Wellhead Protection Plan

Part I

Wellhead Protection Area Delineation
Drinking Water Supply Management Area Delineation
Well and Aquifer Vulnerability Assessment

For

The City of Coleraine

February 12, 2007

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Minnesota Department of Health

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Glossary of Terms

Assimilative Capacity. The ability of the saturated or unsaturated zones of a formation to attenuate the concentrations of contaminants to acceptable levels before they reach the well. (U.S. EPA, June 1987). An assimilative capacity boundary can be any combination of 1) surface and subsurface geologic materials, and 2) groundwater flow paths that prevent contaminants from reaching a public water supply well at levels that present a risk to human health.

Capture Zone. The subsurface area surrounding a well or well field that supplies a public water supply system through which water is likely to move toward and reach the well. The capture zone and the surface water contribution area, when needed, comprise the wellhead protection area (WHPA).

Conjunctive Delineation. A WHPA that is defined by two components, consisting of 1) the capture zone for a well that is based on generating flow pathlines within the subsurface area(s) of contribution, and 2) a surface area that may contribute recharge to the capture zone.

Drinking Water Supply Management Area (DWSMA). The area delineated using identifiable land marks, defined in this report, that reflects the scientifically calculated wellhead protection area boundaries as closely as possible (Minnesota Rules 4720.5100, subpart 13).

Source Water Protection Area (SWPA). A source water assessment includes a description of 1) the area to be protected, 2) potential contamination sources that may impact the source of drinking water, and 3) the susceptibility of the public water supply to potential contamination sources. For the purposes of this delineation report, the SWPA and the DWSMA are the same.

Wellhead Protection Area (WHPA). The surface and subsurface area surrounding a well or well field that supplies a public water system, through which contaminants are likely to move toward and reach the well or well field (Minnesota Statutes, Part 103I.005, subdivision 24).

Introduction

This report documents the technical information necessary to prepare Part I of a wellhead protection plan that will help ensure an adequate and safe drinking water supply for the city of Coleraine, public water supply identification number 1310006. It documents the delineation of the wellhead protection area (WHPA), the drinking water supply management area (DWSMA), and the vulnerability assessments for the public water supply wells and DWSMA. An updated source water assessment with a new protection area (SWPA) also is included. Definitions explaining the differences between the terms WHPA, DWSMA, and SWPA are provided in the "Glossary of Terms" at the beginning of this report.

The delineation was performed in accordance with Minnesota Rules 4720.5100-4720.5590 for preparing and implementing wellhead protection plans for public water supply wells. The Minnesota Department of Health (MDH) administers these rules and the results described in this report reflect those of the MDH to 1) identify the capture zones for delineation of the WHPA, and 2) prepare well and DWSMA vulnerability assessments. Also, this report presents the findings of the public water supplier to identify the boundaries of the DWSMA.

The public water supplier operates two wells, termed Wells No. 1 and 4 (Unique Nos. 241430 and 110457). The wells are located in Section 32 of Township 56 North, Range 24 West in Itasca County. Appendix I contains Table 1 that presents some of the key information about these wells that affects their vulnerability assessments.

The WHPA for the Coleraine city wells was determined using a computer model to simulate groundwater flow towards it. The DWSMA boundaries were determined using U.S. Public Land Survey boundaries, city streets, and roads. Figure 1 shows the boundaries for the WHPA and the DWSMA.

Source Water Assessment

The MDH is required under Section 1453 of the 1996 Amendments to the federal Safe Drinking Water Act to prepare source water assessments for all public water supply systems. Congress intends that assessments should be used to educate public water suppliers and the customers they serve about the source of their drinking water and potential contaminants that may affect people's health. The following Source Water Assessment for the public water supplier contains the information specified in Minnesota's source water assessment program description.

Source Water Assessment for
The City of Coleraine

Public Water Supplier ID Number: 1310006

Water Supplier Contact:
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Status of the Source Water Protection Plan –

The Minnesota Department of Health has approved the 1) delineation of the wellhead protection area, 2) delineation of the drinking water supply management area, and 3) assessments of well and aquifer vulnerability. The public water supplier is proceeding with the development of the remainder of the wellhead protection plan.

Source Water Protection Area - See Figure 1.

Description of the Source Water - The water supply for the city of Coleraine comes from a sand and gravel aquifer that exhibits confined hydraulic conditions at the city wells. The aquifer is about 50 feet thick and is covered by approximately 70 feet of clay rich till. Generally, groundwater moves in a southerly direction in the wellhead protection area, although the flow directions are variable and influenced by the water level within the Canisteo Mine Pit.

Table 2
Wells Used by the Public Water Supplier

Well No.	Unique No.	Well Use	Aquifer Type	Well Depth (ft)	Well Sensitivity	Aquifer Sensitivity
1	241430	Primary	Sand and Gravel	121	High	Moderate
4	110457	Primary	Sand and Gravel	120	Low	Moderate

Aquifer Sensitivity - The sensitivity of the aquifer used by the public water supplier is variable throughout the drinking water supply management area. It ranges from highly sensitive where the aquifer is exposed at the land surface, such as around the Canisteo Mine Pit and some areas around Trout Lake, to moderately sensitive where covered by till. Existing data suggest that the overlying till is leaky. Tritium samples taken from Wells 1 and 4 (241430 and 110457) on February 9, 2004, showed 16.3 and 17.6 tritium units, indicating that most of the water pumped by the wells entered the ground within the last 50 years.

Well Construction Assessment - Existing construction information for Well 1 (241430) suggests that grout was not drawn into the annular space of the well casing as it was driven when the well was constructed in 1918. Proper grouting is currently required by the State Well Code. This factor could provide a pathway for near-surface contamination to enter the source water. As a result, the sensitivity of this well is considered to be high. However, it is possible that the limited annular space created during cable tool well construction may have become sealed due to swelling of clay minerals present in the surficial till.

Construction information for Well 4 (110457) shows that this well was constructed in accordance with current standards. As a result, the sensitivity of this well based on its construction is low.

