Evaluation of Groundwater and Surface-Water Interaction: Guidance for Resource Assessment

Twin Cities Metropolitan Area, Minnesota

Prepared for
Metropolitan Council

June 2010

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1.0 Introduction

Surface water features, and the natural and recreational resources that they support, are a recognized asset to the region. The hydraulic connection between the region's surface water and groundwater systems makes our lakes, streams, and wetlands vulnerable to increasing groundwater withdrawals for growing urban demand.

In development of the Twin Cities Metropolitan Area Master Water Supply Plan, the Metropolitan Council identified the need for a screening method to identify areas where groundwater withdrawals were most likely to have an impact on surface waters. In these areas, further characterization of the groundwater-surface water connection may be an important part of local water supply development. Initial screening methods indicated several areas with potential for groundwater pumping to impact surface water features (Metropolitan Council, 2009). This current study was conducted to: (1) prioritize surface water features for impact monitoring and resource assessment and (2) recommend monitoring and analysis techniques that will provide early warning to water supply managers to help avoid impacts on surface water features from groundwater pumping.

This information and the tools generated through this project are intended to support water appropriation permitting, sub-regional water supply management plan development, re-calibration of the Metropolitan Council's regional groundwater flow model (Metro Model 2), and future updates of the Twin Cities Metropolitan Area Master Water Supply Plan.

The method presented here was designed to incorporate new information as it is generated; the Council intends to apply this method again as new information becomes available, including local water balance and resource assessment studies, geologic mapping, and effective management strategies.

2.0 Assessment of the Potential Vulnerability of Surface-Water Features to Groundwater Pumping

Recognizing the seemingly insurmountable challenge of protecting the eleven-county metro's 120,000 lakes, wetlands, streams, and springs from degradation due to groundwater withdrawals, this project recommends monitoring and management strategies be prioritized based on the vulnerability of surface water features to impacts from pumping.

To assess the vulnerability of surface-water features to groundwater pumping, a vulnerability scoring system was developed. Use of a scoring system approach allows for a systematic and transparent process to determine the vulnerability of each surface-water feature. A scoring system is also able to account for some uncertainty and can incorporate small datasets that may be applicable to only a few surface-water features. Potential vulnerability to pumping for each surface-water feature can also be easily updated or modified as additional data are collected.

The scoring system used to assess the potential vulnerability of surface-water features to groundwater pumping involves several components. First, the connection of the surface water feature to groundwater is evaluated. Then, based on geology, the potential vulnerability of the feature to groundwater pumping is evaluated. Finally, characteristics of the features, such a bathymetry or sensitive biota, are considered. A flow chart showing the different components is shown in Figure 1.

2.1 Scoring System Datasets

The main data components used for the scoring system include wetland, lake, stream, and spring GIS feature classes (and associated attributes such as depth and biota); geology raster grids representing the top and bottom elevation of low permeability units; and a regional water table surface. The source and development of these data are discussed in the following sections.

2.1.1 Surface-Water Features

Surface-water features analyzed for potential vulnerability to groundwater pumping were compiled from several different sources. Lake and wetland data from the U.S. Fish and Wildlife Service National Wetlands Inventory (NWI) dataset (U.S.F.W.S., 2008) and Minnesota Department of Natural Resource (DNR) Public Waters Inventory (PWI) Basin Delineations dataset (MN DNR, 2008a) were combined; where overlap occurred, feature geometry and attributes from the PWI were used. Wetlands from the NWI that overlap calcareous fens, as mapped by the Minnesota DNR

(MCBS et al., 2008), were given attributes of calcareous fens. Details regarding data processing to merge the NWI, PWI, and DNR calcareous fen datasets are presented in the GIS metadata for the lake and wetland basin features.

Streams and river data were taken from the Minnesota DNR PWI Watercourses Delineations dataset (MN DNR, 2008b). Streams in this dataset were broken down arbitrarily into approximately 1,000 meter segments for analysis. A segment length of 1,000 meters was chosen as it allows for sufficient detail in determining stream segments that are disconnected from groundwater without having too many segments making the analysis for the entire eleven-county metro area overwhelming. For each 1,000 meter segment, a polygon was created using stream widths approximated from aerial photos. Each stream segment polygon was then analyzed for potential vulnerability to groundwater pumping in a similar manner as wetland and lake basins.

