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# AN INVESTIGATION OF THE HYDROGEOLOGIC CONDITIONS

# **RESPONSIBLE FOR SPRINGS IN A GLACIATED TERRAIN**

Final Report to the Wisconsin Department of Natural Resources, August 2000

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#### I. INTRODUCTION

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Within Dane County, Wisconsin numerous springs exist in and around the Nine Springs watershed, the Token Creek watershed, Pheasant Branch Creek, the Sugar River watershed, and Garfoot Creek (WRM, 1996; WRM, 1997). The springs are poorly understood, but there is growing public interest in how the springs will be affected by urban development and increases in municipal pumping. Groundwater flow models are often useful in addressing questions pertaining to changes in the hydrologic budget of a system. The Dane County regional groundwater flow model (Krohelski et al., 2000) provides a valuable starting point from which to create watershed-scale models in the county, which would be better suited to addressing questions related to spring flow. However, until the geologic features and hydrogeologic system responsible for the springs are better understood, the springs cannot be accurately incorporated into watershed-scale models.

The research completed under Wisconsin Department of Natural Resources (WDNR) funding involved a combination of field and numerical modeling exercises intended to test several conceptual models of the geologic features and mechanisms controlling spring flow in the Nine Springs watershed (Figure 1) and similar glaciated terrains. Fieldwork included the installation of two deep groundwater monitoring wells and continued water quality monitoring of the established shallow groundwater monitoring network within the watershed (Bahr et al., 1999). The well installations provided the opportunity to characterize the bedrock units in the immediate vicinity of the springs through lithologic description, geophysical logging, and hydraulic testing using straddle packers.

Because there are field restrictions due to the ecological and hydrological sensitivity of springs, and because the features responsible for spring formation are ultimately inaccessible, alternative tests are needed. Numerical models can be useful tools for interpreting field data and for hypothesis testing (Winter, 1976; Remson et al., 1980; Jamison and Freeze, 1983; Pennequin, 1983; Krabbenhoft and Anderson, 1986; D'Agnese et al., 1997). Using the finite-difference code MODFLOW (McDonald and Harbaugh, 1988), generic models for a hypothetical and simplified glaciated terrain were constructed to provide additional tests of the conceptual models.

Future work will include the construction of a site-specific watershed-scale MODFLOW model, which will be based on the updated conceptual model and calibrated using the universal inverse code UCODE (Poeter and Hill, 1998). Benefits of the inverse approach that are especially

useful in hypothesis testing include (i) quantification of the quality of the model calibration procedure and (ii) provision of statistics that describe the reliability and uniqueness of the estimated parameters (Hill, 1998).

This final report to the WDNR includes

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- descriptions of the initial conceptual models,
- a summary of the monitoring well installations,
- an interpretation of the geophysical logging,
- an interpretation of the straddle-packer test results,
- a summary of groundwater monitoring results,
- the assumptions and results of the generic groundwater flow modeling, and
- an explanation of the updated conceptual model of springs in glaciated terrains, refined on the basis of the fieldwork and generic modeling exercise.

#### **II.** CONCEPTUAL MODELS OF SPRINGS IN THE NINE SPRINGS WATERSHED

The lowermost bedrock units in vicinity of the Nine Springs watershed are igneous and metamorphic rocks of Precambrian age. These rocks represent a lower boundary to groundwater flow in the area. The overlying sequence of bedrock units is composed primarily of sandstones and dolomitic sandstones of Cambrian age including, from oldest to youngest, the Mt. Simon, Eau Claire, and Wonewoc Formations (Elk Mound Group), the Tunnel City Group, the St. Lawrence Formation, and the Jordan Formation (Cline, 1965; Bradbury et al., 1999). The uppermost unit found in the Nine Springs watershed is the Jordan Formation.

The uplands in the Nine Springs watershed are composed primarily of sandy till, which is part of the Horicon Member of the Holy Hill Formation (Clayton and Attig, 1997). The bedrock surface gradually declines from the uplands to form a pre-glacial bedrock valley below the wetlands and Nine Springs Creek. The bedrock valley is filled with varying thicknesses of fine sandy glacio-lacustrine deposits overlain by till and peat (Mickelson and McCartney, 1979; Mickelson, 1983; Clayton and Attig, 1997).

Several conceptual models of the geologic features and mechanisms controlling spring flow in the Nine Springs watershed were formulated on the basis of background geologic information (Figure 2). It is possible that combinations of the conditions represented in the

models or other models are equally valid. However, based on the composition of the bedrock units in the area, it is unlikely that karstic features and conduit flow contribute to the formation of springs in the study area.

*Models A* and *B* are based on the idea that zones of high hydraulic conductivity in the uppermost bedrock units focus groundwater flow and influence the location of springs. The zones of high hydraulic conductivity could be caused by structural joints or fractures in the sandstone bedrock (A) or by bedding planes in the sandstone that are intersected by the edge of the preglacial bedrock valley where overlying unlithified materials are relatively thin (B). In a discharge area, it is likely that a lower hydraulic conductivity bedding plane would need to exist above the high hydraulic conductivity zone so that upward movement of groundwater is restricted until the bedding plane is intersected by the valley.

In low-lying areas, low-permeability glacio-lacustrine deposits or alluvial silt and clay fill the pre-glacial bedrock valleys. The fine-grained materials form a confining layer, and in discharge areas springs could form where the fine-grained deposits thin or coarsen (*Model C*).

In much of Dane County, the upper part of the Eau Claire Formation contains shale and siltstone (the Eau Claire aquitard) that create an important leaky confining unit between the Mt. Simon sandstone (lower bedrock aquifer) and the younger Cambrian sandstone units (upper bedrock aquifer). The Eau Claire aquitard varies in thickness across the county and is probably absent in the northeastern part of the county. It is also absent in the vicinity of the Madison Lakes, where the bedrock surface has been eroded into the Mt. Simon sandstone (Bradbury et al., 1999). The lateral extent of the Eau Claire aquitard could be important in the formation of springs in the Madison Lakes area, and specifically within the Nine Springs watershed, because a thin or absent Eau Claire aquitard could allow more vertical groundwater movement from the deep to shallow bedrock aquifers (*Model D*).

#### **III. MONITORING WELL INSTALLATION**

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Two monitoring wells were installed in the Nine Springs watershed in November and December 1999. The wells were drilled on WDNR property south of the Nine Springs Creek and north of Lacey Road (Figure 3). The first well (Mt. Simon well, DN-1441) was drilled to a depth of 385 feet below ground surface (bgs). The well was drilled through approximately 70 feet of

unconsolidated materials using mud-rotary techniques, at which point 6-inch flush-beveled steel casing (ASTM 853, grade B) was set approximately 12 feet into the top of the bedrock surface and grouted in place. A 6-inch borehole was then drilled in the bedrock (using air-hammer techniques) through the upper Paleozoic bedrock units (St. Lawrence Formation, Tunnel City Group, Wonewoc Formation), the shaly facies of the Eau Claire Formation, and 20 feet of the Mt. Simon sandstone. A thickness of 15 feet of Eau Claire shale was encountered during drilling. Four-inch casing was then set into the top of the Mt. Simon sandstone and grouted in place across the Eau Claire shale before continuing to advance a 4-inch borehole another 20 feet to the final depth of the borehole (385 feet bgs). The finished borehole is open to a 20-foot interval of the uppermost portion of the Mt. Simon sandstone. Geologic samples were collected every 5 feet during drilling. The samples were described and are on file at the Wisconsin Geological and Natural History Survey (WGNHS). The geologic log, the WDNR monitoring well construction form, and the well construction report for the Mt. Simon well are provided in Appendix A.

The second well (Upper Paleozoic well, DN-1442) was drilled to a total depth of approximately 315 feet bgs, which is approximately 15 feet above the depth of the Eau Claire shale. The well was drilled through the unconsolidated materials using mud-rotary techniques, at which point 5-inch casing was set 18 feet into the top of the bedrock surface and grouted in place. A 5-inch borehole was then drilled in the bedrock and to the final depth using air-hammer and airrotary techniques. The finished borehole is open to approximately 230 feet of the Tunnel City Group and Wonewoc Formation. The WDNR monitoring well construction form and the well construction report for the Upper Paleozoic well are provided in Appendix A.

#### **IV. BOREHOLE GEOPHYSICS**

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Both of the newly-installed monitoring wells were logged using borehole geophysics in cooperation with the WGNHS. Natural gamma, single point resistance, and spontaneous potential logs were collected at the Mt. Simon well, and natural gamma, single point resistance, spontaneous potential, fluid temperature, fluid resistivity, and caliper logs were collected at the Upper Paleozoic well. Geophysical logs are provided in Figures 4 and 5.

The geophysical logs were compared and correlated to fluid temperature, fluid resistivity, natural gamma, single point resistance, spontaneous potential, and video logs from wells #7 and

#8 at the WDNR Nevin Fish Hatchery (fish hatchery), which were collected in cooperation with the WGNHS in April 1999. The fish hatchery wells are both flowing wells that are located on the northern side of the preglacial bedrock valley that underlies the Nine Springs Creek and its associated springs and wetlands. The newly installed monitoring wells are located on the southern side of this erosional bedrock valley, approximately 3000 feet to the southeast.