Susceptibility of the Source Water to Contamination - The source water used by the public water supplier is considered susceptible to potential sources of contamination principally because of the geologic setting, although the construction of Well 1 (241430) may also provide an avenue for contamination. The land uses within the drinking water supply management area may potentially contribute contaminants that may present a health concern to the users of the public water supply.

Contaminants of Concern - Routine testing of water from the Coleraine city wells has shown that they have generally been free from contaminants and meet all potability standards of the federal Safe Drinking Water Act. However, the wells are considered susceptible to contamination from a variety of sources. These include contaminants that may persist in groundwater for long periods of time and which are not susceptible to retardation or removal by movement through fine-grained sediment.

Delineation of the Wellhead Protection Area

Physical Setting

The City of Coleraine is located in Itasca County near the western end of the Mesabi Iron Range. The town is surrounded by features associated with a nearly 100-year old history of iron mining, which ceased in this area in the mid-1980s (Jones, 2002). These features include tailings ponds, waste rock stockpiles, and, most prominently, the Canisteo Mine Pit lake (Figure 2). The Canisteo Mine Pit lake is situated approximately 3,200 feet northwest of the city wells. It has an average depth of approximately 100 feet, but is up to 300 feet in depth locally. It is nearly five miles in length, averages approximately 0.5 miles in width, and was created when water levels rose following the cessation of mining at a series of closely-spaced, abandoned natural ore mine pits.

Assessment of Data Elements

This section documents how the data elements specified under Minnesota Rules 4720.5400 were used to describe the physical environment.

<u>Soils</u>: The aquifer used by the city of Coleraine is buried beneath a layer of till, except where exposed locally along the margins of the Canisteo Mine Pit lake. As a result, soils maps are not useful for delineating its boundaries. However, the Itasca County soils survey (Nyberg, 1987) was useful for assessing the vulnerability of the aquifer.

<u>Precipitation</u>: The mean annual precipitation for the area is 27.54 inches (Minnesota State Climatologist, 2001). Jones (2002) derived estimates of groundwater recharge for the area using stream-hydrograph analysis methods on daily streamflow records for the Prairie River near the city of Taconite for the 1968-1982 time period. These recharge estimates were used in the WHPA delineation.

<u>Geology</u>: Figures 2 and 3 show the distribution of the aquifer and its stratigraphic relationships with adjacent geologic materials. They were prepared using existing geologic maps (Jennings and Reynolds, 2005) and well record data that is contained in the County Well Index database. A complete listing of the geological maps and studies that were used to further define local hydrogeologic conditions is provided in the section of this report entitled “Selected References.”

The natural landscape of the Coleraine area was strongly affected by late-Pleistocene glaciation. Although the town of Coleraine is situated on relatively flat ground, the surrounding area consists of an irregular topography of small hills and depressions (Figures 2 and 3). This distribution of landforms is attributed to rapidly shifting depositional environments commonly found near the margins of glacial ice, probably of the Koochiching lobe (Jennings and Reynolds, 2005). Dominant glacial landforms in the Coleraine area include Trout Lake, attributed to a subglacial drainage feature known as a tunnel valley, and the irregular hills adjacent to and west of Trout Lake, indicative of ice contact deposits (Jennings and Reynolds, 2005).

Although surficial materials in the Coleraine area are dominated by sediments of the Koochiching lobe, interpretations are complicated by apparent admixture with sediments of the Rainy lobe. This was probably caused by collapse of both units related to late melting of buried ice (Jennings and Reynolds, 2005). The total thickness of glacial sediments in the Coleraine area is on the order of 160 feet. Generally, drift thickens to the south and thins to the north, approaching zero along the crest of the Giants Range, a linear ridge composed of Archean granitic and metasedimentary rocks that trends northeast to southwest (Jones, 2002). It is located north of the Canisteo Mine Pit.

Winter (1971) identified three major morainal till units and associated glaciofluvial outwash deposits in this general area, but only two appear to occur in Coleraine. These are the upper surficial and middle boulder till units (Jones, 2002). The surficial till is brown in color, sandy, silty, and calcareous, and is generally less than 30 feet thick (Jones, 2002). The boulder till ranges widely in color from gray to yellow, consists of sands and silts with abundant cobbles and boulders, and is generally less than 50 feet thick (Winter, 1971). Glaciofluvial outwash deposits lie stratigraphically between the surficial and boulder tills, and often lie between the boulder till and deeper tills or bedrock (Winter, 1973a). Those that occur between the surficial and boulder tills are the thickest and most continuous outwash deposits in the Coleraine area. They are often greater than 50 feet thick, and sometimes exceed 100 feet in portions of buried valleys (Winter, 1973a). These outwash deposits consist of fine-grained sands throughout much of the study area. However, they are highly transmissive, coarse-grained sands, gravels and boulders occurring within buried valleys and at other locations where the bedrock surface is low (Jones, 2002). These deposits form the aquifer that is tapped by the Coleraine city wells.

The uppermost bedrock beneath the city of Coleraine consists of the Virginia Formation, a Paleoproterozoic package of argillites, siltstones and greywackes (Jones, 2002). This unit thins to the north so that the uppermost bedrock present within the Canisteo Mine Pit is the Biwabik Iron Formation (Jirsa and others, 2005).

<u>Groundwater Quantity and Quality</u>: Minnesota Department of Natural Resources permits high-capacity wells and documents their pumping volumes in the State Water Use Database (SWUDs). It is important to identify other high-capacity wells in the vicinity of the Coleraine wells because they may affect the boundary of the capture zone in the WHPA. The only high-capacity wells identified within two miles of the Coleraine wells are the municipal wells for Bovey and Taconite. The Taconite city wells are completed in the Biwabik Iron Formation and are unlikely to constitute a flow boundary to the Coleraine wells. The Bovey municipal well is completed in the same aquifer as the Coleraine city wells and, therefore, may constitute a flow boundary.