Spring features were obtained from the Minnesota DNR Karst Feature Inventory Points dataset (MN DNR, 2003).

2.1.2 Geology Datasets

Surficial geology maps and Quaternary stratigraphy models published by the Minnesota Geological Survey were used in the scoring system. Quaternary stratigraphy models have been developed for Carver, Chisago, Scott, and Washington counties and part of the northwest metro (Meyer and Tipping, 1998; Meyer and Tipping, 2007; Lusardi and Tipping, 2006; Lusardi and Tipping, 2009; Meyer, 2010). In these areas, the top and bottom of till and sand units have been defined from ground surface to the top of bedrock. Surficial geology maps are available in most of the areas where Quaternary stratigraphy models have not been developed, but they define only the uppermost geologic unit (Meyer and Patterson, 1999; Meyer and Lusardi, 2000; Meyer et al., 2001; Meyer, 2007; Meyer, 2008). No surficial geology map or Quaternary stratigraphy model exists for western Wright County.

2.1.3 Regional Water Table

A regional water table map was created to evaluate the connection of each surface-water feature to groundwater. The regional water table surface is different than a map of the phreatic surface in that the phreatic surface includes perched groundwater zones and small local flow systems. Inclusion of perched groundwater zones are not appropriate for this study as they likely show no response to changes in regional pumping of deeper aquifers. Small, local flow systems could potentially be affected by groundwater pumping but are beyond the scope of this regional assessment.

To construct the regional water table map, water-level data from a number of different sources were compiled. The main sources of data included; Minnesota Department of Natural Resources (DNR) water table observation wells, static water levels from the Minnesota County Well Index (CWI), and monitoring well data compiled from numerous environmental studies conducted by Barr Engineering. Results from regional groundwater flow models and surface-water elevations for reaches of some streams known to be gaining were also used as a control, particularly where data from other sources were sparse. Surface-water elevations for lakes and wetlands are commonly used in defining the water table surface; however, they were not used for this study as they would skew the intended purpose of the regional water table map – evaluating the connection of surface-water features to groundwater.

A significant amount of data processing and filtering was conducted to eliminate outliers in the datasets and remove data points representing perched zones. The majority of the data processing focused on static water levels from the CWI. The CWI is a valuable source of data as it extensively covers most of the study area; however, the disadvantage of the county well index is the large degree of erroneous and conflicting data. Sources of error in the CWI include:

- Inaccuracy of water level measurement – drilling contractors (especially for wells drilled decades ago) may not have used precise measuring devices.
- Inaccuracy in well location – many wells are identified only to the nearest quarter-quarter-quarter section (300 to 600 feet of location error).
- Inaccuracy in well elevation – well elevations are typically estimated using 7.5-minute topographic maps and are also subject to errors in location.
- Water levels may not have stabilized at the time of measurement – water levels are typically collected during or immediately after well installation or development and may not have reached equilibrium with the aquifer.
- Hydrostratigraphic units misidentified or screened/opened intervals not correctly assigned in the databases – the well may actually be screened in a different unit or in multiple units.
- Water level affected by seasonal pumping – depending on where the well is located and at what time of year it was installed, the water level measured by the drilling contractor may have been affected by seasonal pumping.
- Water levels affected by season and year of installation – water levels from different wells typically represent the entire range of possible dates and times of the year and thus are a composite of many years of data.

Given these sources of unavoidable uncertainty, water levels are typically assigned a likely error of at least +/- 20 feet. It is not uncommon to find two nearby measurements in the same aquifer with substantially different values.

