DEPARTMENT OF HEALTH

Guidance for Preparing a Conjunctive Delineation

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Guidance for preparing a conjunctive delineation

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Acronyms

ERA – Emergency Response Area

DWSMA – Drinking Water Supply Management Area

GWCA – Groundwater Capture Area

IWMZ – Inner Well Management Zone

MPCA – Minnesota Pollution Control Agency

MWL - Meteoric Water Line

NRCS – Natural Resources Conservation

PWS – Public Water Supplier

WHPA – Wellhead Protection Area

WHPP – Wellhead Protection Plan

SSURGO – Soil Survey Geographic Database

SWCA – Surface Water Contribution Area

SWCD – Soil and Water Conservation Districts

Definitions

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, 1987). An assimilative capacity boundary can be any combination of the following:

- surface and subsurface geologic materials,
- a hydrogeochemical boundary, and
- natural attenuation along groundwater flow paths.

that prevent contaminants from reaching a public water supply well at levels that present a risk to human health. Assimilative capacity is sensitive to the chemical constituent, regulatory threshold value, and time.

Conjunctive Delineation. A delineation process which accounts for the potential contribution of surface water to the GWCA. A conjunctive delineation may lead to a wellhead protection area that includes three components:

- the GWCA of the well,
- an area of land surface outside the GWCA that contributes recharge to the aquifer by means of overland flow (e.g., runoff), and
- a surface water feature (and corresponding catchment area) that is intersected by the GWCA.

Degraded Water Quality. The presence of a human-caused contaminant at one-third or greater of the health-based drinking water standard or guidance value.

Drinking Water Supply Management Area (DWSMA). The surface and subsurface areas surrounding a public water supply well, including the WHPA, that must be managed by the public water supplier identified in the wellhead protection plan, Minnesota Rule (MR) 4720.5100, subpart 13. This area is delineated using identifiable landmarks that completely enclose the scientifically calculated WHPA boundaries as closely as possible.

Emergency Response Area (ERA). The component of the GWCA defined by a one-year time of travel.

Geologic Protection. Laterally extensive geologic materials of low hydraulic conductivity and sufficient thickness providing natural protection to water quality in the aquifer from surface contamination. The granular texture of these materials are generally: silt, clay, and/or shale. These types of materials generally impede the vertical movement of surface water to the aquifer. A lack of geologic protection implies that surface and ground waters can be directly interconnected.

Groundwater capture area (GWCA). The subsurface area surrounding a well or well field through which water moves toward and reaches the well over a given span of time, commonly based on computer modeling of ground water flow. For surficial aquifers, this area generally extends to the land surface given the relatively short lag times for water traveling from the land surface to the aquifer in such settings. The terms 'capture zone' and 'capture area' are used interchangeably. Where no conjunctive delineation is required, the GWCA is equivalent to the WHPA.

Hydrologic Connection. The exchange between surface and ground waters commonly expressed as recharge or discharge. Rapidity of the connection is dependent on the thickness and texture of geologic materials in the vadose zone.

Hydrogeochemical Boundary. A localized environmental process that changes the biological, chemical, and/or physical properties of the water. The concentration or occurrence of many contaminants are known to be affected by these processes.

Surface Water Contribution Area (SWCA). The geographic area that may provide recharge to the aquifer within the groundwater capture zone and within the relevant vertical time of travel from the land surface, attributed to:

- a surface hydrologic feature and associated watershed; and/or
- overland flow and infiltration of precipitation or meltwater, with the contributing area defined by topography.

Surface Water Feature. Naturally occurring or human-made features where water collects at the land surface and may provide recharge to the groundwater. Examples are lakes, mine pits, ponds, reservoirs, rivers, streams, ditches, wetlands, and stormwater infiltration basins.

Wellhead Protection Area (WHPA). The surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach the well or wellfield within the selected time-of-travel (usually ten years). At a minimum, this area is the GWCA of the well. However, depending on the interconnection of surface water and groundwater, it may include a SWCA.

Introduction

This document presents guidance to determine if it is necessary to append a Surface Water Contribution Area (SWCA) to the ground water component of a wellhead protection area (WHPA), thereby forming a conjunctive WHPA delineation (U.S. EPA, 1987). A SWCA may be necessary because of recharge to a groundwater flow system from:

- transient and/or seasonal events, such as precipitation, snow melt, overland flow; and/or
- surface water features that the groundwater capture zone intersects and are expected to contribute water to the well.

By definition, a WHPA includes surface and sub-surface areas through which contaminants may travel to reach a PWS well. All potential pathways by which contaminants may enter a well, including those attributed to surface water, must be addressed in a wellhead protection plan (WHPP). Therefore, an assessment of the connection of surface water to ground water is a necessary step in performing a technically defensible delineation in the interests of protecting public health.

This guidance defines the circumstances under which a conjunctive delineation must be performed, identifies the types and sources of information needed to conduct the assessment, and provides a methodology for using these data to delineate the SWCA component of a WHPA.

Federal and state authority to require a conjunctive delineation

Amendments to the Federal Safe Drinking Water Act (SDWA) in 1986 define a wellhead protection area as “the surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or wellfield.” The Minnesota Wellhead Protection Rule (Minnesota Rules, Parts 4720.5100-4720.5590) defines Wellhead Protection as a “method of preventing well contamination by effectively managing potential contaminant sources in all or a portion of the well's recharge area.”

Parts of the Rule (MR 4720.5510) that apply to the conjunctive delineation process are found in subpart 3 and subpart 5:

- Subpart 3. Flow boundaries - The location and influence of flow boundaries must be identified using existing information. Hydrologic flow boundaries include lakes, rivers, streams, drainage ditches, or other surface hydrologic features; as defined under MR 4720.5100, subpart 15, item B.
- Subpart 5. Groundwater flow field - Under this criterion, when the ambient groundwater flow field cannot be determined due to transient hydrologic conditions, seasonal differences in the hydrologic gradient and angle of groundwater flow must be accounted for when delineating the WHPA.

Since surface hydrologic features can constitute flow boundaries and be responsible in part for establishing groundwater flow fields, they and their catchment areas must be considered when delineating a WHPA and may be included as part of the WHPA based on state and federal rules regarding wellhead protection.

Practical application of this guidance

This guidance is intended to supplement other Wellhead Protection delineation guidance documents already in use (see Selected References). These foundational guidance documents discuss important concepts that bear on this delineation process. Those concepts include the assessment of vulnerability to contamination, modeling of flow through porous media and fractured or solution weathered materials, and the impact of sensitivity and uncertainty on a WHPA delineation.

This document does not apply to the process used to determine whether public wells are classed as receiving “Ground Water Under the Direct Influence of Surface Water (GWUDI)” as defined by the U.S. EPA. (U.S. EPA, 1999). The determination of whether a system is receiving GWUDI is a separate process that has specific regulatory requirements for water treatment and is beyond the scope of this document.

How to determine when a conjunctive WHPA delineation is required

The following decision matrix is intended to guide the user on whether a conjunctive delineation is required for a WHPA. It is summarized in flowchart format in Figure 1.

Step 1: Results of initial assessment of the hydrogeologic setting and water chemistry:

a. Is the ERA or GWCA based on a fracture flow or karst setting?
b. Does the PWS well(s), or other wells in the same aquifer that are located in the ERA or GWCA, show evidence of degraded water quality* that may be attributed in part to impaired runoff or surface water features?

   **Degraded water quality means a human-caused contaminant is present at one-third or greater of the health-based drinking water standard or guidance value*.

c. If the answer to both scenarios is no, continue to Step 2.
d. If the answer to either scenario is yes, go to Step 2A.

Step 2: Does the ERA contain areas where the DWSMA vulnerability is high?

a. If not, no conjunctive delineation is needed.
b. If yes, continue to Step 3.

Step 3: Does the ERA intersect a surface water feature?

a. If not, no SWCA is needed.
b. If yes, continue to Step 4.

Step 4: Do adequate physical and chemical data exist to confirm the connection with a surface hydrologic feature suggested by delineation results? See Appendix 1 for a discussion of data adequacy.

a. If adequate data do not exist for making this determination, no SWCA is needed at this time. However, recommendations for data collection must be added to the WHP plan so this can be reevaluated at the time of the next plan amendment. Such recommendations may benefit from a data worth assessment, consult with MDH hydrologist or supervisor to discuss.

   Note that exceptions to this cautious approach may be warranted where the water quality of the surface water feature or the land uses that drain to its present a significant potential health concern. In those instances, the surface water feature and its watershed may be included on a precautionary basis, and data collection measures should be proposed for plan implementation that can help support or refute the need for the conjunctive delineation at the time of the next plan amendment.

   In cases where the WHPA being amended already includes a SWCA that was delineated prior to this guidance and for which adequate data do not exist for making this determination (based on the thresholds established in this guidance), then the SWCA is to be retained for the time being until adequate data collection can be conducted to refute or confirm the need for the SWCA at the time of the next plan amendment.

b. If adequate data do exist, and they do not confirm a connection with the surface hydrologic feature, no SWCA is needed. The groundwater flow model should be re-evaluated to ensure that the conceptual model and parameters are consistent with the results.

c. If adequate data do exist, and they confirm a connection with a surface water feature within the ERA, you must delineate a SWCA for the surface water feature.

Step 2A: Does the **GWCA** contain areas where the DWSMA vulnerability is high?

a. If not, no conjunctive delineation is needed.
b. If yes, continue to Step 3A.

Step 3A: **For porous media aquifers** - Does the GWCA intersect a surface water feature or receive runoff from surrounding lands that are characterized by: 1) higher elevation and 2) near-surface bedrock or soils likely to promote runoff (Hydrologic Groups C and D), or slopes that exceed 6% if Hydrologic Group B soils?

a. If not, no SWCA is needed.
b. If yes, continue to Step 4A.

For karst or fractured aquifers where depth to bedrock is 50 feet or less - Does the GWCA intersect 1) a surface water feature, sinkholes and/or dry drainage ways or 2) receive runoff from surrounding lands that are characterized by: A) higher elevation and B) near-surface bedrock or soils likely to promote runoff (Hydrologic Groups C and D), or slopes that exceed 6% if Hydrologic Group B soils?

a. If not, no SWCA is needed.
b. If yes, continue to Step 4A.

Step 4A: If the SWCA is to be based on a surface water feature, do adequate physical and chemical data exist to confirm the connection with the feature as suggested by delineation results? See Appendix I for a discussion of data adequacy. If the SWCA is to be based on runoff, sinkholes, or dry valleys, proceed to Step 5A.

a. If adequate data do not exist for making this determination, no SWCA is needed at this time. However, recommendations for data collection must be added to the WHP plan so this can be reevaluated at the time of the next plan amendment. Such recommendations may benefit from a data worth assessment, consult with MDH hydrologist or supervisor to discuss.

   Note that exceptions to this cautious approach may be warranted where the water quality of the surface water feature or the land uses that drain to it, present a significant potential health concern. In those instances, the surface water feature and its watershed may be included on a precautionary basis, and data collection measures should be proposed for plan implementation that can help support or refute the need for the conjunctive delineation at the time of the next plan amendment.

   In cases where the WHPA being amended already includes a SWCA that was delineated prior to this guidance and for which adequate data do not exist for making this determination (based on the thresholds established in this guidance), then the SWCA is to be retained for the time being until adequate data collection can be conducted to refute or confirm the need for the SWCA at the time of the next plan amendment.

b. If adequate data do exist, and they do not confirm a connection with the surface hydrologic feature, no SWCA is needed. The groundwater flow model or delineation technique should be re-evaluated to ensure that the conceptual model and parameters are consistent with the results.

c. If adequate data do exist, and they confirm a connection with a surface water feature within the ERA or GWCA, you must delineate a SWCA for the surface water feature.

Step 5A: For karst or fractured rock settings, features such as sinkholes and/or dry drainage ways and their contributing areas may be used to create a SWCA regardless of supporting physical or chemical data.

a. Features such as sinkholes or dry drainage ways may contribute recharge to the aquifer in short, intermittent bursts according to heavy rainfall or snowmelt events that may not coincide with routine compliance sampling or even investigative studies that would ordinarily be used to confirm the importance of these events on water quality. Therefore, they may be used as a basis for SWCA delineation in recognition of this unique hydrogeologic setting.

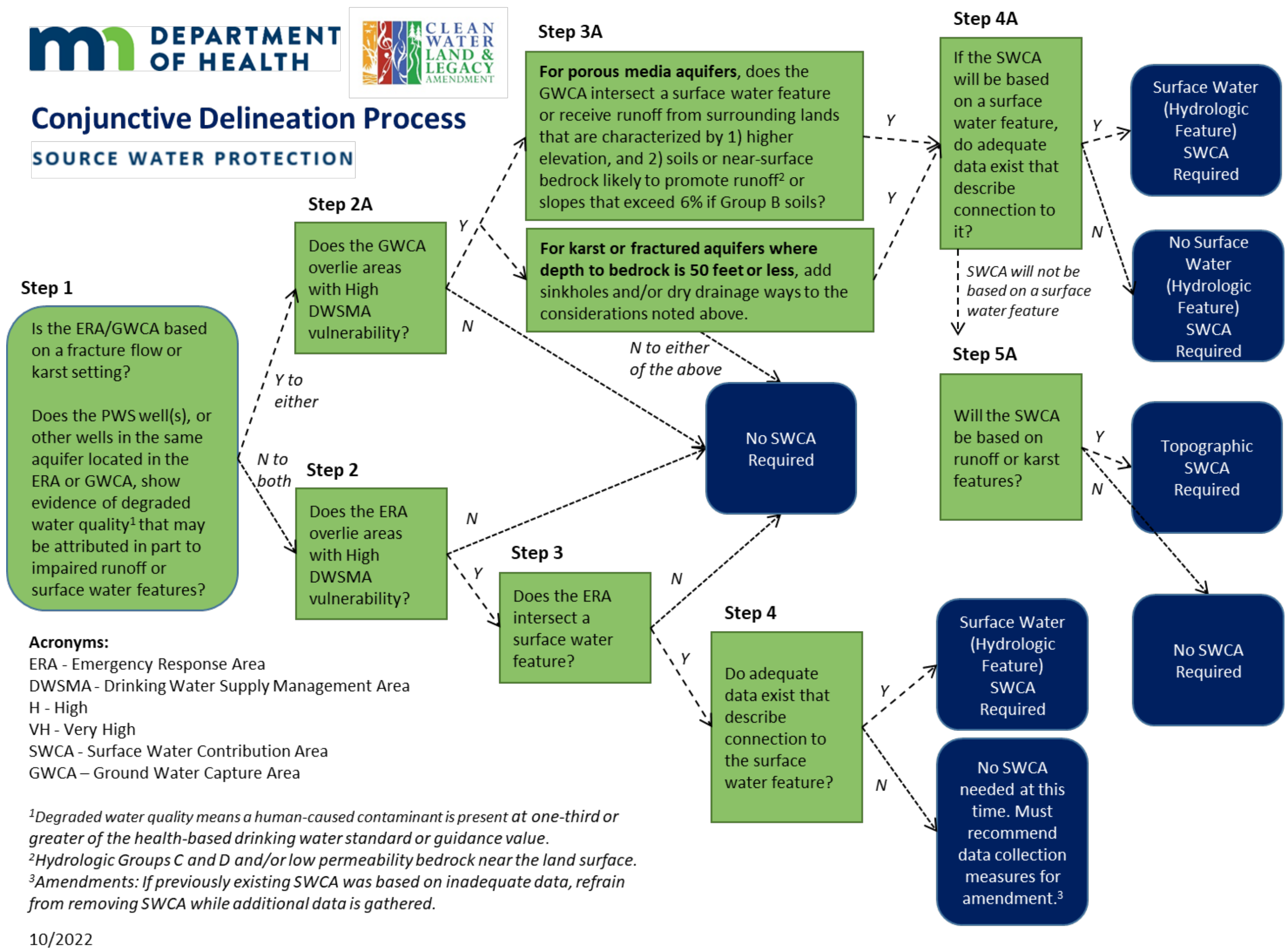

Figure 1. Flowchart for determining if a surface water contribution area (SWCA) is needed as part of a conjunctive wellhead protection area (WHPA).

Conjunctive delineation process

Surface Water Runoff Area Delineation:

If you answered yes to **Step 5A** above, a conjunctive delineation based on surface water runoff is required. In this case, you must determine what areas are likely to shed surface water runoff onto the GWCA where it contains land ranked as high vulnerability. These areas will constitute the SWCA, which is to be appended to the GWCA to form the conjunctive WHPA. This procedure is described below, and an example is provided in Appendix 3.

1) **Map the preliminary SWCA based on topography.** Work outward from the ERA capture zone to determine what land surface areas exhibit a higher topographic elevation and could potentially shed runoff in that direction. This area will constitute the potential surface watershed for the SWCA. This mapping can be accomplished in GIS using either established catchment area boundaries where available and relevant or be determined from scratch using an accurate depiction of topography such as LiDAR. The DNR Level 09 auto catchments are a useful resource and may provide the most reasonable boundaries due to their relatively fine scale. However, these catchments were derived prior to LiDAR so should be reviewed relative to more recent land elevation data. Note that Level 08 catchments may also be relevant due to their dependence on LiDAR data, but these are at a coarser scale. In any case, the user must be aware of local high spots such as roadways that may not be reflected in these delineated boundaries and adjust their SWCAs accordingly.

2) **Determine the hydrologic group for soils within the preliminary SWCA.** In GIS, add the NRCS soils layer (SSURGO) and determine the portion of the area within the preliminary SWCA that is characterized by soils likely to shed runoff. These are classified as hydrologic groups C and D or group B soils where slopes are greater than 6%. Areas underlain by more permeable soils (hydrologic group A) are to be discarded, as are areas where group B soils are less than 6% in slope. Those areas are more likely to promote infiltration than runoff. It is noted that there may be preliminary SWCAs where the soil types are mixed. In such settings, it may be more practical to lump soil types together from the perspective of implementing wellhead management strategies. In mixed soil settings, the potential SWCA should contain at least 80% C and D soils, or B soils greater than 6% slope, and be at least 10 acres in size.

3) **Consider ditches or other man-made water conveyance features (such as culverts).** If ditches or other stormwater conveyance features exist in the vicinity of the proposed SWCA and will add runoff to that zone, the land surface areas for those must also be included in the SWCA. Conversely, if the areas delineated in the above steps are artificially drained away from the proposed SWCA, then those areas can be removed from the final SWCA.

4) **Consider reasonable management area boundaries.** In the event that a level 09 auto catchment is considered too large to manage by the consultant or MDH hydro-planner team, in consultation with supervisory staff, consider trimming using physically identifiable or otherwise justifiable boundaries.

5) **Append the SWCA to the GWCA to form the conjunctive WHPA.**

Surface Water Feature Delineation:

If you answered yes to **Steps 4 or 4A** above, a conjunctive delineation based on a surface water feature is required. In this case, you must determine the surface watershed for the hydrologic feature in question (lake, river, wetland) and append this to the GWCA to form the WHPA. This procedure is described below, and an example is provided in Appendix 4.

1) **Establish the surface watershed for the hydrologic feature of interest.** In GIS, determine if a surface watershed has been delineated for the surface water feature. The DNR Level 9- auto catchment data file is a good resource to begin the assessment. If a relevant catchment area has not been delineated, use an accurate depiction of topography such as LiDAR to establish this area. Append this watershed area to the surface hydrologic feature.

2) **Consider ditches or other man-made water conveyance features***.* If ditches or other stormwater conveyance features exist within the mapped area that potentially drains runoff to the surface hydrologic feature from outside the surface watershed, the land surface areas for those must also be included in the SWCA. Conversely, if parts of the surface watershed are artificially drained outside of the watershed, those areas can be removed from the SWCA.

3) **Consider reasonable management area boundaries.** SWCAs for rivers and streams, and some lakes that are part of lake chains, can be unreasonably large to manag*e*. Consider trimming these using one of the following rationales:

    a. **Scientifically determined time of travel reaches.** In those rare instances where a time of travel has been determined for a stretch of river or lake chain, consider subdividing the SWCA so it only reflects a relatively short time of travel area. For a river system this might be a matter of minutes or hours and reflect the time needed for a spill to be reported and well use altered to minimize the risk of contaminant capture. For a lake chain this might be a longer time period and therefore reflective not only of a public water supplier’s response time but also persistence of acute contaminants such as pathogens.

    b. **Artificial boundaries such as bridges and dams.** These can provide helpful physical bounds to an otherwise unreasonably large SWCA.

c. **Subdivision into priority management areas**. In those cases where it is beneficial to include the entire watershed or there are no physical features available for shortening it, consider breaking the composite WHPA into priority A and B areas. Priority A areas might consist solely of the ERA or the GWCA, and priority B might consist of the remainder of the SWCA. In some cases, portions of the SWCA may also be included in priority A. Those would be portions of the watershed that contain land uses considered potentially harmful to drinking water quality.

4) **Append the SWCA to the GWCA to form the conjunctive WHPA.**

Addressing contribution from surface water features at longer times of travel

The decision matrix presented above in flowchart and text form allows for inclusion of a surface water feature and its SWCA in cases where groundwater contamination stemming from that feature has been documented, either within the ERA or elsewhere in the GWCA. There may be other instances where model results, supported by other forms of physical or chemical data, suggest that a surface water feature is a significant source of recharge to the PWS well(s) at some time of travel beyond the ERA. In these settings, a SWCA is not required. However, the surface water feature may still be highlighted in the WHP plan, whereby the boundaries of the feature are included as an area or line source of potential contamination.

The relative significance is to be determined based on the potential contamination threat posed by the surface hydrologic feature. A surface water feature characterized by degraded water quality, as defined in this document, could constitute a threat at relatively low contribution thresholds, whereas a relatively clean water body may constitute a threat only at high thresholds. Since contaminated surface water features that have been documented as having impacted groundwater quality may already be included in a conjunctive WHPA, this analysis focuses on cases where groundwater quality has not yet been shown to be degraded. As a starting rule of thumb for a typical surface hydrologic feature not known to be grossly contaminated, it is suggested that at least 25% of the well water must be derived from that feature based on particle tracking and/or physical/chemical data for it to be considered significant. A lower threshold (e.g., >=10%) may be more appropriate when considering a surface water feature that is deemed to pose a significant threat based on water quality degradation that exceeds the minimum threshold described herein. Note that relatively pristine surface hydrologic features that are not expected to be impacted by changing land uses or transportation accidents over the life of the WHP plan may be excluded from this consideration altogether. This determination should be arrived at in consultation with relevant planning staff during the first part of WHP plan development.