Water quality information on the Coleraine city wells was obtained from MDH records, as well as published data (Cotter and others, 1965). These data show that some changes have occurred in the chemical makeup of the city water over time (Figures 4 and 5). The earliest data for Coleraine Well 1 (241430) date to 1957 and 1971, at which time the Canisteo Pit was dewatered. Chloride and sulfate values recorded from that time period show values of 3.5-5.0 mg/l and 50-68 mg/l, respectively. Follow-up sampling conducted in 2004 showed markedly different results. The chloride and sulfate values for Coleraine Well 1 (241430) had risen to 32-34 mg/l and 160-190 mg/l, respectively; whereas, the values for Well 4 (110457) were slightly lower. The changes observed at Well 1 (241430) may be attributed to changing groundwater flow patterns in the area related to rising Canisteo Mine Pit water levels, as described below.

When the Canisteo Mine Pit was dewatered, it functioned as a drain, collecting groundwater from surrounding aquifers in addition to precipitation and surface water runoff. At its lowest levels, the dry pit floor would have been approximately 200 feet below the level of Trout Lake. As a result, groundwater flow in the Coleraine area would have been directed from Trout Lake towards the Canisteo Pit. It is likely that the Coleraine municipal wells would have captured a large component of water from Trout Lake during this time. This theory is supported by 1) water level observations of the lake and the city wells noted in Cotter and others, (1965), and 2) historic water chemistry data from Trout Lake and the municipal wells of Coleraine and Bovey. Trout Lake water quality data were obtained from published data (Cotter and others, 1965) and compared with sampling conducted in 2004 in support of this delineation. The chloride and sulfate results from Trout Lake were consistent over this time period, with values of 5.9-6.2 mg/l and 39-52 mg/l, respectively. These values are very similar to those observed from the early samples from the Coleraine and Bovey municipal wells. Note that the 2004 sample results for the Coleraine city wells suggest that they were still capturing some Trout Lake water at that time (Figure 5).

As the Canisteo Pit water level has risen since the cessation of mining, now exceeding that of Trout Lake by 20 feet, the groundwater flow dynamic in the Coleraine area has changed. Water level data now suggest that groundwater is flowing from the Canisteo Pit towards Trout Lake, at least locally (Jones, 2002). Because of this change in groundwater gradient, the capture areas for the Coleraine city wells have likely shifted from a southerly direction to more northerly. Stable isotope data obtained on samples from the Coleraine city wells taken in 2004 show significant evidence of evaporated surface water. The evaporative signature from some of the Coleraine samples exceeded that of the Canisteo Mine Pit lake, but was less than that observed at Trout Lake. This suggests that the Coleraine city wells were capturing a significant component of Trout Lake water, although the presence of some Canisteo Mine Pit water cannot be ruled out (Figure 6).

The elevated levels of chloride and sulfate observed in the 2004 samples from the Coleraine city wells likely reflect ambient water quality in the aquifer within the current northerly capture area. Elevated chloride is likely related to road de-icing salt, although commercial fertilizer and wastewater are other possible sources. Elevated sulfate is generally related to naturally-occurring minerals, although wastewater is also a possible source. Common mineral sources include gypsum, a soluble calcium sulfate mineral that occurs in minor amounts in some rocks, or the oxidation of sulfide-bearing minerals such as pyrite. Gypsum is not known to occur in the Biwabik Iron Formation or associated Precambrian rocks of the Coleraine area, although it could be present in minor amounts in glacial drift.

Pyrite is known to occur at some locations within the Biwabik Iron Formation, the Virginia Formation, and the Cretaceous Coleraine Formation. It is possible that some of the waste rock stockpiles in the Coleraine area contain pyrite, and result in localized occurrences of sulfate-rich groundwater. Evidence for this comes from water quality sampling conducted in 2004 on a ditch that drains into the north side of Trout Lake. The ditch originates at a wetland located at the toe of a waste rock stockpile along the south shore of the Canisteo Pit north of Coleraine (Figure 2). The chloride and sulfate values determined for the ditch water were 69 mg/l and 210 mg/l, respectively. These values are significantly higher than those observed at the Coleraine city wells in 2004, but may be indicative of surface water that slowly infiltrates into the buried aquifer within the wells capture areas. Alternatively, the sulfate values at the Coleraine city wells may reflect the onset of captured Canisteo Mine Pit lake water. The sulfate values observed at the city wells were similar, though slightly lower than values noted from the Canisteo Mine Pit (Figure 5).

Hydrogeological Setting

In the geographic area that includes the WHPA, the aquifer from which the city wells pump has the following characteristics:

- It is composed of sand and gravel and is 30 to 50 feet thick;
- It exhibits a porosity that is estimated to be 25%;
- It exhibits a base elevation of approximately 1,184 feet above sea level at the city wells and probably rises to the north, consistent with the bedrock surface;
- It exhibits a stratigraphic top elevation of approximately 1,235 feet above sea level at the city wells and probably rises to the north, consistent with the bedrock surface;
- It exhibits a wide range of aquifer transmissivity, as described below, and these zones of differing transmissivity may constitute flow boundaries. An attempt has been made to subdivide the aquifer into zones of differing transmissivity based on existing geologic mapping and aquifer test data (Figure 8).

The ambient flow field in the aquifer is upgradient of the city wells, currently oriented southeasterly (approximately 160 degrees) with an average hydraulic gradient of approximately 0.006 (Figure 7).

The aquifer generally exhibits confined hydraulic conditions. This was determined by comparing the static water level measurements from wells completed in the aquifer with its stratigraphic top (Figure 3). In most instances, the static water levels occur in the till that commonly overlies the aquifer. However, the aquifer is unconfined where it is intersected by the Canisteo Mine Pit and at some other locations where ice contact deposits are prevalent, particularly around Trout Lake (Figures 2 and 3).

The Minnesota Department of Natural Resources (DNR) has developed a procedure for determining geologic sensitivity that is based on an “L” score (DNR, 1991). The “L score increases 1 point for every 10 feet of overlying clay. The Coleraine city wells exhibit an “L” score of 6 using the DNR criteria. Therefore, the geologic sensitivity for the aquifer is very low at the city wells.