Several methods were used to filter the CWI data. First, wells not screened near the water table, or wells open to multiple aquifers, were removed. A cutoff of 30 feet between the top of the screen and the static water level was used as defining wells screened near the water table. A distance of 30 feet was chosen based on potential error in the CWI dataset and distribution of wells remaining after this step. A smaller cutoff, such as five, or ten feet, could have been used but would have left a small number of wells with an uneven distribution.

After filtering the CWI data to those wells representative of the water table, cross validation was performed to remove outliers. Cross validation compares an observed value to that of an estimated, or interpolated, value at the location of the observed value. It is an iterative process where, first, a single data point is removed from the dataset. Then, a value is interpolated at the location of the removed data point. A residual, or error, is then calculated as the difference between the interpolated value and the observed value. The value that was removed from the dataset is then put back into the dataset and the process is repeated for all observed data points. All observations with an absolute residual of 20 feet from the cross validation were removed.

After cross validation of the CWI dataset, data from all sources were combined and interpolated to a regional water table surface. The regional water table surface was visually inspected for localized highs and lows potentially representing outliers or perched zones. In suspect areas, the local geology and, if available, results from groundwater flow models were used to determine if the data point(s) should be removed from the dataset. This process was repeated several times until a satisfactory regional water table surface was established (Figure 2).

2.2 Connection with Regional Groundwater System

The first step in assessing the vulnerability of each surface-water feature to groundwater pumping was to determine if the feature is hydraulically connected to the regional groundwater system. Surface-water features not connected to the regional groundwater system (i.e. perched or disconnected features) were automatically classified as being not vulnerable to groundwater pumping.

Perched features were identified by comparing the regional water table elevation to the elevation of the bottom of the surface-water feature (e.g. elevation of lake at maximum depth). Bottom elevations for features were determined by subtracting the maximum depth from the water surface elevation. Feature depths were determined in several ways. Where available, the maximum depth from the MN DNR Lake Finder database was used. For features not in the Lake Finder database estimates were used. Lake and wetland depth estimates were based on Cowardin class as defined in the NWI dataset. Table 1 lists the different wetland classes and assigned depths. For rivers and streams an assumed depth of 5 feet was assigned to all. Surface-water elevations were determined using the Minnesota DNR lake stage data, stream gauge data, or minimum surface elevation from a 30m digital elevation model.

Surface-water features greater than 25 feet above the regional water table were considered to be perched, and assessed as not vulnerable to groundwater pumping. The connection between groundwater and surface-water features was considered to be indeterminate for surface water features 5 feet to 25 feet above the regional water table. Surface-water features less than five feet above the regional water table surface are generally considered connected to groundwater.

Surface-water features connected to groundwater, and features with an indeterminate connection, were further evaluated to determine the vulnerability of the feature to groundwater pumping. Additional data were considered, including the presence or absence of local low permeability geologic units, biota data (trout stream, calcareous fen, etc), and selected local studies (e.g. water balance studies).

2.3 Low Permeability Unit Score

The nature of the geologic units beneath a surface-water feature affects the way that feature responds to groundwater pumping. The presence of low permeability units may attenuate or eliminate effects of groundwater pumping, depending upon their hydraulic properties, thickness, and horizontal extent. Each surface-water feature was assigned a low permeability unit score (LPU-score) which reflects the thickness and extent of low permeability units near each feature. Calculation of the LPU-score considers three components (Figure 3): (1) relationship of the surface-water feature to surficial low permeability units (i.e. does the feature reside within a low permeability unit), (2) cumulative thickness of unconsolidated low permeability units below the water table, and (3) the presence of shallow bedrock confining unit(s).

2.3.1 Low Permeability Unit Score – Part 1 – Connection with Surficial Low Permeability Units

The fist component of the LPU score, represented as an 'LPU connection score', is an evaluation of the connection between the bed of the surface-water feature and surficial low permeability units. It is assumed that a lake that sits directly within a large till body is likely influenced very little by changes in groundwater levels, with the lake water-budget more likely controlled by surface-water flows. Alternatively, a lake that sits within a higher permeability outwash unit is likely very sensitive to regional groundwater changes and a larger component of the water budget for the lake is likely controlled by groundwater flows.

