Methods to Estimate Near-Surface Pollution Sensitivity

GW-03

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Introduction

This document defines the methods, data references, and guidelines used by the Minnesota Department of Natural Resources (DNR) for creating near-surface pollution sensitivity maps for County Geologic Atlases (CGA) and Minnesota Hydrogeology Atlases (MHA). The sensitivity to pollution for near-surface materials is an estimate of the time it takes for water to infiltrate the land surface to a depth of 10 feet. It is intended to estimate the travel through the unsaturated zone to reach the water table, which is is assumed to be 10 feet below land surface everywhere for the purposes of this method.

Matrix texture is defined as relative amounts of sand, silt, and clay. It is used as a proxy for estimating the transmission rate, as coarse-grained materials have transmission rates greater than fine-grained materials because of the larger and more connected pore spaces between the grains. The transmission rate is estimated with a two-layer approach using two primary inputs of matrix texture values: the soil layer (0–3 feet) and the underlying geologic materials (3–10 feet).

The estimated transmission rates used in this model have changed over time as new data became available (Appendix B). In 2015 the Minnesota Geological Survey (MGS) created a statewide textural database of shallow geologic materials and the DNR defined specific transmission rates for two additional surficial geologic units: thick, glacial lake clays and loess. This document provides supporting documentation for the transmission rates currently used.

Estimates of transmission rates begin by using an empirical approach to convert a range of representative textures from saturated hydraulic conductivity (K_s) rates to unsaturated rates (K_{unsat}). These are then applied to develop maps in a geographic information system (GIS). The two-layer method was applied to large portions of the state. Special conditions override this approach for regions where the geology dominates: karst within 50 feet of the land surface, bedrock conditions at or near surface, peatlands, and disturbed lands.

The maps generated through this process are generalized interpretations of near-surface sensitivity. They are intended to be used for resource protection planning and to help focus the information gathering for site-specific investigations.

Data Sources - Matrix Texture

Soil Texture (0–3 feet)

Hydrologic Soil Group (HSG), as determined by the Natural Resources Conservation Service (NRCS), is used to estimate transmission through the top 3 feet of the soil profile. Soils are are classified into one of four HSGs based on their hydrologic properties. The HSGs represent a continuum of texture, from the coarse-grained soils of “group A” through the fine-grained soils of “group D” (Table 1). Dual HSGs are assigned to soils that are saturated but can be drained: A/D, B/D, C/D. The model described in this paper assumes unsaturated conditions to a depth of 10 feet, therefore dual hydrologic soil groups do not apply. These are reclassified using the first letter of the dual hydrologic soil group.

Numerous investigators have determined saturated hydraulic conductivity rates for a range of soil textures. Rawls and others assembled a comprehensive dataset for fourteen NRCS soil texture classes (Rawls and others, 1998). These values generally agree with investigations conducted by others (NRCS, 2007, and Ferguson and Debo, 1990). The range of saturated hydraulic conductivity values (K_s) from these sources are grouped by HSG and textural description (Appendix A). Hydraulic conductivity variability within each HSG depends on a number of factors including the method used in rate determination, relative percentages of sand, silt, and clay, antecedent moisture conditions, the presence or absence of macropores, and hydraulic head.

Surficial Geologic Texture (3–10 feet)

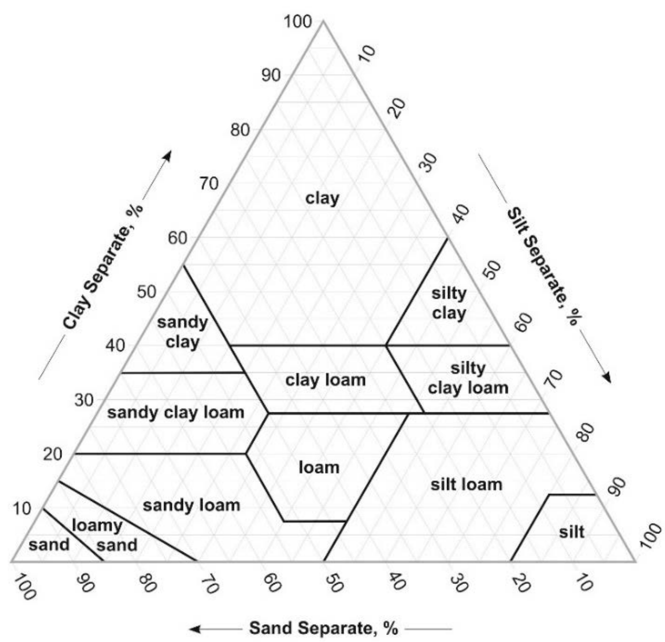
The matrix texture of unconsolidated geologic units, commonly glacial sediments, is used to estimate transmission from a depth of 3–10 feet. Currently, the matrix texture of a geological unit (described as percent sand-silt-clay) is determined by separating out the fraction of a sample that is less than 2 millimeter in size. This is completed by the MGS using a wet sieve and hydrometer method (Patterson, and Wright, 1998) and entered into the MGS Quaternary Data Index.