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The natural gamma logs are the most illustrative of the geophysical logs that show correlation of lithology between the wells. The natural gamma intensity of clay-bearing sediments is much higher than that of quartz sand and/or carbonates; this makes natural gamma a very useful tool in the identification of clay- or shale-bearing sediments (Keyes and MacCary, 1971). Natural gamma logs for the four wells are shown in Figure 6. The shaly facies of the Eau Claire Fm. is clearly visible in the Mt. Simon well log from approximately 540 to 555 feet above mean sea level (ft.amsl). The Mt. Simon and Wonewoc Formations are both composed of fine to medium grained thick-bedded quartzarenite (Ostrom et al., 1970). Both formations can be identified on the Mt. Simon well log by their characteristic low natural gamma intensities, and the contact between the Wonewoc Formation and the overlying Tunnel City Group can be identified on all four logs.

The Tunnel City Group is described as a medium-grained, cross-bedded, dolomitic, and in some places glauconitic, sandstone (Ostrom et al., 1970). The natural gamma logs from all four wells show that this bedrock unit is composed of beds of variable clay content. A significant finding of this work is that individual beds of presumably high clay content (and corresponding layers of low clay content) can be correlated between the wells and therefore across the erosional bedrock valley. Some of these beds are identified on Figure 6 by dashed lines. Flow logs from the fish hatchery wells identify discrete zones within the Tunnel City Group and at the contact of the Wonewoc Formation and Tunnel City Group that contribute significant volumes of water to the wells (Figure 7). These discrete zones presumably exist where high hydraulic conductivity zones allow increased transmission of water. Corresponding natural gamma logs and video logs of the fish hatchery wells show that the majority of water entering the wells does in fact enter in zones with low clay content. These findings suggest that the discrete zones of flow and/or similar zones of flow corresponding to other thin high-hydraulic conductivity layers within the Tunnel City Group could be laterally continuous in the vicinity of the Nine Springs watershed. These

high-hydraulic conductivity layers may be critical to the existence of the springs found throughout the watershed and in similar hydrogeologic settings.

#### V. STRADDLE-PACKER TESING

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The hydraulic conductivity of the upper Paleozoic dolomitic sandstone units was estimated at discrete intervals using slug tests conducted with a straddle-packer assemblage (Figure 8). The packers, which were designed by Bill Batten (WGNHS) to isolate 3.7-foot intervals of the aquifer, were positioned at various depths in the borehole with the aid of the WGNHS drilling rig. A total of 42 intervals were tested over a period of 4 weeks. Tests were conducted continuously over the entire section of the Tunnel City Group (30 intervals) by consecutively raising the straddle-packer assemblage by increments of 3.7 feet. An additional 12 intervals were tested in the Wonewoc Formation; intervals were spaced from 3.7 to 10 feet apart.

At each interval, a slug test was conducted by measuring the recovery of the hydraulic head in the well to static conditions after the introduction of a "slug," which is usually a solid object of known volume and in this case consisted of a solid section of PVC rod. At many intervals, a second test was also completed by measuring the recovery of the hydraulic head in the well after the slug was removed. Hydraulic head was measured and recorded during each test using a pressure transducer and data-logger. All tests continued until at least 90% recovery to static conditions was observed; however, most tests achieved full recovery.

Most of the tests were analyzed using the mathematical model presented by Hvorslev (1951). Hydraulic conductivity and the initial displacement of the water in the well were estimated using a least-squares fit to the exponentially distributed response data. This inverse solution to the Hvorslev model was coded in MATLAB (version 5.3) and greatly reduced the time involved to analyze each slug test. Response data from several of the slug tests were oscillatory in nature. These tests were analyzed using a solution derived by McElwee et al. (1992) for an underdamped response in a confined formation. Hydraulic conductivity values estimated from all slug tests are shown on Figure 9. Hydraulic conductivity estimates range from 2.6E-04 to 4.0E-01 cm/second (0.7 to 1,100 ft/day) for the dolomitic and glauconitic sandstone of the Tunnel City Group, with a geometric mean of 4.3E-03 cm/second (12 ft/day). The geometric mean hydraulic conductivity of only the high-hydraulic conductivity zones is 7.6E-02

cm/second (220 ft/day), and the geometric mean hydraulic conductivity of the remaining sandstone is 9.3E-04 cm/second (3 ft/day). Hydraulic conductivity estimates range from 2.1E-04 to 3.0E-01 cm/second (0.6 to 850 ft/day) for the quartz sandstone of the Wonewoc Formation, with a geometric mean of 7.1E-03 cm/second (20 ft/day). The geometric mean hydraulic conductivity of only the high-hydraulic conductivity zones in the Wonewoc Formation is 2.3E-01 cm/second (660 ft/day), and the geometric mean hydraulic conductivity of the remaining sandstone is 2.2E-03 cm/second (6 ft/day).

A comparison of the hydraulic conductivity test results to the natural gamma log for the Upper Paleozoic well and the fish hatchery wells' flow logs shows that (i) the measured highhydraulic conductivity zones occur in the Tunnel City Group where clay content is low and (ii) several of the high hydraulic conductivity zones also correlate to the discrete zones of flow in the fish hatchery wells. To illustrate this point, Figure 10 shows the natural gamma logs for the Mt. Simon well, the Upper Paleozoic well, WDNR#7, and WDNR#8 with the measured highhydraulic conductivity zones in the Upper Paleozoic well and the discrete zones of increased flow measured in the fish hatchery wells. Changes in temperature and fluid resistivity observed at each of the wells are also plotted.

#### **VI. GEOCHEMISTRY RESULTS**

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The geochemistry results are summarized in a paper recently submitted for publication in the journal <u>Chemical Geology</u>. The abstract of the paper follows and the entire paper is attached in Appendix B.

The magnitude and temporal variation of major ion concentrations in groundwater proved to be useful in distinguishing source waters for springs in the Nine Springs watershed. The use of summary statistics resulted in the identification of three "groups" of waters and two-way cluster analysis of the geochemical data further identified subtle geochemical characteristics of the three groups. One spring, which is representative of smaller springs and seeps found in the watershed, belongs to a group that is characterized by variable nitrate and chloride concentrations. Water discharging from this spring has a groundwater residence time of approximately 8 years based on the tritium/helium-3 dating method and is thought to be representative very local groundwater flow. Most of the springs in the watershed belong to a group that is characterized by elevated, but consistent nitrate, sodium, and chloride concentrations. Apparent groundwater ages for this group range from 10 to 15 years. The water discharging from the majority of the springs in the watershed is thought to travel through the unlithified glacial materials and the uppermost bedrock units before discharging into the former glacial lakebed wetland complex. Due to the relatively short groundwater residence times, spring water quality and flow are likely to be vulnerable to the rapid urban expansion occurring within the watershed.

#### VII. GENERIC GROUNDWATER FLOW MODELING

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Conceptual models, including those pictured in Figure 2, were used as the basis for generic groundwater flow models that were constructed using the finite-difference code MODFLOW (McDonald and Harbaugh, 1988). These models were designed to evaluate factors that contribute to the magnitude of spring flow and the unusually steady nature of spring flow observed in the Nine Springs watershed. While the models are generic in nature, they are based on hydrogeologic data from the Nine Springs and surrounding watersheds. Therefore, the results are transferable to springs in similar hydrogeologic settings.

The following subsections (A-E) describe the "base-case" generic model that was used for the first two sets of simulations. Some model layers were modified and/or added as simulations became more complex. Changes to the base-case model will be discussed in subsection F, which presents the results of the simulations.

#### A. AQUIFERS AND CONFINING UNITS

Bradbury et al. (1999) define three regional aquifers in the Dane County area including the surficial sand and gravel aquifer, the upper bedrock aquifer, and the lower bedrock aquifer. On the basis of the observed bedrock stratigraphy in the Nine Springs area, we further subdivided the upper bedrock aquifer into two aquifers that represent the dolomitic and glauconitic sandstone of the Tunnel City Group and the quartz sandstone of the Wonewoc Formation. In addition, in the Nine Springs area a confining unit, composed of a shaly facies of the Eau Claire Formation, is present and separates the upper and lower bedrock aquifers. The lower bedrock aquifer overlies Precambrian crystalline bedrock that forms the base of the aquifer system in the area (Bradbury et al., 1999).

#### **B.** BOUNDARIES

The generic models are designed to represent a slice of a larger watershed (Figure 11). The up-gradient external boundary is no-flow and represents a groundwater divide. River nodes are used to simulate a fully-penetrating stream in layer 1 at the down-gradient external boundary. The approximate stage of the Nine Springs Creek is used as the river stage, and river conductance was calculated using an estimate of hydraulic conductivity for glacio-lacustrine deposits (discussed below). General head boundaries are assigned to the down-gradient nodes in layers 2,

3, 4, and 5. The approximate elevation of the Madison lakes is used as the boundary head, and the hydraulic conductivity values assigned to active nodes in each of the layers (discussed below) were used to calculate conductance terms. The remaining lateral boundaries are no-flow; they represent flow lines from the groundwater divide towards the river.