Each surface-water feature was evaluated to determine if it is in direct connection with surficial low permeability units. Quaternary stratigraphy model grids representing the tops and bottoms of low permeability units were processed to evaluate the thickness of the units at the surface. If a low permeability unit at the surface is directly underlain by another low permeability unit (i.e. no sand or gravel between the units) they were combined to establish a total thickness. In areas where Quaternary stratigraphy models have not been developed, and only surficial geology maps are available, the thickness of low permeability units at the surface was estimated based on nearby stratigraphy models and geology from the CWI.

For a surface water feature to be considered to sit within a low permeability unit the feature must be entirely surrounded by the low permeability unit and the unit must extend at least 10 feet below the bottom of the surface-water feature. For features that meet this criterion three points are assigned to the LPU score.

Springs are not considered for Part 1 of the LPU score as the influence of surficial geology plays no role it their vulnerability to groundwater pumping.

2.3.2 Low Permeability Unit Score – Part 2 – Thickness Score

The second component of the LPU-score, represented as an 'LPU thickness score', is an evaluation of the cumulative thickness and extent of unconsolidated low permeability units below the water table. It should be emphasized that the LPU thickness score is only applicable to assessing the vulnerability of surface water features to pumping from bedrock sources. The vulnerability of a surface-water feature to pumping from the surficial aquifer should not consider the LPU thickness-score; Part 1 of the LPU score (connection with low permeability units) is more applicable in assessing the vulnerability associated with pumping from the surficial aquifer.

The unconsolidated sediment within a 2,000-meter buffer area around each surface-water feature was analyzed. The analysis extent was chosen based on an expected cone of depression from a typical high capacity well open to a lower bedrock aquifer. The thickness of each unit below the water table was evaluated using grids representing the top and bottom of each unit and the regional water table surface as described in Section 2.1.3. The saturated thicknesses of each unit were then summed together to established a cumulative saturated thickness of low permeability units below the water table.

For every ten feet of cumulative low permeability thickness one point was assigned, up to a maximum of 10 points (equivalent to 100 feet of low permeability sediments below the surface-water feature). If, anywhere within the analysis extent, the cumulative thickness of low permeability units was less than 10 feet, a score of zero was assigned (indicating that low permeability sediments are either not present or are less than 10 feet thick).

An alternative methodology tested was to consider each low permeability unit individually when assigning a score, rather than using a cumulative thickness. However, this method proved to be problematic for several reasons. In areas of complex stratigraphy, or areas mapped in greater detail, small sand lenses within larger till bodies had the effect of limiting the ability of the till bodies to contribute to the score. Also, at the boundaries between different datasets it is difficult to correlate till units as they are often mapped in varying degrees of detail. This results in surface-water features along these boundaries receiving lower LPU scores. After several iterations comparing the results of the two methodologies it was chosen to lump the units together into a cumulative thickness.

2.3.3 Low Permeability Unit Score – Part 3 – Shallow Bedrock Confining Units

The final component of the LPU-score considers the presence of shallow bedrock confining units beneath surface-water features. Bedrock units considered in this analysis are the Decorah Shale, Cummingsville Formation, Platteville Formation, and the Glenwood Formation (Mossler and Tipping, 2000). The analysis for Part 3 of the LPU-score is similar to Part 2, except a thickness of the shallow bedrock confining units is not considered. Thickness of the bedrock units was not considered because the continuity of the bedrock units is much more certain than with till units, which are typically discontinuous. Also, experience has shown that these bedrock units nearly always result in the development of significant head difference with respect to underlying units. If one or more of these units are present within the entire 2,000 m analysis extent of a feature an additional three points are assigned to the LPU-score.

2.4 Biota Data

Some surface-water features have biotas that are extremely sensitive to changes in groundwater levels or flows. Two types of these features, trout streams and calcareous fens, are protected by Minnesota Statutes and Rule. Minnesota Rule 6264.0050 Subpart 4 lists the reaches of designated trout streams in Minnesota. Minnesota Statute 103G.223 and Rule 8420.0935 protect calcareous fens. Because of the special groundwater dependence of these features, and protection provided by Minnesota Statue, small-scale local studies are necessary to assess the vulnerability of these features to groundwater pumping. For this study the vulnerability of trout streams and calcareous fens are automatically considered vulnerable regardless of local geologic conditions.

