Procedure for Determining Buried Aquifer and Bedrock Surface Pollution Sensitivity

based on

Cumulative Fine-grained Sediment (CFGS) Thickness

GW-02

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Introduction

This document provides documentation for procedures that Minnesota Department of Natural Resources (DNR) uses for determining buried aquifer and bedrock surface pollution sensitivity. DNR produces pollution sensitivity maps to assist local governments in protecting and managing their groundwater resources. Two types of pollution sensitivity maps are produced by the through the County Geologic Atlas Program, in collaboration with the Minnesota Geological Survey (MGS).

1. Near-surface pollution sensitivity (Minnesota DNR, 2012)
2. Pollution sensitivity of buried aquifers

The second is the topic of this reference document. These pollution sensitivity maps are a component of part B atlases and are available from the DNR County Geologic Atlas website: (http://www.dnr.state.mn.us/waters/groundwater_section/mapping/status.html).

Ratings for sensitivity to pollution are based on the estimated time required for water that is at or near the land surface to travel to and enter a subsurface water resource. Contaminants dissolved in water migrate through unsaturated and saturated sediments in a complex process. It is affected by biological degradation, oxidizing or reducing conditions, vertical hydraulic head gradient, and other factors, but these all cannot be considered in this method. The following assumptions are used in calculating estimated aquifer sensitivity to contamination from surficial sources.

- Flow paths are vertical and downward from the land surface through the soil and underlying sediments to an aquifer.
- A contaminant is assumed to travel at the same rate as water.
- A contaminant that is dissolved and moving within water from the surface is not chemically or physically altered over time.
- The sediment layers burying and separating buried sand and gravel aquifers are fine-grained and have low hydraulic conductivity. This method does not consider differences in sediment texture or permeability of nonaquifer materials. The method only considers the thickness of fine-grained sediment between aquifers.
- No vertical hydraulic head gradient is specified. Changes in hydraulic head conditions are induced by groundwater withdrawals or other temporal changes and are not considered.

The sensitivity rating for the buried sand and gravel aquifers (subsequently referred to as *buried sand aquifers*) and the bedrock surface are shown in Figure 1. The ratings are based on estimated vertical travel time to the aquifer of interest as defined by the Geologic Sensitivity Workgroup (1991). The travel time to buried sand aquifers varies from days to thousands of years. Areas with relatively short travel times of less than a few years are rated high or very high. Areas with estimated travel times of decades or longer are rated low or very low.

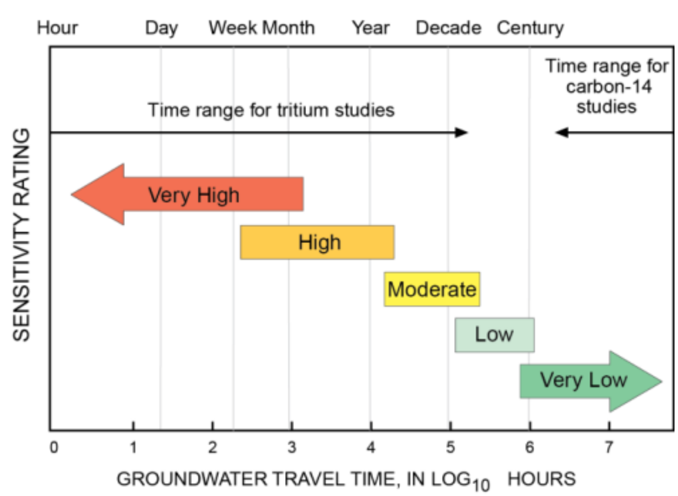

Figure 1. Geologic sensitivity rating for the buried sand aquifers and the bedrock surface, as defined by vertical travel time (Geologic Sensitivity Workgroup, 1991)

Sensitivity Methods and Maps

The DNR uses geographic information systems (GIS) for mapping pollution sensitivity of buried sand aquifers and the bedrock surface based on the cumulative fine-grained sediment (CFGS) thickness overlying a target aquifer. The method uses the spatial analyst functions of ArcMap to determine this thickness and to interpret pollution sensitivity. The procedures used in this method are applicable when working in an area that has a stacked series of fine-grained sediments (usually glacial tills) and sand aquifers, but it is not readily applied to regions dominated by shallowly buried bedrock.