Criteria Used to Delineate the Wellhead Protection Area

The criteria for delineating the WHPA, as required in Minnesota Rules 4720.5510, were addressed as follows.

Time of Travel - A 10-year time of travel was used to characterize groundwater movement in the aquifer and the pumping of the water supply wells. Also, a one-year time of travel was used to define the emergency response area (ERA), as specified under Minnesota Rules 4720.5250. The 1- and 10-year capture zone boundaries are shown in Figure 1.

Daily Volume of Water Pumped - Information provided by the city of Coleraine was used to determine the maximum discharge from their wells. The results are presented in the following table. The daily volume of discharge used as an input parameter in the model was calculated by dividing the greatest annual pumping volume by 365 days.

Table 3
Annual Volume of Water Discharged From Coleraine Water Supply Wells

Well No.	Unique No.	2001	2002	2003	2004	2005	Future Pumping
1	241430	27,109,000	**33,502,500**	30,418,500	26,109,000	21,618,000	
4	110457	27,109,000	**33,502,500**	30,418,500	26,109,000	21,618,000	

(Expressed as gallons. Bolding indicates greatest annual pumping volume.)

The values shown in Table 3 are the total number of gallons pumped annually by the Coleraine city wells and reported to the Minnesota Department of Natural Resources under Groundwater Appropriations Permit No. 842085. The city of Coleraine indicates that it intends to pump approximately the same amounts of water during the next five years. As a result, the maximum amount of annual pumping, shown in bold above, was used to express the daily volume of water pumped from the city wells.

The maximum annual volume pumped by the Coleraine city wells over the 2001-2005 time period was incorporated as a daily volume in the groundwater flow model used to designate the capture zones for the wells. For delineation purposes, the following pumping rates were applied to the wells in the groundwater flow model. The rate selected is consistent with WHP rule requirements because the maximum volume is used.

Table 4
Pumping Rates Used for WHPA Delineation

Well Number	Equivalent Annual Volume (gallons)	Model Input (cubic meter/day)
1	33,502,500	347.5
4	33,502,500	347.5

Groundwater Flow Field - The groundwater flow field was determined by compiling static water level elevations from 1) wells that are completed in the same aquifer used by the city of Coleraine, and 2) fully-penetrating surface water features such as the Canisteo Mine Pit lake and Trout Lake (Figure 7). The ambient flow field in the aquifer upgradient of the city wells is currently oriented southeasterly (approximately 160 degrees) with an average hydraulic gradient of approximately 0.006 (Figure 7).

Aquifer Transmissivity - The transmissivity of the aquifer used by Coleraine Wells 1 and 4 (241430 and 110457) was estimated from 1) single well aquifer tests on monitoring wells conducted as part of USGS Water Resources Investigations Report 02-4198 (Jones, 2002), and 2) specific capacity data from the Coleraine and Bovey city wells, including other wells completed in the same formation (Figure 8). The specific capacity data were corrected for partial penetration, assuming an aquifer thickness of 50 feet using the method described in Appendix III.

These results suggest an aquifer transmissivity that ranges from approximately 220 ft^2/day to 6,800 ft^2/day. The wide range in transmissivity probably reflects variations in aquifer grain size, and possibly differences in well development. The low end of the range is representative of data from Jones (2002). The upper value represents the geometric mean from the specific capacity data for the five wells that were pumped in excess of 50 gallons per minute for at least two hours. The geometric mean of the entire 14-well data set is 1,480 ft^2/day.

The groundwater flow model developed for this area by Jones (2002) utilized relatively low values of aquifer hydraulic conductivity to achieve calibration for the aquifer used by Coleraine. Those values spanned from 13.1 ft/day to 32.8 ft/day, which yield aquifer transmissivity values of approximately 650 ft^2/day in the area of the Coleraine city wells. However, based on the specific capacity data set, an aquifer transmissivity value of 6,800 ft^2/day is considered representative of the area around the Coleraine city wells. Apparently the aquifer consists of narrow, high transmissivity zones within a broader, moderate transmissivity domain. The high transmissivity regions probably correspond with glacial drainage pathways where coarse sediment was locally deposited. As indicated by Jones (2002), the Coleraine-Bovey aquifer generally consists of fine sand, but coarse sand and gravel are present locally, generally in low spots on the bedrock surface. Figure 8 shows a possible channel configuration that accommodates most of the high transmissivity wells analyzed for this study, and aligns with 1) a bedrock valley of Jirsa (2005), and 2) an exposure of potential aquifer material in a wall of the Canisteo Mine Pit mapped by Jennings and Reynolds (2005). This channel morphology was used in the model simulations used to delineate the WHPA. This method of determining transmissivity meets the requirements of Minnesota Rules 4720.5510, subpart 6. The aquifer test plan was approved by MDH on January 10, 2007.

Flow Boundaries - The following conditions define the extent to which flow boundaries must be considered:

> The aquifer used by the city of Coleraine appears to be laterally persistent, except where it was removed within the Canisteo Mine Pit. However, it does appear to vary widely in transmissivity, and boundaries to groundwater flow undoubtedly occur where significant contrasts are found. In addition, the overlying and underlying tills that are generally present serve to retard vertical movement of groundwater into or out of the aquifer and constitute flow boundaries.

The aquifer generally exhibits confined hydraulic conditions in the vicinity of the city wells. However, the aquifer is unconfined where it is intersected by the Canisteo Mine Pit and at some other locations where ice contact deposits are prevalent, particularly around Trout Lake (Figures 2 and 3). These fully-penetrating hydraulic features constitute hydrologic flow boundaries.

