time since the peak, however, the area contributing recharge would decrease as portions of the watershed complete their melt. Downstream areas that receive runon from upgradient would have the longest period with recharge. The baseflow hydrograph would be shaped similarly to the recharge pattern. Baseflow would decrease according to a function of the contributing area and the flow time from that area. The actual discharge would be related to the gradient at the stream which would decrease as the groundwater level in the banks decreases; this could not be directly related to contributing area because the water table is not linear and the groundwater flow times from portions of the watershed differs according to gradient and transmissivity. At minimal baseflow, the entire drainage area is not contributing. Just southwest of the Laurentian Divide, Myers (2013a) found that the lowest baseflow cannot equal the average recharge because of the long time period since recharge would have occurred (the previous snowmelt period) and the short travel time through the aquifers due to the high conductivity and thinness of the surficial aquifers. A similar process controls through the study area here.

Estimate of Baseflow and Low Flows for Headwaters Streams

Baseflow was estimated for all US Geological Survey gaging stations in the area using methods of Lim et al. (2010, 2005) found at https://engineering.purdue.edu/~what/main.html (accessed 4/29/14) (Table 4). Essentially, the method determines a recession index[3], similar to Lorenz and Delin (2007), which is then used to back calculate a baseflow hydrograph from under the peak of each runoff peak. If the flow rate decrease is relatively smooth, it is assumed to be controlled by drainage from one primary component controlling continuing flow, such as release from surface storage or groundwater.

Total flow was divided into direct runoff and baseflow. The sum of average flow for each day of the period of record is total flow in cfs-days (cubic feet per second x days) which divided by number of days yield average flow in cfs (Table 4). The same applies to direct runoff and baseflow (Table 4). 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 baseflow per area, assuming that all recharge becomes baseflow (Cherkauer 2004, Scanlon et al 2002). The estimate is the average of distributed recharge (through the ground surface over the watershed) and runoff recharge. The actual location of recharge depends on the distribution of soils, geology, rainfall, and recharge from streams. The heterogeneity of these features was discussed above. Flow management may also affect the baseflow, including reservoir control of flow releases and the discharge of mine pit dewatering discharges.

Total and baseflow yield is higher for gages on the east portion of the study area, in the Rainy Uplands including the Kawishiwi River drainages, than in the west. Total and baseflow yield ranges from 9.5 to 12.3 and from 6.5 to 9.5 in/y, respectively, for gages in the Rainy Headwaters, with gages on smaller watershed having the most extreme values. The total and baseflow yield in the Little Fork and Vermilion River watersheds is less than 9.8 and 7.3 in/y, respectively. The largest watershed, the Little Fork, #1, has the lowest baseflow yield of large watersheds.

The baseflow index varies from about 0.65 to 0.79, with a few outliers. The lowest values, occurring for stations 17 through 20, are for streams with very small watersheds; without a large proportion of lakes. Filson Creek, #27, also has a low value at 0.61. Filson Creek is a 25.2 km^2 tributary described by Siegel (1981) as having two significant lakes and being 60% covered

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[3] The recession index is the time for a flow hydrograph to decrease, or recede, by one base 10 logarithmic interval from a peak flow.

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. Based on Siegel's (1981) description of Filson Creek, the presence of ground cover that limits recharge may also cause low BFI because runoff is higher.

Of the larger watersheds, the Little Fork at Littlefork MN gage has a BFI on the low end of the range, which may reflect a lack of lakes affecting drainage. On the other extreme, the Basswood River at Winton gage, the largest drainage area in the study, has a BFI equal to 0.78. This probably reflects the substantial string of lakes above the gage (Myers 2014b).

Baseflow yield tends to become smaller moving west from the Rainy Headwaters, along with the decrease in rainfall. Based on the BFI, the proportion of rainfall that becomes recharge also decreases. The average recharge for the Little Fork watershed is 5.6 in/y, for the Vermilion River watershed is 7.1 in/y, and for the Rainy Headwaters ranges from 7.5 to 8.2 in/y; these estimates are simply the baseflow yield for the gages with the largest watershed. Again, these averages do not account for local variation due to the various heterogeneities.

The recharge estimates derived herein are less than the range as determined using the Delin et al (2007) methods. For the Kawishiwi watershed, Delin et al (2007) yields recharge equal to 8 to 11 in/year (Myers 2013b). Further west through the Little Fork watershed, Delin et al (2007) would yield from about 5.8 to 9.6 in/y. The trend using the Delin et al (2007) method is similar to that described here but it has slightly higher rates.

Low flow conditions occur during baseflow but represent the extreme lower flows. Groundwater is the primary source of flow, but from only a portion of the watershed. It is during these low flow periods that conditions most critical both ecologically and economically occur. Two studies have estimated low flows for Minnesota streams (Arnston and Lorenz 1986; Winterstein et al 2007). The earlier study estimated low flow return intervals for gage stations with ten or more years of record (Arnston and Lorenz 1986) and the latter study provided similar estimates for stations with twenty or more years of record (Winterstein et al 2007) (Table 4). The ten-year seven-day low flow (7Q10) is considered here because it is long enough for contaminant concentrations to become critical. The low flow values, and baseflow estimates, are determined from available data for a gage without regard to whether the periods of record (Table 4) are overlapping.

Table 4: US Geological Survey gaging stations used for this study, various station parameters, and flow values. The Armston and Lorenz and Winterstein et al columns are the ten-year seven-day low flow value for the specified station.

Number	Site Number	Site Name	Altitude (ft amsl)	Area (sqmiles)	Avg Flow (cfs)	Direct Runoff (cfs)	Base flow (cfs)
1	5131500	LITTLE FORK RIVER AT LITTLEFORK, MN	1083.59	1680	1045.72	348.13	697.59
4	5131455	NETT LAKE RIVER NEAR NETT LAKE, MN		128	90.94	30.51	60.43
5	5131448	WOOD DUCK CREEK NEAR NETT LAKE, MN	1275	31.8	21.25	7.84	13.41
8	5130500	STURGEON RIVER NEAR CHISHOLM, MN	1305.7	180	122.18	36.33	85.85
9	5131000	DARK RIVER NEAR CHISHOLM, MN	1316.8	50.6	36.50	11.31	25.18
10	5129115	VERMILION RIVER NR CRANE LAKE, MN	1180	905	613.01	137.51	475.50
11	5129000	VERMILION RIVER BLW VERMILION LK NEAR TOWER, MN	1347.36	483	319.67	68.77	250.91
13	5128500	PIKE RIVER NEAR EMBARRASS, MN	1410.27	115	79.04	26.63	52.41
14	5127205	BURNTSIDE RIVER NEAR ELY, MN		69	59.44	13.89	45.55
15	5127210	ARMSTRONG CREEK NEAR ELY, MN		5.29	4.57	1.84	2.72
16	5127215	LONGSTORFF CREEK NEAR ELY, MN	1360.67	8.84	7.75	3.02	4.73
17	5127207	BJORKMAN'S CREEK NEAR ELY, MN		1.36	1.07	0.51	0.57
18	5127219	SHAGAWA RIVER Trib AT ELY, MN		0.71	0.11	0.06	0.04
19	5126000	DUNKA RIVER NEAR BABBITT, MN	1488.98	53.4	38.73	13.95	24.78
20	5127220	BURGO CREEK NEAR ELY, MN		3.04	3.26	1.42	1.84
21	5126500	BEAR ISLAND RIVER NEAR ELY, MN	1388.86	68.5	42.93	11.62	31.31
22	5127230	SHAGAWA RIVER AT ELY, MN		99	89.58	20.14	69.44
23	5126210	SOUTH KAWISHIWI R ABV WHITE IRON LAKE NR ELY, MN		837	642.53	181.30	461.23
24	5127000	KAWISHIWI RIVER NEAR WINTON, MN		1230	988.03	304.77	683.26
26	5125000	SOUTH KAWISHIWI RIVER NEAR ELY, MN	1430		404.86	101.68	303.17
27	5124990	FILSON CREEK IN SESW SEC. 24 NEAR WINTON, MN		9.66	7.61	2.95	4.67
28	5127500	BASSWOOD RIVER NEAR WINTON, MN	1296.8	1740	1341.27	295.83	1045.44
29	5125500	STONY RIVER NEAR ISABELLA, MN	1632.45	180	125.72	36.65	89.06
30	5124480	KAWISHIWI RIVER NEAR ELY, MN		254	188.35	44.20	144.15
31	5124500	ISABELLA RIVER NEAR ISABELLA, MN	1453.1	341	280.57	104.72	175.85