Internal boundaries include drain nodes that represent a hypothetical spring and the surrounding wetlands. Drain elevations are based on the approximate elevation of the water table in the vicinity of major springs in the Nine Springs watershed. Drain conductance terms were calculated using typical rates of inflow to a wetland (Hunt, 1993) and measured vertical gradients in the wetlands surrounding major springs in the Nine Springs watershed. The conductance term for the hypothetical spring was similarly calculated using measured spring discharge rates and measured groundwater gradients in the vicinity of two large springs in the Nine Springs watershed.

Recharge is applied uniformly over the entire model domain at a rate of 8 inches/year in the steady-state simulations. Recharge is also applied uniformly during transient simulations; however, it varies monthly in order to simulate a spring recharge event followed by a smaller fall recharge event.

#### C. MODEL GRID

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The base-case model grid is formed by 49 columns, 78 rows, and five layers that represent the four aquifers and one confining unit discussed above (Figure 11). The grid spacing is variable and ranges from 25 to 400 feet with finer resolution near the hypothetical spring. The model grid was modified to include additional layers as the complexity of the simulations increased.

The uppermost layer that represents the surficial sand and gravel aquifer (layer 1) is unconfined and has a variable thickness. The top elevation of layer 1 is defined by the elevation of the watertable. The bottom elevation of layer 1 decreases near the location of the hypothetical spring and the down-gradient model boundary in order to represent a preglacial erosional bedrock valley (Figure 11). The layer that represents the dolomitic and glauconitic sandstone of the Tunnel City Group (layer 2) is confined and has a variable thickness. Most of the layer is approximately 120 feet thick; however, the layer thins to 20 feet near the down-gradient model boundary in order to represent the bedrock valley filled with the upper sand and gravel aquifer. Layers 3, 4, and 5, which represent the quartz sandstone of the Wonewoc Formation, the shaly

facies of the Eau Claire Formation, and the quartz sandstone of the Mt. Simon Formation, respectively, are confined and do not vary in thickness. Thicknesses are based on observed thicknesses from the newly installed monitoring wells discussed above and on geologic logs from municipal wells in the vicinity of the Nine Springs watershed. Layer 3 is 140 feet thick, layer 4 is 15 feet thick, and layer 5 is 600 feet thick.

#### **D. PROPERTIES**

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#### Hydraulic conductivity

Layer 1 is heterogeneous and isotropic. Most of the nodes in layer 1 are assigned a hydraulic conductivity of 1.53 feet/day, which is similar to the estimated hydraulic conductivities for sand and gravel and sandy diamicton within the Horicon Member of the Holy Hill Formation (Rayne, 1993; Swanson, 1996). Nodes in the vicinity of the preglacial bedrock valley represent glacio-lacustrine deposits and are assigned a hydraulic conductivity of 8.2e-02 feet/day, which is similar to the estimated hydraulic conductivity of silt and clay deposits within the Horicon Member of the Holy Hill Formation (Swanson, 1996).

Layers 3 and 5 are homogeneous and isotropic and are each assigned hydraulic conductivity values of 10 feet/day. Layer 5 hydraulic conductivity values were assigned on the basis of estimates by Bradbury et al. (1999) for the lower bedrock aquifer. The quartz sandstone of the Wonewoc Formation is assigned a hydraulic conductivity of 10 feet/day as well due to its lithological similarities to the quartz sandstone of the Mt. Simon Formation. Layer 2 is homogeneous and isotropic and is assigned a hydraulic conductivity value of 5 feet/day. The layer 2 hydraulic conductivity value was assigned on the basis of estimates (Bradbury et al., 1999) and final simulated values in the county-scale model (Krohelski et al., 2000) for the upper bedrock aquifer. Layer 4, which is the confining unit, is anisotropic ( $K_h:K_v = 100:1$ ) and is assigned a value of 3.0E-07 feet/day on the basis of tabulated values of hydraulic conductivity for various unlithified materials and rock types (Freeze and Cherry, 1979).

#### Storage

Storage properties were required for transient simulations. Because estimates of storage properties are unavailable for the major hydrogeologic units in the county, values were estimated on the basis of tabulated ranges of storage properties for various materials (Anderson and Woessner, 1992; Johnson, 1967). Layer 1 is assigned a specific yield of 0.20; layers 2, 3, and 5

are assigned a specific storage term of 2.1e-05 ft<sup>-1</sup>; and layer 4 is assigned a specific storage term of 2.8e-04 ft<sup>-1</sup>.

#### E. CALIBRATION

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Because of the generic nature of the models, a formal calibration procedure was not conducted; however, initial simulations were checked to confirm that the model produced reasonable hydraulic head distributions. Starting heads for the transient simulations consisted of the dynamic average steady-state conditions produced by using an average recharge rate (8 inches/year) in the steady-state simulations. Furthermore, dynamic cyclic initial conditions were generated by running the transient models with temporally-varying monthly average recharge rates. Generally, five years was enough time to produce a head distribution with an unchanging cyclic pattern. In other words, after five years the head distribution in the transient models vary within a given year; however, the head distribution for a given month of every cycle is essentially the same. Models were generally run a for total of eight years.

#### F. SIMULATIONS

The objective of the exercise is to identify a hydrostratigraphy that is capable of producing the magnitude of flow that is commonly observed in the field and to simulate the steady nature of the spring flow. The methodology essentially consists of a series of sensitivity analyses designed to assess the sensitivity of the magnitude and variability of spring flow to changes in hydrogeologic properties for each change in hydrostratigraphy.

#### Sets 1 and 2

The first and second sets of simulations test conceptual model C shown in Figure 2, which suggests that the formation and characteristics of the springs are due to the thinning or coarsening of fine-grained glacio-lacustrine deposits at the margins of preglacial bedrock valleys. The simulations in set 1 test the sensitivity of spring flow to changes in storage properties of the aquifers and the confining unit described for the base-case model, which includes heterogeneity in layer 1 that represents fine-grained glacio-lacustrine deposits. Eleven simulations were completed as part of the first set. Specific yield for layer 1 was varied by a factor of 1.5, while specific storage terms for layers 2, 3, 4, and 5 were varied by up to an order of magnitude. While transient fluctuations in discharge rates to the spring are very small in all of the simulations (<0.002 cfs) and would not be measurable in the field, spring discharge rates are unreasonably low

(approximately 0.025 cfs). The first set of simulations show that fluctuations in spring flow decrease as storage properties increase; however the magnitude of flow is not sensitive to changes in storage properties. Table 1 presents a summary of all set 1 simulations and Figure 12 shows the magnitude and variation in spring flow for each simulation in set 1.

The second set of simulations test the sensitivity of spring flow to changes in hydraulic conductivity of the aquifers and the confining unit described for the base-case model. Thirteen simulations were completed as part of the second set. Hydraulic conductivity values for layers 1 and 4 were varied by an order of magnitude, while hydraulic conductivity for layers 2, 3, and 5 were varied by factors of 1.5 to 3. Storage properties were also varied for selected simulations (Table 1). Once again, transient fluctuations in discharge rates to the spring are very small in all of the set 2 simulations (<0.002 cfs). Spring discharge rates increase when the hydraulic conductivity of layer 2 is increased by a factor of 2; however, the discharge rate is still unreasonably low (approximately 0.045 cfs). In order to produce a reasonable flow rate at the spring (>0.1 cfs), the hydraulic conductivity of layer 2 would need to be increased to greater than 20 feet/day; however, on the basis of the packer testing results a value greater than 20 feet/day would not be a representative estimate of hydraulic conductivity for the entire thickness of the dolomitic and glauconitic sandstone of the Tunnel City Group. Spring discharge is relatively insensitive to changes in the hydraulic conductivity of the other model layers. Table 1 summarizes the set 2 simulations, and Figure 13 shows the magnitude and variation of spring flow for each simulation in set 2.

#### Set 3

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The third set of simulations test conceptual model B shown in Figure 2, which suggests that the formation and characteristics of the springs are due to thin zones of high hydraulic conductivity in the sandstone bedrock units. On the basis of the geophysical logs and packer testing results, it is unlikely that the zones of high hydraulic conductivity are due to structural joints or fractures in sandstone as depicted in conceptual model A. The geophysical logs and packer testing results suggest that high-hydraulic conductivity layers within the Tunnel City Group may have a significant influence on the formation and characteristics of the springs. Therefore, the simulations in set 3 were designed to evaluate horizontal and laterally-extensive high-hydraulic layers within model layer 2. Simulations in set 3 test the sensitivity of spring flow to changes in hydrostratigraphy by adding thin (3-5 feet) layers to the model, but also to changes

in hydraulic conductivity, anisotropy, and storage properties of the thin and overlying layers. Due to the addition of the thin high-hydraulic conductivity layers, the number of model layers ranges from 7 to 9 for the thirteen simulations that were completed as part of the third set.

Transient fluctuations in discharge rates to the spring are very small in all of the set 3 simulations (<0.002 cfs), and spring discharge rates increase to a reasonable magnitude with the addition of high-hydraulic conductivity layers (0.10 - 0.18 cfs). The magnitude of spring flow is sensitive to the hydraulic conductivity of the thin layers; however, increasing hydraulic conductivity by only a factor of 2 over the initial hydraulic conductivity value assigned to the model layer representing the Tunnel City Group (5 ft/day) is enough to focus flow to the spring and increase spring discharge to a reasonable magnitude. Table 2 presents a summary of all simulations run as part of set 3, and Figure 14 shows the magnitude and variation of spring flow for each simulation in set 3.