The State Water Use Data System maintained by the DNR was accessed and identified the following high-capacity well, in addition to those operated by the city of Coleraine, that may impact the delineation of the WHPA:

* City of Bovey Well 1 (228834)

Method Used to Delineate the Wellhead Protection Area - The WHPA for Coleraine Wells 1 and 4 (241430 and 110457) was delineated using the three-dimensional, numerical groundwater flow model Modflow 2000, along with Modpath particle tracking software. These programs were accessed using the GMS modeling software, Version 6.0. This program is capable of simulating complex hydrologic scenarios, such as spatial variability in aquifer recharge and geology, including the presence of flow boundaries. The model input and solution files are on file at the MDH and available upon request.

Groundwater Flow Model Used to Define the Well Capture Zones - The groundwater flow model used to delineate the WHPA for Coleraine was derived from an existing regional model of the Canisteo Mine Pit area (Jones, 2002). The model simulates flow in the complete glacial drift package, plus the uppermost bedrock. Because the original model consists of a relatively coarse (100 m) uniform grid, it was deemed necessary to create a subset of the model with a grid that was refined based on the locations of the pumping wells in the Coleraine area. The local model used for WHPA delineation was extracted from the regional model using the telescopic refinement process in GMS (Figure 9). In this process, boundary conditions and hydraulic properties assigned to individual cells in the original three-dimensional model are exported to two-dimensional scatter points. Following creation of the new, refined grid for the local model, grid cells are re-populated with the original boundary conditions and hydraulic properties via interpolation from the two-dimensional data sets. Finally, constant head boundary conditions are applied along the boundaries of the model. It should be noted that the grid for the local model was oriented in such a way that at least two of the four local model boundaries approximately parallel potentiometric contours from the original model, therefore satisfying constant head conditions at those boundaries.

Glaciofluvial sediments, such as those tapped by the Coleraine city wells, are predominantly represented in two layers of the model (Layers 2 and 4). Layer 2 represents the aquifer utilized by the cities of Coleraine and Bovey. Glacial clays and till are present in three layers of the model (Layers 1, 3 and 5). Layer 6 represents the uppermost bedrock. The geometry of these bodies was determined from surficial geologic maps and well record data. The porosity of the aquifer material was set at 0.25, typical of a sand aquifer (Fetter, 1988). The hydraulic conductivity and recharge values assigned to these units are shown in Table 5.

In addition to the grid refinement, the local model used to delineate the Coleraine WHPA differs from the regional model of Jones (2002) in that 1) the hydraulic conductivity of the Coleraine-Bovey aquifer was increased within the outwash channel, as shown in Figure 8, and 2) the conductance of the Trout Lake bed material was increased from 0.02 $m^2/d/m$ to 1.0 $m^2/d/m$. The latter change was implemented to allow a better fit to the chemical and isotopic data obtained from the Coleraine city wells, as described in the section of this report dealing with model calibration.

Table 5
Parameters Used for WHP Area Delineation

		Hydraulic Conductivity (ft/day)	
Type of Simulated Cell	**Recharge (ft/day)**	**Calibrated Values from Regional Model**	**Values Used to Create WHPA**
Glaciofluvial Sediments	1.1×10^{-3}	13.1 – 32.8	13.1 - 136
Glacial Tills	3.9×10^{-6}	7.0×10^{-2}	7.0×10^{-2}
Bedrock	2.3×10^{-4}	7.0×10^{-3}	7.0×10^{-3}
Canisteo Mine Pit	1.4×10^{-3}	3.28×10^{4}	3.28×10^{4}

Lakes and perennial wetlands are represented in the model as general head boundaries. The most locally significant of these is Trout Lake. The water level elevation at this lake has ranged from 1,283.9 to 1290.1 feet above sea level over the period from 1911 to present, and most recent readings place the level at approximately 1,288 feet. An hydraulic conductivity of 0.07 ft/day and a vertical thickness of 3.28 feet were used in calculating the conductance in these cells. The thickness value is an estimate of Jones (2002), whereas the hydraulic conductivity was derived from single well hydraulic tests (Jones, 2002) and from values determined for lake-bed material at Shingobee Lake (Kishel and Gerla, 2002).

Perennial streams and rivers not simulated as part of wetlands were simulated using the river module. The same hydraulic conductivity and bed thickness values applied to wetlands and lakes noted above were applied to the river segments. River stage values were assumed to be 6.56 feet above the altitude of the riverbed (Jones, 2002).

Recharge was applied to the surficial layer of the model using a specified flux boundary. Initial recharge rates were proportioned based on results from stream hydrograph analyses and geology in the surficial layer of the model. The largest recharge rates were simulated where glaciofluvial sediments were present at the land surface. Smaller rates were applied where clay, till or bedrock were present at the land surface (Table 5).

The Canisteo Mine Pit was represented in the model as a series of highly conductive, constant head cells. An hydraulic conductivity value of 3,280 ft/day was used for these cells (Table 5). This value was used because it allows water levels in the pit cells to be relatively consistent and to respond similarly to a lake (Jones, 2002). The water level in this pit has varied greatly over the past 100 years in response to mining activities, which ceased in the mid 1980s (Jones, 2002). Since 1989, the water level in the pit has risen from 1,250 feet above sea level to its current elevation of approximately 1,310 feet above sea level (DNR records). For the purposes of the WHPA delineation, Canisteo Pit water levels were simulated at 1,300, 1,310 and 1,320 feet in separate model runs. The 1,300-foot level is consistent with the original model of Jones (2002) and represents the level at which the DNR proposes to control the pit level in the future (Bob Liebfried, personal communication, 2006). The 1,310-foot level represents current conditions (DNR data). The 1,320-foot level represents the approximate overflow elevation for the pit. Given the past rate of water level rise within the pit, this level could be reached within the next ten years, which is the time period that the city's WHP plan is intended to cover.

The capture zones generated by the model were created by releasing particles from the wells and tracing backward. The particles were released at the center of the model cell containing the well, and twenty path lines were generated for each well. The groundwater component of the WHPA for the city of Coleraine is a composite of each of the model scenarios shown in Figure 9. Note that some of the particle tracks from the Coleraine city wells intersect Trout Lake and the Canisteo Mine Pit within a 10-year time of travel. This occurs at Trout Lake for both the 1,300-foot and 1,310-foot Canisteo Mine Pit lake water level simulations, and at the Canisteo Mine Pit lake for both the 1,310-foot and 1,320-foot pit water level simulations. This observation is consistent with the original results presented by Jones (2002), although no time of travel estimates accompanied the flow paths shown in that document.