There are three steps for determining buried aquifer pollution sensitivity:

1. **Map the geology**
   Map and create three-dimensional geologic surfaces (rasters) of the area being investigated. Include land surface elevation, Quaternary units, and the bedrock surface if relevant.
2. **Combine the fine-grained sediments**
   Combine the fine-grained sediment thickness rasters to determine the cumulative thickness of fine-grained sediments overlying each buried sand aquifer (or the bedrock surface).
3. **Limit the extent**
   Limit the extent of the cumulative thickness rasters to match the buried sand aquifer, so that the end map is only showing areas where the aquifer or bedrock surface is present.

1. Map the geology

Map all of the fine-grained sediment layers and sand aquifers in the study area using a GIS raster format. A raster grid layer consists of regularly spaced squares or cells, each having a numeric value. The scale for the cell size can vary depending on the type of resolution that is appropriate for a given application. A 30-meter cell size is adequate for 1:100,000 scale mapping. The method requires rasters of the fine-grained sediment thickness across the area of interest (calculated by subtracting the base of a fine-grained sediment from its top), as well as GIS rasters indicating the mapped extent of each buried sand aquifer (for this method we use the top of the buried sand aquifer to represent the aquifer extent).

Elevation and thickness rasters for the fine-grained sediments and buried sand aquifers have been generated for county geologic atlases during production of the Part A since 2007. These can be accessed through the Minnesota Geologic Survey (MGS) and most can be downloaded from the MGS County Geologic Atlas website (http://www.mngs.umn.edu/county_atlas/countyatlas.htm).

2. Combine the fine-grained sediments

Develop a simplified vertical recharge model that describes how water from precipitation infiltrates the surface materials and recharges the surficial or shallow aquifers, then migrates vertically downward to recharge portions of underlying deeper aquifers. The central concept of this process is *focused recharge*. Focused recharge occurs where aquifers overlie each other and are connected vertically by pathways that allow water to penetrate from the land surface into even the deepest aquifers.

The sensitivity model for buried aquifers assumes the thickness of fine-grained sediment overlying an aquifer is inversely proportional to the sensitivity of an aquifer. In other words, the thicker the cumulative fine-grained material overlying an aquifer, the longer it will take for water infiltrating at the land surface to reach the aquifer. A cumulative thickness of 10 feet or less is rated very high, a cumulative thickness greater than 40 feet is rated very low, and an intermediate thickness has an intermediate sensitivity rating (Figure 2).

Cumulative thickness of fine-grained sediment overlying the aquifer (in feet)				
≤ 10	>10 to 20	>20 to 30	>30 to 40	>40
VH	**H**	**M**	**L**	**VL**

Figure 2. Pollution sensitivity rating matrix for the buried sand aquifers and the bedrock surface. Thicknesses were modified from the discussion of fine-grained layers in "Criteria and Guidelines for Assessing Geologic Sensitivity of Ground Water Resources in Minnesota" (Geologic Sensitivity Workgroup, 1991).

The ArcGIS raster calculator is used to generate a cumulative thickness grid for all the fine-grained sediments overlying a buried sand aquifer (or bedrock surface).

Note that the raster calculator will not add null values in rasters. Running the following conditional statement will convert null cells to zero, but otherwise keep the original raster value.

Con(IsNull("fine-grained sediment thickness raster"), 0, "fine-grained sediment thickness raster")

After converting null values, adding the thickness rasters for all the fine-grained sediments above an aquifer together determines the cumulative fine-grained sediment thickness above an aquifer (Figure 3-4 and Table 1).