#### Set 4

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The fourth set of simulations test conceptual model D shown in Figure 2, which suggests that the formation and characteristics of the springs are due to windows in the lower confining unit that may allow more vertical groundwater movement from the deep to shallow bedrock aquifers. On the basis of the geologic log from the newly-installed Mt. Simon monitoring well, 15 feet of shale is present in the Nine Springs watershed, and an approximate 60-foot hydraulic head *drop* exists over the shale. This hydraulic head drop is probably due in part to the effects of pumping in the Madison area. Therefore, it is highly unlikely that conceptual model D applies to the springs in the Nine Springs watershed; however, the conceptual model was tested using the generic models in order to quantify the effects of a window in the confining unit.

Only two simulations were run as part of set 4. In both cases a window in the confining unit was created by assigning the properties of the quartz sandstone of the Wonewoc and Mt. Simon Formations to a portion of the layer representing the shaly facies of the Eau Claire Fm. For the first simulation, a window was created in the base-case model. In the second simulation, a window was created in a model that includes a thin high-hydraulic conductivity layer. In both cases, spring flow is reduced by approximately 30% over the spring flow observed before the window was created. A summary of the simulations is provided in Table 4, and the results of the simulations are included in Figures 12 and 14 for comparison.

#### VIII. CONCLUSIONS: REFINED CONCEPTUAL MODEL

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It is likely that thin high-hydraulic conductivity layers in the Tunnel City Group and at the contact between the Tunnel City Group and the Wonewoc Formation are critical to the formation of springs in the Nine Springs watershed. Flow logs from flowing wells at the Nevin State Fish Hatchery show that the majority of flow to the wells enters at discrete zones that correspond to layers with very low clay content. On the basis of lithologic and geophysical logs from the two newly installed monitoring wells and geophysical logs from the fish hatchery wells, these layers appear to correlate across a preglacial bedrock valley in the vicinity of the springs. The results of slug tests (using a straddle-packer assemblage in the newly installed wells) confirm the existence of thin high-hydraulic conductivity zones within the dolomitic and glauconitic sandstone of the Tunnel City Group and to a lesser extent within the quartz sandstone of the Wonewoc Formation. Some of these high-hydraulic conductivity zones correlate to the discrete zones of increased flow measured in the fish hatchery wells. By including thin high-hydraulic conductivity layers that are intersected by a preglacial bedrock valley in generic numerical models, a spring with a reasonable magnitude of very steady flow can be simulated, while models without the high-hydraulic conductivity layers produce steady, but unreasonably low spring flow.

A 60-foot hydraulic head drop exists across 15 feet of Eau Claire shale in the vicinity of the Nine Springs watershed. In other areas of the county that are close to the Madison lakes, which historically are regional discharge areas, but are not within the cone of depression created by combined effects of the municipal wells in the Madison area, an upward gradient could exist across the shale. Under these conditions, a window in the confining unit could contribute to the magnitude of flow discharging from springs, but it is unlikely that a feature of this nature could fully explain the volume of flow typically observed at the springs.

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FIGURES

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Figure 1. Nine Springs watershed



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Figure 2. Conceptual models of springs



 Approximate location of Mt. Simon and Upper Paleozoic wells

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Figure 3. Location of monitoring wells

Wisconsin Geological and Natural History Survey Geophysical Log Files from Mt Sopris digital logger Logged 7/3/00 by K. Bradbury and S. Swanson

Elevation:888.40 ft. asl.Depth to water:96.05 ft. btocCasing:82 ft. bgs

# Well: DN1441 Sue Swanson Deep Mt Simon well

T6N, R9E, section 10, NE1/4, SE1/4



Figure 4. Geophysical logs for the Mt. Simon well

Wisconsin Geological and Natural History Survey Geophysical Log Files from Mt Sopris digital logger Logged 7/3/00 by K. Bradbury and S. Swanson

Elevation: 888.55 ft. asl. Depth to water: 38.86 ft. btoc Casing: 88 ft. bgs

# Well: DN1442 Sue Swanson Shallow Paleozoic well

T6N, R9E, section10, NE1/4, SE1/4





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Figure 6. Natural gamma logs for the Mt. Simon well, the Upper Paleozoic well, WDNR#7, and WDNR#8

#### Wisconsin Geological and Natural History Survey Geophysical Log Files from Mt Sopris digital logger Logged 4/29/99 by K. Bradbury and S. Swanson

Elevation: 867.04 ft asl. Depth to water: flowing Casing: 68 ft bas (determined by geophysics)

#### Gamma, cps



Well:

Nevin Fish Hatchery Well #7

T6N, R9E, section10, NW 1/4, NE1/4

Wisconsin Geological and Natural History Survey Geophysical Log

Files from Mt Sopris digital logger Logged 4/29/99 by K. Bradbury and S. Swanson

Elevation: 856.46 ft asl. Depth to water: flowing Casing: 84 ft bas (determined by geophysics)

### Gamma, cps

# Well:

#### Nevin Fish Hatchery Well #8-

T6N, R9E, section10, NW1/4, NE1/4



Figure 7. Natural gamma and flow logs for WDNR#7 and WDNR#8

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# Figure 8. Straddle-packer assemblage

#### Figure 9. Slug test results

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Hydraulic Conductivity (cm/s)





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Figure 10. Correlation of geophysical logs and hydraulic conductivity data for the Mt. Simon well, the Upper Paleozoic well, WDNR#7, and WDNR#8



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## Mean and standard deviation spring discharge rates (ft3/sec) Generic Model Run Set 1

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Figure 12. Spring flow and variation, set 1



## Mean and standard deviation spring discharge rates (ft3/sec) Generic Model Run Set 2

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Figure 13. Spring flow ans variation, set 2



## Mean and standard deviation spring discharge rates (ft3/sec) Generic Model Run Set 3

Figure 14. Spring flow and variation, set 3
TABLES

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#### Input Simulation Number of number Description layers Layer 2 Layer 3 Layer 4 Layer 5 Layer 1 K (ft/day) K (ft/day) K (ft/day) K (ft/day) K (ft/day) 3.0E-07 3.0E-06 15.30 0.153 1.53 52 50 9 12 10 12 S<sub>y</sub> S, S, S, S, ം S ŝ base run:layer 1 two isotropic zones, 5 0.2 2.10E-05 2.10E-05 2.80E-04 2.10E-05 1 base layers 2-5 homogeneous and isotropic х х х х х b vary storage, L1(increase) x 0.3 2.10E-05 x 2.10E-05 2.80E-04 2.10E-05 X х х х c vary storage, L1 (decrease) 0.07 X 2.10E-05 х 2.10E-05 х 2.80E-04 X 2.10E-05 x 2.10E-05 d vary storage, L2 (decrease) 0.2 x 1.05E-05 X 2.10E-05 2.80E-04 x X vary storage, L2 (increase) X 0.2 X 3.15E-05 2.10E-05 2.80E-04 2.10E-05 е x х x vary storage, L3 (decrease) х 2.10E-05 2.10E-06 2.80E-04 2.10E-05 f 0.2 х х х X storage vary storage, L3 (increase) х 0.2 х 2.10E-05 X 2.10E-04 x 2.80E-04 X 2.10E-05 f2 2.10E-05 X 2.10E-05 2.80E-05 2.10E-05 vary storage, L4 (decrease) 0.2 х х х х g x 2.10E-05 vary storage, L4 (increase) 0.2 X X 2.10E-05 2.80E-03 X 2.10E-05 g2 х vary vary storage, L5 (decrease) x 0.2 2.10E-05 х 2.10E-05 2.80E-04 2.10E-06 X х h х vary storage, L5 (increase) x 0.2 2.10E-05 2.10E-05 2.80E-04 2.10E-04 h2 x х x х 2 0.2 2.10E-05 2.10E-05 2.80E-04 2.10E-05 a increase K, L1 5 x х x х х 2.80E-04 decrease K, L1 0.2 2.10E-05 2.10E-05 2.10E-05 b х X х X x decrease K and increase storage L1 0.3 x 2.10E-05 х 2.10E-05 2.80E-04 х 2.10E-05 С х х 2.10E-05 2.80E-04 d increase K, L2 0.2 2.10E-05 2.10E-05 х х х increase K and increase storage L2 х 0.2 x 3.15E-05 х 2.10E-05 X 2.80E-04 x 2.10E-05 е e2 increase K. L2 х 0.2 2.10E-05 х 2.10E-05 2.80E-04 2.10E-05 х х х conductivity decrease K, L2 0.2 2.10E-05 2.10E-05 2.80E-04 2.10E-05 f х х decrease K and increase storage L2 x 0.2 x 3.15E-05 х 2.10E-05 2.80E-04 x 2.10E-05 X g h decrease K, L3 х 0.2 2.10E-05 х 2.10E-05 х 2.80E-04 2.10E-05 х х /ary increase K. L3 х 0.2 X 2.10E-05 2.10E-05 2.80E-04 2.10E-05 i х х х increase K, L4 х 2.10E-05 2.80E-04 0.2 х 2.10E-05 х 2.10E-05 T. х х increase K, L5 х 0.2 2.10E-05 х 2.10E-05 2.80E-04 х 2.10E-05 х х k decrease K, L5 x 0.2 X 2.10E-05 2.10E-05 x 2.80E-04 x 2.10E-05 х