Results of Model Calibration and Sensitivity Analysis - The local model used for the WHPA delineation was extracted from the original calibrated Canisteo Pit regional model of Jones (2002). As a result, no additional attempts were made to further calibrate the model to hydraulic heads. However, 16 of the 18 monitoring wells from the original model that were located within the boundaries of the local model were used to generate calibration results for the local model runs, where synoptic water level data existed for comparison (Table 6). Water level data for all 16 of the monitoring wells were available from the DNR for 2001 for the 1,300-foot pit level simulation, and from 13 of the wells in 2006 for the 1,310-foot pit level simulations. A representative plot of measured versus simulated water level elevations for the 1,310-foot level simulation is shown in Figure 10, and a plot of model-generated potentiometric contours for Layer 2 versus water level data from wells is shown in Figure 11.

Table 6
Model Calibration Data (all values in meters)

Model Run	Mean Error	Mean Absolute Error	Root Mean Squared Error
Canisteo Pit Level = 1,300 ft	**-0.83**	**4.1**	**5.21**
Canisteo Pit Level = 1,310 ft	**-0.25**	**4.71**	**5.47**

Although no efforts were made to improve the head calibration, the conductance of the Trout Lake bed materials was varied in the local model to better reflect the chemical and isotopic data obtained from the municipal wells of Coleraine and Bovey. Water sampling conducted in 2004 showed that the Coleraine municipal wells were strongly affected by surface water capture. Water from Trout Lake appeared to be a significant component, although the presence of some Canisteo Mine Pit water could not be ruled out. In contrast, the Bovey city well water showed no significant evidence of surface water influence. The local model was calibrated to the

1,300-foot Canisteo Mine Pit level because it most closely simulates the period prior to the 2004 water-sampling episode. The calibration was considered successful when 1) a significant number of particles traced from the Coleraine city wells terminated at, or passed-through, the Trout Lake general head boundary cells, and 2) none of the particles released from the Bovey well passed through Trout Lake or the Canisteo Mine Pit lake within a 3-year time of travel. This time of travel criterion was selected because it represents the elapsed time between the dates when the Canisteo Mine Pit water level was simulated (2001) and the sampling was conducted (2004).

In his sensitivity analysis of the regional model, Jones (2002) varied horizontal hydraulic conductivity by 0.2-10 times the calibrated values, vertical hydraulic conductivity by 0.1-10 times the calibrated values, and recharge by 0.5-1.5 times the calibrated values. He found that the regional model was most sensitive to changes in horizontal hydraulic conductivity and much less sensitive to changes in vertical hydraulic conductivity and recharge. When varied over the ranges described above, maximum water level differences from the calibrated model, as observed at all monitoring wells, ranged from -21.13 to +59.91 feet for horizontal hydraulic conductivity, -17.29 to +21.69 feet for vertical hydraulic conductivity, and –10.93 to +9.28 feet for recharge.

Conjunctive Delineation - As noted above, some of the particle tracks from the Coleraine city wells intersect Trout Lake and the Canisteo Mine Pit within a 10-year time of travel for the some of the pit water level simulations (Figure 9). As a result, these surface water features must be considered to be a component of the city's WHPA unless an assimilative capacity boundary can be established (see glossary of terms). At this point, data are insufficient to establish an assimilative capacity boundary for Trout Lake or the Canisteo Mine Pit. Existing chemical data appear limited to a relatively narrow range of parameters, leaving many parameters on the National Primary Drinking Water Standards list uncharacterized at this time. Any attempt to establish the basis for an assimilative capacity boundary would need to factor the modeled travel time from the pit to the wells, which is believed to range from a minimum of 5 years at a pit water level of 1,320 feet, to at least 8 years when assuming a pit water level of 1,310 feet.

Figure 12 depicts the final WHPA for the city of Coleraine. This area was determined by merging 1) the 10-year time of travel groundwater capture zones for the city wells, and 2) the surface watershed areas for Trout Lake and the Canisteo Mine Pit lake, as determined by the DNR (Bob Liebfried, personal communication, 2006).

Uncertainty Analysis - A primary source of uncertainty in the WHPA delineation is the actual three-dimensional geometry of the coarse-grained outwash channel that is thought to provide a high transmissivity pathway for groundwater flow between the Coleraine city wells and both the Canisteo Mine Pit and Trout Lake. The boundaries of this feature have a significant impact on the groundwater capture zones for the Coleraine city wells. In addition, the transmissivity of this feature could be more accurately quantified to provide greater confidence in the model output. The following section describes steps that could be taken to provide a greater degree of certainty in the modeled capture zone.

Recommendations for Future Data Collection

1) Enhancing the Understanding of Local Hydrogeologic Conditions.

Subsurface Geology -

Every five years, the city of Coleraine should work with the MDH so that the locations of new wells constructed within one mile of the city's well field can be verified and accurate elevations obtained. This information will help address uncertainties related to 1) the areal extent, thickness, and compositional variability of the Coleraine-Bovey aquifer, and 2) the distribution of hydraulic head in this aquifer.

Aquifer Transmissivity -

The transmissivity of the Coleraine-Bovey aquifer in the vicinity of the Coleraine municipal wells was estimated from specific capacity data. Such estimates tend to be less accurate than those determined from aquifer test data. In order to confirm that the estimates derived from specific capacity tests are appropriate for the area around the city wells, it would be helpful if the city were able to conduct an appropriate aquifer test. Such a test would benefit from an observation well that is located within relatively close proximity to a city well. The MDH can work with the city to design a proper aquifer test that provides drawdown and recovery data from both the pumping well and the observation well.

2) Surface Water/Groundwater Exchange.