Table 4: continued

Map #	Base Flow Index (BFI)	Yield (in/y)	Baseflow yield (in/y)	Arntson and Lorenz (1987)	Winterstein et al (2007)
1	0.67	8.45	5.64	40.20	43.9
4	0.66	9.64	6.41		
5	0.63	9.07	5.72		
8	0.70	9.21	6.47	8.10	8.4
9	0.69	9.79	6.76	3.00	3
10	0.78	9.19	7.13		55.4
11	0.78	8.98	7.05	9.9	10
13	0.66	9.33	6.19	1.50	
14	0.77	11.69	8.96	0.2	
15	0.60	11.72	6.99	0.00	
16	0.61	11.91	7.26	0.00	
17	0.53	10.71	5.66		
18	0.40	2.02	0.81		
19	0.64	9.84	6.30	0.1	
20	0.56	14.55	8.21	0.00	
21	0.73	8.51	6.20	0.2	
22	0.78	12.28	9.52	1.7	
23	0.72	10.42	7.48		
24	0.69	10.90	7.54	38.7	42.9
26	0.75			42.8	
27	0.61	10.70	6.56		
28	0.78	10.46	8.16	191	194
29	0.71	9.48	6.72	7.7	
30	0.77	10.07	7.70	12	16.8
31	0.63	11.17	7.00	31.4	

Seven stations have 7Q10 flows determined by each method and all have similar values regardless of the study. That the studies were completed 20 years apart and rely at least in part on data collected before and after 1986, low flow characteristics have not changed substantially with time.

Low flows can be a very small proportion of baseflow, which reflects that only a small portion of the aquifers in the area are contributing to flow during low flows. Most larger watersheds have low flows less than 10% of the baseflow, although the Basswood River nr Winton MN is an exception with the lowest flows being about 19% of baseflow. Low flows from most of the smaller watersheds, if they were estimated at all, were only a few percent or even near zero. The low flows at a gage just below large reservoirs may be unrealistically low if the reservoir operators were not required to maintain minimum releases, as was the case in earlier time periods (Luce and Metcalfe 2014).

Lakes

The watersheds draining to VNP contain many lakes of many different sizes and morphometric characteristics (Table 5). Rainy Lake is by far the largest but it is also mostly within and downstream of VNP, lying on the north boundary with a majority within Ontario; contaminants will not flow through it on a pathway to VNP. Contaminants from the Rainy Headwaters would pass through top seven lakes on Table 5 prior to reaching VNP. Contaminants from the gold deposits in the Vermilion River watershed would pass through the very large Vermilion Lake before reaching VNP.

Table 5: Morphometric characteristics for lakes along the flow paths to VNP and within VNP (Figures 1 and 16). 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. Littoral area is that portion of the lakes less than 15 feet deep. Source: http://www.dnr.state.mn.us/lakefind. Source for volume on Kabetogama, Namakan and Rainy Lake is Kallemeyn et al. (2003).

Lake	Area (ac)	Littoral area (ac)	Max Depth (ft)	Volume (acre-feet)
Birch	1267	754.9	45	28,715
White Iron	3238	1603	47	87,251
Farm	1292	459	56	45,505
Garden	653	239	55	22,509
Fall	2258	1178	32	50,433
Newton	516	358	47	9964
Basswood Lake	22722	7034	111	1,276,419
Vermilion Lake	39272	15006	76	1,580,638
Kabetogama Lake	24034	7440	80	769,000
Rainy Lake	230301	18949	161	7,392,000
Namakan Lake	24065	5026	150	1,121,000
Little Vermilion Lake	1288	231	52	52,997
Iron Lake	3238	1603	47	87,233
Upper Bottle Lake	459	176	55	15,470
Lower Bottle Lake	641	311	110	27,908
Lac La Croix	34750	8500	168	2,859,375

Conceptual Flow Model at Voyageurs National Park

The majority of VNP is covered with water of reservoirs, lakes, and wetlands (Christensen et al 2013) (Figure 15). As noted above, the Rainy Headwaters watershed flows directly into the east end of VNP and the Vermilion River watershed flows into the east end of VNP from the south (Figure 1). These watersheds are the sources of contaminants and host the rivers which would transport contaminants into the park and into Namakan and Rainy Lakes (Figures 1 and 15).

The park is within the Rainy River – Rainy Lake watershed which also drains lands from south of the park into and through the park to Rainy Lake. Kabetogama Lake lies completely within the park. Most of the watershed lying south of VNP drains through Kabetogama Lake which is also connected to Namakan Lake (Figure 15). The water levels in those two lakes are essentially the same due to the connection (see Attachment 2 which shows water levels at Gold Portage (Kabetogama Lake) and Kettle Falls (Namakan Lake).

The operating rules for Kabetogama Lake were changed in 2000 to instill more natural level fluctuations to the reservoir (Christensen et al 2013, 2004). This change resulted in increased high flows at the outlet from the lake since 2000 (Figure 16, upper). All of the recorded daily flows exceeding 900 cfs since 1982, more than two hundred occurrences, have occurred since 2000. During both periods however, there are many zero flows (Figure 16, upper and lower, almost 1500 zero flows) because flow does not commence until the Namakan Reservoir water elevation reaches 1113.5 ft (Kallemeyn et al. 2003). Figure 16 demonstrates the increased variability in the flow resulting from the operating rules, however flow leaving the lake at Kettle Falls and Squirrel Narrows far exceeds that at Gold Portage. For example, at Squirrel Narrows averaged 13,100 cfs. Surface water flowed in an unpredictable pattern, in both directions, between Kabetogama Lake and Namakan Lake during 2008, 2009, and 2011 (Christensen et al. 2013).

VNP contains 26 interior lakes, although all quite small (Figure 15). Only one of the interior lakes exceeds 247 acres in area, and they are quite variable in lake area to drainage area ratio and in average and maximum depths (Kallemeyn et al. 2003). The interior lake basins have no threat from mining and do not serve to route contaminant flows, so their flows and morphometric characteristics will not be discussed further here.