2.5 Local Studies

The scoring system is designed so that additional local studies can be incorporated as they are completed. Because these studies often range in the level of detail and applicability to assessing potential impacts from groundwater pumping they need to be incorporated manually. A typical local study may involve the installation of piezometers to monitor for potential pumping influences in the shallow groundwater near a surface-water feature. If the results of such a study indicate that pumping does not affect the feature, the vulnerability may be manually adjusted noting the results of the study.

The one exception to manual adjustment based on local studies is a water balance study. If a water balance study indicates that groundwater makes up less than 10 percent of the total inflow and/or outflow for a lake, indicating the lake is mostly controlled by surface-water flow, an additional two points are added to the vulnerability score.

2.6 Physical Characteristics

The bathymetry, or geometry, of a lake basin is important in determining potential impacts from groundwater pumping. While the bathymetry plays no role in determining if a lake is vulnerable or not, it does indicate how changes in the water table may impact the lake. Lakes with wide littoral zones have a greater potential of being negatively impacted by changes in water levels. For lakes where bathymetry grids are available from the Minnesota DNR, additional basin characteristics were calculated. For this study, lakes that are less than five feet deep over more than 20 % of the total surface area are considered to be more sensitive to changes in lake level. These lakes are generally disproportionately shallow as indicated by the relative hypsographic curves presented in Appendix A. Many of these lakes may be relatively deep but tend to have broad, shallow shorelines. Lakes that are considered vulnerable to groundwater pumping and fall within this criteria may require greater priority is setting up potential monitoring and management plans. Detailed records of lake stage are particularly import for these lakes.

3.0 Results of Vulnerability Assessment

Results from the vulnerability assessment are shown in Plate 1 and Plate 2. Plate 1 represents the potential vulnerability of surface-water features to groundwater pumping from bedrock aquifers. Plate 2 represents the potential vulnerability of surface-water features to pumping the surficial aquifer. The potential vulnerabilities shown in Plate 2 only includes the LPU-score part 1, as the other LPU-score components are not appropriate for assessing vulnerability from pumping the surficial aquifer. Features with a total vulnerability score greater or equal to three, or features that are disconnected from groundwater, are considered not vulnerable to groundwater pumping; all other features are considered vulnerable. A value of three was chosen as it represents surface water features that sit within a low permeability units and features where at least 30 feet of low permeability sediments are present below the water table within the analysis extent around each feature.

The potential vulnerabilities as shown in Plates 1 and 2 are intended as a screening tool (1) to help prioritize surface water features for impact monitoring and resource assessment and (2) help guide monitoring and management plans. It is important to recognize, that for this assessment, all surface water features were initially considered to be vulnerable to groundwater pumping unless components of the scoring system suggested otherwise. In areas where specific data are lacking, particularly in counties outside the core seven-county metro area, many surface-water features may be classified as potentially vulnerable simply as a result of a lack of data.

As additional data are collected, and specific monitoring plans implemented, the vulnerability of a surface water feature is subject to change. Successful resource protection is more likely if additional monitoring and data collection, geared toward evaluating the relationship between surface-water features and groundwater pumping, are conducted proactively prior to impacts occurring.

In the eleven-county metro area 33 percent of the surface water features were determined to be potentially vulnerable to groundwater pumping. Certain geographic areas tend to have fewer vulnerable features compared to others; general regional trends are discussed below.

The majority of surface-water features in Scott County, Carver County, western Hennepin County and eastern Wright County are classified as not vulnerable to pumping. The low vulnerability of these features is primarily due to thick and extensive sequences of low permeability till, particularly at the surface. In these areas many of the deeper lakes are classified as being potentially vulnerable, most often because the low permeability tills at the surface do not extend as deep as the lakes.