Chemical and Isotopic Data -

Groundwater modeling results suggest that the Coleraine city wells were capturing a significant amount of surface when sampled in 2004. Also, the component attributable to the Canisteo Mine Pit lake is likely to become dominant within the next ten years, assuming the water level in the pit remains at or exceeds current levels. The MDH recommends that the city initiate an annual program of water sampling from their wells in order to track such changes. The results will help to validate the groundwater model and refine resulting capture zones in the future. To support the proposed sampling program, the MDH will assist with the selection of sampling points and analytical parameters. The city will be responsible for most of the sampling, but the MDH will pay for the analyses using funding that it has dedicated for this work. There would be no cost to the city for these analyses and related MDH staff time.

3) Water Use and Water Level Considerations.

Revisions to the WHPA -

The following water use factors should be monitored to determine if a revision of the WHPA or DWSMA is required: 1) the installation of any new high-capacity wells within 1.5 miles of the city well field, 2) increased discharge from the city wells over the values used in this report, and 3) changes in water levels at the Canisteo Mine Pit lake and Trout Lake. The third point refers to the fact that the groundwater gradient in the Coleraine area is largely set by the water level elevations of these two water bodies. If the water level of Trout Lake is maintained around current levels and the Canisteo Mine Pit level is dropped to 1,300 feet or less, then it is unlikely that the Coleraine city wells will capture Canisteo Mine Pit water within a 10-year time of travel, based on current data. If such a scenario were to be maintained for at least a 10-year time period, then the Canisteo Mine Pit and its surface watershed could be removed from the city of Coleraine WHPA.

Delineation of the Drinking Water Supply Management Area

Method Used to Designate the Drinking Water Supply Management Area – The Drinking Water Supply Management Area (DWSMA) was determined by overlaying the WHPA on a map of area roads, railroads, and public land survey boundaries, using a geographic information system to select the closest such feature. This area was then reviewed and modified by staff from the city of Coleraine and the MDH.

Assessment of Well Vulnerability

This part documents the vulnerability of the wells used by the public water supplier and is required under Minnesota Rules 4720.5210. The protocol for determining well vulnerability is defined in the MDH document entitled Methodology for Phasing Wells into Minnesota's Wellhead Protection Program (1993), which was approved by the U.S. Environmental Protection Agency as part of its review of Minnesota's wellhead protection program description. The MDH uses the protocol to maintain a database defining the potential vulnerability of community and noncommunity public water supply wells. A score is calculated for each well using 1) construction criteria defined in the State Well Code, 2) geologic sensitivity, and 3) the results of water quality monitoring conducted by the MDH. A numeric score is assigned to each well based on the results of the three areas of evaluation. A cutoff score is used to define wells that are most likely to be vulnerable based on their construction, geologic setting, and sampling history. The printouts of the vulnerability ratings for each well are presented in Appendix I.

The results of the well vulnerability assessments suggest that the wells used by the city of Coleraine are potentially vulnerable to contamination. This conclusion is based primarily on water samples collected from the city wells on February 9, 2004, that showed 16.3 and 17.6 tritium units, indicating that most of the water pumped by the wells entered the ground within the last 50 years. An additional factor for Well 1 (241430) is that it does not meet current State Well Code standards for construction.

Vulnerability Assessment for the Drinking Water Supply Management Area

The aquifer used by the Coleraine city wells was evaluated for its vulnerability to contamination throughout the extent of the DWSMA on the basis of 1) surficial geologic and soils maps, 2) geologic logs from wells in the area, and 3) the chemical and isotopic data noted above.

The Itasca County Soil Survey includes an assessment of the geologic sensitivity at the water table based on the criteria of the DNR (1991). The geologic sensitivity ratings within the Coleraine DWSMA range from very high to low (Figure 13). These ratings correlate strongly with the surficial geologic mapping of Jennings and Reynolds (2005). Geologic sensitivity ratings of very high or high correspond to the occurrence of relatively coarse sediments associated with glacial outwash or ice contact deposits. These are most prevalent around Trout Lake, which has been interpreted to be the remnant of a sub-glacial drainage feature (Jennings and Reynolds, 2005). Very high geologic sensitivity ratings are also assigned within the Canisteo Mine Pit lake, where till that originally overlay the city's aquifer has been removed by mining. Geologic sensitivity ratings of moderate and low are assigned where the soil has a relatively high clay or loam content, suggesting that till was the parent material. These areas are strongly correlated with those areas mapped as Koochiching lobe till by Jennings and Reynolds (2005).

The geologic sensitivity ratings described above were compared with those determined from the geologic logs for wells located within and immediately adjacent to the city's DWSMA (Figure 13). In general, a strong correlation was noted between the two data sources. Wells located adjacent to Trout Lake generally show vulnerability ratings of high to moderate, whereas those located away from the lake and associated ice-contact deposits generally show ratings of moderate to low. Although a very low rating is documented at some wells, this amount of geologic protection appears to be very localized.

The chemical and isotopic data for the Coleraine and Bovey city wells suggest that even where the geologic sensitivity rating for the aquifer is low to moderate, it is characterized by the presence of young water that is elevated in chloride. As a result, the overlying till cover is considered to be leaky. Those areas determined to exhibit a low geologic sensitivity rating were increased to a vulnerability rating of moderate to reflect the leaky nature of the till. Finally, mapped areas smaller than approximately 10-acres in size were incorporated within the surrounding mapped area to avoid small slivers of land that would be difficult to identify and manage.

In summary, the vulnerability of the Bovey-Coleraine aquifer ranges from moderate to very high. Within areas rated as moderate, the time required for water moving vertically from the land surface to reach the aquifer is probably on the order of several years to decades (DNR, 1991). Within areas rated as very high or high, water from the land surface can probably reach the aquifer in weeks to years.