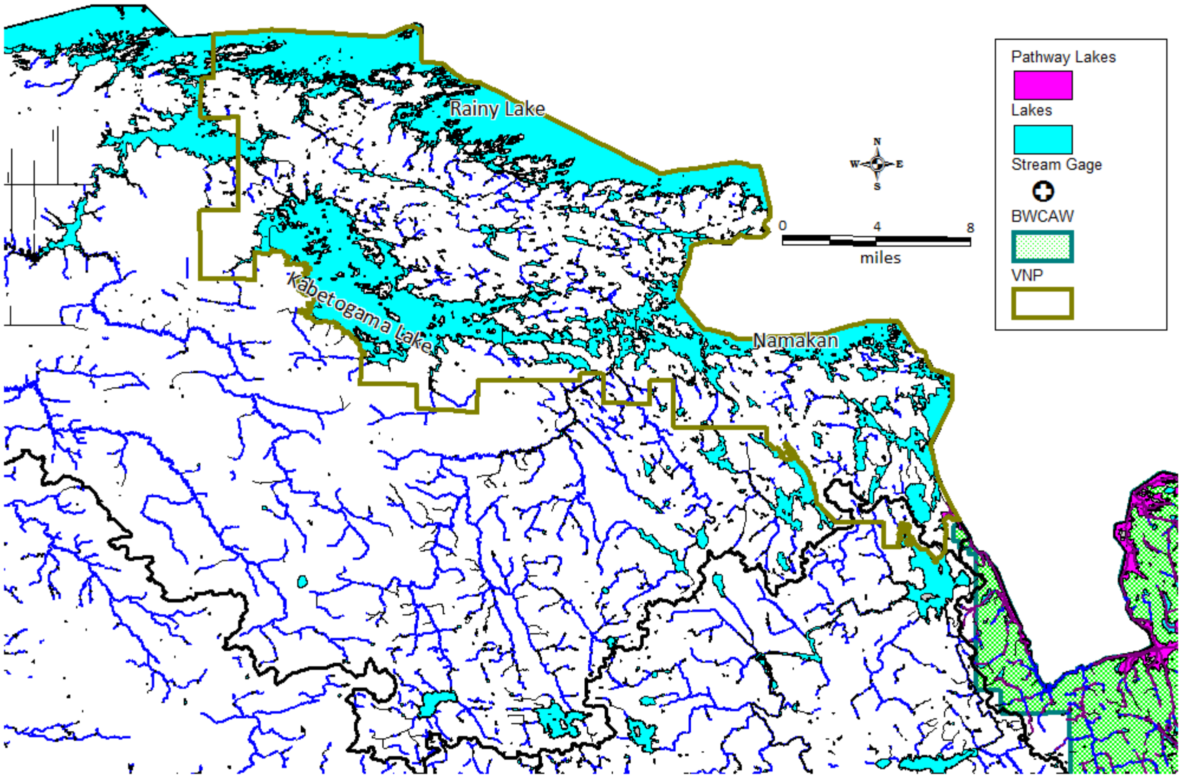

Figure 15: Map showing Voyageurs National Park (VNP) and the three largest lakes within the park. The map also shows the northwest portion of the Boundary Waters Canoe Area Wilderness (BWCAW) and lakes that are on the pathway for contaminants to reach VNP.

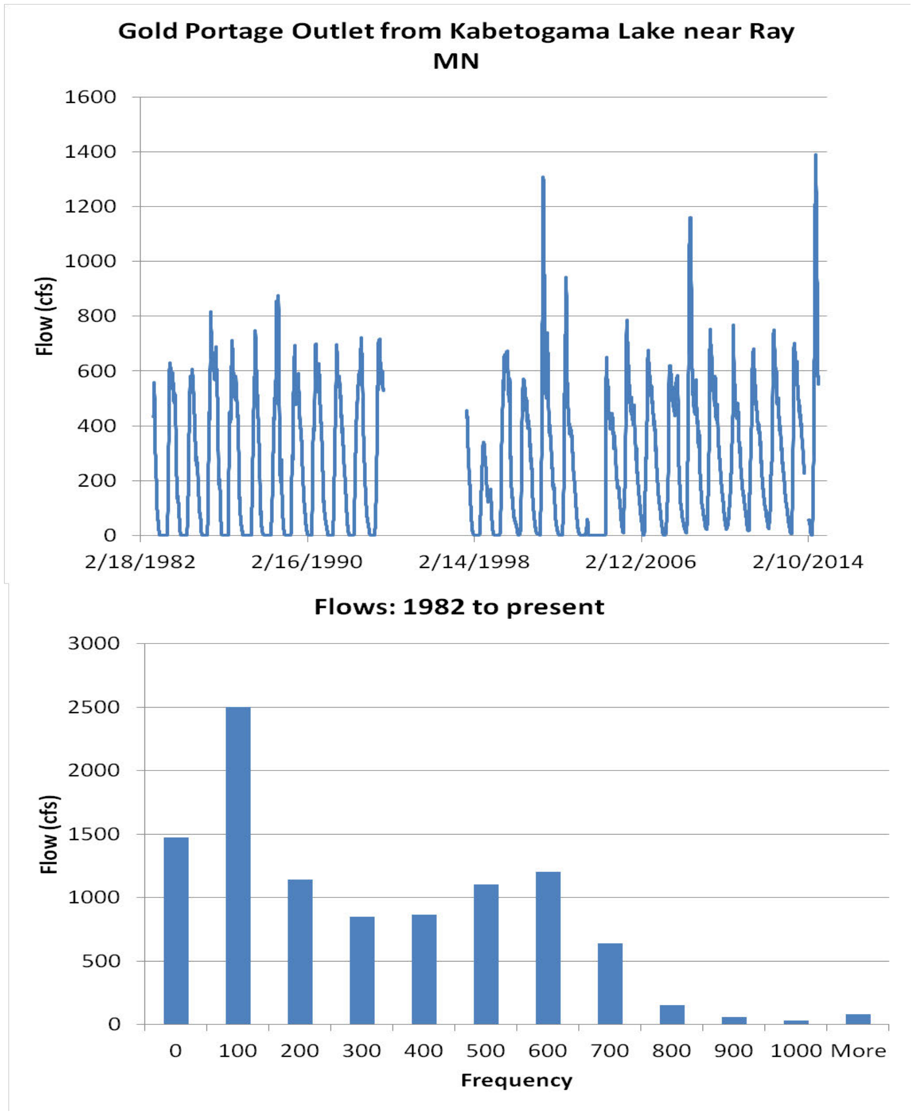

Figure 16: Measured flow (upper) and frequency of measured flow (lower) at the Gold Portage Outlet from Kabetogama Lake near Ray MN, gaging station # 05129290. Data source: http://waterdata.usgs.gov/mn/nwis/sw/

Groundwater Chemistry

Groundwater in shallow sand and gravel aquifers is a magnesium bicarbonate type typical of groundwater that has either a short residence time or has been collected in a recharge zone (Olcott 1992; Siegel and Ericson 1981). In till, the groundwater is either calcium magnesium bicarbonate or calcium magnesium sulfate; the latter occurs near mineralized zones where oxidation may occur (Id.). The till has a smaller particle size and therefore larger surface area to volume ratio which leads to more dissolution and faster chemical reaction times and therefore higher concentrations of various constituents (Id.). For example, “mean values of major dissolved constituents are significantly higher for water from till than from sand and gravel.

Mean and median concentrations of the major ions, specific conductivity, and hardness in water from till are about twice that found in sand and gravel" (Siegel and Ericson, 1981, p 19).

Concentrations of copper, cobalt, and nickel can exceed 100 ug/l in surficial material located above mineralized areas (Id.). This indicates there is an exchange of groundwater between the surficial and bedrock aquifers or an upward flow gradient in these areas. Higher concentrations of copper and nickel extend over an area of 5 to 10 miles from the center of the contact zone (Id.). Iron concentrations are sometimes very high. These trends are also reflected in stream concentrations, as observed in ongoing studies by the USGS described in the next section.

In the bedrock, concentrations are highly variable because they reflect localized concentrations in fracture zones and sometimes increase with depth. Duluth Complex water is either sodium chloride or sodium bicarbonate and Biwabik Iron and Virginia Argillite water is a calcium magnesium bicarbonate type similar to the overlying surficial materials. Metals concentrations are generally lower than in the surficial aquifer near contact zones. This may relate a lack of oxygen for oxidation rather than a lack of the presence of metals at depth. At depth the groundwater may contain substantial concentrations of salt (Olcott 1992).