Historically, matrix texture was typically presented in ternary diagrams or data tables in Part A of the county geologic atlases. Prior to 2015, if a surficial geologic unit's texture was not reported, either the geologist who created the plate was contacted for the texture data, or the matrix texture was estimated from the map unit description. In the latter category, the transmission rate was assigned based on the dominant texture.

In 2015, the MGS created a database of surficial geological unit textures for all units they had previously mapped, with consultation from the DNR (MGS Geological Mapping Database, MGS, written communication, 2015). Field samples from surficial units were assumed to be laterally and vertically homogenous and were used to assign the dominant texture for 3–10 feet. MGS geologists provided estimates where sample data were not available. The DNR used these dominant textures to assign transmission rates across the state.

This new approach allows users to assign objective and reproducible transmission rates to units that have results for grain-size analysis. This analysis is completed by plotting the matrix texture for geologic units on the USDA soil texture classification ternary diagram (Figure 1) and then determining a texture class. For example, when a surficial geologic unit has a matrix texture composition of 55 percent sand, 30 percent silt, and 15 percent clay, this composition classifies the unit as a sandy loam. Chosing the appropriate transmission rate based on this texture is the next step in this procedure.

Figure 1. United States Department of Agriculture (USDA) Soil Textural Triangle (Soil Survey Division Staff, 1993).



Estimating Transmission Rates Using Textures

An estimate of transmission begins with converting of a range of representative matrix textures from saturated hydraulic conductivity (K_s) rates to unsaturated values. This model assumes that soils are unsaturated to a depth of 10 feet. The conversion uses an empirical approach (Bouwer, 2002). Bouwer states that "…because the wetted zone is not completely saturated but contains entrapped air, *K[unsat]* is less than K_s at saturation, about 0.5 K_s for sandy soils, and 0.25 K_s for clays and loams." Additional references for saturated to unsaturated hydraulic conductivity are found in American Society of Testing Materials (ASTM) D 5126 (1992) and Jammal and Assoc., 1989.

Table 1 is a modified version of *Table 2.4 Design Infiltration Rates* from the Minnesota Pollution Control Agency's Stormwater Manual (MPCA, 2005). The MPCA table was used as a starting point as it breaks down hydrologic soil group rates by texture, allowing flexibility to the user. It lists a range of saturated hydraulic conductivity values based on HSG that are primarily from the *National Engineering Handbook* published by the NRCS (2007), but is supplemented with values from Rawls (1998). Columns "I" and "II" list the transmission rates to be used with this model. Rates were determined by applying Bouwer's technique for estimating *K[unsat]* from K_s [sat], listed under column *% Ks*. The saturated K values that were empirically corrected for unsaturated conditions fall within published ranges of infiltration from a number of investigations (Appendix A).

The following geologic texture classifications were added for determining near-surface sensitivity in 2015: the presence of extensive wind-blown silt (loess) deposits (Peoria Loess and Roxana Loess, as defined in Johnson and others, 2016) and thick, clayey glacial lake sediment (Table 1). Mason (1995) measured infiltration rates through the Peoria Loess in Houston County, southeastern Minnesota, and assigned it a transmission rate of 0.218 inches per hour, based on a mean K_s of 0.482 in/hr (Mason, written communication, 2015). Remenda and others (1994) found that saturated transmission rates though Lake Agassiz sediment in northwestern Minnesota was very low: mean $K_s = 3x10^{-10}$ m/s. This transmission rate was extended to glacial Lake Duluth sediments due to the age and environment of the glacial lakes.

The transmission rates used to develop near-surface pollution sensitivity maps have evolved over time with new data. These changes are outlined in Appendix B.