Where this process of including a surface hydrologic feature as a potential contaminant source is to be invoked, MDH hydrologist, in conjunction with the PWSs consultant if applicable, should:

a. ensure that a relevant line or polygon layer for this feature be included in the package of GIS files to be archived for the project, and

b. identify the surface hydrologic feature as a potential contaminant source during the pre-Scoping 2 meeting, and

c. with assistance from planning staff, advance the surface water feature for potential management or remediation options to relevant partner agencies such as Soil and Water Conservation Districts (SWCDs) or the MPCA.

Travel time uncertainty and fractured bedrock aquifer settings

In certain hydrogeologic settings, basing the need for a conjunctive SWCA on the ERA for the public well may not be adequately protective. The ERA, which is a composite of one-year capture zones, was chosen because that time period represents a conservative estimate of the viability of pathogens and viruses in the natural environment as well as a relevant travel time to address acute contamination incidents. In some settings, however, there can be considerable uncertainty in determining well capture area boundaries, especially with respect to travel time estimates. Where significant travel time uncertainty exists, and/or the ERA is smaller than the IWMZ, it may be prudent to composite the IWMZ zone with the ERA for the assessment or use a longer time of travel (e.g., three-years).

In addition, fractured and/or solution-weathered bedrock aquifers represent sensitive geologic settings where the ERA may not be sufficiently protective for assessing the need for a conjunctive delineation. Travel times can be less predictable, comparatively rapid, and subject to seasonal variations, such as during frequent and intense rainfall events in fractures and/or solution weathered bedrock aquifers. In karst or fractured aquifer settings that are relatively vulnerable to contamination, this guidance allows for including SWCAs based on the GWCA rather than a shorter time of travel boundary such as the ERA.

Selected references

Bowen, GJ, and Revenaugh, J. (2003) *Interpolating the isotopic composition of modern meteoric precipitation.* Water Resources Research 39, 1299, doi:10.129/2003WR002086MDH (1997a).

Landwehr, J.M. and Coplen, T.B. (2004) *Line-conditioned excess: A new method for characterizing stable hydrogen and oxygen isotope ratios in hydrologic systems*. In Isotopes in Environmental Studies, Edition: 1, Chapter: IAEA-CN-118/56, Publisher: IAEA, pp.132-135.

Minnesota Department of Health (1997) *Assessing Well and Aquifer Vulnerability for Wellhead Protection,* Minnesota Department of Health*,* St. Paul, Minn., 47 p.

Minnesota Department of Health (1997b), *Minnesota Rules Parts 4720.5100 to 4720.5590 - Guidance Pertaining to Wellhead Protection Requirements for Public Water Supply Wells,* Minnesota Department of Health, St. Paul, Minn., 61 p.

Minnesota Department of Health (2011), *Assessment Monitoring Pilot Study*, Unpublished Report, Minnesota Department of Health, St. Paul, Minn., 58 p.

Minnesota Department of Health (2011), *Guidance for delineating wellhead protection areas in fractured and solution-weathered bedrock in Minnesota*, St. Paul, Minn., 81 p.

Minnesota Department of Natural Resources (2013), DNR Watersheds - DNR Level 09 - DNR AutoCatchments, Geospatial Data Resource Site (GDRS) Minnesota Geospatial Commons accessed on April 6, 2022, MNDNR Watershed Suite (https://gisdata.mn.gov/dataset/geos-dnr-watersheds).

Minnesota Department of Natural Resources (2009), DNR Watersheds - DNR Level 08 – All Catchments, Geospatial Data Resource Site (GDRS) Minnesota Geospatial Commons accessed on April 6, 2022, MNDNR Watershed Suite (https://gisdata.mn.gov/dataset/geos-dnr-watersheds).

U.S. Environmental Protection Agency (1987), *Guidelines for Delineation of Wellhead Protection Areas*, Office of Ground-Water Protection, U.S. Environmental Protection Agency, Washington, D.C., 212 p.

U.S. Environmental Protection Agency (1999), *Guidance Manual for Conducting Sanitary Surveys of Public Water Systems: Surface Water and Ground Water Under Direct Influence (GWUDI) of Surface Water*, Washington, D.C., 432 p.

Appendix 1: Assessing adequacy of data

Surface Water Runoff Areas - It is difficult to independently document a surface water runoff area using physical or chemical data. Effects may be subtle and transient, and therefore difficult to monitor. Water temperature and chemical and isotopic parameters in the aquifer may vary seasonally depending on the rapidity of recharge, but this variability alone is not necessarily proof of contribution from the surface water runoff area. Locally elevated concentrations of select parameters known to be elevated in the runoff, such as chloride or nitrate, would tend to confirm this connection, but would likely require appropriately placed monitoring wells and frequent monitoring. The intermittent or seasonal development of groundwater mounds within the aquifer at the contact (confluence) with the SWCA could also be a confirmatory sign, but again would probably require a significant investment in observation wells and monitoring equipment. For these reasons, there are no specific data adequacy requirements for delineating a surface water runoff area.

Surface Water Features – These types of features may acquire distinct physical or chemical signatures that allows for evidence of their capture to be documented. The following factors, summarized briefly in Table 1, should be considered when deciding if existing data are adequate to confirm a significant connection exists between a surface hydrologic feature and a groundwater capture area:

1) **Physical data**.

    a. **Rationale and what data to measure/consider:** Data of this type may be less readily available than the chemical and isotopic data often required by MDH for WHP projects. Therefore, physical data are not required to support or refute a conjunctive WHPA. However, if such data are available, the following can be used to assess their adequacy.

        i. **Water level data**: Accurate, synoptic water level data from both the surface hydrologic feature and aquifer may be used to confirm or refute the likelihood of a hydraulic connection. A downward or flat vertical hydraulic gradient between a surface hydrologic feature and the aquifer may support that a significant connection exists. An upward hydraulic gradient would argue against a significant connection, although it is important to realize that changing groundwater withdrawals can alter this dynamic.

        ii. **Flow data**: For river systems, flow data can be used to determine whether the stretch in question is gaining or losing. The presence of a losing stretch would support a conjunctive relationship, while a gaining stretch would not.

    b. **Determining adequacy**

        i. **Water level data:** At least one round of water level data from groundwater observations (wells or springs, for example) are required for comparison with elevation for the surface hydrologic feature to establish similarity for inclusion in a SWCA. The surface water elevation data can be obtained from the state LiDAR coverage or other data sources (staff gages, surveys, etc.). The well data may be from static water level measured at the time of construction or from later readings but should be from within a reasonable time frame relative to the surface water data. For relatively static hydrologic settings where groundwater and surface water withdrawals and levels have been relatively constant, this time period during which comparisons may be relevant can stretch for many years. As an arbitrary rule of thumb in such settings, it is recommended that the well data fall within 10-years of the date of the surface water reading. For more dynamic hydrologic settings where water appropriations or levels have been fluctuating within the past 10-years, it is recommended that water level data from wells be gathered within a much shorter time period to be determined in consultation with MDH hydrologist. In general, it is recommended that no more than one-year separate surface and ground water elevation readings in these dynamic settings, and they may need to be truly synoptic.

ii. **Flow data:** Because flow data are generally hard to come by, a single pair of readings that cover the relevant stretch may be considered adequate for analysis although multiple sets of measurements are better. These data should represent a period of base flow (winter is best) and be reflective of the pumping conditions currently in place for the well(s) in question. If the data are of poor quality, ambiguous, or otherwise present an unclear picture of gain or loss, these data should be discarded in favor of other methods. Alternatively, the acquisition of better-quality data might be suggested in the context of WHP planning so that grant dollars might be made available to gather such data in the future.

2) **Chemical and isotopic data**.

a. **Rationale and what data to measure/consider**: If a surface hydrologic feature has developed a chemical or isotopic signature that is distinct from that of the aquifer and is reliably known, then comparing data from these two sources may reveal information about the strength of that connection. The parameters that should be evaluated include field parameters (water temperature, specific conductance, pH, dissolved oxygen, oxidation reduction potential), oxygen-18, deuterium, bromide, chloride, alkalinity, and total organic carbon. Sulfate, nitrate, ammonia, and arsenic should be added where these are suspected of being relevant. For example, sulfate can be an important indicator in some mine settings, and nitrogen compounds may be important in some agricultural settings. Arsenic can be helpful for discerning whether reducing conditions exist in the aquifer.

For surface water samples, sample collection should take place away from shore, off of a dock, pier, or bridge, and the sample should be taken approximately one-two feet below the water surface. These measures should help avoid entraining any surface debris or a thin film of strongly evaporated water. The well samples must be representative of typical well use (i.e., not taken shortly after a period of disuse or lower than normal use).

b. **Determining adequacy:**

   i. **Dependency on residence time**: The frequency of sampling should be dependent on the estimated residence time of water in the surface feature. Rivers, wetlands, ponds, and mine pit lakes adjacent to active mining and dewatering should be considered short-residence time systems. Other lakes may have short or long residence times. Information on lake residence times can be obtained from Hydrolakes (http://www.hydrosheds.org/page/hydrolakes), and the layer file is available as a Quicklayer at V:\gdrs\data\org\water_hydrolakes

      1. **Short residence time systems (rivers, wetlands, and lakes with residence times of 90 days or less)**:

         a. A minimum of four quarterly pairs of synoptic data from both the surface water and the well within a given 12-month period is considered necessary to adequately characterize their relationship. If possible, add a comparison well that is completed in the same aquifer, located in the same geographic setting, and known to not be influenced by surface water based on factors such as low geologic sensitivity, absence of tritium or other indicators of young water and flow modeling results. Because of the seasonal nature of the sampling noted here, complications may arise due to dry or frozen conditions. Sampling beneath frozen water may be accomplished via ice auger, but only if it can be accomplished safely. Consult with MDH hydro or supervisor about options for dealing with these conditions.

2. **Long residence time systems (lakes with residence times more than 90 days)**:

    a. A minimum of two sets of synoptic results from the well and lake within a given 12-month period, separated in time by four-seven months, is required. Spring and fall sets are optimal. This assumes that the morphology of the lake is such that that it behaves as a single water mass. Lakes that include lobes or bays of significant volume may develop variable chemical and isotopic signatures and these would need to be considered for additional sampling if they are potentially impactful on the GWCA. As with short residence time systems, consider adding a comparison well that is known not to be influenced by surface water.

Surface Water Conclusions: If data adequacy is proven by comparison with the benchmarks noted above, then it is appropriate to move onto assess whether the data support or refute the need for a conjunctive WHPA delineation, as described in Appendix 2. If existing data are shown to be inadequate, then it is appropriate to develop and implement a monitoring plan to address inadequacies. Monitoring plans should be developed in consultation with relevant MDH hydrologists and supervisors and may benefit from a data worth assessment for establishing sampling targets that may be most effective at addressing shortcomings.

Table 1. Assessing adequacy and utility of data to support a conjunctive WHPA involving surface water bodies.

Type of Data	Required?	Adequacy	Evidence to Support	Evidence to Refute
Vertical Hydraulic Gradient	No	Single round of water levels from aquifer and surface water body from sometime within the current hydrologic regime (10-years for static systems). See additional information on *page 13, item 1b.*	Flat or downward gradient between surface water body and aquifer.	Upward gradient between surface water body and aquifer
Flow Gain or Loss	No	Single round of flow analyses from within the time period of the current hydrologic regime (10-years for static systems).	Surface water body loses flow to aquifer within relevant stretch.	Surface water body gains flow from aquifer within relevant stretch.
Chemical/Isotopic	Yes	1. Short residence time systems (<90 days) = Quarterly for one year. 2. Long residence time systems (>90 days) = Semi-annual for one year.	1. Time-series trends mimic each other. 2. Well isotopes deviate significantly from MWL, similar mixing ratios for isotopes and conservative ions.	1. Time-series trends appear unrelated. 2. Well isotopes don't deviate significantly from MWL, dissimilar mixing ratios for isotopes and conservative ions.

Appendix 2: Data assessment for surface water bodies

The following discussion pertains to whether existing physical and chemical data that meet the adequacy requirements noted above support or refute the need for a conjunctive delineation with a surface hydrologic feature. It includes reference to tools and datasets accessible to MDH staff. Outside parties should consider access to equivalent approaches or consult with an MDH hydrologist for sharing these resources.

1) **Physical data**. Data of this type may be less readily available than the chemical and isotopic data often required by MDH for WHP projects. Therefore, physical data are not required to support or refute a conjunctive WHPA. However, if such data are available and meet adequacy requirements, the following can be used to guide the analysis.

    a. **Water level data**: A downward or flat vertical hydraulic gradient between a surface hydrologic feature and the aquifer would support that a significant connection exists. An upward hydraulic gradient would refute a significant connection, although it is important to realize that changing groundwater withdrawals can alter this dynamic. It is recommended that physical data be used in conjunction with chemical and isotopic data to confirm or refute the presence of a significant hydraulic connection with a surface water body.

    b. **Flow data**: The presence of a losing stretch within the area of concern would support a conjunctive relationship, while a gaining stretch would not. To have confidence in this assessment, the determination of gaining or losing must come from a result that falls outside of the measurement error for the method. It is recommended that physical data be used in conjunction with chemical and isotopic data to confirm or refute the presence of a significant hydraulic connection with a surface water body.

2) **Chemical and isotopic data**.

    a. **Short residence time systems (rivers, wetlands, and lakes with residence times of 90 days or less)**:

        i. *Time Series comparisons:* Plot the chemical and isotopic results from the well(s) and surface water for each parameter on time-series graphs, looking for comparable trends. These trends may align directly in time or be offset. Where directly aligned, they likely indicate a very short response time between the well and surface water feature. Where offset, longer response times are suggested. If the surface water feature is within the ERA and either outcome is noted, it can be considered supportive of a strong connection and need for a conjunctive WHPA. For longer time of travel features, the response time may indicate some multiple of one-year response times or may suggest that the feature is actually within the one-year time of travel zone and the particle tracking results are erroneously long. Where no comparable trends are noted, for example, flashy results for the surface water feature and flat results for the well, the need for a conjunctive WHPA is refuted. This is especially true if the well in question shows results that mimic that of a background well.

Note that it is important to have a good conceptual understanding of the flow system for this time-series approach to be effective. In some cases, well water and surface water trends may align simply because the both the well and surface water body are primarily fed by the same groundwater source. Also, note that comparable trends should be observed for all conservative parameters such as the stable isotopes of water, temperature, specific conductance, chloride and bromide. Non-conservative parameters such as alkalinity, nitrate, ammonia, TOC, and sulfate may be altered during transport and may not as clearly reflect the hydraulic relationship. Correlation between some conservative parameters and not others may point to an incomplete understanding of the flow system, or to very localized point sources that have not mixed evenly either in the aquifer or the surface water body.

Time-series graphs can be done in an automated fashion for MDH staff by using Water Chemistry Graphing (state.mn.us)

ii. *Meteoric Water Line comparisons*: Compare water isotope data with the Minnesota Meteoric Water Line (MWL) (Landon et al., 2000). Note that short residence time surface waters may or may not acquire an evaporative isotope signature. If they have acquired one, and the surface water is strongly connected to the aquifer, it should be reflected in the well data.

While graphical comparisons of isotope pairs with the MWL are informative, a more quantitative method of assessing deviations is provided by the line-conditioned excess method (Landwehr and Coplen, 2004). This is a measure of the magnitude and direction of separation of an isotope pair from a water sample when compared with the MWL. Negative values plot below the MWL and reflect likely evaporative fractionation. Positive values plot above the MWL and reflect other processes. Larger numbers correspond with a larger magnitude of separation. MDH has implemented an automated process for calculating these values, which can be accessed via an internal website: Water Chemistry Graphing (state.mn.us). This output provides an answer as to whether a sample or set of samples deviate significantly from the MWL (Figure 2).

Table 1: ^{18}O Summary Information

ID (link to Table 2)	Number of Samples	Minimum Value	Maximum Value	Mean Value	Coefficient of variation (CV)[1]	Do 1 or more samples show evidence for evaporated surface water? (#)	% of samples showing evidence for evaporated surface water	% evap SW times the mean LC Excess*	% rank of the % evap SW times the mean LC Excess* (includes Virus Study wells: 88 wells total)	Open water (sq.m.) in 1 year Capture Zone	Open water (sq.m.) in 10 year Capture Zone	Primary Groundwater Classification	Most conservative Geologic Sensitivity	Most recent Tritium result	Temporal Variability	Vertical Hydraulic Gradient Mean	Surface Water Impact Assessment
0000607440 (1480017S01)	4	-10.06	-9.304949	-9.643889970975	**4%**	Yes (1 of 4)	25%	-0.251172331029927	1%	n/a/	n/a		L	6.6			possibly impacted by long-residence time surface water at long time of travel
0000846426 (1480017S02)	1	-9.087298	-9.087298	-9.087298	Not calculated	Yes (1 of 1)	100%	-1.35762576565062	38%	n/a/	n/a		H	-1			possibly impacted by long-residence time surface water at long time of travel
SWS0000140	1	-5.78	-5.78	-5.78	Not calculated	Yes (1 of 1)	100%	-7.4505785010293	93%	n/a/	n/a			-1			possibly impacted by long-residence time surface water at long time of travel

(1) - A **highlighted** CV indicates it meets or exceeds the threshold value for high variability of 3% and may indicate rapid or seasonal recharge (https://dwpreports.web.health.state.mn.us/DWP_Reports/gw_categories_11.pdf).

Table 2: Isotope Analysis

^{18}O	^{2}H	ID (link to Table 1)	Collection Date	LC Excess* (1)	Does the LC Excess* show that the sample is significantly different than the MWL?(2)	Evidence for evaporated surface water?(3)	Estimated Annual Precipitation (Bowen grid for North America for ^{18}O values) (4)	Is the sample ^{18}O value significantly different than the Estimated Annual Precipitation value (Bowen, 2003)?(5)	Precipitation month most closely matching ^{18}O	Precipitation for month most closely matching ^{18}O	Precipitation difference for month most closely matching ^{18}O
-10.06	-68.48	0000607440 (1480017S01)	4/15/2008	0.89107309	No	No	-10.1400	No	April	-10.1300	0.0700
-9.3744208839	-65.2274864271	0000607440 (1480017S01)	1/29/2013	-0.31839453	No	No	-10.1400	Yes	September	-9.0750	0.2994
-9.304949	-65.90634	0000607440 (1480017S01)	11/8/2021	-1.00468932	Yes	Yes	-10.1400	Yes	September	-9.0750	0.2299
-9.83619	-66.585521	0000607440 (1480017S01)	11/8/2021	0.96172166	No	No	-10.1400	No	April	-10.1300	0.2938
-9.087298	-64.818249	0000846426 (1480017S02)	11/8/2021	-1.35762577	Yes	Yes	-10.1400	Yes	September	-9.0750	0.0123
-5.78	-49.59	SWS0000140	4/15/2008	-7.45057850	Yes	Yes	-10.1400	Yes	July	-7.0450	1.2650

(1) - Landwehr, J.M. and Coplen, T.B. (2004) Line-conditioned excess: A new method for characterizing stable hydrogen and oxygen isotope ratios in hydrologic systems. In Isotopes in Environmental Studies, Edition: 1, Chapter: IAEA-CN-118/56, Publisher: IAEA, pp.132-135. See pp. 99-100 in: http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/36/003/36003223.pdf

(2) - Absolute values of LC Excess* that are greater than 1 are considered significant deviations from the Minnesota MWL.

(3) - Evidence of evaporated surface water is set to 'Yes' only for those samples where the LC Excess* was both negative and significant, and ^{18}O is heavier than the Estimated Annual Precipitation.

(4) - Bowen GJ, Revenaugh J (2003) Interpolating the isotopic composition of modern meteoric precipitation. Water Resources Research 39, 1299, doi:10.129/2003WR002086

(5) - Differences between ^{18}O and Estimated Annual Precipitaion that are greater than 0.4 are considered significantly different.

Isotope Mixing Calculator

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Figure 2. Output from MDH Water Chemistry Graphing web tool (HTML Report of Isotope Analysis).

Table 1 generated by this application provides a statistical summary of the isotope data for ^{18}O (only a single parameter need be assessed, and this isotope is most precisely measured), as well as information on 18O-2H pairs. Relevant fields include:

1. **Coefficient of variation (CV):** Values in excess of 3% are considered highly variable. This comes into play more with well data but may provide you some insights into how dynamic your surface water system may be in response to seasonal inputs.

2. **Do one or more samples show evidence for evaporated surface water?** This field indicates the number of samples from this feature that plot significantly below the MWL. The next column breaks this out as a percentage of all samples collected from this feature.

3. **Percentage evaporated surface water times the mean LC Excess:** This value is the sum of the percent of samples from this feature that plot significantly below the MWL times the average distance those samples plot from the MWL. The more negative the number, the stronger the evaporative effect. The range observed to date is approximately -10 to near zero.

4. **Percentage evaporated surface water times the mean LC Excess rank:** The normalized rank of the value from the preceding field relative to all isotopic data statewide. Lower values imply a surface water body that is relatively unfractionated isotopically. Such features may be primarily groundwater-fed, which would be supported by a relatively low CV (item #1 above). Conversely, higher values reflect a surface water body that is strongly affected by evaporation or drains an area containing numerous evaporative surface water features (for example, long residence time lakes).

5. **Surface Water Impact Assessment:** A text output that indicates the nature of the surface water impact at the well, if any, based on the information derived above, as well as other information on the groundwater residence time (Most Recent Tritium Result) and other hydrogeologic factors (Hydrologic Features within the well capture zone, Groundwater Classification based on chemistry results, Geologic Sensitivity, Temporal Variability of chemical results and presence of a downward hydraulic gradient). Note that the well capture zone information still needs to be linked via a yet-to-be developed GIS application, so should not yet be considered accurate.

Table 2 generated by this application provides a detailed breakdown of each sample result. The following columns are especially important:

6. **LC Excess**: This is a measure of the magnitude and direction of separation of an isotope pair from a water sample when compared with the MWL. Negative values plot below the MWL and reflect likely evaporative fractionation. Positive values plot above the MWL and reflect other processes. Larger numbers correspond with a larger magnitude of separation.