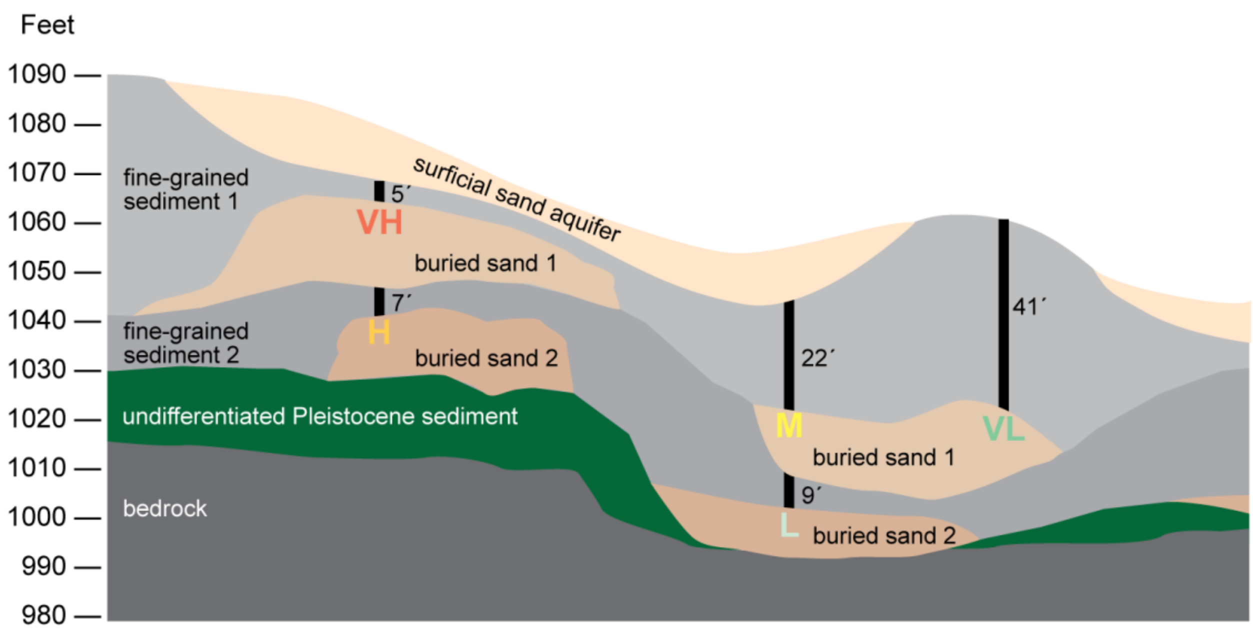

Figure 3. Cross section showing examples of pollution sensitivity ratings based on the cumulative thickness of overlying fine-grained sediments. Each of the vertical black lines in the figure is labeled with the thickness of fine-grained sediment. The letter designator at the base of the line indicates the sensitivity rating that the cumulative thickness corresponds to.

Table 1. Example of a stratigraphic column (based on Figure 3), with the fine-grained sediment layers that would be added together to determine the cumulative thickness overlying the buried sands.

Geologic Unit	Cumulative Fine-grained sediment Thickness
Surficial Sand	
Fine-grained sediment 1 (FGS1)	
Buried Sand 1	FGS1
Fine-grained sediment 2 (FGS2)	
Buried Sand 2	FGS1 + FGS2
Undifferentiated Pleistocene Sediment (UPS)	
Bedrock Surface	FGS1 + FGS2 + UPS

Raster Calculator Expression:
FGS1 Thickness + FGS2 Thickness = Buried Sand 2 Cumulative Fine-grained Sediment Thickness Raster

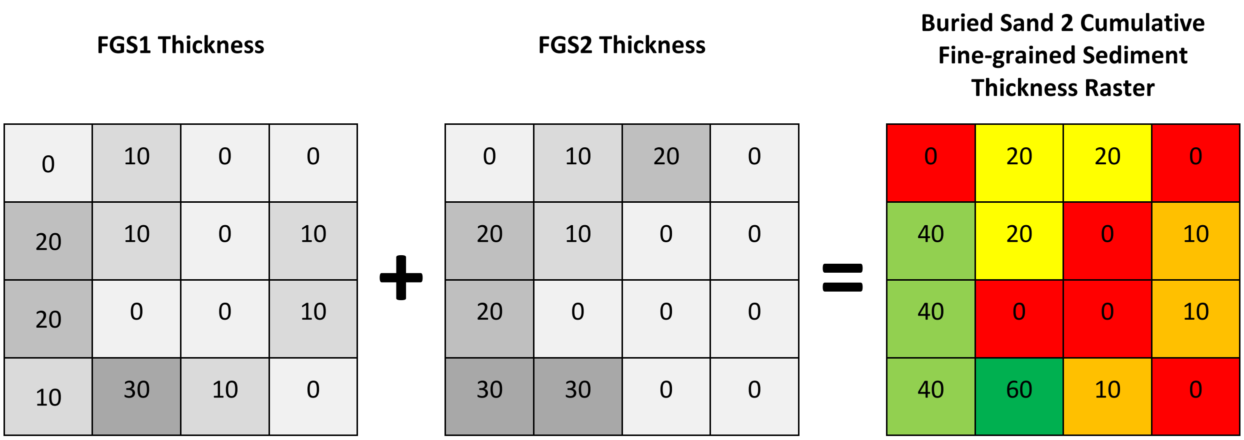

Figure 4. GIS raster calculations used to create pollution sensitivity maps. In this example, a hypothetical "Fine-grained Sediment 1 Thickness (FGS1)" is added to "Fine-grained Sediment 2 Thickness (FGS2)" to yield the "Cumulative Fine-grained Sediment Thickness Raster for Buried Sand 2." The two FGS rasters are color coded based on the thickness: darker gray represents thicker areas of fine-grained sediment. The end result is the cumulative fine-grained sediment thickness for Buried Sand 2. This raster is color coded based on the pollution sensitivity rating matrix (Figure 2).