Surface Water Chemistry

There is little information on basinwide chemistry of surface water in this study area. The USGS has commenced a study on two headwaters watersheds, Filson Creek and Keeley Creek near Birch Lake and near the copper-nickel deposits currently being explored by Twin Metals (Jones et al 2014). Their study will run through 2016 and any results presented were preliminary. Filson Creek has Duluth Complex rocks with copper/nickel mineralization (Jones et al 2014; Siegel 1981) and Keeley Creek has no mineralization (Jones et al 2014) so they provide a comparison between watersheds with various levels of mineralization. In general, the water from Filson Creek is very dilute with pH generally acidic, ranging from 5.0 to 7.2. Jones (presentation of Jones et al 2014) stated that the lower pH was likely the effect of mineralization as well as the effect of bogs in the watershed; the dissolved organic carbon was relatively high and sulfate was low. The concentration of Ni and Cu was generally less than 10 ug/l in both watersheds, although it was slightly higher in Filson Creek. Concentrations increase in a downstream direction reflecting the inflow of groundwater from bedrock. In response to a question, Jones stated that the buffering capacity in the watershed was very low (Id.).

The position of a lake in its watershed controls its chemistry and how well it can absorb acid. In general, headwaters lakes that receive mostly precipitation with little groundwater inflow will be softer or more poorly buffered (Blann and Cornett 2008). Myers (2014a) verified with a numerical groundwater flow model that there was little discharge to headwaters lakes. Lakes in Minnesota Arrowhead and Northern Lakes and Forests regions commonly have alkalinity less than 50 ppm (Blann and Cornett 2008).

Electrical conductivity (EC), a surrogate for total dissolved solids, generally is lower when river flow includes surface runoff. Surface runoff has less salt because it has less contact time with the surficial aquifer during which salts would be dissolved. The lakes in VNP maintain EC less than 100 umhos/cm, however the Ash River which enters VNP from the west has substantially higher EC at 150 to 200 umhos/com (Kallemeyn et al 2003). On the Little Fork River, EC decreases nonlinearly with flow during the time the USGS collected the data concurrently (Figure 17). Minimum EC occurs at around 100 umhos/cm, although a few values at between 1500 and 2000 cfs were as low as 80 umhos/cm. The high EC at baseflow reflects that most flow is groundwater with higher salt content and verifies the assumption that baseflow is groundwater discharge. The scatter at higher values is likely due to the variable amount of surface runoff and groundwater baseflow in the total flow.

The EC – flow relation at the Dunka River nr Dunka MN gage is similar but more variable to that on the Little Fork River (Figure 18). Low EC values at flows as low as 20 cfs suggests that even at lower flows the river is mostly surface runoff, rather than groundwater. Above about 180 cfs, the variability decreases substantially because the flow is predominantly low-salinity runoff. Together, the EC-runoff relations show how salinity depends on the hydrograph.

The salinity entering the Rainy River system from Ontario is also extremely low, with EC in Beaver House Lake, Seine River[4], and Turtle River being 28, 50-55, and 25 uS/cm, respectively (Kallemeyn et al. 2003). Flow from Canada therefore effectively dilutes the already very low salinity in the river system.

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[4] See the discussions elsewhere in this report regarding past and potential future pollution problems in the Seine River**.**

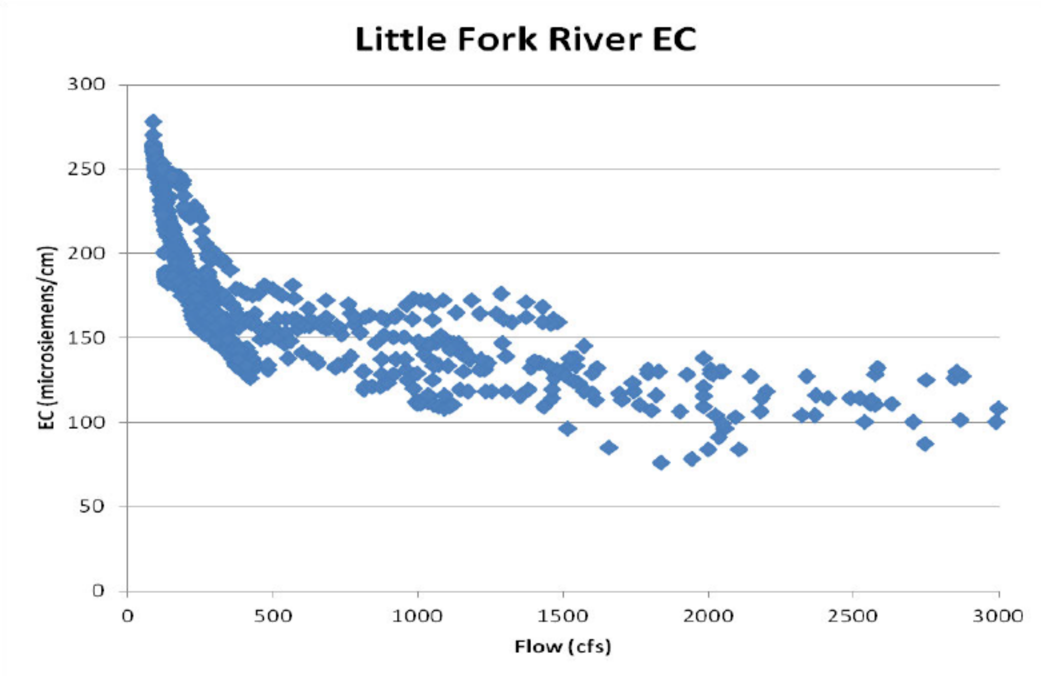

Figure 17: Relation of electrical conductivity with flow at the Little Fork River at Littlefork MN gage (#05131500). Years 1980 through 1983. Data source: http://waterdata.usgs.gov/mn/nwis/sw/

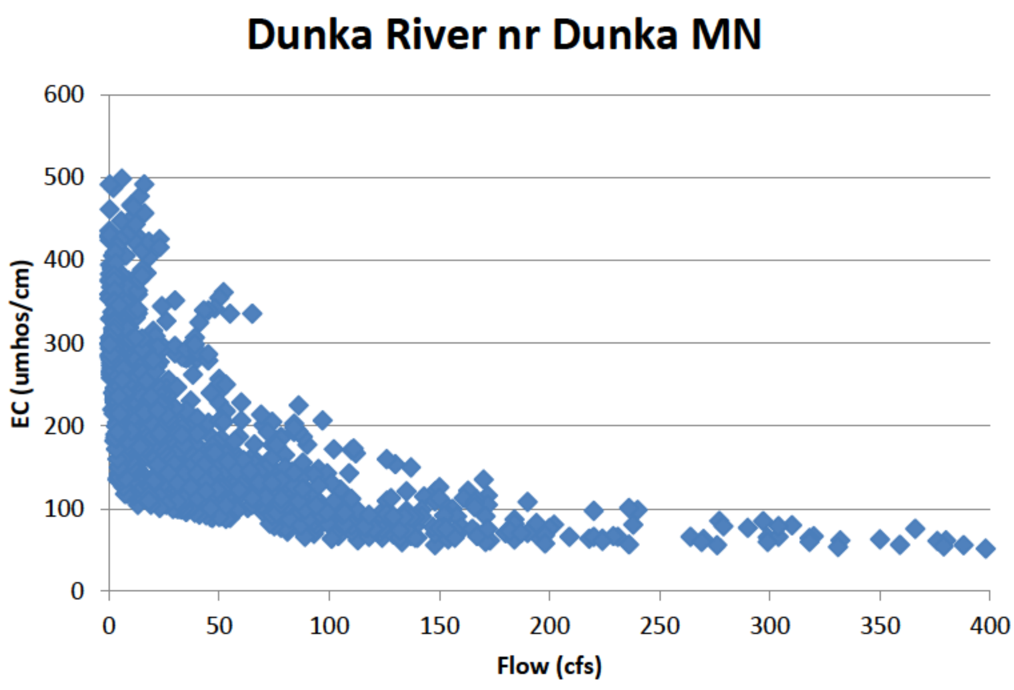

Figure 18: Relation of electrical conductivity to flow at the Dunka River nr Dunka MN gage (#05126000). Years 1975 to 1980. Data source: http://waterdata.usgs.gov/mn/nwis/sw/

The lowest salinity observed in the watershed occurred during sixteen measurement collected in 1976 at the South Kawishiwi River above White Iron Lake near Ely gage (#05126210). The highest observed total dissolved solids concentration was about 35 mg/l and occurred during baseflow when the river would have predominantly been groundwater discharge.