#### Table 1. Summary of set 1 and 2 simulations

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																Input	t										
													La	yer 3		L	aye	r 4		l	Laye	er 5		Layer 6		La	yer 7
			Number									{Lay	ers 3	and 5 of 9	(L	ayers	s 4 a	nd 6 of 9	{La	ayer	s 5 a	and 7 of 9	{La	ayer 8 of 9	{La	ayer 9	of 9 layer
Simulatio	n number	Description	of layers		l	ayer	1			Laye	ər 2		layer	model}	1. J.	lay	er m	odel}		lay	er m	nodel}	lay	ver model}		m	odel}
			-	K	(ft/da	y)		ĸ	(ft/d	ay)		K (ft/	'day)		K	(ft/da	y)		K (	ft/da	iy)		К		K (ft	/day)	
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				ß	5.3	8	c		0	Ś	G	6	0	9		0	<b></b> ני	s	0		5	s	B.	s	0		s
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										1																1 - A	1
													1														
3	а	add 5-foot bigb K laver 1 aver 3	7	×			0.2	x			2.10E-05	×		2.10E-05	x	1		2.10E-05	x			2.10E-05	x	2.80E-04	x		2.10E-05
Ŭ		3a, vary storage of high K laver		<u> </u>					-	1		<u> </u>			-												
	ь	(increase)		x			0.2	x			2.10E-05	1 x	1	3.15E-05	x			2.10E-05	x			2.10E-05	x	2.80E-04	x		2.10E-05
		3a, vary storage of layers 2 and 4																									
	c	(increase)		x			0.2	x			3.15E-05	x	1	2.10E-05	x			3.15E-05	x			2.10E-05	x	2.80E-04	x		2.10E-05
		3a, vary specific yield of layer 1							1							1											
2	d	(increase)		x			0.3	х	1		2.10E-05	x		2.10E-05	X	1		2.10E-05	x			2.10E-05	x	2.80E-04	x		2.10E-05
lay.																											
×	е	decrease K of high-K layer		x			0.2	x			2.10E-05		X	2.10E-05	X			2.10E-05	X			2.10E-05	X	2.80E-04	x		2.10E-05
đ					1														1								<b>i</b>
- P	- f	use 3-foot high K layer, Layer 3		x			0.2	x		1	2.10E-05	x		2.10E-05	x			2.10E-05	x			2.10E-05	x	2.80E-04	x		2.10E-05
ğ		3f, vary specific yield of layer 1			1					1				1			]										1 1
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		3f, vary specific yield of layer 1											1				1			-							
	h	(decrease)		×	<u> </u>		0.1	x			2.10E-05	×	I	2.10E-05	X	I	<b> </b>	2.10E-05	X			2.10E-05	X	2.80E-04	×	<u> </u>	2.10E-05
		add anisotropy to high K layer in									0.405.05			0.405.05				0.405.05			·	0.405.05		0.005.04			0.405.05
	1	model 3a, Kx=Ky=28, Kz=5		×			0.2	X	·	<u> </u>	2.10E-05	×		2.10E-05	X	<b> </b>		2.10E-05	×			2.10E-05	X	2.80E-04	×		2.10E-05
ø		use two 3-foot high K layers,		1							0.405.05			0.405.05		1		0.405.05				0.405.05		0.005.04			0.405.05
лө́	I	Layers 3 and 5	9	×			0.2	×		_	2.10E-05	×	<b> </b>	2.10E-05	<u>×</u>			2.10E-05	X		-	2.10E-05	×	2.80E-04	⊢×		2.10E-05
a)		3i, vary specific yield of layer 1									0.405.05			0.405.05	1			0.105.05				0.105.05		0.005.04			0.105.05
× £		(increase)		⊢×́	I		0.3	X	-	<u> </u>	2.10E-05	<u>⊢×</u>		2.10E-05	<u>⊢×</u>	<u> </u>		2.10E-05	⊢× ∣	-		2.10E-05	×	2.00E-04	⊢×́		2.10E-05
Į		31, vary specific yield of layer 1									0.105.05	Ι	1	0.105.05				0 105 05				0.105.05		0.005.04		1	0.105.05
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ă		add anisotropy to high K layers in								1		1	1		1	1											
	m	model 3i, Kx=Ky=28, Kz=5		X	1		0.2	X	ł .	1	2.10E-05	I X	1	2.10E-05	X			2.10E-05	X			2.10E-05	X	2.80E-04	X	1	2.10E-05

#### Table 2. Summary of set 3 simulations

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														Inp	ut						
Simula num	ation ber	Description	Number of layers			Laye	er 1			Laye	er 2			Lay	/er 3		La	yer 4		La	iyer 5
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				1.53	15.30	0.153	S <sub>y</sub>	5	10	2.5	S <sub>s</sub>	10	5	15	S₅	3.0E-07	10	Ss	10	5	Ss
4	а	use 1base model; window in Layer 4	5	x	-		0.2	x			2.10E-05	x			2.10E-05	x	x	2.80E-04 & 2.10E-05	x		2.10E-05
window in deep confining unit	ь	use 3a model; window in Layer 6	7	x			0.2		(se	e Ta	able 2)	×			2.10E-05	x	x	2.80E-04 & 2.10E-05	x		2.10E-05

#### Table 3. Summary of set 4 simulations

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## **APPENDIX A**

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State of Wisconsin Department of Natural Resources Route to: Sol Env. Response	id Waste 🛛 Haz. Waste 🗆 & Repair 🗖 Underground	Wastewater 🗆 d Tanks 🔲 Other 🔲	MONITORING WELL CONSTR Form 4400-113A	UCTION Rev. 4-90
Facility/Project Name	Local Grid Location of We		Well Name Nine Springs	
9 Springs	ft. 🖬 S.	ft. 🗖 w.	Mt. Simon Monite	rinewell
Facility License, Permit or Monitoring Number	Grid Origin Location	3	Wis. Unique Well Number - DNR We	H Number
	Lat L	ong or	T70402 DN-14	A county
Type of Well Water Table Observation Well 11	St. Plane ft	. N, ft. E.	Date Well Installed 11 10-12,9	19
Piezometer de 12	Section Location of Waste/	Source	9(NP417) mm' a a' y	<u>y</u>
Distance Well Is From Waste/Source Boundary	<u>SE 1/4 of NE 1/4 of Sec.</u>	10, T. 6 N, R. 9	Well Installed By: (Person's Name and	d Firm)
N.A. ft.	Location of Well Relative t	o Waste/Source	Water Wells In	IC.
Is well A Point of Enforcement Std. Application?	u 🗆 Upgradient s d 🗖 Downgradient r	Sidegradient	Micheal + Kevin	L
A. Protective pipe, top elevation	it. MSL	1. Cap and lock?	Yes	
P Well ensine ten elevation 890 401	i. MSL	2. Protective cov	ver pipe:	h 0.
B. well casing, top elevation	FEIH	a. Inside diame	eter:	0.0 in.
C. Land surface elevation 000 40	h. MSL	b. Lengin:	2.1	0 <u>5</u> .0m.
D. Surface seal, bottom ft. MSL or	- ft.	c. Material:	Steel	A 04
12 LISCS elegification of soil near arrange		d Additional	Other	
		If yes desc	protection?	
			nite:	- 30
Bedrock Mt. Simon Sandstone	8-12	3. Surface seal:	Bentonite	. bar 01
13. Sieve analysis attached?  Yes	$v_0 \rightarrow \chi = 1$		Concrete	
14 Drilling method used: Now d Rotary	50 50 20	4. Material betw	een well casing and protective nine:	
Hollow Stem Auger	41 58 1	×	Bentonit	e 🗖 30
Air hammer Other A		Bontoni	Le - Cement Annular space seal	
	82' X /	Sentoni	Other	দ্ব 📰
15. Drilling fluid used: Water 02 Air X	01 bgs 6" 1	5 Annular space	a Granular Bentonite	
Drilling Mud 🖾 03 None 🗖	99 casing	ы Lbs/g	al mud weight Bentonite-sand shurry	35
	AU /	c. Lbs/g	al mud weight Bentonite slurry	<b>□</b> 31
16. Drilling additives used?  Yes		d% Ber	ntonite Bentonite-cement grou	t 🖾 50
		е	Ft <sup>3</sup> volume added for any of the above	
Describe		f. How instal	led: Tremie	01
17. Source of water (attach analysis):	交に綴		Tremie pumped	<b>X</b> 02
Potable water source			Gravity	0 08
	+&/	6. Bentonite seal	l: a. Bentonite granules	5 🗖 33
E. Bentonite seal, top ft. MSL or	00 ft_ 5%	b. □1/4 in.	$\square$ 3/8 in. $\square$ 1/2 in. Bentonite pellets	S 🗖 32
		cNot	applicable Other	
F. Fine sand, top ft. MSL or	ft. 3	7. Fine sand mai	terial: Manufacturer, product name & 1 pplicable	nesh size
G. Filter pack, top ft. MSL or	- ft.	b. Volume ad	kled ft <sup>3</sup>	
Cosino Battorn 34	5.0	8. Filter pack m	aterial: Manufacturer, product name and	d mesh size
H. Sereen joint, top ft. MSL or	ft.	a Not	applicable	
	APE	b. Volume ac	itled ft <sup>3</sup>	
I. Well bottom ft. MSL or 39	85 O ft.	9. Well casing:	Flush threaded PVC schedule 40	23
		ASTM 853 (	and B Flush threaded PVC schedule 80	□ 24
J. Filter pack, bottom ft. MSL or	ft	Flush-b	eveled steel casing Other	ধ্য 📖
7	A	10. Screen materi	ial: open borehole	- 55
K. Borehole, bottom ft. MSL or 2	05 0 ft.	a. Screen typ	e: Factory cu	t 🗖 11
8.75" to 82ft.			Continuous slo	i 🗖 01
L. Borehole, diameter 6" to in. 365++	- 2000	۹	Not applicentele Other	r 🗖 📃
4" to 300th		b. Manufactu	rer	
M. O.D. well casing in.		c. Slot size:		) in.
4	-	d. Slotted ler	igui: open interval	<u>20.0</u> ft.
N. I.D. well casing $400$ in.		11. Backfill mater	rial (below filter pack): None	
and the second s		Not	applicable Other	
I hereby certify that the information on this	s form is true and cor	rect to the best of my	knowledge.	
Signature	Lin -	Madisan		
Support Successor 1	000			