Table 1. Transmission rates through unsaturated materials for Hydrologic Soil Groups and Surficial Geologic Textures

Hydrologic Soil Group (0'-3')				Surficial Geologic Texture (3'-10')	
Group	Saturated K_s [in/hr]	% K_s	"I" Unsaturated Transmission rate [in/hr]	Classification	"II" Unsaturated Transmission rate [in/hr]
A, A/D	2*	0.5	1	gravel, sandy gravel, silty gravel	1
	1.42*	0.5		sand, silty sand	0.71
B, B/D	1*	0.5	0.50	silt, loamy sand, units with eolian sand designation	0.50
	0.57*	0.5		sandy loam, peat***	0.28
--	0.482****	0.5	--	loess (Peoria)	0.218
C, C/D	0.3**	0.25	0.075	silt loam, loam	0.075
	0.14**	0.25		sandy clay loam	0.035
D	≤0.06*	0.25	0.015	clay, clay loam, silty clay loam, sandy clay, silty clay	0.015
--	0.000043*****	0.25	--	Glacial lake sediments of lakes Agassiz and Duluth	0.000011

** Values derived from range of values published within NRCS, 2007*
*** Values derived from range of values published within Rawls, 1998*
**** Assumes Hemic Peat*
*****Values derived from range of values published within Mason, 1995 and written communication, 2015*
****** Values derived from range of values published within Remenda and others, 1994*

Applying Transmission Rates to Determine Sensitivity of Near-Surface Materials

The sensitivity rating of near-surface sediment is determined using the transmission rates (Table 1) to calculate an estimated travel time for a contaminant that moves conservatively with water to a depth of 10 feet below land surface. The steps below offer the general approach used to create the maps.

1. GIS polygons from soil and surficial geologic units are converted to 30-meter raster cells, with their transmission rates as the cell value.
   a. Soil polygons are a product of the NRCS and obtained from the NRCS Soil Data Mart, available on-line at: http://soildatamart.nrcs.usda.gov/Default.aspx.
   b. The surficial geology polygons are a product of the MGS Part A (Geologic) mapping and obtained from the MGS and are available on-line at: http://www.mngs.umn.edu/county_atlas/countyatlas.htm.
2. Conditional statements are used to calculate travel time given the availability of soil and surficial geology data at a specific location where two cells overlap.
   a. The travel time for 0–3 feet below land surface is calculated using the transmission rates from the Hydrologic Soil Group (0–3 feet) column labeled "I" in Table 1.
   b. The travel time for 3–10 feet below land surface is calculated using the transmission rates from the Geologic Texture (3–10 feet) column labeled "II" in Table 1.
   c. If a location is not populated with hydrologic soil group data, then the surficial geologic unit texture is used for the entire 0–10 foot range.
3. Special conditions: transmission rates are not assigned to certain areas because the two-layer approach cannot be applied to unique geological environments, such as the following.
   a. Karst: terrain with distinctive landforms and hydrology created primarily from the dissolution of soluble rocks, allowing a direct, very rapid exchange between surface water and groundwater and significantly increased groundwater contamination risk from surface pollutants (Adams and others, 2016).
   b. Bedrock at or near surface: bedrock mapped in surficial geology maps as at or near surface, or shallow bedrock. No information on transmission rates through bedrock are available for this method.
   c. Peatlands: large, thick areas of peat in northern Minnesota that are consistently saturated at or near surface, and composed of various levels of decomposition.These areas do not fit into the two-layer method because the method assumes unsaturated conditions.
   d. Disturbed lands: mapped as disturbed lands in surficial geology maps (e.g., pits, quarries, and mine tailings).

Table 2 illustrates the approach used to calculate the estimated travel time for a cell with both Hydrologic Soil Group and Geologic Texture inputs, and the approach used to calculated travel time for a cell for which there is no soil data available.