Carbonate is nondetect at the South Kawishiwi River above White Iron Lake which along with there being almost no carbonate rock in the watershed indicates a very low acid buffering capacity. Buffering is the ability of the water to absorb an acid without the acidity increasing. In this river system, the addition of an acid would significantly increase the acidity. Soils throughout the study area had low pH which also reflects an inability to neutralize acid.

Alkalinity in the Rainy Lake and Namakan Lakes in VNP is less than 20 mg/l, or very low (Kallemeyn et al 2003), which also reflects cumulative lack of buffering. Kabetogama Lake has higher alkalinity, up to 40 mg/l (which is still quite low) (Id.), which probably reflects the much higher values from Ash River (75 to >100 mg/l). Kabetogama Lake receives drainage from calcareous drift and Lake Agassiz sediments south and west of the lake whereas the Rainy River drains thin glacial till and bedrock (Id.).

Kallemeyn et al (2003) found that 13 of 19 lakes were moderately sensitive to acid precipitation and that 2 more lakes were extremely sensitive. Only two smaller lakes, Mukooda and O'Leary, were non-sensitive. Acid neutralizing capacity increased moderately in the smaller lakes and sulfate deposition has moderately decreased with time (Id.). In the headwaters, Siegel (1981) found that snowfall contributed the vast majority of sulfate to Filson Creek. Any areas that had been found sensitive to acid precipitation would also be sensitive to AMD.

Mercury contamination is a current issue in all watersheds draining to VNP, based upon the streams and lakes listed as impaired under the current Minnesota Clean Water Act Section 303d impaired waters list (http://www.pca.state.mn.us/index.php/water/water-types-and-programs/minnesotas-impaired-waters-and-tmdls/impaired-waters-list.html, accessed 12/3/13). In the Kawishiwi watershed, with the river, Birch Lake, and many other streams and ponds are listed as impaired for mercury. The impairment is often due to "mercury in fish tissue" rather than a water column measurement. This reflects the tendency for mercury to be bound in sediment, the tendency for methylation to occur due to bacterial activity (Greeson 1973), and the Hg to bioaccumulate up the food chain to the fish (Greeson 1973). Methyl mercury, or CH3Hg, is soluble in water and it can be incorporated into the body tissues of organisms in the aquatic environment where it bioaccumulates (Greeson 1973).

The sources and transport of mercury through streams varies greatly around the nation (Scudder et al. 2009). Basin geology has been shown to be the primary source in some basins, such as the Colorado (Graf 1985), but in northern Minnesota the source is almost totally airborne mercury emissions (Wiener et al. 2006). Although methyl mercury is soluble, total mercury (THg) often moves through the watershed adsorbed to sediment during high flows, especially during the spring (Jenne 1973). This is a very common transport process in areas where the mercury source is mining (Scudder et al. 2009, Miller et al. 1996). Also, mercury moves as total mercury simply because it takes a while to convert to the more soluble methylmercury – this is especially true where there is a significant Hg loading (Randall and Chattopadhyay 2013), such as at mine. Balogh (2010) presented data from Minnesota rivers that show THg peaks with suspended sediment, and flow rate, indicating that fluvial processes are responsible for a large portion of Hg transport.

The lakes within VNP have been responding in a varying fashion to the general decrease in atmospheric mercury (Hg) deposition since 2000 (Brigham et al 2014). Two lakes had decreasing, one lake had increasing concentrations of methylmercury ($MeHg_{(aq)}$) and one lake had no discernible trend. Contrary trends probably related to the amount of overland runoff and dissolved carbon or the amount of $MeHg_{(aq)}$ reaching lakes (Brigham et al 2014). In the long run, Hg in the lakes should continue to decrease due to decreased deposition, but the rate of decrease will vary throughout the systems depending on local conditions. Increased sulfate or H+ ions (acid) in lakes or wetlands can increase the rate of methylation and the concentration of $MeHg_{(aq)}$ in the lakes (Brigham et al. 2014; Greeson 1973).

Metals concentrations in various VNP lakes exceed standards at least occasionally (Kallemeyn et al 2003). There are few measurements, but in the larger lakes that drain the study area watershed, the Rainy Lake and Namakan Lake, cadmium and lead exceeded standards during the only observations taken (Id.). Nickel, copper, and zinc also exceeded standards occasionally (Id.). In the Lake of the Woods, the sediments contain large arsenic concentrations especially in bays that receive inflow of waters draining historic gold mining areas (Clark and Sellers 2014). These lakes apparently reflect the cumulative water quality of the watersheds upstream of them, meaning they are a repository for metals from all of the natural and anthropogenic sources in the watershed.

Nutrient loading becomes significant moving downstream through the watershed, with more critical conditions occurring downstream of VNP. Phosphorus loads during the 1970s and 80s were very high but regulations causing decreased discharges from the International Falls area had decreased those loads about fivefold (Clark and Sellers 2014). Even so, the Rainy River watershed currently provides about half of the phosphorus load to the Lake of the Woods (Id.).

Surface water sediment transport is generally low in the Kawishiwi River, at about 5 tons/year/mi^2; this is less than half that found in the Partridge River and Embarrass River basins (Siegel and Ericson 1981). Presumably the peak load occurs during spring runoff. There was also no data related to contaminant loads on the sediment.

Upstream sediment, but from the Ontario side, has been a problem to VNP in the past. Sediment removal from the original Steep Rock Lake to access iron ore deposits caused a massive release of about 4 million cubic meters of colloidal silt and clay (Conly et al. 2010) causing Rainy Lake to become brown and seriously harming aquatic life and fishing (Sowa et al. 2001). This is an example of large-scale fine sediment transport through a river system which had essentially no lakes between the source and Rainy Lake.

Between 1967 and 1977, water temperature at the Kawishiwi River near Ely gage peaked at near 20°C during July and August based on a 1967 to 1977 average (Siegel and Ericson 1981). Interestingly, the air temperature averaged several degrees lower than the water temperature. The significant wetland area probably causes the higher summer water temperature due to higher insolation over the large surface water area.

The temperatures of the epilimnion of the larger lakes at VNP remained relatively constant up through the late 1990s, but showed a definite increase by the early 2000 (Kallemeyn et al 2003). An upward trend in degree days, measured with a 10^{o} C base, is more apparent. With climate change, that is a trend that could continue. AMD has been shown to potentially increase with temperature due to global warming (Street 2003) and it is possible that increased temperature could hasten the acid/base reactions occurring in the river systems downstream from AMD sources, such as at VNP.

Climate Change

A general rule of thumb regarding climate change is that wet areas will become wetter and dry areas will become drier. Northern Minnesota is projected to have a small increase in annual runoff due to climate change (IPCC 2007). Increased precipitation and temperature can have variable effects depending on the relative and seasonal changes, with increased ET decreasing runoff at some parts of the year while increased precipitation can increase runoff at other times.

Minnesota streamflow has a linear relationship with non-winter precipitation and summer temperatures (Nichols and Verry 2001). Historic stream flow data shows that summertime rainfall runoff peaks have increased as have summertime baseflows (Novotny and Stefan 2007). During 2012, rainfall and flooding estimated at a return interval in excess of 500 years, wreaked heavy damages in the Duluth area (Czuba et al 2012). This is primarily due to increased precipitation, which manifests as heavier individual events rather than more storm events. More recently in 2014, many river gages the Lake of the Woods watershed have recorded their highest flows on record (http://mn.water.usgs.gov/), this was rain on spring snowmelt. Attachments 2 through 4 provide some hydrographs of 2014 flows.