Please complete both sides of this form and return to the appropriate DNR office listed at the top of this form as required by chs. 144, 147 and 160, Wis. Stats., and ch. NR 141, Wis. Ad. Code. In accordance with ch. 144, Wis Stats., failure to file this form may result in a forfeiture of not less than \$10, nor more than \$5000 for each day of violation. In accordance with ch. 147, Wis. Stats., failure to file this form may result in a forfeiture of not more than \$10,000 for each day of violation. NOTE: Shaded areas are for DNR use only. See instructions for more information including where the completed form should be sent.

- 14/1	Well	Constru	iction Repor	tFor		NP	Δ1	7	Private Water Department o	Systems-D f Natural Re	G/2 sources			
Prope	ny De Uni	pt. q versi	f. Geology ty of Win	Tel Nur	ephone mber 6	08	262-	-9467	Box 7921 Madison, WI	53707 (F	Please typ sing a bla	pe or print ack pen.)	lear Wei	5
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# Mt.Simon Well



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Boring	, Drilled	By				Drilling Method		/		~		
Wa	ter u	Jells	s, In	с.		Mud Rotary,	Airho	mme	vr,	Hir	·ro	any
Drill F	lig	3		2 1	Common Well Name Mt.Simon Well	Initial Water Level	Surface Ele 888.	evation 4 Ha	ms) B	orehole Varia	Diame 61C Ir	eter aches
Boring	Locati Plane	on	Ea	sting	Northing		Local Grid	Locatio	on (If a	applical	ble)	קר
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Count	y Do	ine			State DNR Co	unty Code Civil Town/C	chbura	ge				
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Number	Length (In Recovered	Blow Count	Depth In Feet	Grou, Size Densia Ge	p Name, Percent & es, Plasticity, Color ty/Consistency, Ad eologic Origin (Stre	Range of Particle , Odor, Moisture, ditional Comments, atigraphic Unit)		Sample Type	PID/FID	Standard Penetratic	Well Diagram	RaD∕ Comments
		<u>-</u>		Mud notary +	hrough unconsol	idated deposits	; poor	E				
				Ton of had	wery.	AL A DA . 72 P		F				
				Get cosina	to 87 feet the	$\omega \sim 70-75$ fe	et bgs.	E				
		2 0]						E				
			82 -			معموم معموم معموم معموم معموم مراجع	philippi etchigite escripe i	R. Martin				
				Dolomite,	2.57 5/4 lig	nt olive brown		2 de				
			=					2.1	St.	Law	ence	Fm.
	1		85 -	-As above				24				
							* B	14				
			140 =	glauconite	Sandstone, fin	e-grained, so	ne	<u> </u>				
			95=	- increasing	alouronite 9	5-1001	2	Ē	Tu	nnel		
				J	Judicontro					CI	Y Fno	
-			100	-someshal	e 54712,1	ight gray						
	i i		105	Asabove								
				1300000								
			10=	-decreasing s	shale, becomin	ig sandier						
				10 YR 576	yellowish bro	wn		E				
	1		=	as above,	fine - med. gro	lined dolomitic	A	三心				
			120	glauconit	te, love 5/11	Idspar content,	some	<u>+::</u>				
				9	, 107K 574 \	AGILOMIZAT OLDONA						
									<u> </u>			
Logge	ed By:	Luc	no C	1.10.10.10		Checked By:						
		Jus	scan (	Juanson								

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Project Name					Start Date		End Date		E	Boring N	lumber	r
Boring Drilled By	e e			)	Drilling M	ethod						
orill Rig	e e		Common W	ell Name	Initial Wa	er Level	Surface Ele	evation	I	Borehole	Diam I	eter nches
oring Location State Plane 1/4 of	Ea: 1/4	sting of Section	No T	N,R	unty Code	Civil Town/(	Local Grid Fe		on (If N S	applical I	ble) [ Feet [	∃ E ] W
Number Length (In) Recovered Blow Counts	Depth In Feet	Grou Size Densi Ge	p Name, P es, Plastici ty/Consist eologic Ori	ercent & ity, Color eency, Ad igin (Stra	Range of , Odor, M ditional C utigraphic	Particle oisture, comments, Unit)		Sample Type	PID/FID	Standard Penetration	Well Diagram	RaD/
	120 125 130 130 140 140 155 160 175 180	As above - Asabove - As above - As above - becomina brown, bi- - sand store As above, - As above, - As above, - As above, - As above, - As above, - Shale, 5 - Fine-grain 10y R 5/4 - As above	lighter ecoming medgr fine-gr fine-gr fine-gr l 612 lin red date yellowi	, 2.5% medi- ained, ained, ained shale ained ght oli sh bro	6/4 lig ium-gr less clo some dolon -54 6/2 dolomi ue gra sands wn	ht yellow ained 3 Shale nitic so Lighto tic sar Y tone ao	uish andstone live above					

susan swanson

F-204A (R 12-94)

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Field Soil Boring Log Information

Projec	t Name						Start Date	,	End Date		I	Boring N	lumber	:
Boring	Drilled	Ву			1		Drilling M	ethod	<u> </u>					
Drill F	lig				Common Wel	l Name	Initial Wa	ter Level	Surface Ele	vation	]	Borehole	Diam	eter nches
Boring State	g Locati Plane 1/4	on	Ea 1/4	sting f of Section	Nor T N	thing			Local Grid	Locatio	on (If N S	applical I	ole) [ Peet [	] e ] w
Count	у				State	DNR Co	unty Code	Civil Town/C	ity/ or Villa	ze				
Number	Length (In) Recovered	Blow Counts	Depth In Feet	Group Size Densit Ge	Name, Per s, Plasticity y/Consister plogic Orig	rcent & y, Color ncy, Add in (Stra	Range oj , Odor, M ditional ( ntigraphic	f Particle Ioisture, Comments, : Unit)		Sample Type	PID/FID	Standard Penetration	Well Diagram	RaD/ Comments
			180	As above								Tun	nel	
<u> </u>			185	-As above									Cit	У
,			190	- increasing	glauco	nite (	and sh	ale						Fm
			200	Fine - med Sorted, re to 7/2 lig -As above -As above	grained unded gi ht grau	quar rains z	72 arev , 10 Y	R 8/1 W	y well hite			Wo	neu	xoc Fr
			215	-As above					7. ber 1					
			225	- As above	, but me	dco	ninc .	and, 10	YR7/3					
			230	- As above - As above, 1 arou	out med	gro	iined,	104R 772	light					
-			240	Asabove						<u> </u>				
Logge	ed By:		<u> </u>	ſ			Checked E	By:		<u> </u>	I		1	

F-204A (R 12-94)

Project	t Name		••••••	1 - jij - 2			Start Date		End Date		Fag	Boring N	lumber	<del>.</del>
Boring	Drilled	Ву	u an su				Drilling Me	ethod	L					
Drill R	lig				Common	Well Name	Initial Wat	er Level	Surface Ele	vation	F	Borehole	e Diam I	eter nches
Boring State County	Locati Plane 1/4 d	on of	Ea:	sting of Section	T State	Northing N,R DNR Co	ounty Code	Civil Town/Ci	Local Grid Fee ty/ or Villag	Locatio	on (If N S	applica I	ble) Feet [	] e ] w
Number	Length (In) Recovered	Blow Counts	Depth In Feet	Grouj Size Densit Ge	o Name, os, Plastic y/Consi. ologic O	Percent & city, Color stency, Ad rigin (Stro	Range of , Odor, M ditional C utigraphic	Particle oisture, 'omments, Unit)		Sample Type	PID/FID	Standard Penetration	Well Diagram	RQD/ Comments
			240	- As a hour		1). 			_				1	
			AD	As a base										
				- HS above	hat a	talamit	10	18 7/4						-
		2	855	to Layre 7	Ha		10,10							
26			260	- AS above	1				-					
			265	_ As above					-			-		
			270	- As above					-					
		<u>.d</u>	275	- As about dolomite	, but	2.547	12,114	le to no	-					
			280	- As above					-					
			285	-As above	, but	2.577	19		<sup>и</sup> )с. <u>–</u>					
1			2995	- As above	-				-					
			295	- As above	., but	fine-1	ned. gn	ained	-					
			300	- As above	-				-					
Logge	d By:		<u> </u>				Checked By	/:	3 E	l	I			I