7. **Does the LC Excess show that the sample is significantly different than the MWL?** - This is a yes/no result based on a comparison between the LC Excess value from the previous column and the standard deviation for 18O and 2H from either the reported lab precision for these parameters or sample duplicate data from relevant batches. Only those data that result in a “yes” result are considered significantly removed from the MWL to document evaporative fractionation.

8. **Evidence for evaporated surface water?** A yes/no result directly related to the answer for #2 above, but also including an evaluation of whether the isotope pair that is significantly removed from the MWL is also heavier (less negative) than the background value estimated for annual average precipitation for the area as derived from Bowen and Revenaugh (2003 – see #9 below).

9. **Estimated Annual Precipitation**: The expected average annual value for the location of your sample, as derived from a grid of expected isotope values published by Bowen and Revenaugh (2003). Conformance with this value suggests that isotopic composition of your surface water samples is well-integrated over time and may reflect relatively short residence times that have not been long enough to acquire a significant evaporative signature. Discordance reflects the opposite.

10. **Precipitation month most closely matching 18O**: This value compares the monthly gridded estimates of Bowen (2003) for 18O with your samples to determine which month of the year most closely matches your result. Conformance with the actual sampling month suggests short residence time flow systems, whereas discordance may reflect longer residence times. The following two columns provide additional information relative to the monthly comparison but should not require additional explanation.

If the results show that the surface water samples do deviate significantly from the MWL (items 2, 8, and 9 above provide this answer), then move ahead with analyzing the well water data in the same fashion. Possible outcomes include:

- If both the surface water samples and well water samples deviate from the MWL, these results support the inclusion of a SWCA in the WHPA.
- If the surface water samples deviate from the MWL and the well water samples do not, then these data refute the need for a SWCA.
- If the well water samples deviate from the MWL but the surface water samples do not, it is likely that the surface water body that was sampled is not the relevant surface hydrologic feature impacting the well and should result in revisiting the conceptual model and flow model before pursuing a conjunctive WHPA.

iii. *Mixing analyses*: The percentage of surface water present in a well water sample can be estimated if the concentrations of conservative chemical parameters are known with a reasonable degree of certainty for both, as is as a value that represents “background,” or groundwater not impacted by the surface water body. If the preceding analyses show that the chemical or isotopic signatures of the well and surface water body are distinct and either track one another in a seasonal fashion or represent different steps from the MWL along an evaporative trend line, then conducting a mixing analysis is a reasonable next step for evaluation the amount of surface water contribution at the well. Although no minimum percentage of surface water is required for including a SWCA in a WHPA where the surface water body is intersected by the ERA, inclusion of surface waters at longer times of travel is recommended only where the percentage of surface water is high (greater than 25%) and/or the surface feature represents a significant risk to the aquifer due to poor water quality or high-risk land uses in its watershed.

A mixing calculator can be accessed via the HTML *Report of Isotope Analysis* generated by the MDH Water Chemistry Graphing Tool (see button in lower left of Figure 2). The following procedure describes how to estimate the relative contribution of the surface water feature to the well water:

1) Input representative values for a conservative tracer chemical (18O, 2H, chloride, bromide, specific conductance and temperature) for the well water in question (pumped well sample), a background value for non-surface water impacted groundwater (background groundwater) and for the surface water body in question. As described on the application page, background groundwater values can be derived from

actual analytical data from a background well identified for this analysis or from literature references, including the interpolated raster values for 18O from Bowen and Revenaugh (2003).

2) Press the "Calc" button and view the results. Note that similar mixing ratios should be observed for all conservative constituents. Correlation between some conservative parameters and not others may point to an incomplete understanding of the flow system, or to very localized point sources that have not mixed evenly either in the aquifer or the surface water body.

b) Long residence time systems (lakes with residence times of 90 days or more). These will generally lack the long-duration time-series data required for short residence time systems. For that reason, time-series analysis is not automatically included here. However, if time-series data happen to exist for such a system, it is recommended that the procedure described above be used to conduct such an analysis. Otherwise, the following analyses should be conducted routinely on long residence time systems:

i. *Meteoric Water Line comparisons*: Establish whether the surface water feature has acquired an evaporative signature relative to the MWL. Detailed information on how to do this is provided in item #2 above. Long residence time surface waters are likely to acquire an evaporative isotope signature. If they have acquired one, and the surface water is strongly connected to the aquifer, it should be reflected in the well data.

- If both the surface water samples and well water samples deviate from the MWL, these results support the inclusion of a SWCA in the WHPA.
- If the surface water samples deviate from the MWL and the well water samples do not, then these data refute the need for a SWCA.
- If the well water samples deviate from the MWL but the surface water samples do not, it is likely that the surface water body that was sampled is not the relevant surface hydrologic feature impacting the well and should result in revisiting the conceptual model and flow model before pursuing a conjunctive WHPA.

ii. *Mixing analyses:* Conduct the mixing analysis as described above to determine the relative contribution of the surface water body to the well water. Although no minimum percentage of surface water is required for including a SWCA in a WHPA where the surface water body is intersected by the ERA, inclusion of surface waters at longer times of travel is recommended only where the percentage of surface water is high (greater than 25%) and/or the surface feature represents a significant risk to the aquifer due to poor water quality or high-risk land uses in its watershed.

Note that water quality trend data that is generated from or coincident with remedial land use changes in an area under consideration for inclusion in a SWCA may be used to support such inclusion. For example, water quality improvements observed at the PWS wells associated with cropping changes or easement programs in the prospective SWCA can support the inclusion of those lands within the SWCA.

Appendix 3: Degraded water quality examples

Example 1 – City of Adrian

Background

The city of Adrian (PWS 1530001) is a small community located in Nobles County in southwestern Minnesota. The city's wellfield is comprised of three shallow wells, ranging in depth from 26 feet to 42 feet. Information about the construction of the wells and their vulnerability is provided in Table 2.

Table 2. Adrian Water Supply Well Information

Local Well Name	Unique Number	Use/ Status	Casing Diameter (inches)	Casing Depth (feet)	Well Depth (feet)	Date Constructed	Well Vulnerability	Aquifer[1]
Well #5	149184	Primary	12	19	26	1984	Vulnerable	QWTA
Well #6	149187	Primary	12	31	42	1985	Vulnerable	QWTA
Well #7	721689	Primary	18	23	42	2006	Vulnerable	QWTA

Notes: 1. QWTA means Quaternary Water Table Aquifer.

The city's wells are constructed in a water table aquifer that consists of sand and gravel deposits located within the valley of the Kanaranzi Creek, and which trends in a northeast to southwest direction in the vicinity of the wellfield (Figure 3). The landscape around the city of Adrian formed over a long period of glaciation and stream erosion. The upland areas adjacent to the valley of the Kanaranzi Creek exhibit a gently rolling topography that has formed in clay-rich glacial deposits. Small intermittent streams drain the landscape and contribute flow into the main branch of the Kanaranzi Creek (Olsen, 2002).

In the vicinity of the wellfield, groundwater flows from the southeast toward the Kanaranzi Creek. In addition, a small (unnamed) stream and several intermittent tributaries drain from the upland areas, flowing across agricultural fields, past the wellfield, and eventually discharging to Kanaranzi Creek.

The runoff of precipitation and snow melt from the upland areas recharge the outwash channel aquifer in addition to contributing seasonal increases in the flow of Kanaranzi Creek and local streams. Given the shallow nature of the aquifer, changes in the amount of precipitation and corresponding groundwater recharge may have a significant effect on the available saturated thickness of the aquifer.

Method Used to Delineate the Groundwater Capture Area (GWCA)

For the 2013 amendment to the city's WHP plan, a single layer 3D, cell centered, finite difference, saturated flow model, called MODFLOW (McDonald and Harbaugh, 1988; Harbaugh et al., 2000) was developed by MDH staff (Djerrari and Clemens-Billaigbakpu, 2013). Surface water features, such as the creek and tributaries, were represented in the model using river conductance cells. The river elevations were extracted from Nobles County LiDAR data acquired in 2010 from the Minnesota Department of Natural Resources. The conductance of the Kanaranzi Creek was set using a vertical hydraulic conductivity of 0.02 cm/s. The conductance of the creek that flows from the south toward the wellfield was set using a vertical hydraulic conductivity of 0.01 cm/s. With this smaller value, the Adrian wells extract less than 20 percent of their water from the creek under the base case scenario. The model grid was refined around the Adrian wells. Variable grid spacing was used, ranging from two meters near the city wells to 250 meters at the edge of the grid. This refinement was required for an accurate computation of the particle flow paths for determining the GWCA delineation.

To determine the one- and 10-year capture zones, the MODFLOW model was used with a particle tracking program called MODPATH (Pollack, 1994). MODPATH was used to evaluate advective transport of simulated particles moving through the simulated flow system. A series of 50 particles were launched at each well. A porosity of 25% was used for the sand and gravel aquifer. The final capture zone boundaries area a composite of the zones calculated as part of the sensitivity and uncertainty analysis. To assess the potential impact of the pumping wells on the nearby stream, two additional model runs were performed by increasing and reducing riverbed conductance by an order of magnitude.

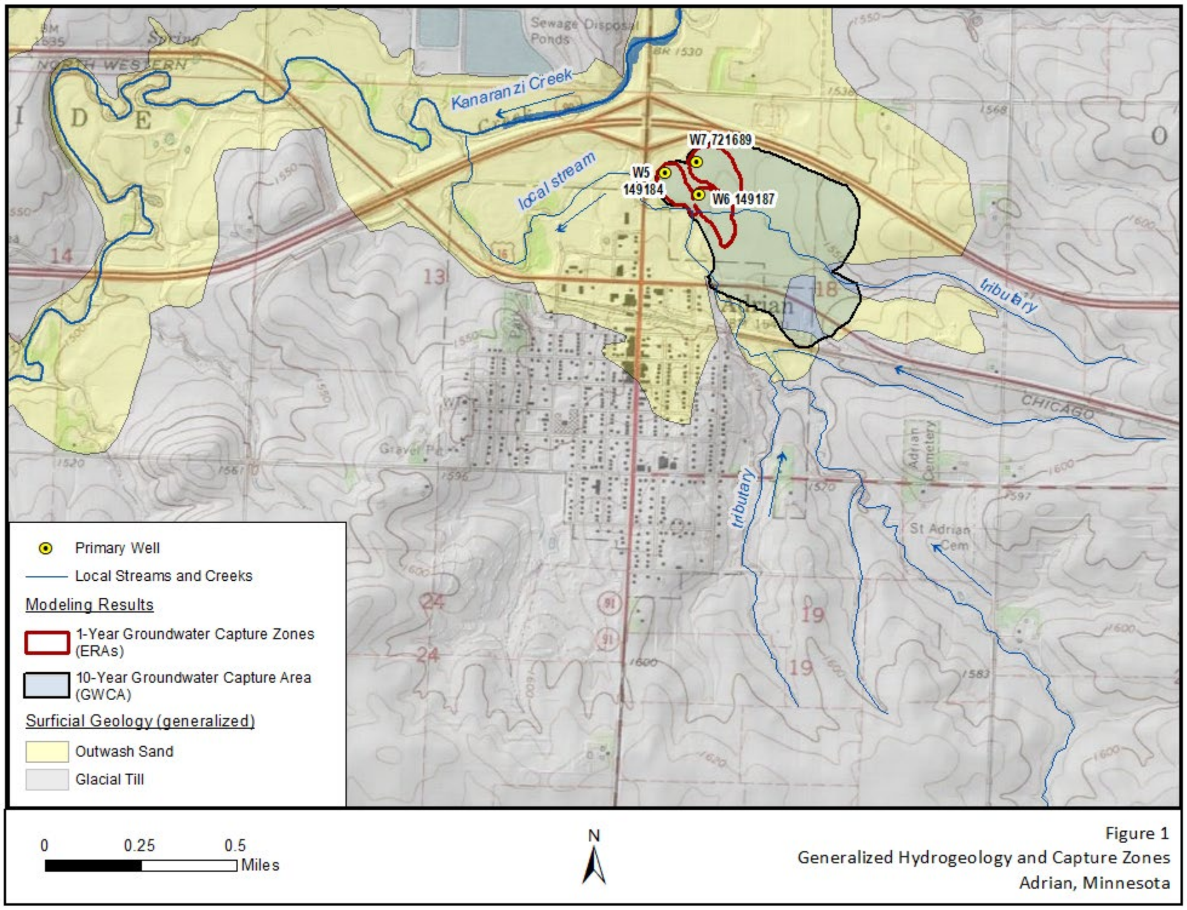

Figure 3. Generalized hydrogeology and capture zones: Adrian, MN.

Assessing the Conjunctive Delineation

A surface water contribution area (SWCA) was included with the initial delineation in 2002 WHPA. The need for a conjunctive delineation was re-assessed as part of the amendment in 2013 (Djerrari and Clemens-Billaigbakpu, 2013*).* Consideration was given to the potential runoff contribution from the upland areas to the shallow channel aquifer serving the city wells. The runoff contribution area was determined using 7.5-minute topographic maps, the potentiometric surface of the aquifer as generated by the groundwater flow model, and personal observations by city staff. Figure 4 below shows the boundaries of the mapped surface water contribution area. The approach used to assess runoff contribution to the shallow aquifer was consistent with the conjunctive delineation guidance available at the time (MDH, 2006).

During plan implementation, the wellhead team also assessed whether the city wells were receiving a more direct contribution of surface water from the main creek flowing adjacent to and crossing the ERA of Well #5 (149184) (see Figure 5 below). The groundwater flow model indicated that pumping of Well #5 induced flow from the creek to the water table aquifer (Djerrari, 2021). However, there was limited water chemistry to confirm the connection between the wells and the creek, and it was recommended that the city undergo a year-long program of quarterly monitoring from the wells and the creek over the course of plan implementation.

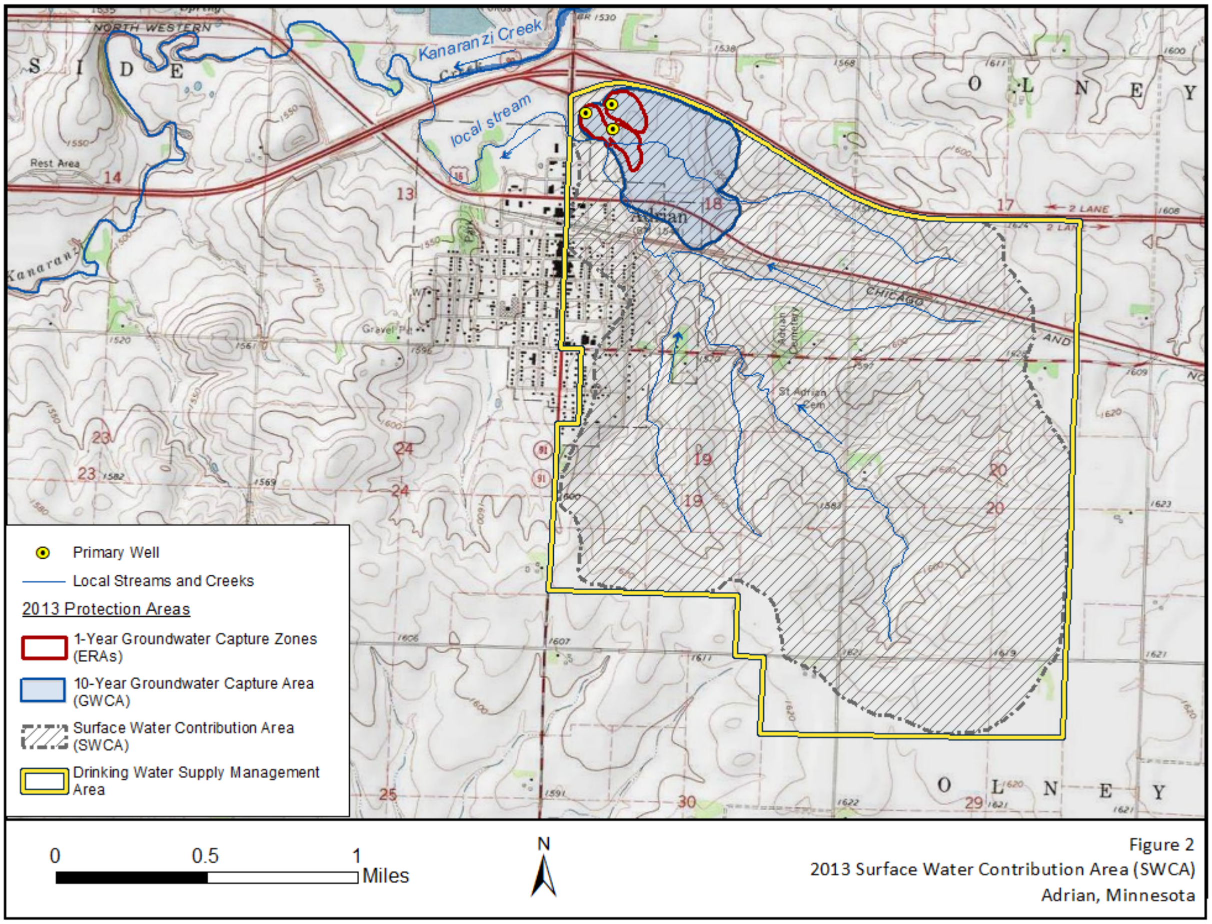

Figure 4. 2013 Surface Water Contribution Area (SWCA): Adrian, MN.

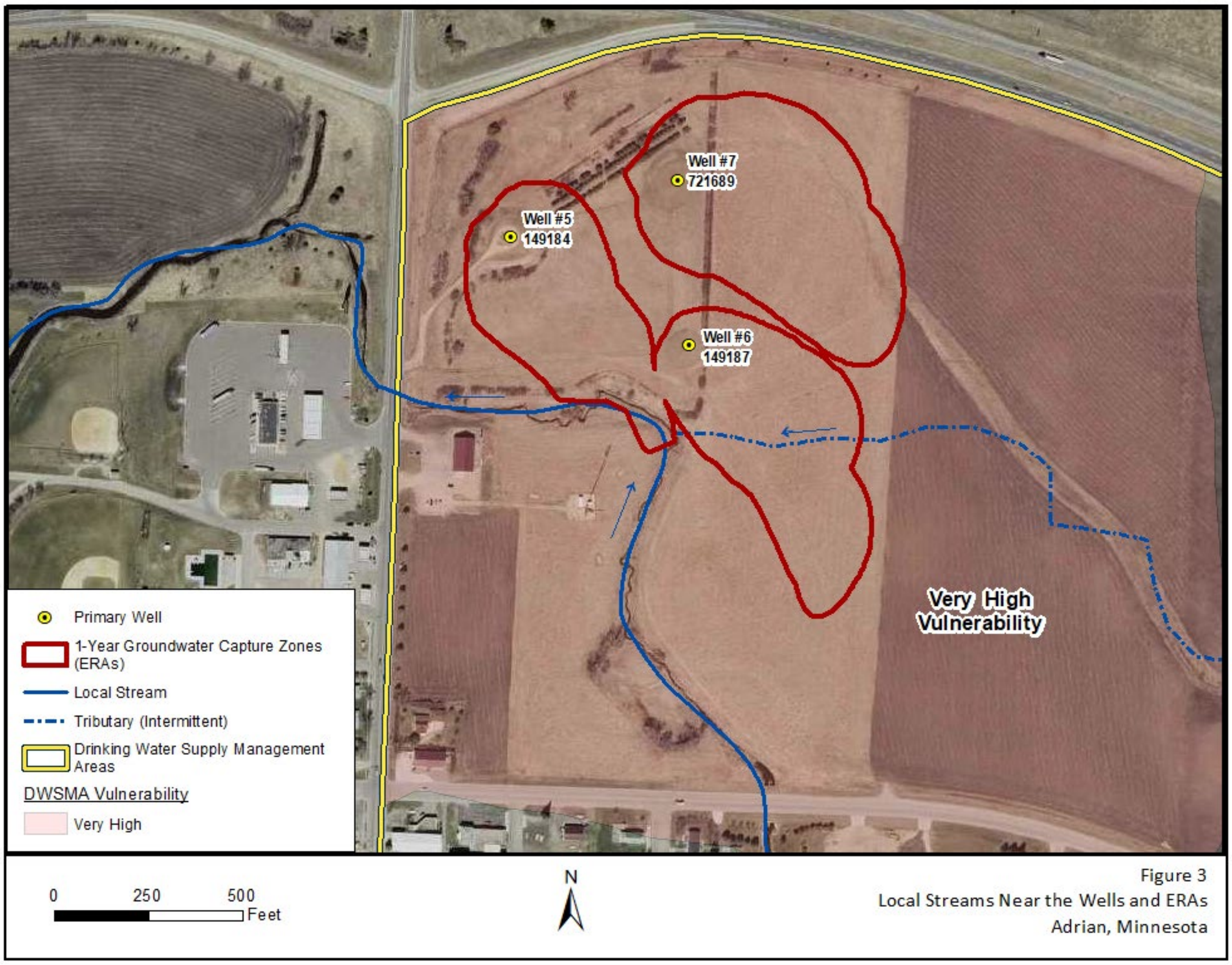

Figure 5. Local streams near the wells and ERAs: Adrian, MN.

Degraded Source Water Quality

The city's wells are relatively shallow and have had detectable levels of nitrate since construction. The source water is treated at a nitrate treatment plant before entering the distribution system. Table 3 below shows the range of nitrate concentrations from monitoring by MDH of the city's wells and, more recently, at two locations along the nearby stream. Elevated nitrate has been observed at the wells and at two monitoring locations along the stream. Diagnostic monitoring also included water isotopes. The water isotope results confirmed the short residence time of the stream, as none of the results from the creek indicated evidence of an evaporative signature.

Table 3. Available Record of Nitrate Results. (MDH MNDWIS and WChem databases)

Well	Period of Record	Lowest Concentration Recorded (mg/l)	Highest Concentration Recorded (mg/L)
Well #5 (149184, S05)	1993-2021 (34 samples)	5.4	19
Well #6 (149187, S06)	1993-2021 (37 samples)	7.7	32
Well #7 (721689, S07)	2007-2021 (30 samples)	4.9	13
SWS 561 (upstream from the city wells)	2018-2021 (3 samples)	7.1	12
SWS 566 (sample location near the wellfield)	2018-2021 (3 samples)	6.8	13

Additional Monitoring Confirm Degraded Water Quality

As part of implementing measures in their wellhead plan, the city also developed a more extensive plan to monitor nitrate in the local streams. Monitoring occurred between March 2018 and July 2020 at six locations along streams within the SWCA. The city was especially interested in monitoring during recharge events. The nitrate results of monitoring over the period of record ranged from 6.3 mg/l to 27.5 mg/l. The city also kept a monthly record of nitrate monitoring at the city wells and provided MDH SWP staff with results from January 2019 through May 2021. Results from Well #5 (149184) exceeded the MCL in 35% of the monitoring events; results from Well #6 (149187) exceeded the MCL in 97% of the monitoring events; and none of the results from Well #7 (721689) exceeded the MCL during the period of record. Well #7 is located furthest from the surface water features.