Large areas of Sherburne, Anoka, and Isanti counties have many potentially vulnerable surface water features. The vulnerability of these features is primarily due to a lack of low permeability units at the surface and a lack of geologic data at depth (mostly in Sherburne and Anoka counties).

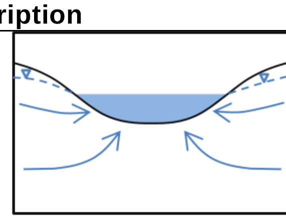
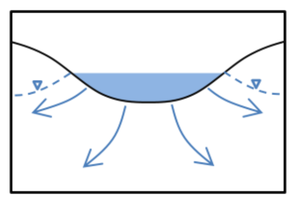
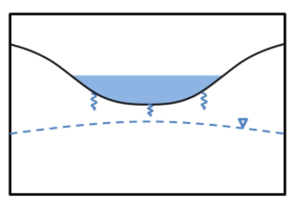
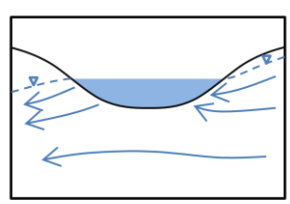
The potential vulnerability of surface-water features within Chisago, Washington and Ramsey counties is mixed and depends mostly on surficial geology and if the feature is connected or disconnected from groundwater.

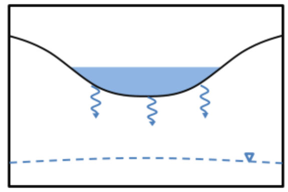
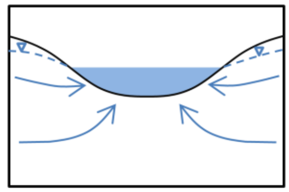
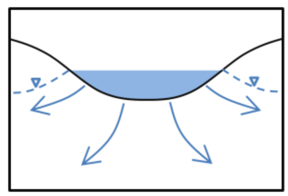
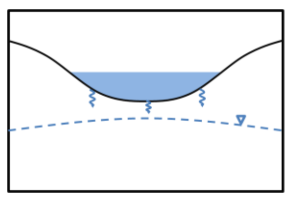
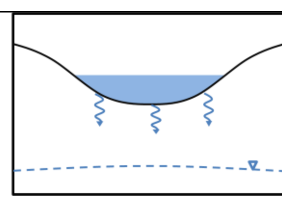
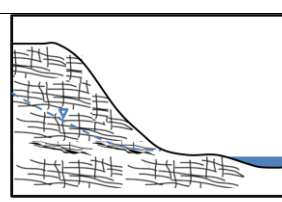
Most surface water features in Dakota County are classified as not vulnerable to impact from groundwater pumping. However, the upper parts of the Vermillion River, Cannon River and associated wetlands are considered potentially vulnerable to groundwater pumping. The Vermillion River is of particular importance because it is a designated trout stream.

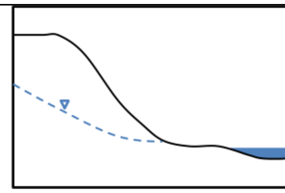
The major rivers (e.g. Mississippi, Minnesota, and St. Croix) are classified as being potentially vulnerable to groundwater pumping, primarily because of their connection to groundwater and lack mapped low permeability units in the major river valleys. The groundwater contribution to these rivers as they flow through the Twin Cities metro area is unknown, and difficult to measure. Further evaluation of the groundwater contribution for these rivers through the metro area may merit a re-evaluation of potential vulnerability to groundwater pumping.

4.0 Groundwater-Surface Water Interaction Type

To aid in developing monitoring and management plans each surface water feature was classified based on how groundwater and surface water interact. This analysis involved comparing the surface water elevation for each feature to the regional water table. Surface water elevations for each feature were obtained from either the Minnesota Lake Finder database; USGS, MN DNR, Metropolitan Council stream stage data; or surface elevations from a 30m digital elevation model. The table below describes each interaction type and qualifiers used in defining the interaction type for each feature.