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Appendix I

Municipal Well Information

Table 1
Municipal Water Supply Well Information
Coleraine, Minnesota

Local Well Name	Unique Number	Use/ Status[1]	Casing Diameter (inches)	Casing Depth (feet)	Well Depth (feet)	Date Constructed/ Reconstructed	Well Vulnerability	Aquifer
1	241430	P	24	75	121	1918	Vulnerable	QBAA
4	110457	P	16	100	120	1976	Vulnerable	QBAA

Note: 1. Primary (P) or Emergency backup (E) well

MINNESOTA DEPARTMENT OF HEALTH
SECTION OF DRINKING WATER PROTECTION
SWP Vulnerability Rating

625 Robert St. N. St. Paul MN 55155
P.O. Box 64975 St. Paul MN 55164 - 0975

PWSID:	1310006	TIER:	3
SYSTEM NAME:	Coleraine	WHP RANK:	
WELL NAME:	Well #1	UNIQUE WELL #:	00241430

COUNTY: Itasca TOWNSHIP NUMBER: 56 RANGE: 24 W SECTION: 32 QUARTERS:

CRITERIA		DESCRIPTION	POINTS
Aquifer Name(s)	:	Quaternary Buried Artesian	
DNR Geologic Sensitivity Rating	:	Very low	15
L Score	:	6	
Geologic Data From	:	Data Inferred From Nearby Wells	
Year Constructed	:	1918	
Construction Method	:	Cable Tool/Bored	0
Casing Depth	:	75	10
Well Depth	:	121	
Casing grouted into borehole?		Unknown	0
Cement grout between casings?		Not applicable	0
All casings extend to land surface?		Yes	0
Gravel - packed casings?		No	0
Wood or masonry casing?		No	0
Holes or cracks in casing?		Unknown	0
Isolation distance violations?			0
Pumping Rate	:	500	5
Pathogen Detected?			0
Surface Water Characteristics?			0
Maximum nitrate detected	:	<1	0
Maximum tritium detected	:	16.3 02/09/2004	VULNERABLE
Non-THMS VOCs detected?			0
Pesticides detected?			0
Carbon 14 age	:	Unknown	0
Wellhead Protection Score	:		30
Wellhead Protection Vulnerability Rating	:		VULNERABLE
Vulnerability Overridden	:		

COMMENTS

NITRATE DATA FROM PWSD 1989, 2/66 SAMPLE GEOLOGY INFERRED FROM WELL #4. Cable tool construction assumed because of the age of the well.

MINNESOTA DEPARTMENT OF HEALTH
SECTION OF DRINKING WATER PROTECTION
SWP Vulnerability Rating

625 Robert St. N. St. Paul MN 55155
P.O. Box 64975 St. Paul MN 55164 - 0975

PWSID: 1310006
SYSTEM NAME: Coleraine
WELL NAME: Well #4
TIER: 3
WHP RANK:
UNIQUE WELL #: 00110457

COUNTY: Itasca
TOWNSHIP NUMBER: 56
RANGE: 24 W
SECTION: 32
QUARTERS:

CRITERIA		DESCRIPTION	POINTS
Aquifer Name(s)	:	Quaternary Buried Artesian	
DNR Geologic Sensitivity Rating	:	Very low	15
L Score	:	6	
Geologic Data From	:	Well Record	
Year Constructed	:	1976	
Construction Method	:	Rotary/Drilled	0
Casing Depth	:	100	10
Well Depth	:	120	
Casing grouted into borehole?		Yes	0
Cement grout between casings?		Yes	0
All casings extend to land surface?		Yes	0
Gravel - packed casings?		No	0
Wood or masonry casing?		No	0
Holes or cracks in casing?		Unknown	0
Isolation distance violations?			0
Pumping Rate	:	800	10
Pathogen Detected?			0
Surface Water Characteristics?			0
Maximum nitrate detected	:	<.4 09/04/1990	0
Maximum tritium detected	:	17.6 02/09/2004	VULNERABLE
Non-THMS VOCs detected?			0
Pesticides detected?			0
Carbon 14 age	:	Unknown	0
Wellhead Protection Score	:		35
Wellhead Protection Vulnerability Rating	:		VULNERABLE
Vulnerability Overridden	:		

COMMENTS

Appendix II

Figures Used in This Report

Appendix III

Method Used to Estimate Transmissivity From Specific Capacity

Method Used to Estimate Transmissivity

The method used to estimate transmissivity from specific capacity data is similar to that of Bradbury and Rotheschild, 1985, and Mace (2000) but with some differences. The method is described in some detail here.

Starting with a rearrangement of Sternberg's (1973) equation that relates specific capacity (Sc) to transmissivity (T), the duration of pumping (t) the well radius (r_w)and storativity (S) for a partially penetrating well:

$$Sc = \frac{4\pi T}{\left[\ln\left(\frac{2.25\,T\,t}{r_w^2\,S}\right) + 2\,s_p\right]} \qquad \mathbf{1}$$

where s_p is the partial penetration factor defined base on the physical properties of the well and aquifer, L is the length of the screen portion of the aquifer and H is the aquifer thickness Brons and Marting (1961):

$$s_p = \frac{1-\left(L/H\right)}{\left(L/H\right)} - \left[\ln\left(H/r_w\right) - G\left(L/H\right)\right] \qquad \mathbf{2}$$

Where the function G is approximated by Bradbury and Rothschild (1985) using the following polynomial with 0.992 correlation coefficient:

$$G\left(L/H\right) = 2.948 - 7.363\left(L/H\right) + 11.447\left(L/H\right)^2 - 4.675\left(L/H\right)^3 \qquad \mathbf{3}$$

Rearranging Equation 1 to solve for transmissivity and substituting for Sc in terms of the discharge of the well (Q) and the observed draw down at tine t (s), Sc=Q/s:

$$T = \frac{Q}{4\pi s}\left[\ln\left(\frac{2.25\,T\,t}{r_w^2\,S}\right)\right] + \frac{Q\,s_p}{2\pi s} \qquad \mathbf{4}$$

The second term in Equation 4 was solved directly from the draw down, discharge, well construction, and aquifer thickness information. The first term was solved iteratively with assumed values of storativity for confined (0.001) and unconfined (0.075) conditions.

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