The flow record at the gage at the Little Fork River at Littlefork MN (Table 1), a river which enters the Rainy River downstream of VNP, has a sufficiently long record (1912-16, 1929-2013) to consider long-term[5] trends in annual flows and possibly the effect of climate change. The annual flows show a variation prior to 1970 that appears cyclic (Figure 19), with 10-year moving average value varying from about 700 to 1400 cfs. After 1970, there is a slight downward trend, which is most obvious in the 10-year moving average. However, the slope for the 1929 through 2013 period is a statistically insignificant (p=0.28) 1.8 cfs/year. The flows commence with the gage's lowest flows on record which causes the positive slope. At least for the Little Fork watershed, the effects of climate change to date on annual flows are inconclusive.

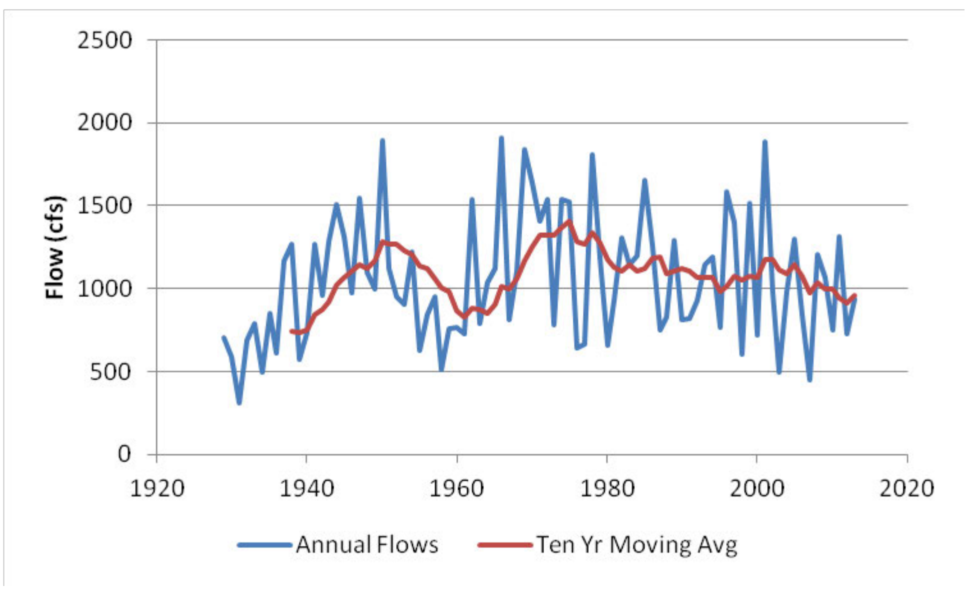

Figure 19: Annual and ten-year moving average flow from 1929 for the Little Fork River at Littlefork MN gage (#05131500). Data source: http://waterdata.usgs.gov/mn/nwis/sw/

The Interagency Climate Adaptation Team (2013) has made several observations of changes already observed in Minnesota and upper Midwest climate and has also made several future projections based on global climate modeling. Since 1895, the average temperature increase in the Midwest has been 1.5 degrees F. The change is most apparent in northern regions, most specifically the northern half of Minnesota. By mid-century, the temperature in northern Minnesota is projected to increase by up to 5°F. Average precipitation across northern

[5] With respect to streamflow, long-term is on the order of several decades. In this case, long-term is near a century which allows consideration of changes that could be due to a changing climate.

Minnesota has increased up to 15%, although over the Rainy Headwaters it has increased about 5%. The percent change in very heavy precipitation[6] is 45%. The projections for mid-century are that annual precipitation will increase from 1.4 to 1.6 inches, there will be at least one more day with heavy precipitation per year, the wettest annual 5-day total precipitation will increase by up to 0.4 inches, and number of dry days will decrease by up to six days. These observations and projected trends all point to a wetter future with more heavy rainfall which of course means more large floods (Interagency Climate Adaptation Team 2013).

Increased precipitation in general would increase the moisture accessing the unsaturated zone, including the unsaturated zone in above-ground waste or tailings impoundments. The additional precipitation could increase recharge if it causes higher flows during traditional baseflow periods or adds rainfall runoff to low snowmelt flows following dry winters. In either instance, climate change should make mine impoundments more susceptible to failing and should increase seepage through mine waste facilities. Without detailed knowledge of a specific facility, it is not possible to estimate how much additional seepage could occur, but it is clear that there would be some increase. Large floods could cause the water level or saturated tails to rapidly increase beyond design capacity which could cause rapid failures; as for seepage it is not possible to assess an actual risk without knowing the location and design of the facilities.

Potential Mine Threats

Myers (2013b) found seven potential threats caused by Twin Metals Mining to the Boundary Waters Canoe Area Wilderness. They are risks to water quantity from mine dewatering and production water development and risks to water quality from the development and seepage of acid mine drainage (AMD), seepage of tailings water, tailings impoundment failures, the runoff of sediment from the site due to stormwater, and wetlands disturbance. Some of these are pertinent to VNP and there are additional factors which have been uncovered as part of this work that could affect both areas.

First, the water quantity factors are not a substantial concern because of the huge intervening area between the deposits in the Rainy Headwaters and the Vermilion Rivers watershed. Mine dewatering would remove water deep from the bedrock and the effects, even during dry periods, would be limited to local areas. Discharge of mine dewatering water could contain very high levels of salinity, however. Water used for ore processing also would be a very small proportion of the flow moving through VNP. Mine development is unlikely to affect the flows through VNP in a noticeable fashion.

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[6] A very heavy precipitation event is the heaviest 1% of all daily events.

Second, sedimentation would also not be a factor as far downstream as VNP. This is because the large volume of lakes lying between the sources and the park would retain significant sediment. Wetlands loss at the scale of the potential mines in a watershed as large as that draining to Rainy Lake would not be a problem, unless the loss of a wetland removed a potential barrier to contaminants reaching the rivers.

The seepage of either AMD or tailings water are long-term risks in that once the seepage commences it may be years before it is even detected, much less remediated. A tailings dam or other catastrophic failure generally results in a large load of contaminants reaching a water body over a period of weeks at most, thereby being a short-term risk.

Pathways

There are two primary mine deposits which could be future contaminant source – the Cu-Ni deposits in the Rainy Headwaters near Birch Lake and the gold deposits above Vermilion Lake in the Vermilion River watershed. Once a seep reaches the surface it will pass through lakes and rivers to reach VNP, as shown in Figures 1, 2 and 15; the lakes are described in Table 5.

Lakes may control most contamination reaching VNP. Most simple analysis methods assume that contaminants from a spill fully mix in a lake, although that assumption may grossly overstate the dilution capability if the contaminants follow a preferred path from their entry point to the lake discharge. Most of the lakes have large surface area but are not relatively that deep so that the river flows may still pass through the reservoir as a slug with less mixing than would occur in deeper lakes with less surface areas. Tributary inflows may further cause the contaminant to flow along a primary thalweg while at the same time diluting the contaminant slug as it moves through the lake.

Contaminants from the Rainy Headwaters would pass through first seven lakes on Table 5 prior to reaching VNP and each would disperse and dilute the flow. Myers (2014b) found that a spill entering Birch Lake would devastate that lake but the concentrations would decrease by five orders of magnitude prior to reaching Garden Lake. It would pass through the much larger Basswood Lake before reaching VNP. Inflow from the Canadian portion of the drainage, including from the Maligne River into the Rainy River prior to entering VNP and Seine River into the Rainy Lake, further dilute the flows in the mainstem portion of VNP. The Seine River average flow ranges from 1000 to 2000 cfs (Attachment 4).