Type	Description		Qualifiers
Discharge lake/wetland	Mostly receives groundwater inflow		Connected to groundwater, surface water elevation below regional water table
	Note: Fens are a type of discharge wetland. Special considerations are necessary for calcareous fens as they are protected by Minnesota Statute.		
Recharge lake/wetland or Indeterminate	Connected to groundwater. Mostly loses water as seepage to groundwater		Groundwater connection is indeterminate, regional water table lower than surface water elevation. Uncertainly in regional water table make it difficult to distinguish between features that are connected and those that are disconnected to groundwater.
	Disconnected to groundwater. Water table slightly below lake bottom. Fluctuations in the water table can affect the flow dynamics out of lake.		
Flow-through lake/wetland	Groundwater flow both into and out of lake/ wetland		Connected to groundwater, surface water elevation above or equal to regional water table

Disconnected lake/ wetland with deep water table	Water table deep below feature. Loss of water into the unsaturated zone. Change in water table has no effect on feature		Disconnected from groundwater
Graining Stream	Groundwater flow into stream		Connected to groundwater, surface water elevation below regional water table
	Note: Trout streams are a type of gaining stream. Special considerations are necessary for trout streams as they are protected by Minnesota Statute.		
Losing Stream or Indeterminate	Mostly loses water to aquifer system		Groundwater connection is indeterminate, regional water table lower than surface water elevation. Uncertainly in regional water table makes it difficult to distinguish between features that are connected and those that are disconnected from groundwater.
	Water table slightly below stream bottom. Loss of water to the unsaturated zone. Fluctuations in the water table can affect the flow dynamics out of the stream.		
Disconnected Stream with deep water table	Water table deep below stream bottom. Loses water to the unsaturated zone. Change in water table has no effect on stream.		Disconnected from groundwater
Karst Spring	Flow from spring controlled by karst flow and/or low-permeability layers		Shallow bedrock

Non-Karst Spring	Flow from spring controlled by porous media flow.		Deep bedrock
Note: Classification of springs is difficult without specific field data. For this study, springs that are in areas where bedrock is near the surface are classified as karst springs. Depth to bedrock mapped by Jirsa et al. (2010) was used. Because of this dataset is relatively coarse and elevations change rapidly where many springs are located (river valleys) a depth of bedrock of less than 75 feet was used to classify karst springs.			

5.0 Uncertainty and Verification of Vulnerability Assessment

Some uncertainty in the assessment of potential vulnerability of surface-water features to groundwater pumping occurs as a result of the data available. The availability of geologic data affects the LPU-score component of the vulnerability scoring system. In areas with less robust data, the LPU-score may overestimate surface-water feature vulnerability to groundwater pumping. For example, in areas where Quaternary stratigraphy models are available, all potential low permeability units above the bedrock are considered in assessing the vulnerability to pumping; in areas where only surficial geology is available, deeper low permeability units that may be present are not considered. The scoring system is set up so that as more geologic data becomes available scores can be updated and vulnerabilities reassessed based on the new data. Plate 3 shows the available data used for the vulnerability scoring system.

As a form of verification of the vulnerability assessment, a limited number of previous studies for specific water bodies and studies of the groundwater surface-water interaction for smaller regions were compared to preliminary results of this study.

Dean Lake

Dean Lake is a shallow lake approximately 200 acres in size, located at the base of a bluff on a terrace of the Minnesota River near the city of Shakopee in Scott County. Results from Samstad (1975) indicate that the lake is well connected to the regional water table and the basin sits within sand and gravel alluvial deposits that lie directly over Prairie du Chien Group limestone and dolomite. Results from Samstad (1975) are consistent with those of this study which indicate that Dean Lake is connected to groundwater, and has a vulnerability score of zero, indicating that it is potentially vulnerable to groundwater pumping.