Assessing the Need for a Conjunctive Delineation

Because the GWCA is geologically sensitive and the water quality of the city wells has been degraded by nitrate, the need for assessing a conjunctive delineation is required. It is noted that the need to assess a conjunctive delineation in this setting would have been required regardless of impaired water quality because the ERA is geologically sensitive and intercepts a local surface water feature.

Steps to SWCA Determination

Step 1. Use information about the delineated ERA and GWCA, the hydrogeologic setting and water chemistry:

a. Is the ERA or GWCA based on a fracture flow or karst setting? *No, the aquifer serving the city wells is comprised of porous media and does not represent a fracture flow or karst setting.*

b. Does the PWS well(s), or other wells in the same aquifer that are located in the ERA or GWCA, show evidence of degraded water quality that may be attributed in part to impaired runoff or surface water features? *Yes, monitoring indicates that the water quality of the wells and local stream have been degraded by nitrate. A generalized surficial geology map, surface water features, and groundwater capture zones are presented in Figure 3 above. The main branch of the local creek runs adjacent to the one-year capture zones of two city wells. In addition, a tributary to the creek from the east flows across the one-year capture zone for Well #6 (see Figure 5 above).*

   It is assumed that some runoff occurs as overland flow from upland areas and recharges the GWCA during precipitation events. However, it is likely that a certain volume of runoff occurring in the upland areas is intercepted by local streams and creeks. The streams merge together near the wellfield and eventually discharge to the Kanaranzi Creek. Agricultural tile drainage is also practiced in the area, and it is likely that the tile lines drain to nearby streams during rainfall events. It is assumed that the water quality of the runoff from the fields is also degraded by nitrate in a manner similar to the documented degradation of the local surface water features.

c. If the answer to both scenarios is no, continue to Step 2.

d. If the answer to either or both scenarios is yes, go to Step 2A.

Step 2A: Does the GWCA contain areas where the DWSMA vulnerability is high?

a. If not, no conjunctive delineation is needed.

b. If yes, continue to Step 3A. *Yes, the vulnerability is high throughout the GWCA.*

Step 3A: **For porous media aquifers** - Does the GWCA intersect a surface water feature or receive runoff from surrounding lands that are characterized by: 1) higher elevation and 2) soils likely to promote runoff (Hydrologic Groups C and D), or slopes that exceed 6% if Hydrologic Group B soils?

For karst or fractured aquifers - Does the GWCA intersect 1) a surface water feature, sinkholes and/or dry drainage ways or 2) receive runoff from surrounding lands that are characterized by:

A) higher elevation and B) soils likely to promote runoff (Hydrologic Groups C and D), or slopes that exceed 6% if Hydrologic Group B soils?

a. If not, no SWCA is needed.

b. If yes, continue to Step 4A. *Yes, this is a porous media setting and the ERA and GWCA intercept local streams of impaired water quality. In addition, the soils in the higher elevation area are comprised of Hydrologic Groups C and C/D and promote runoff.*

Step 4A: If the SWCA is to be based on a surface water feature, do adequate physical and chemical data exist to confirm the connection with the feature as suggested by delineation results? See Appendix 1 for a discussion of data adequacy. If the SWCA is to be based on runoff, sinkholes, or dry valleys, proceed to Step 5A.

a. If adequate data do not exist for making this determination, no SWCA is needed at this time. However, recommendations for data collection must be added to the WHP plan so this can be reevaluated at the time of the next plan amendment. Note that exceptions to this may be warranted where the water quality of the surface water feature or the land uses that drain to it presents a significant potential health concern. In those instances, the surface water feature and its watershed may be included on a precautionary basis, and data collection measures should be proposed for plan implementation that can help support or refute the need for the conjunctive delineation at the time of the next plan amendment.

   In cases where the WHPA being amended already includes a SWCA that was delineated prior to this guidance and for which adequate data do not exist for making this determination (based on the thresholds established in this guidance), then the SWCA is to be retained for the time being until adequate data collection can be conducted to refute or confirm the need for the SWCA at the time of the next plan amendment.

   In this example, a SWCA was originally delineated with the city's initial WHP Plan in 2002, pre-dating this guidance. Overall, the location of the existing SWCA boundaries is consistent with the current guidance.

b. If adequate data do exist, and they do not confirm a connection with the surface hydrologic feature, no SWCA is needed. The groundwater flow model or delineation technique should be re-evaluated to ensure that the conceptual model and parameters are consistent with the results.

c. If adequate data do exist, and they confirm a connection with a surface water feature within the ERA or GWCA, you must delineate a SWCA for the surface water feature.

   For this porous media setting, the ERA and GWCA intercept a local stream. Investigative monitoring indicates that the wells and the local stream are degraded in a similar manner relative to nitrate. In addition, groundwater modeling indicates that pumping of Well #5 (149184) induces leakage from the stream located within the ERA (Djerrari, 2021).

Follow the steps for delineating a SWCA based on a surface water feature with degraded water quality:

1) **Establish the surface watershed for the hydrologic feature of interest**. In GIS, determine if a surface watershed has been delineated for the surface water feature. The DNR Level 09- auto catchment data file is a good resource to begin the assessment. If a relevant catchment area has not been delineated, use an accurate depiction of topography such as LiDAR to establish this area. Append this watershed area to the surface hydrologic feature.

   In this setting, there are several unnamed streams and creeks which drain toward the wellfield from the upland areas. The streams converge near the wellfield and flow past the wells toward Kanaranzi Creek. Seven DNR Level 09 auto-catchment basins exhibit higher topographic areas and likely drain toward the GWCA (see Figure 6 below). However, it is recognized that the auto-catchment dataset represents a general model of surface water flow across the landscape; in some settings, the auto-catchment boundaries do not accurately reflect the impact of certain land features, such as elevated highways. These types of features can be identified at a smaller resolution using LiDAR data. In this setting, LiDAR confirms that Interstate 90 (I-90) has been built up and is elevated along the stretch of highway north of the wellfield. For this reason, I-90 was used as a SWCA boundary north of the GWCA, subdividing the larger auto-catchment area. In addition, LiDAR and highway data was also used to identify a cut-off boundary for a portion of the auto-catchment basin which extends a good distance downstream and west of the GWCA. Minnesota Trunk Highway 91 (H-91) runs north-south across the auto-catchment basin and LiDAR confirmed that runoff drains away from the highway for a distance of about ½ mile south of the I-90. LiDAR was also used to refine the boundary for the southern portion of the same auto-catchment basin. (see Figure 7 below).

   The SWCA for Adrian was originally mapped in 2002, pre-dating this guidance and the availability of the DNR Level 09 auto-catchment shapes and LiDAR data. The wellhead team used 7.5-minute topographic quadrangles and field observations to map the SWCA. Overall, the existing SWCA boundaries are very consistent with the location of the DNR Level 09 auto-catchment areas which were modified using LiDAR.

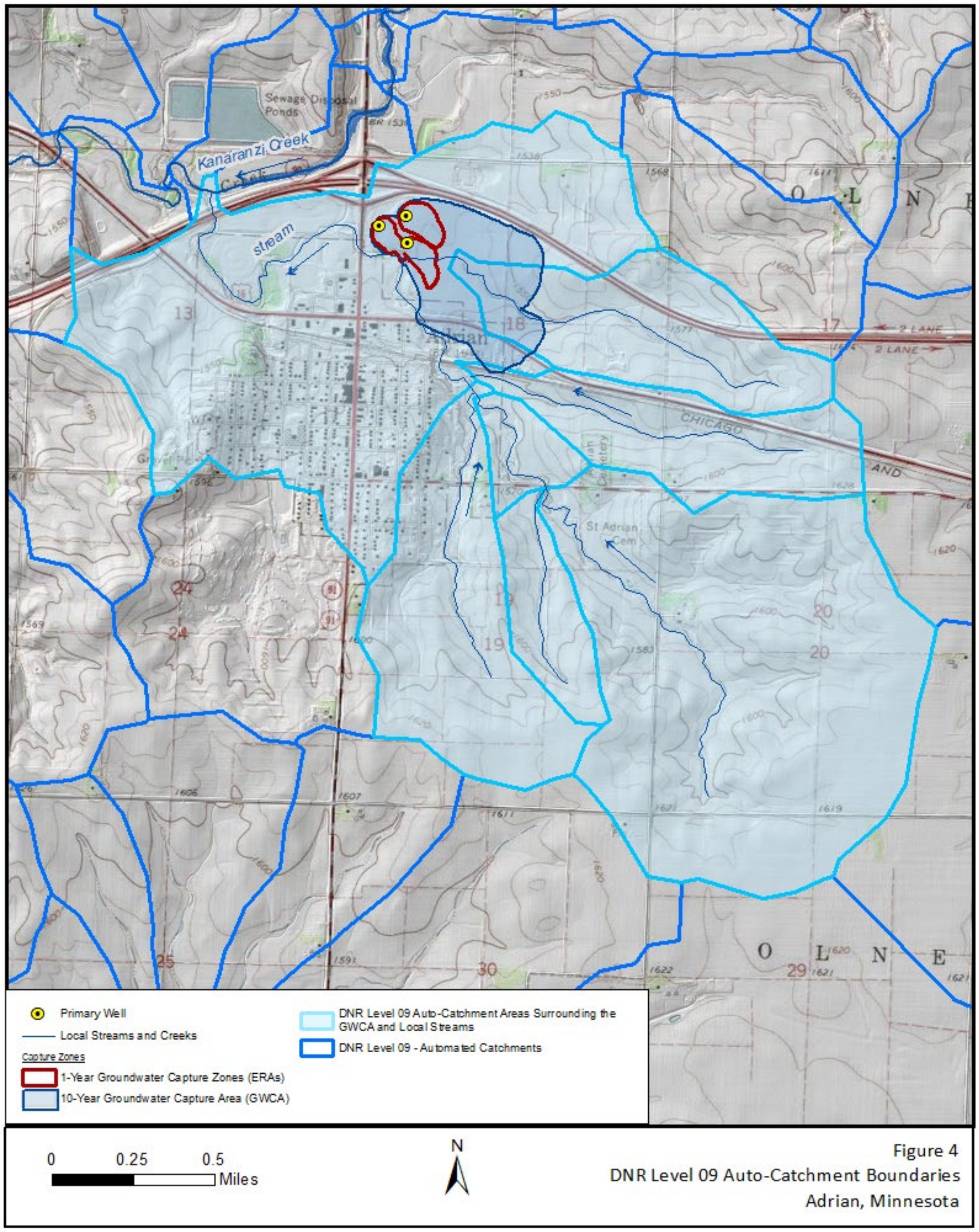

Figure 6. DNR level 09 auto-catchment boundaries: Adrian, MN.

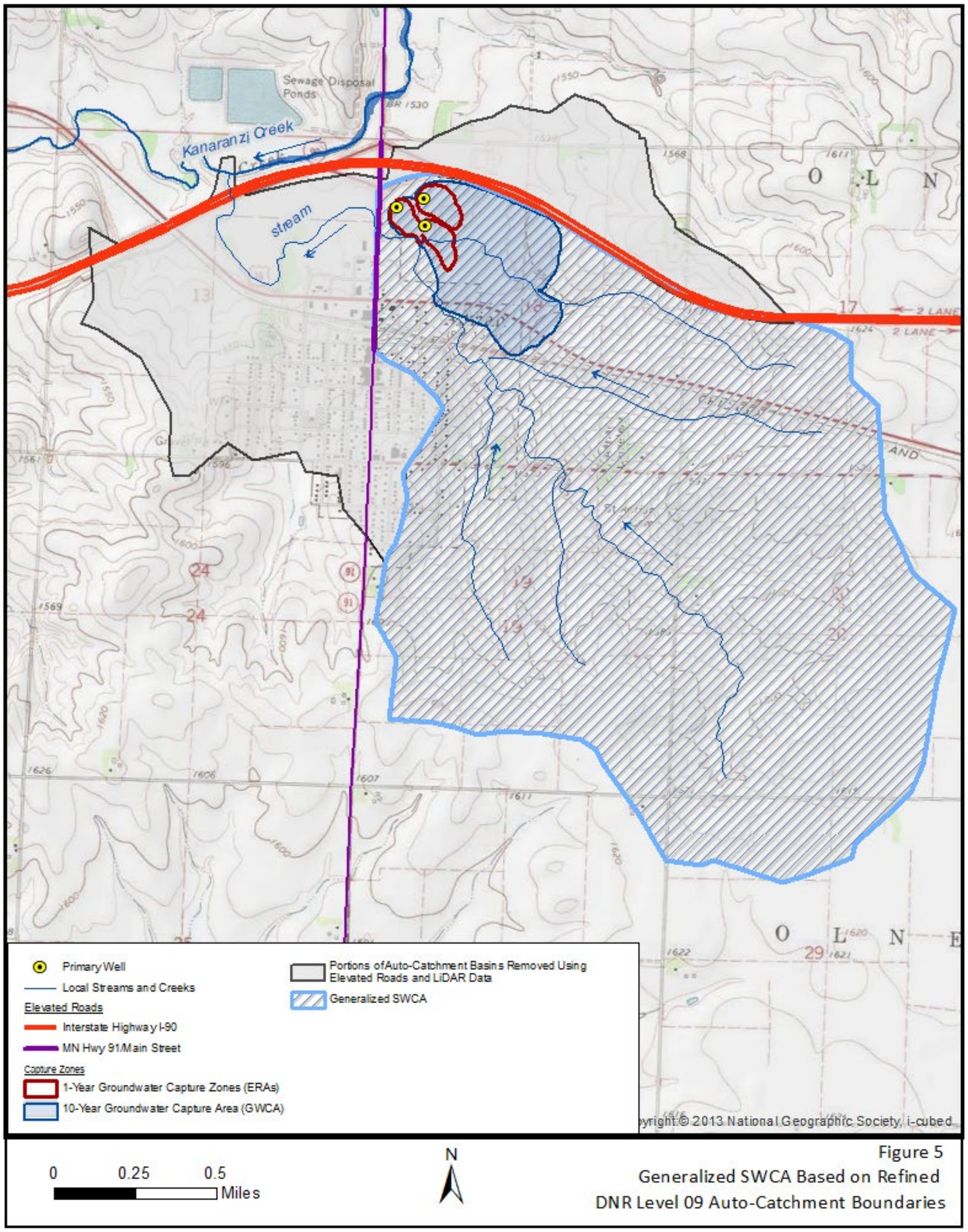

Figure 7. Generalized SWCA based on refined DNR level 09 auto-catchment boundaries.

2) **Consider ditches or other man-made water conveyance features.** If ditches or other stormwater conveyance features exist within the mapped area that potentially drains runoff to the surface hydrologic feature from outside the surface watershed, the land surface areas for those must also be included in the SWCA. Conversely, if parts of the surface watershed are artificially drained outside of the watershed, those areas can be removed from the SWCA. *No ditches or conveyance features are known.*

3) **Consider reasonable management area boundaries**. SWCAs for rivers and streams, and some lakes that are part of lake chains, can be unreasonably large to manage. Consider trimming these using one of the following rationales:

    a. *Scientifically determined time of travel reaches*. In those rare instances where a time of travel has been determined for a stretch of river or lake chain, consider subdividing the SWCA so it only reflects a relatively short time of travel area. For a river system this might be a matter of minutes or hours and reflect the time needed for a spill to be reported and well use altered to minimize the risk of contaminant capture. For a lake chain this might be a longer time period and therefore reflective not only of a public water supplier's response time but also persistence of acute contaminants such as pathogens.

    b. *Artificial boundaries such as bridges and dams.* These can provide helpful physical bounds to an otherwise unreasonably large SWCA.

    c. *Subdivision into priority management areas*. In those cases where it is beneficial to include the entire watershed or there are no physical features available for shortening it, consider breaking the composite WHPA into priority A and B areas. Priority A areas might consist solely of the ERA or the GWCA, and priority B might consist of the remainder of the SWCA. In some cases, portions of the SWCA may also be included in priority A. Those would be portions of the watershed that contain land uses considered potentially harmful to drinking water quality.

    Management area boundaries are reasonable without trimming using one of these criteria. Step 3 was not needed for this delineation.

4) **Append the SWCA to the GWCA to form the conjunctive WHPA.**

Conclusion

Nitrate monitoring of surface water and groundwater confirm impaired water quality with respect to the city wells and local streams in the upland areas. In addition, modeling results indicate that Well #5 (149184) captures a fairly significant component of surface water from the creek within the emergency response area. Though not explicitly modeled, surface water contribution to Well #6 (149187) is also a consideration from the tributary creek that drains across the emergency response area. The SWCA mapped for the streams using the auto-catchment areas and LiDAR match very well with the runoff contribution area of the previous delineation efforts.

References Cited

Djerrari, A.M. (2021), *Re: Adrian WHP Modeling*, Email communication, Minnesota Department of Health, St. Paul, Minn.

Djerrari, A.M., and Clemens-Billaigbakpu, Y. (2013), *Wellhead protection plan for the city of Adrian, Minnesota--Part 1 - Amendment*, Minnesota Department of Health, St. Paul, Minn., 25 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G. (2000), *MODFLOW-2000, the U.S. Geological Survey modular ground-water model--user guide to modularization concepts and the ground-water flow process*, U.S. Geological Survey, Open-File Report, 00-92, Reston, Va., 121 p.

Minnesota Department of Health (2006), *Guidance for preparing a conjunctive delineation--review draft*, St. Paul, Minn., 21 p.

Minnesota Department of Natural Resources (2013), DNR Watersheds - DNR Level 09 - DNR AutoCatchments, Geospatial Data Resource Site (GDRS) Minnesota Geospatial Commons, accessed on April 6, 2022, MNDNR Watershed Suite (https://gisdata.mn.gov/dataset/geos-dnr-watersheds).

Olsen, B.M. (2002), *Wellhead protection plan for the city of Adrian, Minnesota--Part 1*, Minnesota Department of Health, St. Paul, Minn., 27 p.

Pollock, D. (1994), *User's Guide for MODPATH/MODPATH-PLOT, Version 3: A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model,* U.S. Geological Survey, Open-File Report, 94-464, Reston, Va., 242 p.

Example 2 – City of Chandler

Background

The city of Chandler (PWS 1510002) is located in southwestern Murray County along County Road 91. The city's water supply consists of one primary and one emergency well. Both wells are shallow, ranging in depth from 30 feet to 43 feet. Information about the construction of the wells and their vulnerability is provided in Table 4.

Table 4. Water Supply Well Information

Local Well ID	Unique Number	Use / Status	Case Diameter (inches)	Case Depth (feet)	Well Depth (feet)	Date Constructed / Reconstructed	Aquifer[1]	Well Vulnerability
Well #1	241955	Primary	144	30	30	1938	QWTA	Vulnerable
Well #2	241956	Emergency	10	33	43	1959	QWTA	Vulnerable

Notes: 1. QWTA means Quaternary Water Table Aquifer

The city's wells are constructed in a water table aquifer that consists of sand and gravel located within the valley of the Chanarambie Creek. The dominant landform in the area is the Coteau des Prairies, a wedge-shaped upland between the Minnesota River lowland in Minnesota and the James River lowland in South Dakota. The landscape surrounding the city of Chandler formed as the Des Moines lobe ice deposited glacial moraines that covered Cretaceous-age sediments or the Sioux Quartzite of late Proterozoic age. The physiographic and geological conditions of the area impact the yield and vulnerability of the aquifer used by the city. As ice advanced into the area, meltwater deposited sand and gravel along an outwash channel that cuts across the Bemis Moraine and the loess-covered ground moraine. The surficial sand and gravel aquifer used by the city wells consists of the outwash channel deposits (Clemens-Major, 2008). A surficial geology map of the area (see Figure 8 below) shows where the aquifer occurs below the soil horizon.

Chanarambie Creek is a regional discharge feature in the area. Several streams and intermittent creeks drain from the uplands down to the glacial outwash channel and the Chanarambie Creek. The Creek flows northwesterly from the southeast toward the city, making a westerly bend in the vicinity of Well #1 (241955). In addition, a tributary stream flows toward the city from the northeast within a secondary glacial channel; the tributary stream discharges to Chanarambie Creek at a location that is approximately 500 feet south of Well #1.

The runoff of precipitation and snow melt from the upland areas recharge the outwash channel aquifer in addition to contributing seasonal increases in the flow of Chanarambie Creek and local streams. Given the shallow nature of the aquifer, changes in the amount of precipitation and corresponding groundwater recharge may have a significant effect on the available saturated thickness of the aquifer (Clemens-Major, 2008).

Wellhead Plan Monitoring Efforts

The city of Chandler has wells impaired for nitrate. Elevated nitrate levels have been observed in the city's primary well, Well #1 (241955), ranging 4.3 mg/l to 9.3 mg/l. As part of wellhead planning, water samples were collected for isotopic and water quality comparisons between the city well and local surface water features, including Chanarambie Creek and the unnamed creek draining from the upland area northeast of town. The diagnostic chemistry results indicate little or no contribution to the city's well from local surface waters. The isotope results from Well #1 fell along the meteoric water line, however, the results from the stream samples generally showed heavier isotopes and a degree of evaporation. The nitrate results also suggest the lack of surface water contribution to the well. During the monitoring events, nitrate-nitrogen was elevated at the city well (ranging 5.3 mg/l to 6.2 mg/l) but was either not detected or very low in the water samples from the streams (ranging <0.05 mg/l to 0.39 mg/l).

In addition, a leakage analysis of stream cells was done using the groundwater flow model developed by MDH for the 2022 amendment to the city's wellhead protection plan. (The model is described in the following next section). Stream conductance values within the one-year capture zone were varied from the base case values to reflect both lower and higher conductance scenarios. With respect to all three conductance scenarios, the leakage analysis results indicate that Well #1 (241955) receives no contribution from the stream.