Contaminants from the gold deposits in the Vermilion River watershed have a more straightforward pathway to VNP, but would pass through the very large Vermilion Lake. Vermilion Lake has a large littoral area, compared to its total area, and therefore contaminants would be likely to follow a flowpath from inflow to outflow without thoroughly mixing, so that lake could be a less effective barrier to contaminants than its size might otherwise suggest.

More detailed modeling of Vermilion Lake would be necessary to estimate the effects of a spill passing through that lake. If the lake does not substantially mix, long-term leaks or seepage would be much more likely to pass through the lake and reach VNP.

Acid Mine Drainage

AMD is the generation of acid due to mine wastes being exposed to air and water. Specifically, it is the oxidation of sulfide minerals that produces the acid which means that a metal-sulfide complex reacts with water and oxygen to release hydrogen atoms, which are acid. Commonly in northern Minnesota, the mineral is pyrite, which is FeS_2 and the reaction is:

$$\boldsymbol{2FeS_2(s) + 2H_2O + 7O_2 \rightarrow 4H^+ + 4SO_4^{2+} + 2Fe^{2+}}$$

This reaction generates large amounts of acid, as exemplified by the $4H^+$ term, which means that for two molecules of pyrite, four protons are generated. There are several more reaction steps that are outlined in many books of aquatic chemistry and in EPA (1994). The yellow, orange or red deposit so often found on stream bottoms in streams affected by AMD is $Fe(OH)_3$, or yellow boy (EPA 1994).

AMD can be limited by the presence of neutralizing minerals such as calcite or dolomite. The H^+ is consumed ultimately by combining with OH^- to form water. The most serious AMD problems occur whether these minerals are limited. Limestone is sometimes used as an amendment in waste that is considered likely to generate AMD. Other limiting factors can include clay, on which the H^+ can bind, or gypsum precipitation.

AMD production rates also depend on particle sizes. The most optimum conditions will combine particle sizes that are small enough to have a large area to volume ratio but not so small as to limit the flow of air or water through them. Large rocks generate little AMD because the air and water can access only very small volume of the mineral. Very small particles, such as silt, generate little AMD because the pores are so small that water and air flow through them very slowly. Thus, rocks crushed in a blend of gravel and sand sizes leads to the best AMD formation.

Similar considerations apply to acid neutralizing material. Rock piles with large amounts of dolomite will still generate lots of acid if the dolomite is in large sizes while the pyrite is smaller and accessible to air and water. However, there can be too much water. Saturated rock will prevent air from reaching the rock faces. Submergence in a pit lake is one way that mining companies prevent AMD. Rock piles, such as waste rock, that have wetting and drying cycles due to storm infiltration, can generate substantial long-term AMD. AMD from tailings impoundments may be limited if the tails are saturated, but once they dry out, usually after mine closure (or abandonment), water flowing through them can generate AMD. Tails however are often finer-grained so the rate of moisture flow and therefore AMD production may be lessened. Rock around both open pits and underground mines become desaturated during mining so that air can enter and oxidation occurs; as the water levels recover when dewatering ceases there is often a slug of AMD.

AMD is caused almost exclusively by materials already on the mine site. Acid generation occurs prior to mining at a much slower rate than during mining because of the particle size discussion above. In-situ rock has water flow only through existing fractures, thus most of the volume is not accessed by sufficient water and air to generate acid. Mining removes, crushes, and piles that rock so that the surface area of rock that can be accessed by water increases manyfold. It is mining that causes the acid formation because it is mining that removes and crushes the rock.

The largest problem with AMD is not usually the acid itself, but the metals that dissolve in the acid. EPA (1994) lists the following metals and metalloids as being dissolved in AMD from various mines: copper, iron, manganese, lead, arsenic, cadmium, zinc, c obalt, nickel, silver, and sulfate. The last on the list is not a metal but can be very critical in Minnesota because of its effect on wild rice. Selenium and mercury may also be associated with AMD, but the relationships are more complicated. It is these elements that affect the aquatic life most negatively.

Waste from the deposits in the Rainy Headwaters is likely to generate acid because it would meet the requirements just discussed if the operator does not take appropriate and effective measures to prevent AMD. The volume percent of sulfide reported for the Spruce Road deposit is several times that found to produce significant acid mine drainage in Duluth Complex waste (Lapako 1988), so the potential for AMD at these sites must be considered high. The streams and soils between the sources and VNP are poorly buffered meaning that AMD and associated metals would not be chemically attenuated. An AMD seep into waterways reaching VNP would be very difficult to contain or remediate. Lakes in VNP already have metals concentrations that exceed standards. Therefore, any addition of metals to the stream above VNP would be considered a degradation and make it more difficult to bring the lakes' metals concentrations into compliance.

The Dunka Mine in the Kawishiwi watershed and the Soudan Mine in the Vermilion Lake watershed have discharged AMD and could portend future problems for the area. The EPA used the Dunka Mine as an example in its AMD manual because of the amount of pollution it causes (EPA 1994) and AMD from it has been considered important even in the context of the entire Lake of the Woods watershed (Clark and Sellers 2014). The Dunka mine was developed in the Duluth Complex formation and has seeps with pH as low as 5.0 and copper and nickel concentrations at 1.7 and 40 mg/l (ITRC 2010; EPA 1994). The copper maximum level contaminant goal is 1.7 mg/l, which means this water could have toxic effects on people drinking it. The nickel concentration exceeds the former maximum contaminant level by 400 times. This low-quality seepage resulted from a deposit with relatively low sulfide content, averaging around 0.6 ppm in the bulk rock at the site (EPA 1994). The seeps developed over a dozen years, starting in the 1970s (Id.) and new seeps turned acid in 1989 (ITRC 2010). The seepage, estimated at 500,000,000 gallons/year, discharges to a stream which flows into Bob Bay, a part of Birch Lake (EPA 1994, p 40), and increases the concentrations of copper, nickel, cobalt, and zinc in the bay to levels higher than the regional average (Id.). Metals concentrations in sediments are elevated, but less than 40% of the nickel load was removed through natural lake processes (Id.). This indicates that Birch Lake was insufficient to naturally "treat" the AMD seepage from the Dunka Mine.

The underground Soudan Mine[7] closed in 1962 (Eger 2009, 2007), but has been an AMD problem since then (http://www.itrcweb.org/miningwaste-guidance/cs61_soudan.htm). About 60 gpm discharge with high levels of cobalt, copper, and mercury from the shaft (Eger 2007) One specific area causes the problem with up to 10 gpm discharging with acid pH near 4.0 (Eger 2007). Mercury is a large problem (Eger 2009) especially since the watershed draining to VNP is stressed due to mercury (Kallemeyn et al. 2003).

Waste from proposed mining from any of the underground deposits in the Rainy Headwaters could generate seepage just as degraded as from the Dunka Mine, since they are hosted in the same formation and have as much or more sulfide. Based on metals expected from sulfide ore at the Polymet Mine (Polymet 2013a), arsenic, copper, nickel, lead, zinc, and possibly mercury could be included in seepage. The low buffering capacity of the rivers could allow contamination to be transported a long distance downstream, including to VNP (Myers 2014b). Seepage may require decades to transport from the underground sources to the river, but once it reaches the river there would be little chance of preventing it from reaching VNP.