Vadnais Lake

Vadnais Lake, located in Ramsey County, consists of two basins, east and west. The west basin is approximately 215 acres and the east basin is approximately 390 acres. Ruhl (1994) studied the interaction of groundwater and surface water for the east basin, and concluded that the lake is connected to groundwater, with groundwater flow into the lake on the northern shoreline and groundwater flow out of the lake on the eastern, southern, and western shorelines. These results are consistent with this study, which classifies Vadnais Lake as a flow-through lake. Ruhl (1994) also concluded that the groundwater component of the lake water-budget is small relative to surface-water flows. However, discrepancies in different methods for determining the groundwater net seepage make it difficult to apply points to the vulnerability score based on the groundwater component of the lake water-budget (see section 2.5). Vertical gradients between the lake and the Prairie du Chien-Jordan aquifer, as measured by Ruhl (1994), are about 4.5 x 10^{-1} downward. Ruhl (1994) suggested that these gradients, and resultant groundwater seepage out of the lake, may be affected by pumping from high capacity wells near the lake. The possibility of pumping affecting seepage out of the lake supports the vulnerability assessment from this study, classifying Vadnais Lake as potentially vulnerable. Further monitoring is necessary to define possible pumping influences and refine the groundwater component of the lake water-budget.

White Bear Lake

White Bear Lake is located in northeastern Ramsey County and northwest Washington County. Large flucuations in the water levels of White Bear Lake have been a concern for many years. A comprehensive study of the hydrology of the lake was conducted by the Minnesota DNR in 1998 (MN DNR, 1998). The results of the DNR study indicate that the lake is connected to groundwater with a net loss of water from the lake to groundwater of 6.5 inches per year. The DNR study also concluded that lake level flucuations are strongly correlated to aquifer fluctuations. Also, pumping from deeper aquifers for lake level augmentation is only 14 percent efficient, and likely increases the volume of water lost from the lake to groundwater. The conclusions of the DNR study (MN DNR, 1998) are consistent with the potential vulnerability analysis conducted for this study. White Bear Lake is classified as flow-through lake connected to groundwater and potentially vulnerable to groundwater pumping. Also, the lake is classified as having a wide and shallow littoral zone, which increases the potential for impacts from changes in lake stage.

Washington County Groundwater and Surface-Water Interaction Studies

Two studies were conducted in Washington County to assess the connection of groundwater and surface water (Barr et al., 2005; EOR, 2003). While these studies did not assess the vulnerability of surface water features to groundwater pumping, they are useful in providing an independent assessment for comparison of the connection between surface-water features and groundwater as classified for this study. In general, results from the Washington County studies are consistent. Discrepancies in classifications of recharge verses discharge/flow-through lakes appears to be mostly due to uncertainly in the regional water table surface. Discussions with the project team for the southern Washington County study (Wuolo, 2010) also indicate that some discrepancies occur as a result of how the surface water features were simulated in a groundwater flow model as part of the southern Washington County study.

6.0 Monitoring and Management Plans

Monitoring guidelines and examples have been prepared as separate documents for different types of surface-water features and are presented in Appendix B.

7.0 Recommendations

Based on the results of this study we recommend the following to help refine and improve the assessment of the vulnerability of surface-water features to groundwater pumping

1. Additional geologic data collection
    - Because geologic data is an integral part of the vulnerability scoring system we suggest that the Council work with the Minnesota Geological Survey in collecting additional geologic data in the following areas:
        - Surficial geology for western Wright County
        - Stratigraphy models in areas not yet completed (southern Hennepin County, Dakota County, Isanti County, Ramsey County, Wright County)
2. Water table monitoring wells
    - Defining if a surface-water feature is connected to groundwater or not is a key component of assessing the vulnerability to pumping. Because the available data for mapping the water table varies tremendously, we recommend that the collection of additional water table data be focused on areas where the surface-water/groundwater connection is indeterminate and where water demand is projected to increases significantly.
3. Following the monitoring protocols established in Appendix B allows for the proper data to be collected to help establish the potential influence of pumping on surface water features. However, analyzing these data can be difficult for water suppliers and the Council may need to provide support. The following article is recommended.
        - Harp D.R., V.V. Vesselinov. 2010. Identification of pumping influences in long-term water level flucations. *Ground Water.* In press

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