Susan Swanson

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Projec	t Name						Start Date		End Date		Pag	ge Boring N	lumber	<u></u>
Boring	g Drilled	By					Drilling M	ethod						<u> </u>
Drill F	lig	- 1 - j			Common Wel	ll Name	Initial Wa	ter Level	Surface El	evation	F	Borehole	Diam	eter
Boring	Locati	on			<u> </u>		I		Local Grid	Locatio	on (If	applica	In ble)	nches
State	Plane		Ea	sting	Nor	thing.					N			
Count	1/4 o y	of	1/4	of Section	T N State	DNR Co	unty Code	Civil Town/C	ity/ or Villa	ige	5		eet L	<u> </u>
Number	Length (In) Recovered	Blow Counts	Depth In Feet	Grouț Size Densit Ge	o Name, Per s, Plasticity y/Consister ologic Orig	rcent & v, Color, ncy, Add in (Stra	Range of Odor, M litional C tigraphic	Particle Joisture, Comments, Unit)		Sample Type	PID/FID	Standard Penetration	Well Diagram	RaD∕ Comments
		9	300_							E.				
			305	- As above						<u> </u>				<u> </u>
			212	- As a hore		*				E:				
				10 00000						E				
			315	- As above								Wo	new	oc
			320	- As above	but tro	ace of	nips of	shale		<u>E. · ·</u>		<u> </u>	E	
				54612						E				r).
			525	- As about,	but inc	lasir	g sho	ly ch	ips	E · :				
			330	-Asabare k	nt into	not is a	ch. A	e el ior		E.		ļ		
				Atalas asamah		eusinc	snal	ey chip:	>					
			335	Shale, som	e ven. fi	Alling th	and at 3	354.)	weight-					
			2415	54 4/1 day	rigray	1C. 301	10 1 511	r				Ea	uC	laire t
				As above, son	neglation	nite					с. Э. Э.			
			345	-Asabove, b	ut in crea	singu	ell-cen	nented we	na			-		
			200	tine sand	stone	0			5	E				
			100	Medium - grades	ned wel		d quar		te			Mt	. Si	non
			355	545/1 gro	y, with	2.5 1	R 4/2 W	eak red o	and.	E'.:			E	
			340	- becoming	2.5/0 bia	ck	3			E			tin	•
				2.54R 6/2	on-med.c	nd 54	d quar R'612 pi	tzalenit nkish gr	e. ay					
Logge	d By:	•			~		Checked B	y:		1	I	1	1	I

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F-204A (R 12-94)

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Field Soil Boring Log Information

Projec	t Name						Start Date		End Date		Pag	se 6 Boring N	of lumber	<u>Ø</u>
Boring	Drilled	By .					Drilling Me	thod				1		
Drill F	tig				Common Wel	l Name	Initial Wat	er Level	Surface Ele	evation	E	Borehole	e Diamo	eter
Boring State	tocati Plane 1/4	on	Ea 1/4	sting of Section	Nor T N	thing ,R	- <b></b>		Local Grid Fe	Locatio et	on (If N S	applica I	ble) Feet [	] E ] W
Count	у				State	DNR Co	ounty Code	Civil Town/C	ity/ or Villa	ge				
Number	Length (In) Recovered	Blow Counts	Depth In Feet	Grou Size Densit Ge	o Name, Per s, Plasticity y/Consister ologic Origi	ccent & , Color ncy, Add in (Stro	Range of , Odor, M ditional C atigraphic	Particle oisture, omments, Unit)		Sample Type	PID/FID	Standard Penetration	Well Diagram	RQD/ Comments
<u></u>			360	As above,	becoming	5YR	8/1 wh	ite.		E	ALLANON A	Casi	ng s	et zic'h
			365							<u> </u>	131		+0	202 0
<u>(</u> no	samp	ne)	370	- As above	, 5YR 71;	z pink	Lishqua	t		<u> </u>				
		V	375	-Asobore		-		0		E.				
			380	- 4		•				<u> </u>				
			205	AS Above	_	1 0	Ð			E.		101		
			262		En	al Dt	Borina			E			-	
	53			-				00	-30			1		
				-						Ē		+		<u></u>
	ļ			- 8						Ē				
	19 <sup>19</sup>									Ē				
										E				
										Ē				
	1									Ē				
										F				1
			2	М.,										
Logge	ed By:	S	usar	n Swansor	)		Checked By	<b>.</b>		_	v.		-L	

F-204A (R 12-94)

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State of Wisconsin Department of Natural Resources	id Waste 🛛 Haz. Waste	e 🛛 Wastewater 🗖	MONITORING WELL CO Form 4400-113A	NSTRUCTION Rev. 4-90
Facility/Project Name	Local Grid Location of	f Well	Well Name Nine Springs	
9 Sorings	ft. 🗖	INft. 🗖	W Upper Paleozoic	Mon. Well
Facility License, Permit or Monitoring Number	Grid Origin Location		Wis. Unique Well Number -DNI	Well Number
	Lat	Long	_ or (JQ703 DN	-1442 Count
Type of Well Water Table Observation Well 11	St. Plane	ft. N,ft	.E. Date Well Installed 12/8-1	999
Piezometer 12	Section Location of W	aste/Source	F Well Installed Put (Person's New	y y
Distance well is from waste/Source Boundary	SE 1/4 of NE 1/4 of S	Sec. 10, T. 6 N, R. 9	W. Went installed By: (Person's Nam	he and rinn)
Is Wall A Point of Enforcement Std Application?	Location of Well Relat	tive to Waste/Source N.A.	Water wens i	<u>nc.</u>
	d Downgradient	n 🔲 Not Known	Richard + H	ievin
A. Protective pipe, top elevation	ñ. MSL	1. Cap and 1	lock?	Yes 🗆 No
B. Well casing, top elevation 890_55	it. MSL	a. Inside	liameter:	6.0 in.
C. Land surface elevation 888_55	ft. MSL	b. Length	Ľ	88. Oft.
D. Surface seal, bottom ft. MSL or	— ft.	c. Materi	al:	Steel 🖬 04
12 LISCS classification of soil near screen.		d Additi	onal protection?	
GP GM GC GW SW G	SP D XY	If yes.	describe:	
SM C SC C MLC MHC CL C	сн 🗖 🛛 🗙		Ben	tonite 🗖 30
Bedrock Tunnel City + Wone wood	Fm.s 2	3. Surface s	eal: Co	ncrete 🖬 01
13. Sieve analysis attached? 🔲 Yes 🔤	No N/			Other 🗖
14. Drilling method used: Mud Rotary	50 3/8	4. Material	between well casing and protective pipe	***:***: **
Hollow Stem Auger		8 🗱	well bore Ber	itonite 🛛 30
Airhammer tri-cone Other M		D.,	Annular spac	e seal 🗖 🔤
	. EA	<u>IJent</u>	onite - Cement	Other 🔛 🚃
Drilling fluid used: water 10 02 Air 10		5. Annular	space seal: a. Granular Ben	tonite 🛛 33
	3/	bI	.bs/gal mud weight Bentonite-sand	slurry 1 35
16. Drilling additives used?  Yes	No XX		bs/gal mud weight Bentonite	slurry L 31
	88'695	d%	Bentonite Bentonite-cement	grout 20
Describe	5" casing	e	Ft volume added for any of the a	remie $\Box 0.1$
17. Source of water (attach analysis):	สไข้		Tremie pu	
Potable water source			G	ravity $\square$ 0.8
	open	6. Bentonita	e seal: a. Bentonite gra	anules $\square$ 33
E. Bentonite seal, top ft. MSL or	0.0 ft.	b. □1/	4 in. □3/8 in. □ 1/2 in. Bentonite	cellets
•		cNo	t applicable	Other 🗖
F. Fine sand, top ft. MSL or	ft.	7. Fine sand	i material: Manufacturer, product nam	ie & mesh size
G. Filter pack, top ft. MSL or	ft.	b. Volum	ne added ft <sup>3</sup>	****
Casing bottom		8. Filter par	ck material: Manufacturer, product nan	ne and mesh size
H. Screen joint, top ft. MSL or	<u> 20 0 ft</u>	a_No	t applicable	
		b. Volur	ne added ft <sup>3</sup>	
L. Well bottom ft. MSL or 3	5_0 ft	9. Well cas	ing: Flush threaded PVC schedu	e 40 🗖 23
I. Filter pack, bottom ft. MSL or -	- ft	Fluch-	hourled steel (asing	
mer prest, content		10. Screen m	aterial: Open borchole	
K. Borehole, bottom ft. MSL or 31	5.0 ft.	a. Scree	n type: Facto	ry cut 🔲 11
0	N		Continuou	is slot 🗖 01
L. Borehole, diameter <u>8.0</u> in. to 88	315 bgs VE	Mon	applicable	Other
M. O.D. well casing in.		c. Slot s	ize:	0 in.
	-	\ d. <del>Slotte</del>	d length: Open Interval	23 <u>5.0ft</u> .
N. I.D. well casing $5.00$ in.		11. Backfill r	naterial (below filter pack):	None 14
	Anna ta Anna Maria	porriegt to the bast of	no appricable	
I nereby certify that the information on this	s torm is true and	correct to the Dest of	my knowledge.	
Supprin Suppring	()(1)-	-Madison		

Please complete both sides of this form and return to the appropriate DNR office listed at the top of this form as required by chs. 144, 147 and 160, Wis. Stats., and ch. NR 141, Wis. Ad. Code. In accordance with ch. 144, Wis Stats., failure to file this form may result in a forfeiture of not less than \$10, nor more than \$5000 for each day of violation. In accordance with ch. 147, Wis. Stats., failure to file this form may result in a forfeiture of not more than \$10,000 for each day of violation. NOTE: Shaded areas are for DNR use only. See instructions for more information including where the completed form should be sent.