3. Limit the extent

Limit the extent of the raster for the cumulative fine-grained sediment thickness to the extent of the buried aquifer. This can be accomplished by using the following expression in the raster calculator:

SetNull(IsNull(''top of sand raster''), ''cumulative fine-grained sediment thickness raster'')

This expression will assign a null value to a raster where the sand does not exist. The end result of this calculation is then color coded to match the pollution sensitivity ratings in Figure 2 to complete the pollution sensitivity map.

Method Limitations

The CFGS thickness method is dependent on the assumption that the thickness of the fine-grained layer is directly related to permeability and vertical flow rate. The matrix texture of fine-grained layers is not considered, unlike the Procedure for Determining Near-Surface Sensitivity (Minnesota DNR, 2012). The texture of sediment layers that are nonaquifer units varies greatly across the State of Minnesota, from sandy loam to clay. Actual rates for flow through the subsurface materials are not calculated in this method. The method assumes only downward vertical flow. Even though horizontal flow paths may be important in specific instances, they are not considered in this sensitivity method. Artificial pathways that may allow contaminants to move across a confining layer are not considered, such as wells that are improperly constructed, maintained, or unsealed.

In areas with thick Quaternary sediment (deeply buried bedrock), the deeper sediment is often mapped as undifferentiated Pleistocene sediment (UPS). In the CFGS thickness method, these undifferentiated sediments are assumed to be fine-grained materials, but could contain sand and gravel deposits that would allow continued focused recharge farther into the subsurface.

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

Verification of pollution sensitivity maps with chemistry data

Chemistry and isotope analysis of groundwater samples are useful for evaluating and verifying the calculated sensitivity ratings of the buried aquifers (or bedrock surface). The chemistry data are compared to the pollution sensitivity rating as an independent check on the sensitivity model. Tritium concentrations are used to indicate the relative residence time of groundwater and are also used to affirm the sensitivity ratings. Because tritium has a relatively short half-life of 12.32 years (Lucas and Unterweger, 2000), the meaning of the absolute tritium concentrations in a groundwater samples changes over time. For atlases produced since 2013, the following definitions for tritium age are used:

- **Cold War era**: water entered the ground during the peak period of atmospheric tritium concentration from nuclear bomb testing, 1958–1959 and 1961–1972 (greater than 15 tritium units [TU]).
- **Recent**: water entered the ground since about 1953 (8 to 15 TU).
- **Mixed**: water is a mixture of recent and vintage waters (greater than 1 TU to less than 8 TU). Mixed tritium-age results indicate that at least a portion of the groundwater has been recharged since the 1950s.
- **Vintage**: water entered the ground before 1953 (less than or equal to 1 TU). Vintage tritium ages are consistent with predominantly very low pollution sensitivity ratings.

Elevated chloride concentration in samples equal to or greater than 5 parts per million (ppm) may indicate a local anthropogenic source of chloride; this usually implies a moderate or higher sensitivity. In water samples with elevated chloride the ratio of chloride to bromide can help determine whether the chloride is natural or anthropogenic. Elevated ratios of chloride to bromide concentrations (Cl/Br) greater than 300 indicate a likely anthropogenic source of chloride that usually implies moderate to high sensitivity (Davis and others, 1998).

In a few cases elevated chloride is found in deeper groundwater samples with no detectable tritium. In such instances, the chloride source is probably from a deeper aquifer. Concentrations of nitrate in groundwater greater than approximately 1 part per million (ppm) indicate anthropogenic sources and aquifer sensitivity (Minnesota Pollution Control Agency, 1998). The drinking water health standard for nitrate is 10 ppm. The Minnesota Pollution Control Agency (2001) found that the concentration of nitrate in groundwater was related to surrounding land use, and that nitrate concentrations were greatest under irrigated agricultural land and unsewered residential land.

References

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