Table 2. Example Time of Travel Calculations

Example A - The cell location has attributes of both the Hydrologic Soil Group (HSG) and the surficial geologic texture. In this example, the cell's HSG is A and the surficial geologic texture is Loamy Sand.		**0-3 ft. below ground surface**	**3–10 ft. below ground surface**	**Total Time of Travel (hours)**	**Sensitivity Category**
	Transmission Determination	36"/ soil transmission rate (in/hr)	84"/ surficial geologic transmission rate (in/hr)		
	Calculation	36"/ 0.50"/hr	84"/ 0.5"/hr		
	Resulting Travel Time in Hours	72	168	240	Moderate, 170–430 hours
Example B - The cell location has no hydrologic soil group attributes (e.g.- gravel pit), only surficial geologic texture attributes (Loamy Sand) are used for the travel time calculation.			**0–10 ft.**		
	Transmission Determination		120"/ surficial geologic transmission rate (in/hr)		
	Calculation		120"/ 0.5"/hr		
	Resulting Travel Time in Hours		240	240	Moderate, 170–430 hours

The total travel time from 0–10 feet below land surface is the sum of the estimated travel times for 0–3 feet and 3–10 feet. The total travel time for each cell is then interpreted using the near-surface pollution sensitivity criteria outlined in Table 3.

Table 3. Near-Surface Pollution Sensitivity Criteria

Near-Surface Pollution Sensitivity	Time of Travel	Description
High	<=170 hours	Hours to a week
Moderate	>170–430 hours	A week to weeks
Low	>430–1600 hours	Weeks to months
Very Low	>1600–8000 hours	Months to a year
Ultra Low	>8000 hours	More than a year
Special Conditions: karst, bedrockat or near surface, peatlands, disturbed lands	Not applicable	See descriptions in this section

Model Limitations

The maps generated through this process are generalized interpretations of near-surface sensitivity. They are intended to be used for resource protection planning and to help focus the gathering of information for site-specific investigations.

This model assumes that the matrix texture of soils and their parent material (surficial geology) are homogenous within mapped units. This model does not explicitly take into account other variables such as hydraulic head, soil compaction, drain tiles, macropores, or other soil heterogeneities. An overlay of dense soils can be created by querying the NRCS data, where appropriate, as dense soils will decrease infiltration. The NRCS may lower the hydrologic soil group if the soil is compacted, but this model does not account for compacted surficial geologic layers. Some investigators have found a correlation between matrix texture and the likelihood of subsurface fracturing (Kim and Christy, 2006).

Minnesota's geologic landscape is complex and there are areas where this sensitivity model cannot fully represent all near-surface materials. The basic two-layer method of estimating infiltration rates through soil and shallow geologic materials was applied to large portions of the state, with the exception of the regions where specific geological conditions dominate. These areas include karst, bedrock at or near surface, peatlands, and disturbed lands. Mapped karst areas were defined within 50 feet of the land surface (Adams and others, 2016), though some areas may have soil or shallow geologic materials within the 10 feet of the land surface. In these cases the karst conditions are assumed to play a larger role in the near surface pollution sensitivity, superseding the two layer method.

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Appendix A

Ranges of Saturated Hydraulic Conductivity (K_s) for Hydrologic Soil Group

Hydrologic Soil Group	NRCS,2007 [in/hr]	Rawls, 1998 [in/hr]	Ferguson & Debo, 1990 [in/hr]	Textural Description
A, A/D	>1.42	>5.3	>8.27	gravel, sandy gravel, silty gravel
	1.42	5.3–4.8	8.27	sand, fine sand, silty sand
B, B/D	1.42	2.6–2.3	2.41	silt, silty fine sand, loamy sand
	0.57	0.9–0.3	1.02	sandy loam, peat*
C, C/D	0.57	0.3–0.2	0.27	silt loam, loam
	0.06	0.14	0.17	sandy clay loam
D	<0.06	0.17-0.04	0.09-0.02	clay, clay loam, silty clay loam, sandy clay, silty clay

** Assumes Hemic Peat*

Appendix B

History of the Evolution of Transmission Rates

The transmission rates used to develop near-surface pollution sensitivity maps have changed over time with new data. The first instance of mapping near-surface time of travel was estimated using transmission rates from the NRCS (Barr, 2005). This approach was further refined by the MGS for the Scott County Geologic Atlas update(Tipping, 2006). The DNR adapted the MGS approach for the Part B atlases from Todd County (Petersen, 2010) through Benton County (Rivord, 2012).

The transmission rates were updated in 2014 for Chisago County (Barry, 2015) and again for the MHA in 2015. The DNR created a statewide transmission rate database in 2015 that defined two additional transmission rates used in the current method, based on the MGS Geological Mapping Database. This document outlines the current approach used by the DNR and provides supporting documentation for the transmission rates that are currently used in the mapping of near-surface pollution sensitivity.

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