Method Used to Delineate the GWCA

The GWCA for the city of Chandler's primary well was determined using a regional groundwater flow model created with the software code MODFLOW-NWT (Niswonger et al., 2011). The resulting GWCA boundaries were determined using a stochastic method and are a composite of the capture zones calculated from several different model scenarios (see Figure 8 below).

The numerical groundwater model that was constructed consisted of 261 rows, 258 columns, and a single layer. The model incorporates a variable areal grid spacing ranging from 7.5 meter near the city's well and grading to 60 meters at the boundaries of the model domain with some of the cells remaining inactive. Layer tops and bottoms were derived from CWI logs within the model domain and digital elevation information. River head boundaries represent cells where water is flowing both into and out of the aquifer and were used to simulate the creeks and wetlands within the model domain. The model domain was limited to the sub-watersheds surrounding the city. Vertical recharge was applied to the model using values calculated using Version 2.0 of the SWB model published by the U.S Geological Survey (Westenbroek et al., 2018). Representative aquifer parameters were used in the base case model scenario.

One hundred additional realizations were calibrated and simulated to reflect uncertainty conditions using the Pest++ IES (White et al., 2020) suite of programs. To determine the GWCA, the many MODFLOW model realizations were used with a particle tracking program called MODPATH (Pollock, 2016). MODPATH is used to evaluate advective transport of simulated particles moving through the simulated flow system. In the capture zone analysis, a porosity of

25 percent was used, and 100 particles were launched at the well and tracked upgradient for one-year for the ERA and 10-years for the GWCA. Each of these potential capture zones were composited into a probability of capture based on the number of times any specific location is included in the generated capture areas, divided by the total number of realizations. The combined output of all model results was composited and those areas with a total probability of capture at the well equal to 0.1 (10 percent), or higher, were delineated to create the final ERA and GWCA (see Figure 8 below). Additional information regarding the delineation method can be found in the Chandler Part 1 Amendment report (Clemens-Billaigbakpu, 2022).

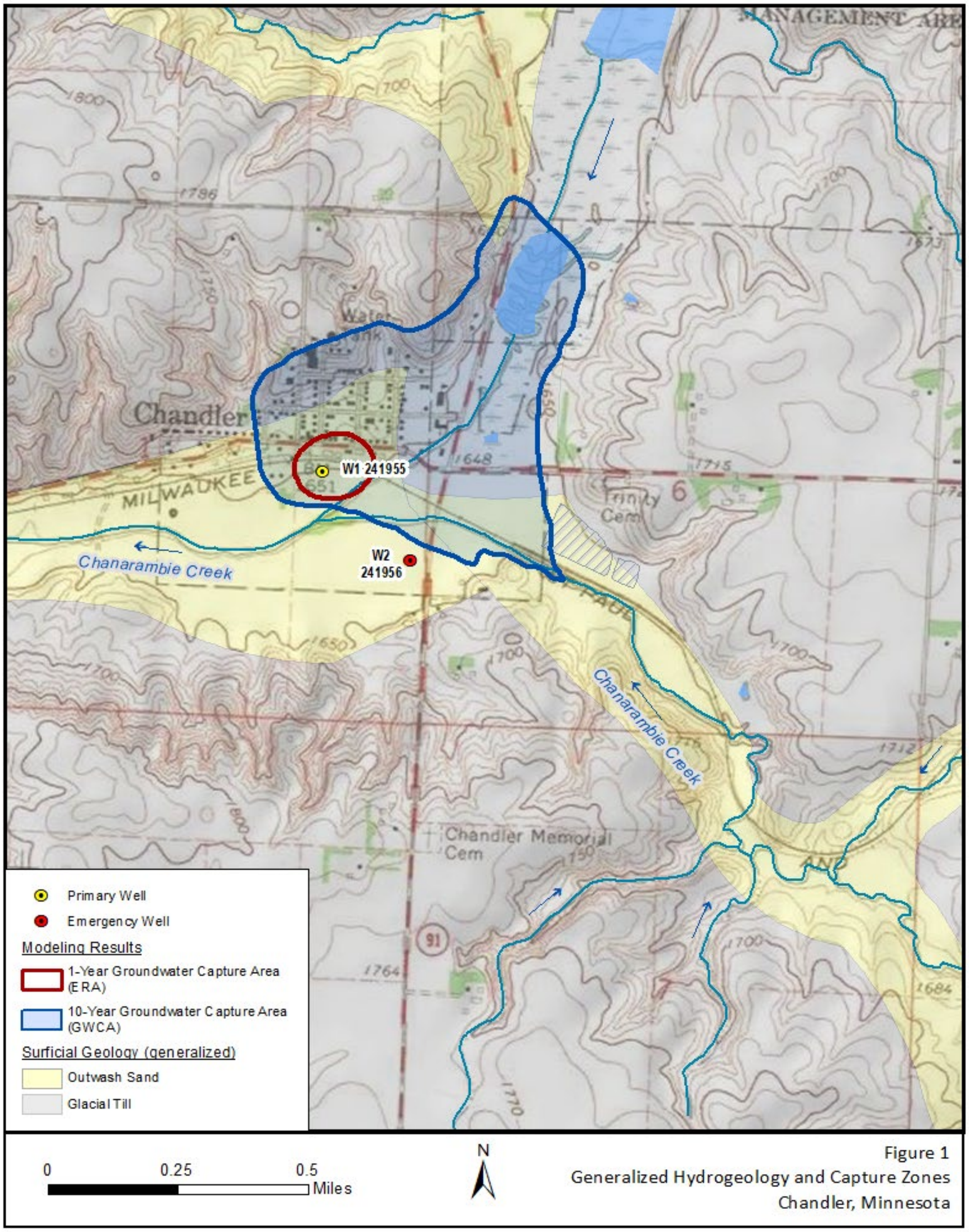

Figure 8. Generalized hydrogeology and capture zones: Chandler, MN.

Assessing the Need for a Conjunctive Delineation

Because the GWCA is geologically sensitive and the water quality of the city wells has been impacted by nitrate, the need for a conjunctive delineation was assessed as part of this delineation. Refer to the steps below for how this was accomplished.

Steps to SWCA Determination

Step 1. Use information about the delineated ERA and GWCA, the hydrogeologic setting and water chemistry:

a. Is the ERA or GWCA based on a fracture flow or karst setting? *No, the aquifer serving the city wells is comprised of porous media and does not represent a fracture flow or karst setting.*

b. Does the PWS well(s), or other wells in the same aquifer that are located in the ERA or GWCA, show evidence of degraded water quality that may be attributed in part to impaired runoff or surface water features? *Yes, the water quality of the wells has been degraded by nitrate that may be coming from runoff draining onto the GWCA.*

c. If the answer to both scenarios is no, continue to Step 2.

d. If the answer to either or both scenarios is yes, go to Step 2A.

Step 2A: Does the GWCA contain areas where the DWSMA vulnerability is high?

a. If not, no SWCA is needed.

b. If yes, continue to Step 3A. *Yes, the vulnerability of the DWSMA beneath the GWCA is high.*

Step 3A: **For porous media aquifers** - Does the GWCA intersect a surface water feature or receive runoff from surrounding lands that are characterized by: 1) higher elevation and 2) soils likely to promote runoff (Hydrologic Groups C and D), or slopes that exceed 6% if Hydrologic Group B soils?

For karst or fractured aquifers - Does the GWCA intersect 1) a surface water feature, sinkholes and/or dry drainage ways or 2) receive runoff from surrounding lands that are characterized by: A) higher elevation and B) soils likely to promote runoff (Hydrologic Groups C and D), or slopes that exceed 6% if Hydrologic Group B soils?

a. If not, no SWCA is needed.

b. If yes, continue to Step 4A. *Yes, the GWCA is likely to receive runoff from surrounding lands that are characterized by: 1) higher elevation and 2) soils likely to promote runoff (Hydrologic Groups C and D), or slopes that exceed 6% if Hydrologic Group B soils (see Figures 8 and 9 below).*

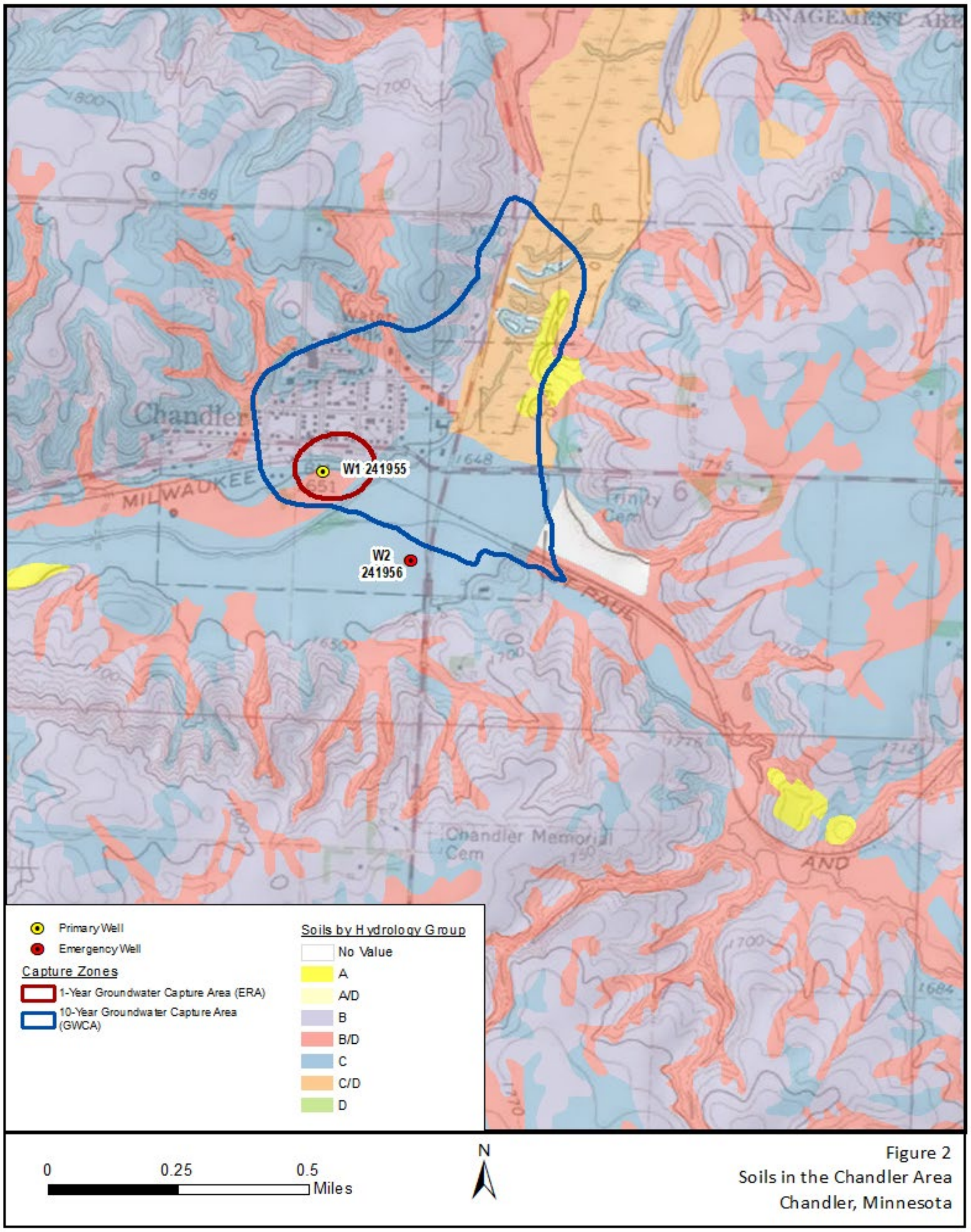

Figure 2
Soils in the Chandler Area
Chandler, Minnesota

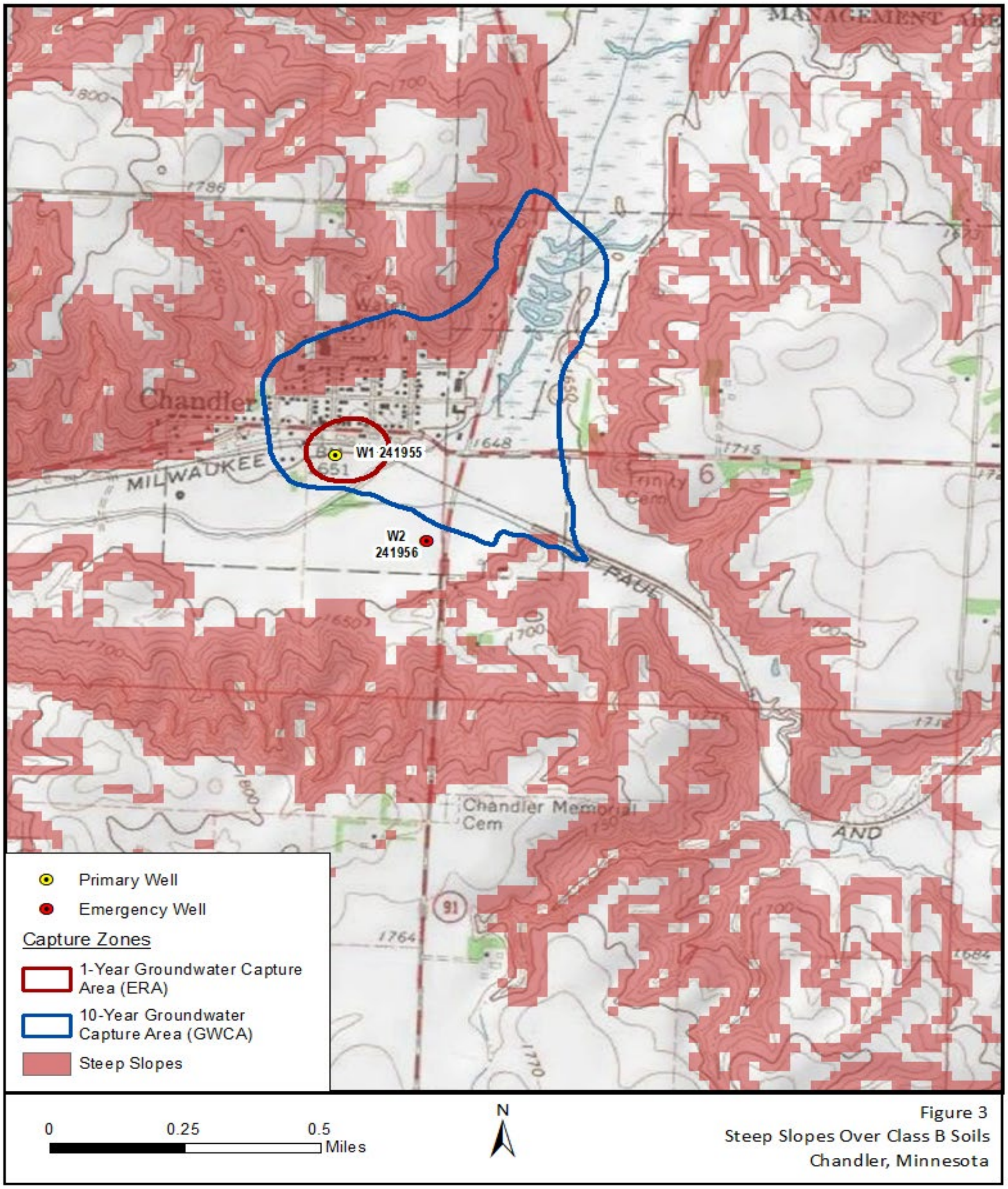

Figure 9. Steep slopes over Class B soils: Chandler, MN.

Step 4A: If the SWCA is to be based on a surface water feature, do adequate physical and chemical data exist to confirm the connection with the feature as suggested by delineation results? See Appendix I for a discussion of data adequacy. If the SWCA is to be based on runoff, sinkholes, or dry valleys, proceed to Step 5A. *The SWCA is to be based on runoff.*

Step 5A: For karst or fractured rock settings, features such as sinkholes and/or dry drainage ways and their contributing areas may be used to create a SWCA regardless of supporting physical or chemical data. The same is true for porous media settings where surface water runoff is suspected of causing water quality impairments in the source aquifer.

a. Features such as sinkholes or dry drainage ways may contribute recharge to the aquifer in short, intermittent bursts according to heavy rainfall or snowmelt events that may not coincide with routine compliance sampling or even investigative studies that would ordinarily be used to confirm the importance of these events on water quality. Therefore, they may be used as a basis for SWCA delineation in recognition of this unique hydrogeologic setting. For this porous media setting, a runoff SWCA is included due to suspected or potential water quality impairments stemming from runoff, without supporting physical or chemical data because none exist for the runoff and gathering such data would be difficult or impossible.

Follow the steps for delineating a SWCA based on runoff:

1) *Map the preliminary SWCA based on topography*. Work outward from the GWCA capture zone to determine what land surface areas exhibit a higher topographic elevation and could potentially shed runoff in that direction. This area will constitute the potential surface watershed for the SWCA. This mapping can be accomplished in GIS using either established catchment area boundaries where available and relevant or be determined from scratch using an accurate depiction of topography such as LiDAR. The DNR Level 09 auto-catchments are a useful resource and may provide the most reasonable boundaries due to their relatively fine scale. However, these catchments were derived prior to LiDAR so should be reviewed relative to more recent land elevation data. Note that Level 08 catchments may also be relevant due to their dependence on LiDAR data, but these are at a coarser scale. In any case, the user must be aware of local high spots such as roadways that may not be reflected in these delineated boundaries and adjust their SWCAs accordingly. Three DNR Level 09 auto-catchment areas exhibit higher topographic elevations and likely drain toward the GWCA. The catchment basin located northeast of the GWCA was deemed to be unmanageably large by consultation between the MDH hydrologist and supervisor, so it was determined to use an artificial cutoff as shown in Figure 10 below*.*

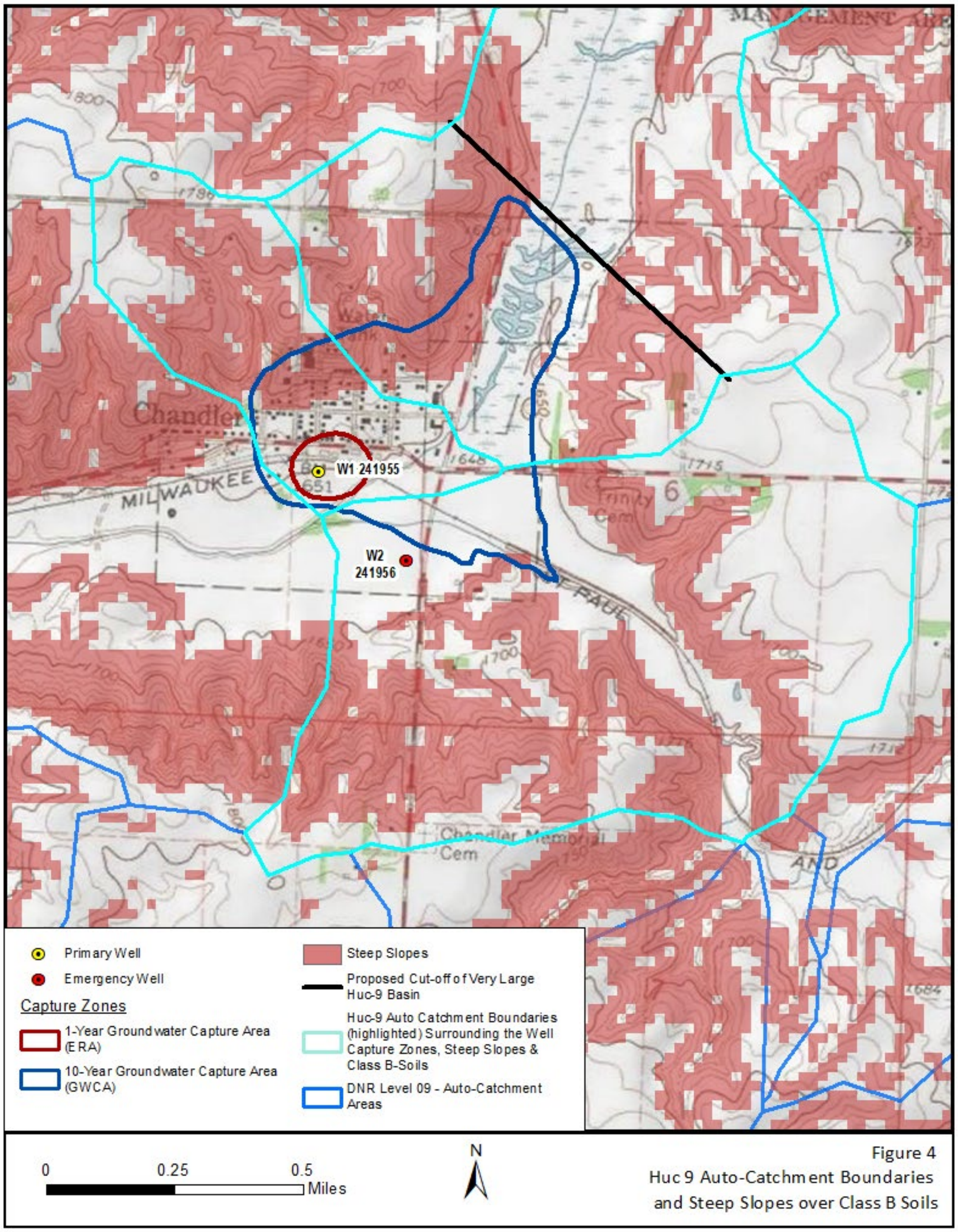

Figure 10. HUC 9 auto-catchment boundaries and steep slopes over Class B soils.

2) *Determine the hydrologic group for soils within the preliminary SWCA.* In GIS, add the NRCS soils layer (SSURGO) and determine the portion of the area within the preliminary SWCA that is characterized by soils likely to shed runoff. These are classified as Hydrologic Groups C and D or Group B soils where slopes are greater than 6 percent. Areas underlain by more permeable soils (Hydrologic Group A) are to be discarded, as are areas where Group B soils are less than 6 percent in slope. Those areas are more likely to promote infiltration than runoff. It is noted that there may be preliminary SWCAs where the soil types are mixed. In such settings, it may be more practical to lump soil types together from the perspective of implementing wellhead management strategies. In mixed soil settings, the potential SWCA should contain at least 80% C and D soils, or B soils greater than 6% slope, and be at least 10 acres in size. (see Figures 8-10 above).