AMD seepage over a long time period could be a more difficult problem once started, as well. This is because the general baseflow through the system would have a higher contaminant concentration. After a long period, it would approach steady state. This is a particular problem with waste sources deep underground. Once mining ceases and groundwater levels recover, the underground mines become part of the groundwater system. AMD could generate in the mine tunnel walls and rock fractures that had been dewatered. The discharge points for bedrock groundwater have not been determined, so AMD discharge could occur at a distance from the mine. Because the porosity of the bedrock is low but fracture controlled, groundwater and contaminants would flow through the bedrock many times faster than the

[7] The mine was originally an open pit, but converted to underground for safety reasons, eventually reaching a depth of 2400 feet (Eger 2009).

estimated groundwater flow rate (because actual water molecules move through the pores whereas the flow rate is determined for the entire cross-section). Areas with bedrock average flow rates equal to 10 feet per year could have contaminant transport rates (through the actual fractures) greater than 1000 feet year, which indicates that a discharge point a few miles away could be affected within a couple of decades. If the AMD is generated near the ground surface, it could discharge quickly to nearby streams. If the source continues for a long time period, it would reach through the river systems to the VNP.

AMD would likely exacerbate an existing problem in the VNP – methyl mercury contamination. Decrease in pH could increase the rate of methylation and increase the concentration in the lakes.

An additional transport mechanism that occasionally causes large load to move along the river is movement on sediments. Metals often adsorb to sediments which can move in large slugs during floods. Additionally, sulfate is often released from mine sites, and wild rice is particularly susceptible to high sulfate concentrations.

Discharge of Pit Lake or Dewatering Water

This study's focus has been threats on the American side of the Rainy Lake watershed with inflows from Canada primarily for their dilution value. The Seine River however also flows through and near the pit lake system at the Steep Rock iron mines. During construction these mines caused significant sediment problems for the Rainy Lake, but their largest threat may occur when the Hogarth and Caland Pits overflow sometime between 2030 and 2060 (Sowa et al. 2010). The overflowing water will contain sulfate concentrations up to 1500 mg/l, a level shown to be chronically toxic in the pit lakes (Sowa et al. 2010). This threat will manifest unless a diversion plan is implemented, but remediating the water will be a high volume treatment problem that, if it fails, would threaten VNP.

The deposits in the Rainy Headwaters are primarily located deep in the bedrock. These deposits would have to be dewatered if they are to be mined. Because of the low conductivity at depth, the amount of dewatering should not be that high, but it could be very salty. No studies have discussed the expected deep bedrock water quality other than to suggest that it could qualify as brine. If Minnesota allows this water to be discharged into the Kawishiwi River system, it could cause increases in total dissolved solids all through the river system to VNP. The problem could be long lasting because of the long time needed to mine the deposits at depth.

The existing Northshore Mine may also be a long-term threat to VNP. The environmental assessment for its current expansion states that, when the mine closes, the pit will fill with water until it overflows into a tributary of the Dunka River. The EA does not analyze the expected pit lake water quality, but it will likely be poorer than the existing groundwater that is being discharged to the Dunka River because of oxidation that will occur in the pit walls thereby contaminating the pit lake water (Castendyk and Eary 2009).

Tailings Impoundments Leaks and Failures

Tailings impoundments could generate AMD or leak other process chemicals. Although they are designed not to leak, liner failures are common (Kuipers et al. 2006). If the leakage is either not detected or not containable, it could reach the surface water system and flow toward VNP. Streams draining toward VNP have high water quality and would be affected by small amounts of contamination for a long time. Once it starts, a leaky tailings impoundment is very difficult to remediate. The leak at the existing tailings near the proposed Polymet Mine (Polymet 2013b) has been contaminating groundwater for a long time. Pumpback wells have been used to contain a nitrate plume at the tailings impoundment near Jerritt Canyon mine in Nevada since the 1980s[8].

The best example of potential contaminants from potential mines in the Rainy Headwaters or Vermilion Lake watershed is the existing contaminants at the Polymet Mine, because of similarities in geology and ore bodies. The following metals are predicted to be present in the tails: arsenic, boron, calcium, cobalt, copper, iron, magnesium, manganese, mercury, molybdenum, nickel, potassium, and sodium (Polymet 2013b). Other parameters of concern are alkalinity, chloride, fluoride, sulfate and total dissolved solids. In sufficient concentrations, any of these could be a problem. Additional mercury reaching the VNP would add to the problems discussed above; in combination with AMD or sulfate loading, the methylmercury problem could be substantially increased.

Immense water resources damage could be caused by a tailings failure. As written by Caldwell and Charlebois (2010): "The thesis of this paper is that tailings impoundments fail as a result of a string of incidents, each of which is trivial and within the bounds of normal events, but which, taken together, constitute an event so unusual that it lies outside of the bound of normal occurrence and experience." Rico et al (2008b) documented over 146 tailings impoundment failures (over an unspecified time period), with the majority occurring in the United States. The vast majority were of dams less than 45 m high. Thirty-six of the failures were due to high rainfall (Rico et al 2008a and b), although as noted by Caldwell and Charlebois (2010), there were probably smaller items that failed leading to the ultimate failure. The run-out distance for tailings dam failures has been as high as 100 km, with the maximum distance occurring when the failure is into a river system (Rico et al. 2008a).

[8] The author has personal experience examining the contamination at this mine.

The recent failure of the Mt Polley Mine in British Columbia apparently resulted from a failure to manage the tailings impoundment properly. Simply, it appears the mining company stored too much saturated tails waste above the dam and it failed. The failure released more than 10 million cubic meters (350 million cubic feet) of water and 4.5 million cubic meters (150 million cubic feet) of sand into downstream Polley and Quesnel Lake, according to estimates from British Columbia's Ministry of Environment. That is enough water to fill 4,000 Olympic-sized pools (http://earthobservatory.nasa.gov/IOTD/view.php?id=84202, accessed 8/28/14). Approximately 2600 tonnes of mercury had been stored in the impoundment since 2009, so the potential contamination is quite large.

The effect of a large spill in a watershed that contains many large lakes is complicated[9]. Water leaving Quesnel Lake, downstream of the Mt Polley spill discussed above, was relatively clean for several weeks after the spill. Much sediment was trapped in the lake. It is likely however that the sediment will be a source of heavy metals to the waters flows through the lake for decades. Myers (2014b) found that a spill into the lake system below the deposits near Birch Lake would dissipate but still be measurable reaching the BWCAW. Over time, metals would continue flowing to VNP. A spill in the Vermilion Watershed, if mines are ever developed there, may be more critical. The pathway is Vermilion Lake and the river before reaching VNP. At more than 1.5 million acre-feet (Table 5), Vermilion Lake has plenty of buffering and dilution capacity. However, if the waste short circuits through the lake rather than mixing, the effects could be much worse. The transport of sediment from Steep Rock lake to Rainy Lake (Conly et al. 2010; Sowa et al. 2001) discussed above is an example of the kind of transport which could occur if a large-enough release were to hit the river system leading into VNP.

The recent occurrence of extreme flooding in northern Minnesota (Czuba et al 2012) accentuates the concerns raised by the potential for large flooding on tailings impoundments. Global warming and the consequent increase in extreme events will affect mines in many ways, but with increasing flood runoff (IPCC 2007) and climate change as discussed above, the proximity of any potential tailings impoundment to the river system, the fact that a tailings impoundment must not fail forever, and the connectivity of surface waters in the watershed, development of tailings impoundments presents a large risk to VNP.

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[9] The description herein is from an email prepared by Ramsey Hart of MiningWatch Canada, so is effectively a personal communication.

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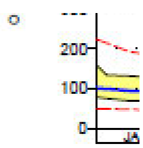
Attachment 1: Map of the Winnipeg River Drainage Basin, from *www.lwcb.ca/*



Attachment 2: Flows and reservoir levels for Namakan Lake, source *www.lwcb.ca/*

Attachment 3: Flows and reservoir levels for Rainy Lake, source *www.lwcb.ca/*

Attachment 4: Flows for various rivers and the Raft Lake water level, source *www.lwcb.ca/*