3). *Consider ditches or other man-made water conveyance features (such as culverts).* If ditches or other stormwater conveyance features exist in the vicinity of the proposed SWCA and will add runoff to that zone, the land surface areas for those must also be included in the SWCA. Conversely, if the areas delineated in the above steps are artificially drained away from the proposed SWCA, then those areas can be removed from the final SWCA. *No ditches or conveyance features are known.*

4). *Append the SWCA to the GWCA to form the conjunctive WHPA.* (See Figures 11 and 12 below.)

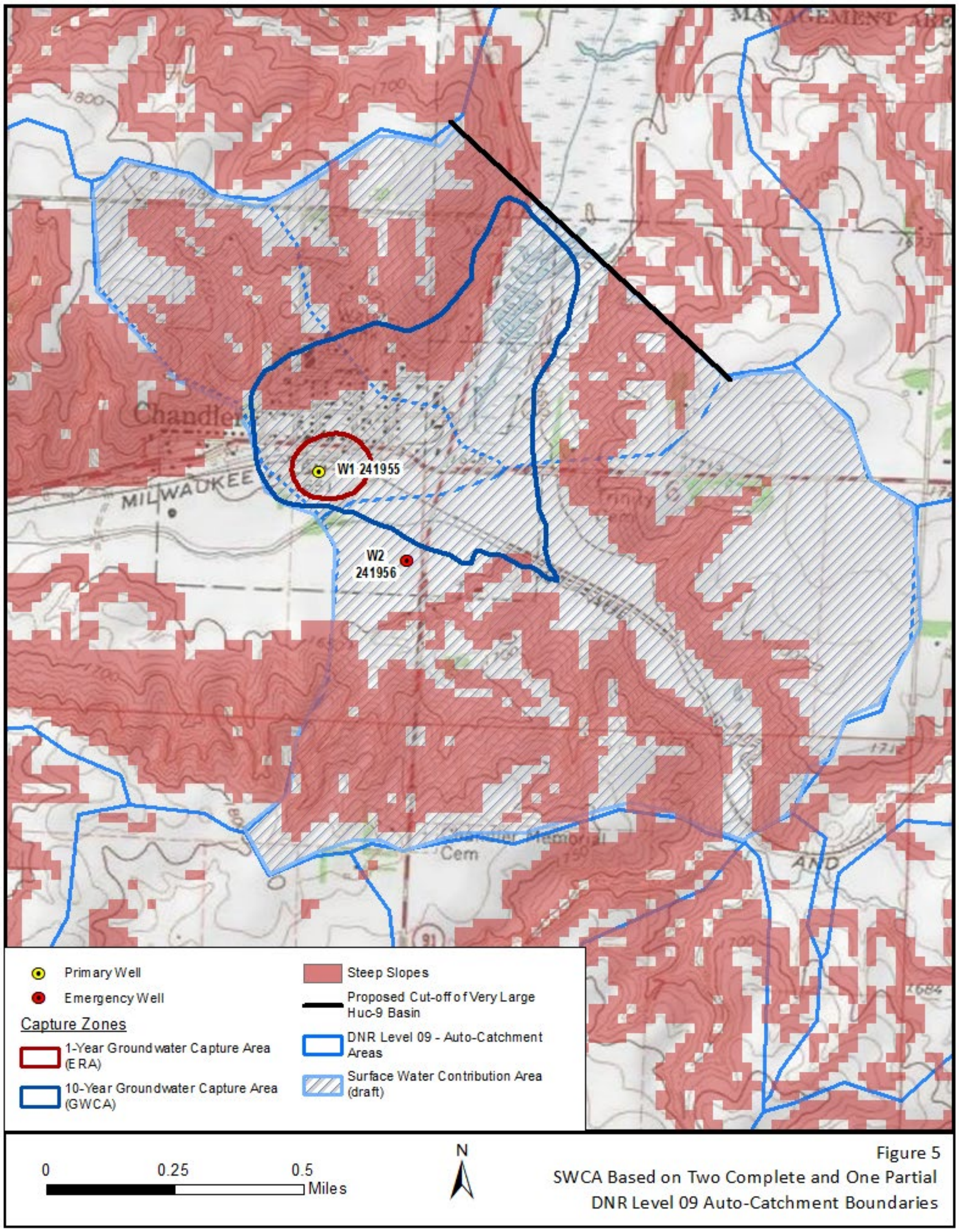

Figure 11. SWCA based on two complete and one partial DNR level 09 auto-catchment boundaries.

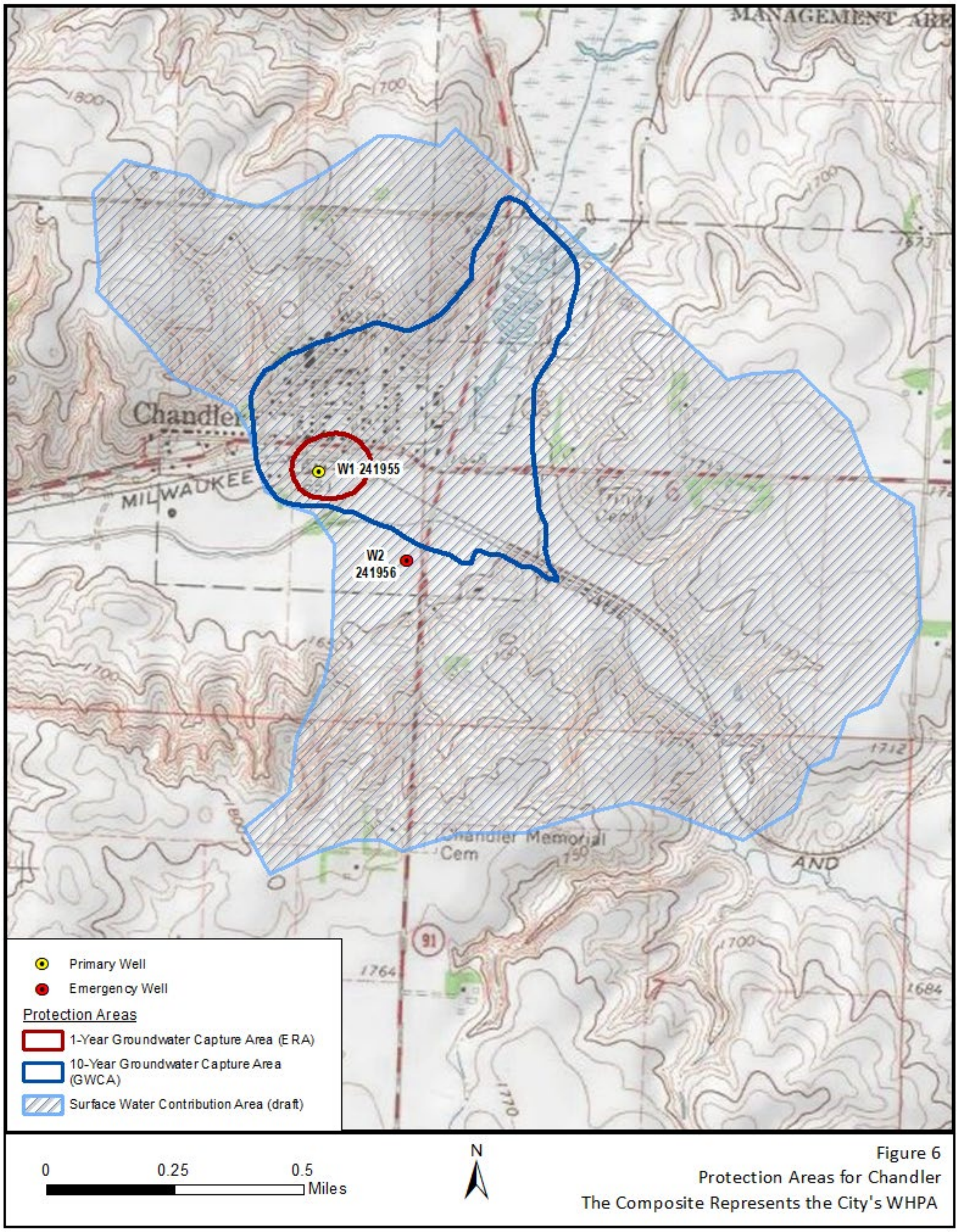

Figure 12. Protection areas for Chandler.

Conclusion

The city of Chandler has wells impaired for nitrate and is surrounded by areas of higher elevation likely to shed runoff onto the well capture zones. The runoff contribution area was mapped using information about local soils, steep slopes, and the DNR Level 09 auto-catchment area boundaries. One of the catchment areas was exceedingly large, so an artificial cutoff was used. The land uses in these areas may generate nutrient-rich runoff, so they were appended to the city's well capture zones to create a conjunctive WHPA based on runoff.

References Cited

Clemens-Billaigbakpu, Y. (2022), *Hydrogeologic Assessment of Drinking Water Source and Wells for the City of Chandler*, Minnesota Department of Health, St. Paul, Minn., 56 p.

Clemens-Major, Y. (2008), *Wellhead protection plan for the city of Chandler, Minnesota--Part 1*, Minnesota Department of Health, St. Paul, Minn., 23 p.

Minnesota Department of Natural Resources (2013), DNR Watersheds - DNR Level 09 - DNR AutoCatchments, Geospatial Data Resource Site (GDRS) Minnesota Geospatial Commons accessed on February 17, 2022, MNDNR Watershed Suite (https://gisdata.mn.gov/dataset/geos-dnr-watersheds).

Niswonger, R.G., Panday, Sorab, and Ibaraki, Motomu. (2011), *MODFLOW-NWT, A Newton formulation for MODFLOW-2005: U.S. Geological Survey Techniques and Methods 6-A37*, 44 p., MODFLOW-NWT, A Newton formulation for MODFLOW-2005 (https://pubs.usgs.gov/tm/tm6a37/)

Westenbroek, S.M., Engott, J.A., Kelson, V.A., and Hunt, R.J., 2018, *SWB Version 2.0—A soil-water-balance code for estimating net infiltration and other water-budget components: U.S. Geological Survey Techniques and Methods,* book 6, chap. A59, 118 p., SWB Version 2.0—A soil-water-balance code for estimating net infiltration and other water-budget components (https://doi.org/10.3133/tm6A59).

White, J.T., Hunt, R.J., Fienen, M.N., and Doherty, J.E., (2020), *Approaches to Highly Parameterized Inversion: PEST++ Version 5, a Software Suite for Parameter Estimation, Uncertainty Analysis, Management Optimization and Sensitivity Analysis: U.S. Geological Survey Techniques and Methods 7C26*, U.S. Geological Survey, Reston, Va., 52 p., Approaches to Highly Parameterized Inversion (https://doi.org/10.3133/tm7C26).

Appendix 4: Surface water feature conjunctive delineation example

Background

The city of Nevis draws groundwater from the Quaternary Water Table Aquifer (QWTA). Information about the construction of the wells and their vulnerability is provided in Table 5.

The city's well field is located in a park immediately adjacent to Lake Belle Taine, which is at the bottom of an extensive watershed located in a glacial moraine complex (Figure 13 below). Lake Belle Taine has no natural surface outlet, and instead drains through the sand and gravel moraine immediately to the south into Seventh, Sixth, and Fifth Crow Wing Lakes in the Crow Wing River watershed, a hydraulic characteristic that has made it the subject of several studies (Rosenberry et al., 2010; Rosenberry, 2000). Groundwater flow mirrors the surface water flow, with flow generally to the south from the northern highlands, and then southward to discharge into the Crow Wing chain of lakes to the south. Sand-rich water table aquifer units can be found quite deep around Lake Belle Taine. The well log for Unique Number 541888, which is to the southeast of Nevis, shows 167 feet of sand, with no clay or bedrock encountered. Bedrock is at a depth of approximately 375 to 450 feet in the area.

Table 5. Water Supply Well Information

Local Well ID	Unique Number	Use / Status	Case Diameter (inches)	Case Depth (feet)	Well Depth (feet)	Date Constructed / Reconstructed	Aquifer	Well Vulnerability
Well #1	181293	Emergency	12	60	85	06/25/1981	QWTA	Vulnerable
Well #2	480068	Primary	12	50	70	10/23/1992	QWTA	Vulnerable

Method Used to Delineate the Groundwater Capture Area

The GWCA for the city of Nevis' well was determined using a regional groundwater flow model created with the software code MODFLOW (McDonald and Harbaugh, 1988). The model was created to delineate the GWCAs for the cities of Akeley and Nevis. The four input files for this delineation are available from MDH upon request.

The model consists of three layers that, in the area of the city's well, represent the city's aquifer and a deeper sandy layer immediately below the city's well. The closest lakes to the cities' well, Eleventh Crow Wing Lake (Akeley) and Lake Belle Taine (Nevis), as well as the major streams within the model, are represented by river conductance cells. Lake bottom conductance was determined from existing USGS studies on Lake Belle Taine and estimated from lake adjacent DNR observation well and lake level data. All other lakes were represented as constant head boundaries. Vertical recharge was applied to the model using shapefiles that represent values approximating rates published by the U.S. Geological Survey (Delin et al., 2007). Recharge was refined somewhat throughout the western half of the model during the calibration process, with final values ranging from one to two inches per year. Final values in and around Akeley were consistent with the rates from Delin et al. at around 6.6 inches per year. The model grid was refined around the city well. Variable grid spacing was used, ranging from 0.26 meters near the two modeled well fields to 474 meters at the edges of the model grid. This refinement was required for an accurate computation of the particle flow paths for delineating the GWCA.

To determine the GWCA, the MODFLOW model was used with a particle tracking program called MODPATH (Pollock, 1994). MODPATH was used to evaluate advective transport of simulated particles moving through the simulated flow system. A series of 50 particles were launched at each well. A porosity of 25 percent was used for the aquifer used by the city and a 10-year reverse time of travel was calculated. The final GWCA boundaries are a composite of the capture zones calculated using the results of the sensitivity analysis. Figure 14 below shows the particle track output from the flow model.

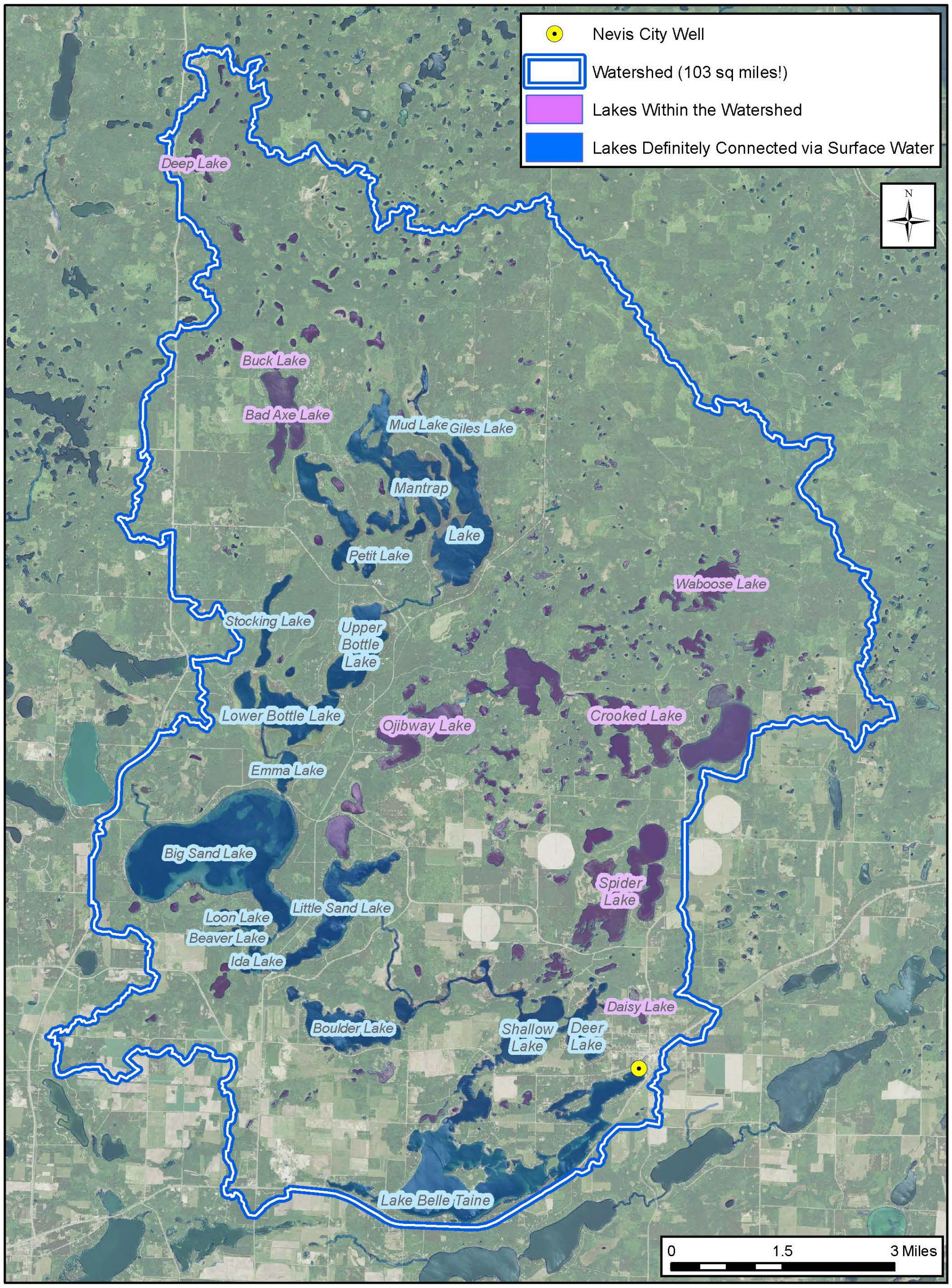

Figure 13. Location of city well with respect to adjoining lakes and watershed boundaries.

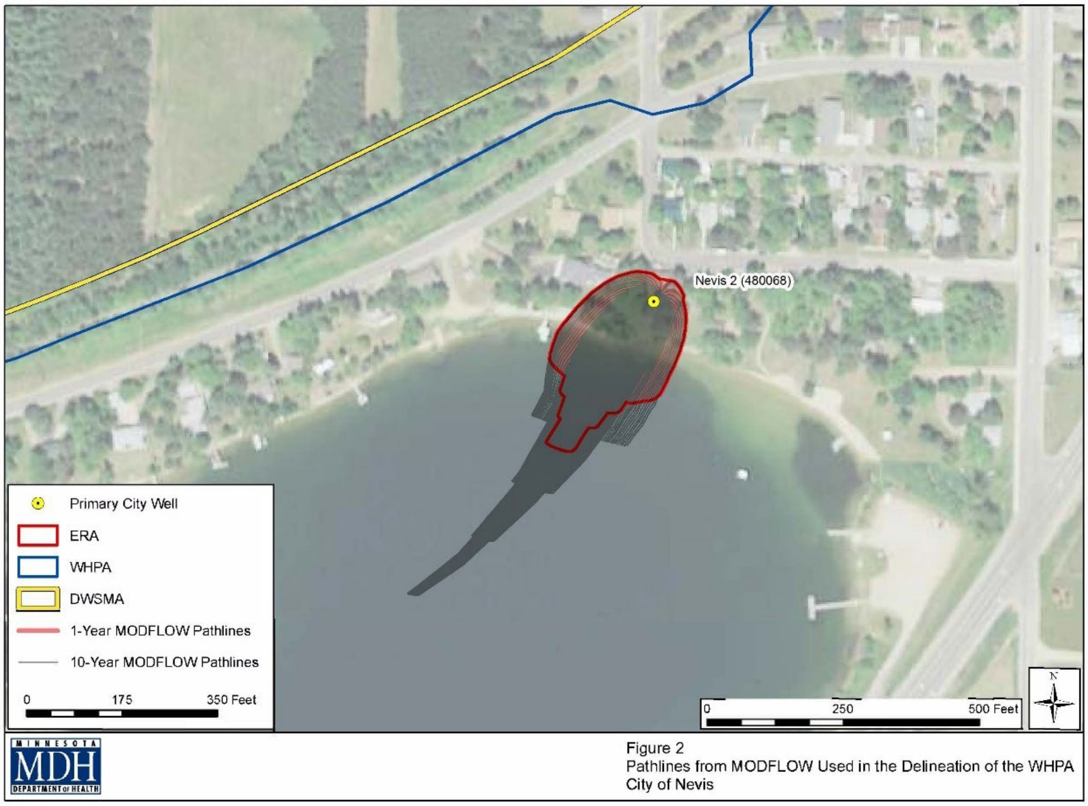

Figure 14. Particle tracks from groundwater flow model, showing capture of lake water within the ERA.

Assessing the Need for a Conjunctive Delineation

Because the ERA is geologically sensitive and intercepts a surface water feature within the ERA, the need for a conjunctive delineation was assessed as part of this delineation. Refer to the steps below for how this was accomplished

Steps to SWCA Determination

Step 1: Use information about the delineated ERA and WHPA, the hydrogeologic setting and water chemistry:

a. Is the ERA or GWCA based on a fracture flow or karst setting? *No, the aquifer serving the city wells is comprised of porous media and does not represent a fracture flow or karst setting.*

b. Does the PWS well(s), or other wells in the same aquifer that are located in the ERA or GWCA, show evidence of degraded water quality that may be attributed in part to impaired runoff or surface water features? *No, the PWS wells show no evidence of degraded water quality that might be due to lake interaction.*

c. If the answer to **both** scenarios is no, continue to Step 2. Go to Step 2.
d. If the answer to **either** scenario is yes, go to Step 2A.

Step 2: Does the ERA contain areas where the DWSMA vulnerability is high?

a. If not, no conjunctive delineation is needed.
b. If yes, continue to Step 3. *Yes, the vulnerability of the DWSMA beneath the ERA is high.*

Step 3: Does the ERA intersect a surface water feature?

a. If not, continue to Step 4
b. If yes, continue to Step 5. *Yes, the ERA intersects Lake Belle Taine* (see Figure 13 above*).*

Step 4: Do adequate physical and chemical data exist to confirm the connection with a surface hydrologic feature suggested by the delineation results? (Appendix I)

a. Physical Data -

i. Water level data –If available, a downward or flat vertical hydraulic gradient between a surface hydrologic feature and the aquifer would support that a significant connection exists. An upward hydraulic gradient would refute a significant connection, although it is important to realize that changing groundwater withdrawals can alter this dynamic. It is recommended that physical data be used in conjunction with chemical and isotopic data to confirm or refute the presence of a significant hydraulic connection with a surface water body. Water level data suggest a downward vertical gradient of -0.26 exists, supporting a connection between the lake and well. Refer to the MDH "Gradiator" tool for assessing vertical gradients.

ii. Flow data – The presence of a losing stretch within the area of concern would support a conjunctive relationship, while a gaining stretch would not. To have confidence in this assessment, the determination of gaining or losing must come from a result that falls outside of the measurement error for the method. It is recommended that physical data be used in conjunction with chemical and isotopic data to confirm or refute the presence of a significant hydraulic connection with a surface water body. *None known.*

b) Chemical and isotopic data –

Lake Belle Taine is a long residence time feature (estimated residence time of 232 days, well in excess of the threshold value of 90 days). As a result, a minimum of two sets of synoptic results from the well and lake for diagnostic water characterization parameters, such as water isotopes and chloride, within a given 12-month period, separated in time by 4-7 months, is required. In this case, two sets of samples were taken from the well and lake just beyond the 12-month period and were not exactly synoptic. However, they are close enough to the required criteria to serve as a relevant example. In addition to these samples that were collected for the wellhead protection plan, a number of water isotope samples were collected from the city well for another study, allowing for additional insights.

Table 6 shows the sampling dates and analytical results for a suite of indicator parameters that are commonly evaluated for assessing hydrologic connection between surface water features and groundwater.

Table 6. Vulnerability Suite Chemistry Results

Place/SampleName	Date Taken	Tritium (TU)	Oxygen-18 (per mil)	Oxygen-18 replicate (per mil)	Deuterium (per mil)	Deuterium replicate (per mil)	Bromide (mg/L)	Chloride (mg/L)	Nitrate (mg/L as Nitrogen)	Ammonia (mg/L as Nitrogen)	Sulfate (mg/L)	Total Organic Carbon (mg/L)	Cl/Br Ratio
Well #2 (480068)	2/19/2013	8.1	-5.56	-5.53	-51.92	-51.21	0.012	10.7	0.26	0.05	1.17	1.9	892
Well #2 (480068)	6/24/2013						0.01	4.31		0.05	1	2.2	431
Lake Belle Taine (SWS348)	9/19/2013		-3.89		-43.21		0.005	3.02	0.05	0.05	1		604
Well #2 (480068)	5/20/2014		-4.92	-4.70	-47.90	-47.4	0.006	3.72			1		676
Lake Belle Taine (SWS348)	5/19/2014		-4.88	-4.70	-47.30	-46.1	0.018	3.2					183

Blue = below method reporting limit (reporting limit listed)
Red = ratio within human impacted range of values (> 250)

The next steps are to compare the isotopic and chemical data from the well and lake to look for similarities. This is done first by evaluating the isotopic data relative to the Minnesota Meteoric Water Line (MWL) and second, by conducting a mixing analysis to estimate the amount of lake water that may be present in the well water.

i. *Meteoric Water Line comparison plot*:

The samples from Lake Belle Taine are uniformly far-removed from the MWL and show a strong overlap with the samples from the city well except for a single sample from the well that plotted on the MWL (see Figure 15 below). These results suggest that the lake and well water is generally strongly correlated.

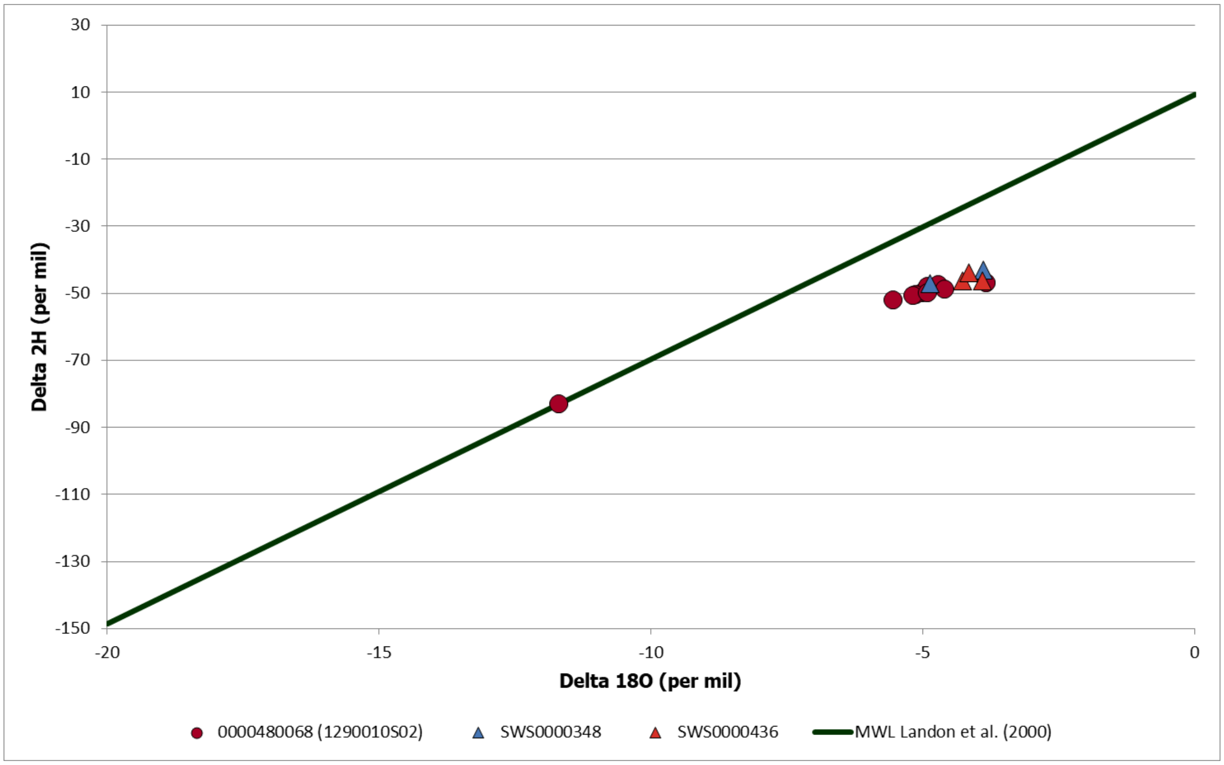

Figure 15. Water isotopes from Lake Belle Taine and the Nevis city well compared to the Minnesota Metoric Water Line.

ii. *Mixing Analysis*:

Table 7 shows the output from the MDH isotope analysis tool. This tool analyzes the distance between a pair of results for delta oxygen-18 and deuterium and the nearest point on the MWL. Points that exceed a threshold distance, known as Line Conditioned Excess or LCE, are considered significantly removed from the line and likely impacted by mixing with evaporated surface water. It also presents a number of supporting pieces of information pertaining to the likelihood of surface water capture. In this case, evidence strongly suggests a high percentage of lake water is present at the city well. This is most evident by referring to the column titled "% rank…" The percentage shown here represents where the samples from this well fall relative to a wide array of other well water samples statewide with varying amounts of surface water influence based on LCE determinations. The Nevis well samples plot in the 97th percentile, suggesting that nearly all of the water pumped by this well originated at the nearby lake. This information is summarized in the text in the final column, which indicates the well is likely impacted by surface water, and within a timeframe that may leave it at risk to microbiological contamination.

Conclusion:

Physical and chemical data support the modeling output, suggesting that the city well captures a significant quantity of lake water within the ERA. As a result, Lake Belle Taine and parts of its watershed were used to create a SWCA, which was merged with the GWCA to form the WHPA. The watershed feeding Lake Belle Taine is approximately 100 square miles, which was deemed too large for effective wellhead protection plan management purposes. The watershed itself has a shallow surface water flow gradient between Mantrap Lake (1,434 feet AMSL) and Lake Belle Taine (1,427 feet AMSL), with most of the head difference occurring between Mantrap and the second and third lakes in the chain, Upper and Lower Bottle Lakes (1,429 feet AMSL). Calculated gradient within the chain between Mantrap and Belle Taine is approximately 0.00009, but the gradient between Lower Bottle and Belle Taine is 0.00003, which is quite flat, and likely leads to long travel times between Lower Bottle and Belle Taine. When this long travel time concept is combined with the sizes of the intervening lakes and the volume of water within the chain overall, any point source pollution upstream would likely be quite diluted by the time it would reach Belle Taine adjacent to the city's well field.

Additionally, a more in-depth bathymetric study of Lake Belle Taine suggested that the southwestern-most pool is the deepest and is presumed to be the most transmissive portion of the lake. To the east of this deeper pool, the lake becomes shallower and is somewhat channelized, with narrow channels connecting pools that, taken together, make up the eastern extent of the lake. Nevis' well is located adjacent to the easternmost and shallowest pool and is somewhat removed from the southwestern pool. Finally, hydrogeologic studies suggest that a significant portion of the water flowing into and out of the lake is via groundwater (Rosenberry et al., 2010; Rosenberry, 2000).

All of these factors support the creation of a smaller SWCA that only includes Lake Belle Taine and its immediate lakeshed. Figure 16 below shows the SWCA that was created by partitioning the Lake Belle Taine lakeshed from the greater watershed using digital elevation data.

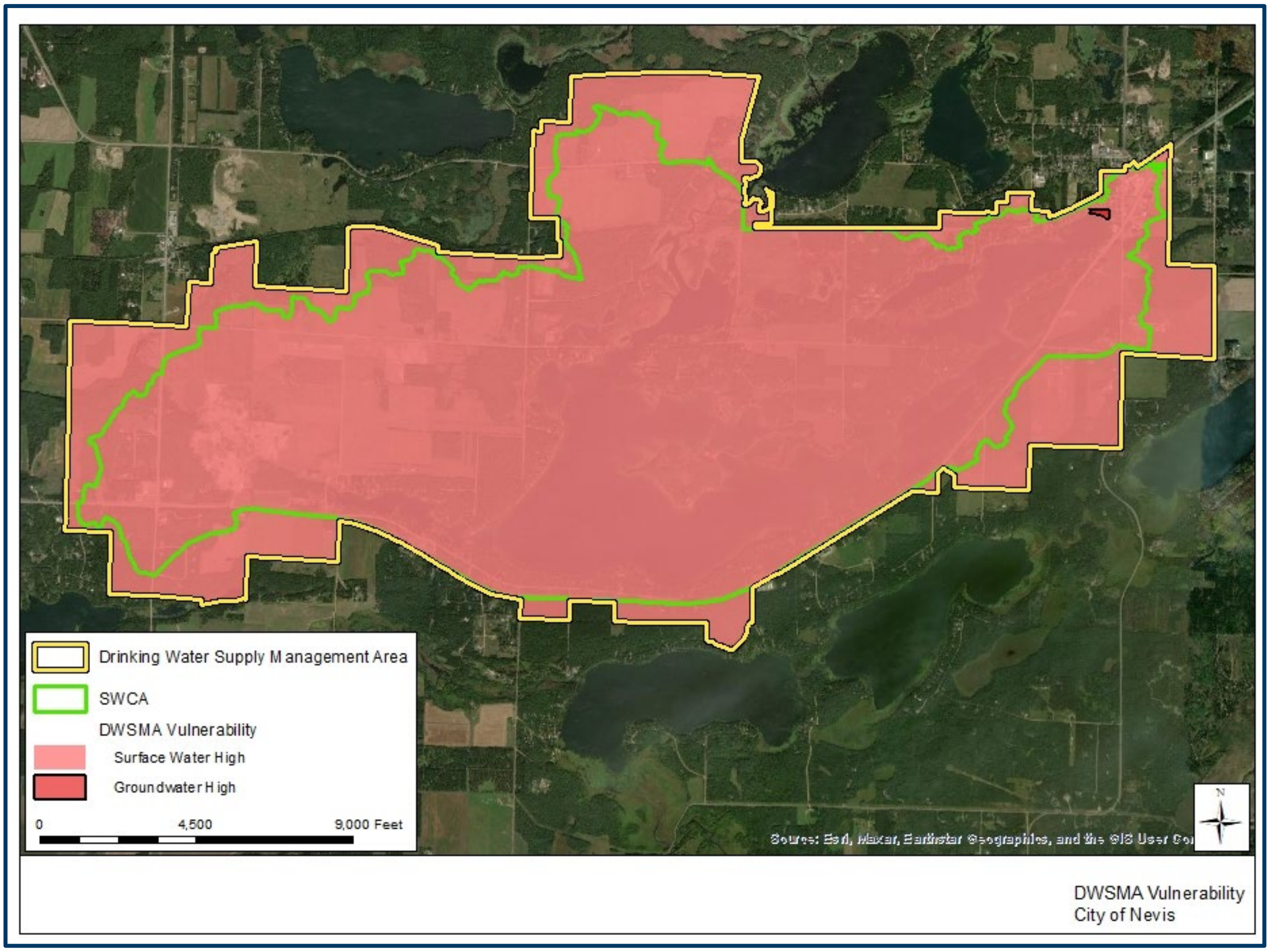

Figure 16. Vulnerability of the DWSMA for the conjunctive WHPA delineation

Table 7. Isotope Analysis

ID (link to Table 2)	Number of Samples	Minimum Value	Maximum Value	Mean Value	Coefficient of variation (CV)[1]	Do 1 or more samples show evidence for evaporated surface water? (#)	% of samples showing evidence for evaporated surface water	% evap SW times the mean LC Excess*	% rank of the % evap SW times the mean LC Excess* (includes Virus Study wells: 87 wells total)	Open water (sq.m.) in 1 year Capture Zone	Open water (sq.m.) in 10 year Capture Zone	Primary Groundwater Classification	Most conservative Geologic Sensitivity	Most recent Tritium result	Temporal Variability	Vertical Hydraulic Gradient Mean	Surface Water Impact Assessment
0000480068 (1290010S02)	11	-11.705188	-3.838615	-5.52513650508182	**38%**	Yes (10 of 11)	91%	-10.189126978054	97%	1,641	4,166	B2	H	6.1	1	-0.259	**possibly impacted by long-residence time surface water; surface water microbiological risk**
SWS0000348	3	-4.8768328308	-3.88804	-4.48347106096667	**12%**	Yes (3 of 3)	100%	-10.909519255137	99%	n/a/	n/a			-1			**possibly impacted by long-residence time surface water at long time of travel**
SWS0000436	**3**	**-4.264765**	**-3.914911**	**-4.110668**	**4%**				**n/a**	**n/a/**	**n/a**			**-1**			

^{18}O	^{2}H	ID (link to Table 1)	Collection Date	LC Excess*[1]	Does the LC Excess* show that the sample is significantly different than the MWL?[2]	Evidence for evaporated surface water?[3]	Estimated Annual Precipitation (Bowen grid for North America for ^{18}O values)[4]	Is the sample ^{18}O value significantly different than the Estimated Annual Precipitation value (Bowen, 2003)?[5]	Precipitation month most closely matching ^{18}O	Precipitation for month most closely matching ^{18}O	Precipitation difference for month most closely matching ^{18}O
-5.5598333167	-51.9198321844	0000480068 (1290010S02)	2/19/2013	-9.72530193	Yes	Yes	-11.1300	Yes	July	-7.8975	2.3377
-5.011932916	-49.8009870391	0000480068 (1290010S02)	4/14/2014	-10.96048801	Yes	Yes	-11.1300	Yes	July	-7.8975	2.8856
-4.7262833553	-47.4368106203	0000480068 (1290010S02)	5/20/2014	-10.90036859	Yes	Yes	-11.1300	Yes	July	-7.8975	3.1713
-4.9150825334	-47.9173513781	0000480068 (1290010S02)	5/20/2014	-10.33521764	Yes	Yes	-11.1300	Yes	July	-7.8975	2.9825
-4.60341	-48.881921	0000480068 (1290010S02)	5/13/2015	-12.25084737	Yes	Yes	-11.1300	Yes	July	-7.8975	3.2941
-11.705188	-82.919265	0000480068 (1290010S02)	7/8/2015	0.08481417	No	No	-11.1300	Yes	April	-11.3075	0.3976

^{18}O	^{2}H	ID (link to Table 1)	Collection Date	LC Excess* (1)	Does the LC Excess* show that the sample is significantly different than the MWL? (2)	Evidence for evaporated surface water? (3)	Estimated Annual Precipitation (Bowen grid for North America for ^{18}O values) (4)	Is the sample ^{18}O value significantly different than the Estimated Annual Precipitation value (Bowen, 2003)? (5)	Precipitation month most closely matching ^{18}O	Precipitation for month most closely matching ^{18}O	Precipitation difference for month most closely matching ^{18}O
-5.1441974279	-50.2970375775	0000480068 (1290010S02)	9/10/2015	-10.65367762	Yes	Yes	-11.1300	Yes	July	-7.8975	2.7533
-5.1764740066	-50.5812861701	0000480068 (1290010S02)	9/10/2015	-10.67003648	Yes	Yes	-11.1300	Yes	July	-7.8975	2.7211
-3.838615	-46.846113	0000480068 (1290010S02)	12/2/2015	-14.49030998	Yes	Yes	-11.1300	Yes	July	-7.8975	4.0589
-5.181232	-50.605902	0000480068 (1290010S02)	4/12/2016	-10.66278474	Yes	Yes	-11.1300	Yes	July	-7.8975	2.7163
-4.914253	-49.871645	0000480068 (1290010S02)	5/10/2016	-11.43136440	Yes	Yes	-11.1300	Yes	July	-7.8975	2.9833
-3.88804	-43.214107	SWS0000348	9/19/2013	-12.24168452	Yes	Yes	-11.1300	Yes	July	-7.8975	4.0095
-4.6855403521	-46.1040888085	SWS0000348	5/19/2014	-10.33528509	Yes	Yes	-11.1300	Yes	July	-7.8975	3.2120
-4.8768328308	-47.2866923116	SWS0000348	5/19/2014	-10.15158815	Yes	Yes	-11.1300	Yes	July	-7.8975	3.0207

(1) - Landwehr, J.M. and Coplen, T.B. (2004) Line-conditioned excess: A new method for characterizing stable hydrogen and oxygen isotope ratios in hydrologic systems. In Isotopes in Environmental Studies, Edition: 1, Chapter: IAEA-CN-118/56, Publisher: IAEA, pp.132-135. See pp. 99-100 in International Conference on Isotopes in Environmental Studies – Aquatic Forum 2004 (PDF) (https://inis.iaea.org/collection/NCLCollectionStore/_Public/36/003/36003223.pdf).

(2) - Absolute values of LC Excess* that are greater than 1 are considered significant deviations from the Minnesota MWL.

(3) - Evidence of evaporated surface water is set to 'Yes' only for those samples where the LC Excess* was both negative and significant, and 18O is heavier than the Estimated Annual Precipitation.

(4) - Bowen GJ, Revenaugh J (2003) Interpolating the isotopic composition of modern meteoric precipitation. Water Resources Research 39, 1299, doi:10.129/2003WR002086

(5) - Differences between 18O and Estimated Annual Precipitation that are greater than 0.4 are considered significantly different.

Appendix 5: Karst conjunctive delineation example

Background

The city of Altura (PWS 1850018) is a small community located in Winona County in southeastern Minnesota. The city's wellfield is comprised of two bedrock wells, ranging in depth from 370 feet to 375 feet. Information about the construction of the wells and their vulnerability is provided in Table 8.

Table 8. Altura Water Supply Well Information

Local Well Name	Unique Number	Use/ Status	Casing Diameter (inches)	Casing Depth (feet)	Well Depth (feet)	Date Constructed	Well Vulnerability	Aquifer[2]
Well #2	219211	Primary	12	225	375	1955*[1]	Vulnerable	CJSL
Well #3	226547	Primary	16	267	370	1974	Vulnerable	CJSL

Notes: 1. *Well #2 later backfilled from 703 feet to 375 feet
2. CJSL means Jordan-St. Lawrence Aquifer. Open hole extends to the top of the St. Lawrence Formation.

The city's wells are constructed with open holes primarily in the Jordan Sandstone. Uppermost bedrock units are the Shakopee and Oneota Formations of the carbonate Prairie du Chien Group. The Jordan Sandstone has mostly primary (intergranular) porosity and permeability with secondary porosity consisting of highly conductive bedding parallel fractures. As characteristic in karst terrain, the dolomitic Prairie du Chien Group has low primary porosity, with permeability dominated by solution-enhanced fractures and conduits. Depth to bedrock in the area is less than 50 feet, resulting in rapid infiltration and sinkholes, particularly near the Shakopee-Oneota contact. In April 1976, city waste treatment holding lagoon, downgradient of the city's wells catastrophically drained through a line of southwest to northeast-trending sinkholes that opened two years after the facility went into operation (Alexander and Book, 1984).

Altura is located on a groundwater divide, with groundwater flowing both northeast and northwest towards bedrock valleys where both the Prairie du Chien Group and underlying Jordan Sandstone have been eroded away. As such, groundwater recharges these bedrock aquifers both locally and to the south of the city, and groundwater flow directions, in part, differ from regional groundwater flow east and northeast towards the Mississippi River and its tributaries.

Method Used to Delineate the WHPA

The WHPA for the city of Altura's wells were determined using a combination of three methods. The first method involved calculating the groundwater capture zones deterministically using representative aquifer parameters that were input into MLAEM, a groundwater modeling code (Strack, 1989). The second method used a fracture flow calculated fixed radius procedure, which is described in the MDH Guidance for Delineating Wellhead Protection Areas in Fractured and Solution-Weathered Bedrock (MDH, 2011). The output from these two methods were combined to create the Groundwater Capture Area (GWCA) component of the WHPA. This approach accounts for the interconnected nature of the Jordan and the fractured Prairie du Chien Aquifers. The third method used the conjunctive delineation guidance in this document for constructing a surface water capture area (SWCA) in karst settings.

Multi-Layer Analytical Element Model

The MLAEM Code was selected because it is a quantitative method capable of simulating the influence of 1) surface water features, 2) localized infiltration, 3) pumping of multiple high-capacity wells, and 4) leaky/confined connection between the layers of the Prairie du Chien – Jordan Aquifer system.

The bedrock aquifer serving the Altura PWS wells was modeled as a three-layer system that is locally unconfined. Model input parameters were determined from the following information: 1) provided by Altura's water operator, 2) interpreted from local well logs and regional pumping test data, and 3) obtained from published reports and maps. For this amendment, the pumping values for Altura's high capacity wells have been updated to reflect the projected future usage.

Fractured and Solution-Weathered Rock Delineation

The fracture-flow delineation procedure was developed to address the increased variability in flow velocities and directions in geologic settings with secondary porosity (MDH, 2011). This guidance describes a modified volumetric analysis and does not use a model based on flow equations. The area that is calculated by this procedure is called a calculated-fixed-radius (CFR) capture zone. MDH fracture-flow delineation procedures also outline methods for lineament extensions. For the purposes of this guidance, lineament analysis is included here to account for conditions where it is part of determining a combined GWCA in karst settings.

Conjunctive Delineation Assessment

In some highly vulnerable geologic settings, surface water can provide a significant amount of recharge to an aquifer within a well capture zone within short times of travel from the land surface. In these instances, MDH guidance provides for the surface water contribution area (SWCA) to be appended to the GWCA generated by flow modeling or fracture flow delineation, thereby creating a conjunctive WHPA (MDH, 2021). In karst settings such as the Altura area, features such as sinkholes and dry or blind river valleys that exist within the WHPA may be used to justify inclusion of a SWCA. These features can be access routes for rapidly infiltrating surface water, so they and their drainage area boundaires were appended to the GWCA thereby creating the WHPA. This has been accomplished as shown in Figures 17 and 18 below.

Assessing the Need for a Conjunctive Delineation in karst settings

Because the ERA and GWCA is geologically sensitive and intercepts topographic runoff within the ERA and GWCA, the need for a conjunctive delineation was assessed as part of this delineation. Refer to the steps below for how this was accomplished.

Steps to SWCA Determination

Step 1. Use information about the delineated ERA and GWCA, the hydrogeologic setting and water chemistry:

a. Is the ERA/GWCA based on a fracture flow or karst setting? *Yes, the Jordan aquifer, serving the city wells, is overlain by the karstic Prairie du Chien Group – characterized by solution-enhanced fracture and conduit flow.*

b. Does the PWS well(s), or other wells in the same aquifer located in the ERA or GWCA, show evidence of degraded water quality that may be attributed in part to impaired runoff or surface water features? *No, they do not.*

c. If the answer to **either** or **both** scenarios in a is yes, go to Step 2A.

d. If the answer to b is no, continue to Step 2 in flow chart.

Step 2A: Does the GWCA overlie areas with High DWSMA vulnerability??

a. If no, no SWCA required.

b. If yes, continue to Step 3A. *Yes, the vulnerability of the DWSMA beneath the GWCA is high.*

Step 3A: **For porous media aquifers** - Does the GWCA intersect a surface water feature or receive runoff from surrounding lands that are characterized by: 1) higher elevation, and 2) soils or near-surface bedrock likely to promote runoff or slopes that exceed 6% if Group B soils?

For karst or fractured aquifers where depth to bedrock if 50 feet or less, add sinkholes and/or dry drainageways to the considerations noted above.

a. If no to **either**, no SWCA required.

b. If yes, continue to Step 4A. *Yes, depth to bedrock if 50 feet or less and the WHPA intersects dry valleys, one containing a mapped sinkhole location. In addition, these valleys likely to receive runoff from surrounding lands that are characterized by: 1) higher elevation and 2) soils likely to promote runoff (Hydrologic Groups C and D), or slopes that exceed 6% if Hydrologic Group B soils (see Figures 19 and 20 below).*

Step 4A: If the SWCA is to be based on a surface water feature, do adequate data exist to that describe connection to it? If SWCA will not be based on a surface water feature, proceed to Step 5A.

Step 5A: Will the SWCA be based on runoff or karst features?

a. If no, no SWCA required.

b. If yes, Topographic SWCA required. *Features such as sinkholes or dry drainage ways may contribute recharge to the aquifer in short, intermittent bursts according to heavy rainfall or snowmelt events that may not coincide with routine compliance sampling or even investigative studies that would ordinarily be used to confirm the importance of these events on water quality. Therefore, they may be used as a basis for SWCA delineation in recognition of this unique hydrogeologic setting. For this karst setting, a runoff SWCA is included due to suspected or potential water quality impairments stemming from rapid infiltration from overland flow events.*

Follow the steps for delineating a SWCA based on runoff:

1) *Map the preliminary SWCA based on topography*. Work outward from the GWCA to determine what land surface areas exhibit a higher topographic elevation and could potentially shed runoff in that direction. This area will constitute the potential surface watershed for the SWCA. This mapping can be accomplished in GIS using either established catchment area boundaries where available and relevant or be determined from scratch using an accurate depiction of topography such as LiDAR. The DNR Level 09 auto-catchments are a useful resource and may provide the most reasonable boundaries due to their relatively fine scale. However, these catchments were derived prior to LiDAR so should be reviewed relative to more recent land elevation data. Note that Level 08 catchments may also be relevant due to their dependence on LiDAR data, but these are at a coarser scale. In any case, the user must be aware of local high spots such as roadways that may not be reflected in these delineated boundaries and adjust their SWCAs accordingly.

   Specific to karst settings, catchments with mapped sinkhole locations along their axes and/or catchments with no clear downstream outlet (blind valleys) are target candidates, but absence of these features does not preclude other catchment basins meeting the location criteria from being included in the SWCA Four Level 09 catchment areas (A-D) exhibit higher topographic elevations that overlap or intersect the composite GWCA (adjacent to the 10 year time-of-travel wellhead protection area and/or the fracture flow capture zone based on lineament analysis). Catchment C includes mapped sinkhole locations along the axis of its drainage channels. (see Figures 17 and 18 below).

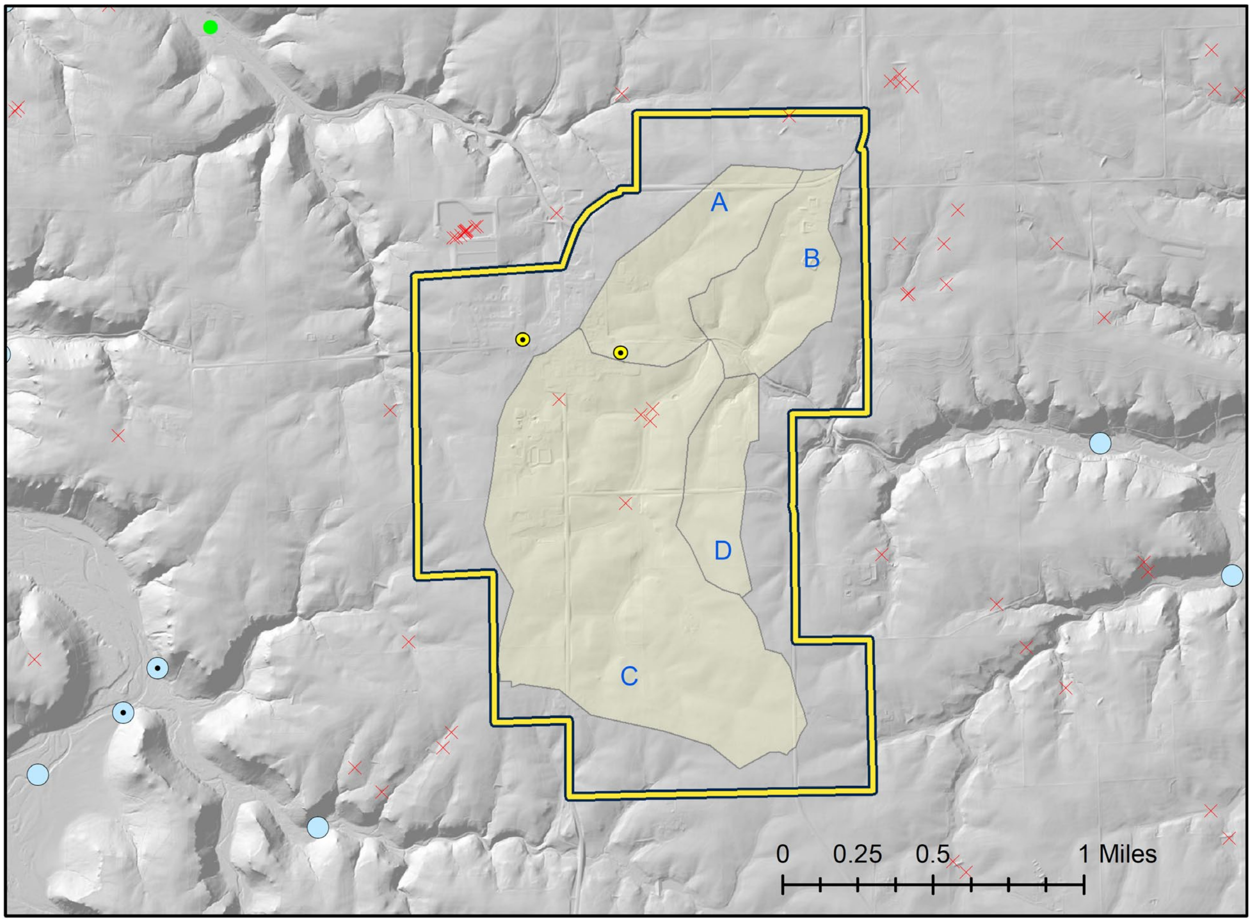

Figure 17. Surface water catchment areas A through D within the Altura Drinking Water Supply Management Area (DWSMA) along with locations of Altura wells 2 and 3.

Boundaries from DNR level 09 auto-catchment feature class are calculated from existing land surface elevation data as of 2013 (DNR, 2013). Mapped sinkhole locations, shown as red x's, fall along the axes of drainage channels in catchment C (DNR, 2022a). Springs in adjacent bedrock valleys shown in blue (DNR, 2022b).

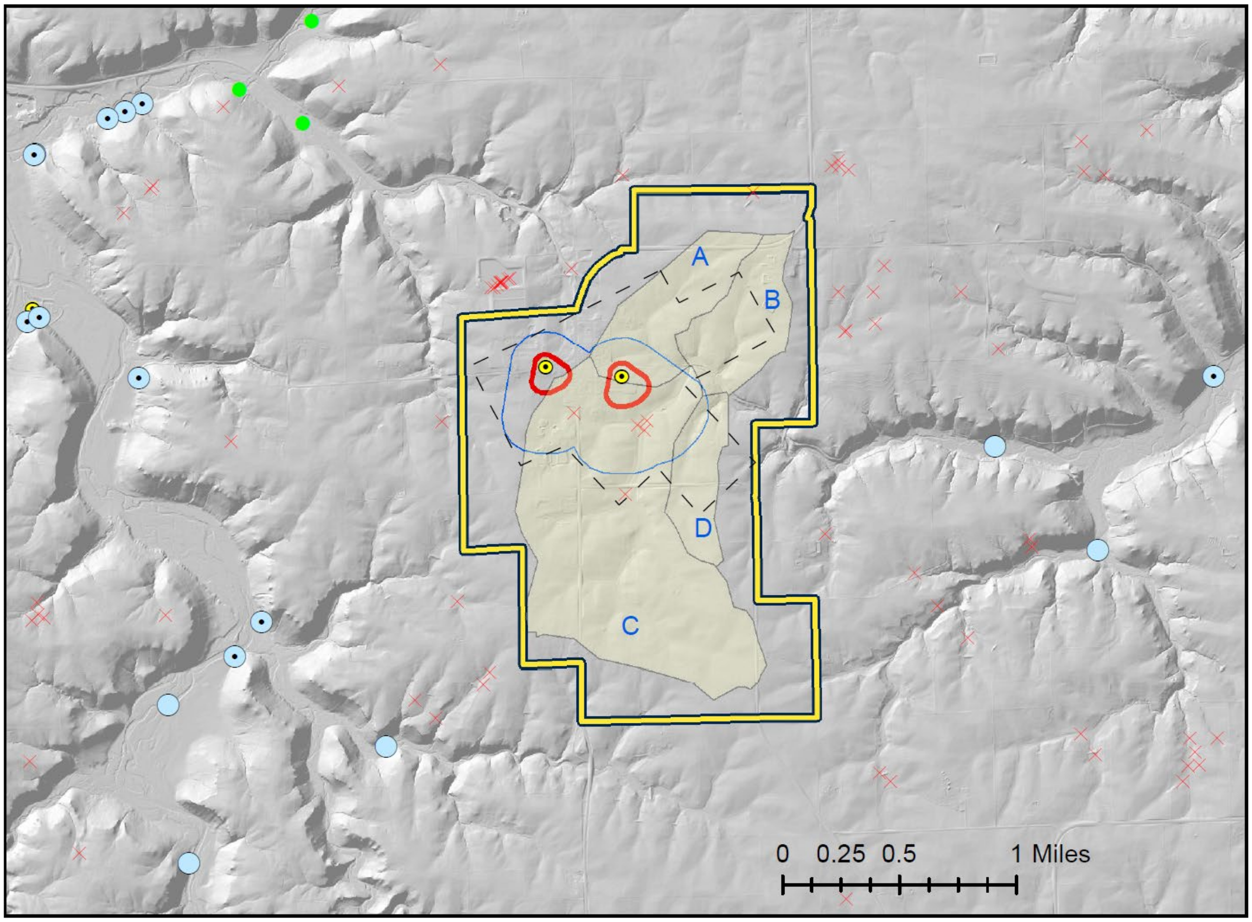

Figure 18. Altura wellhead 10 year time-of-travel capture areas (blue), 2 year time-of-travel emergency response areas (red), and capture zone based on lineament analysis (black dashed), superimposed on surface water catchment areas A through D.

Because of conduit flow within aquifer units, dye traces have documented travel times at rates greater than one mile per day (Runkel and others, 2003)

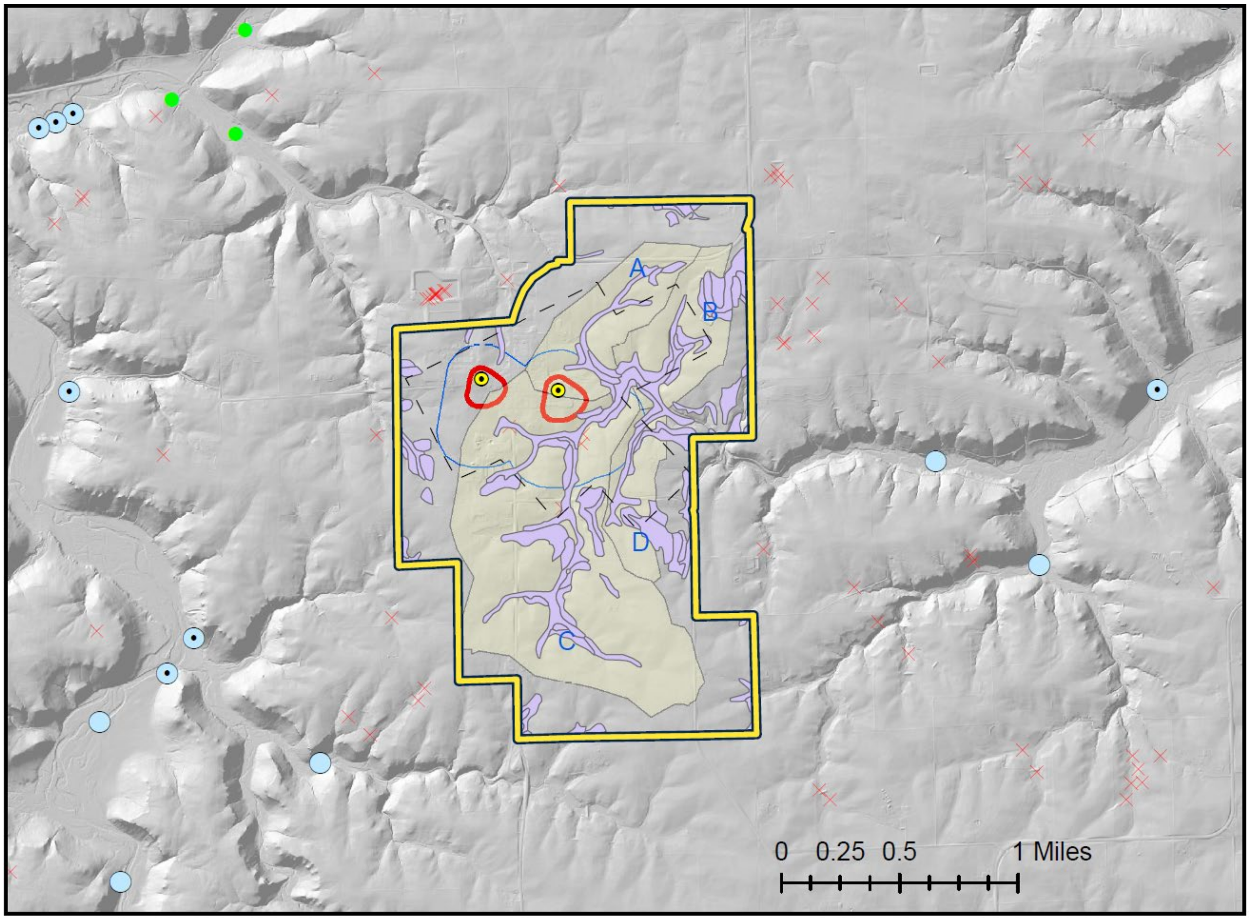

Figure 19. Soil hydrologic groups C and D located along the drainage axes within the Altura DWSMA.

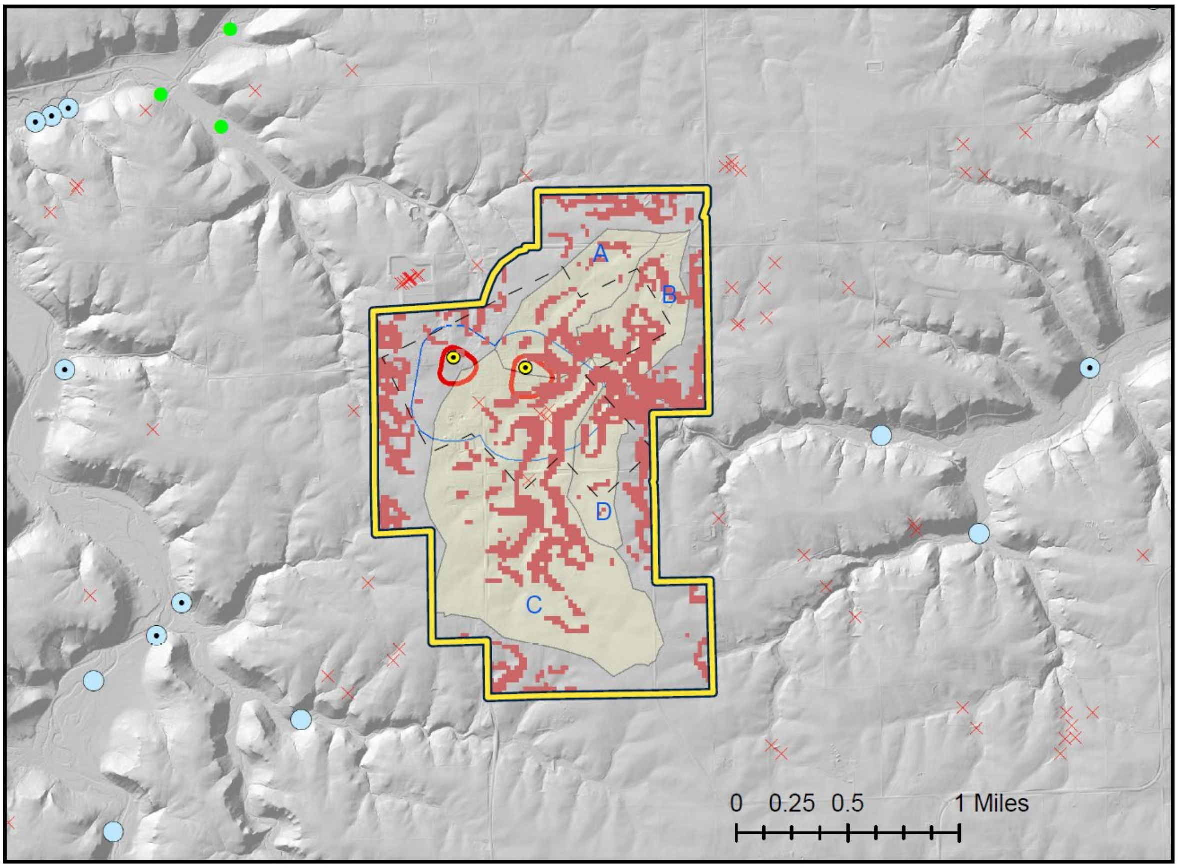

Figure 20. Figure 4: Areas with slopes exceeding 6%; within the Altura DWSMA.

References cited

Alexander, E.C. Jr., and Book, P. (1984), *Altura Minnesota lagoon collapses, in Sinkholes: Their Geology, Engineering and Environmental Impact, Proceedings of the First Multidisciplinary Conference on Sinkholes*, Orlando, Florida, October 15-17, 1984, 9 p.

Minnesota Department of Natural Resources (2013), DNR Watersheds - DNR Level 09 - DNR AutoCatchments, Geospatial Data Resource Site (GDRS) Minnesota Geospatial Commons, accessed on December 14, 2021, [MNDNR Watershed Suite (https://gisdata.mn.gov/dataset/geos-dnr-watersheds)](https://gisdata.mn.gov/dataset/geos-dnr-watersheds).

Minnesota Department of Natural Resources (2022), Karst Features Database, Geospatial Data Resource Site (GDRS) Minnesota Geospatial Commons, accessed on December 20, 2021. [Karst Feature Inventory Points (https://gisdata.mn.gov/dataset/geos-karst-feature-inventory-pts)](https://gisdata.mn.gov/dataset/geos-karst-feature-inventory-pts)

Minnesota Department of Natural Resources (2022), Springs Inventory, Geospatial Data Resource Site (GDRS) Minnesota Geospatial Commons, accessed on December 20, 2021, [Springs in Minnesota (https://gisdata.mn.gov/dataset/env-mn-springs-inventory)](https://gisdata.mn.gov/dataset/env-mn-springs-inventory)

Runkel, A.C.;Tipping, R.G.; Alexander, E. Calvin, Jr.; Green, Jeffrey A.; Mossler, J.H.; Alexander, S.C. (2003), *Hydrogeology of the Paleozoic bedrock in southeastern Minnesota.* Report of Investigations, RI-61, Minnesota Geological Survey, St. Paul, Minn., 105 p., 2 plates. Retrieved from the University of Minnesota Digital Conservancy, [Hydrogeology of the Paleozoic bedrock in southeastern Minnesota (https://conservancy.umn.edu/handle/11299/58813)](https://conservancy.umn.edu/handle/11299/58813).