Wisconsin Universe       Wisconsin Universe       Telephone       0.00       262-29467         Namer       Diffield Strip GP Wiss       Number       60.0       262-9467         Mainer       1215 W. Dayton Staget       Number       60.0       262-9467         Mainer       1215 W. Dayton Staget       Same       20.006         Convol Will Leanon       Weil Convolter       Weil Convolter       No. of Lacey Road         Mainer       No. W       Weil Convolter       No. of Lacey Road         Mainer       No. W       Weil Convolter       No. of Lacey Road         Mainer       No. W       Weil Convolter       No. of Lacey Road         Mainer       No. Of Lacey Road       No. of Lacey Road       No. of Lacey Road         Mainer       Mainer       No. of Lacey Road       No. of Lacey Road       No. of Lacey Road         Mainer       Mainer       No. of Lacey Road       No. of Lacey Road       No. of Lacey Road         Mainer       Mainer       No. of Lacey Road       No. of Lacey Road       No. of Lacey Road       No. of Lacey Road         Mainer       No. of Lacey Road         Mainer       No. of Lacey Road       No. of La		Well C	onstru	iction Report	t For		NP	10	15	State of Wisconsin Private Water Systems-DG/ Department of Natural Reso	2 urces		
Mailing       Autres       1215 W. Dayton Stagest         Mailing       Autres       1215 W. Dayton Stagest         Commy of Wall Location       Stagest       Stagest       Stagest         Commy of Wall Location       Cs. Wall Permit       Wall Composition Nume       Using Stagest       Stagest         Well Connector (Buildings Nume)       License 7       Stagest       License 7       Stagest       N         Well Connector (Buildings Nume)       License 7       Stagest       N       Well Connector (Buildings Nume)       License 7       Stagest       N       Biod, F         Will Care purchase       Will Care purchase       N       Well Care purchase       N       Biod, F         Will Care purchase       Will Care purchase       N       Biod, F       Biod, F         Will Care purchase       N       Stagest       N       Biod, F       Stagest       N         Stagest       Will Care purchase       N       Stagest       N       N       Biod, F         Well Care purchase       N       Stagest       N       N       Difference       N       N       N         Gard on Partic       Operation Partic       N       N       Stagest       N       N       N       N <td>Prop</td> <td>erty De er Un</td> <td>pt. ( ivers</td> <td>f Geolog</td> <td>Tel S Nur</td> <td>ephone nber 6</td> <td>08 :</td> <td>262-9</td> <td>467</td> <td>Box 7921 Madison, WI 53707 (Ple</td> <td>ase type or prin</td> <td>ıt</td> <td></td>	Prop	erty De er Un	pt. ( ivers	f Geolog	Tel S Nur	ephone nber 6	08 :	262-9	467	Box 7921 Madison, WI 53707 (Ple	ase type or prin	ıt	
Ares:       1413       W. 1. 28 2 Col.       State       2p Col.       State       2p Col.       State       City       Will Second Col.       State       2p Col.       State       City       Will Second Col.       State       State       State       State       City       Will Second Col.       State       State       State       City	Mail	ing	1 6 70	Cashi Anna	Dá main à			in a far is	i de la composición de la comp	1. Well Location Please	use decimals in	stead of fra	ctions.
Had is son       Will       53706         Commy of Well Coation       One Well Coation       Well Commod (Similar Mana)       Land Similar Mana)         Date       No. W_link       Well Commod (Similar Mana)       Land Similar Mana)       Land Similar Mana)         Well Commod (Similar Mana)       Land Similar Mana)       Land Similar Mana)       Land Similar Mana)       Land Similar Mana)         Well Commod (Similar Mana)       Sate Zip Code       W       W       Image: Similar Mana)       Land Similar Mana)       Land Similar Mana)         4. Well serves       Go (Similar Mana)       Sate Zip Code       W       W       Image: Similar Mana)       Land Similar Mana)       Land Similar Mana)       Land Similar Mana)       Land Similar Mana)       Mana)<	Addi	ress 14	12 19	. Dayton .	5088ec	State	Zip Code	ng <sup>an</sup> in <sup>a</sup> Nasa		X Town City	Village	Fire # (If a	vail.)
Data       Co. Will composition       Meeting of the set of t		Ma	disor		e la constat <del>Calintacia</del> n	WI.	5370	06		of Fitchbu Grid or Street Address or Ro	CQ ad Name and Numb	xer	1997 - 1997 - 19 
Well Construction (Business Name)       Lease #       2. Mark well control       Duck well contro       Duck well control	Cou	Dane	Jocation	No. W_		$-\frac{12}{2}$		0 - 9	9	N. of Lacy	Road	Risk ging 2	1. 4
Add Ex. # Malles INC.       0       40 are pared of section.       Gov Lot #		Well Cons	structor (B	usiness Name)	49 (SI (C))	License	2. Ma with a	ark well loo dot in cor	ation rect	ESU CLEIRE	WELL	BIO	К. #
6400 Lake Road       Sue ZpCode       W       Image: Construction       Section       10       T       6       NR       9       XXI       E         1       Windsor       WI       53598       W       Image: Construction       I		Address	EK WI	SLUS INC.		1 3	40-ac	re parcel of N	section.	Gov't Lot # or	<u>NW</u> 1/4 of _	NE 1/4	of
Link		640 City	0 Lai	te Road	State 7	in Code		-+-X	XI T T	Section <u>10</u> , T <u>6</u>	N; R9_	_XX e	w
4. Well serves	- 1 - V	Win	dsor:	1990) if i short short sh	WI	<u>53598</u>	W			3. Well Type	New Reconstruction	29-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1	
4. Well serves # of homes and or		1 d 11	-			. E.C.	$\{ f_{i}, f_{i}, q \}$	Lil	il,	(see item 13 below) of previous unique well #	con	structed in 19	
4. Well serves do homes and or Well? Yes [			······································	1. 1975-1997 - 1987 1. 1975-1987 - 1987	No ta general de		High Capa	icity:		Reason for replaced or rec MONITOR W	onstructed well?	- 	
5. Is the well located upslope or sideklope and not downlope from any contamination sources, including those on neighboring properties?       Yes       No       If no, explain on back side.         Well located in Dodplain?       Yes       No       If no, explain on back side.       If No explain on back side.         Diamon in Deep Form Well To Normania Starts:       (no back side.       If No explain on back side.       If No explain on back side.         1. Landfill       1. Expland and properties?       Yes       No if no, explain on back side.         2. Building Overhang       12. Foundation Drain to Clearwater       19. Animal Yard or Shelter         2. Building Overhang       12. Foundation Drain to Sever       20. Silo         3. Septic or Holding Tank (circle oco)       13. Building Drain       21. Barn Gutter         4. Severge Absorption Unit       14. Building Sever:       Gravity:       Pressure         6. Buried Home Heating Oil Tank       15. Collector Sever:       23. Other Manues Storage       Gravity:       Pressure         7. Buried Paroleum Tank       15. Collector Sever:       23. Other NR 812 Waste Source       6. Other NR 812 Waste Source         6. Dnillole Dimensions       10. Removed To restruction       If Method of Construction       If Method of Construction         875       surface       85       15. Clearwater Sump       Geology       Fr	4. Well se (Eg: bar	rves	_# of hom	es and or school, industry, etc.	<b>)</b>	· / · · · · · · · · · ·	Well? Property		s X No	Drilled Driven Poir	t Jetted	Other	
Well locate in locoplain?       1 to Sever       9. Downspoul? and Hydrant       11. Wastewater Sump         Dinance in Feet Form Well To Statute (arele one)       10. Privy       18. Preved Animal Bam Pen         1. Landfill       11. Foundation Drain to Clearwater       19. Animal Yard or Shelter         2. Building Overhang       12. Foundation Drain to Sever       20. Silo         3. Septic or Holding Tank (circle one)       13. Building Drain       21. Bam Guiter         4. Sewage Absorption Unit       13. Building Drain       21. Bam Guiter         5. Sonconforming Pit       Cast Iren or Plastic       Other         7. Burice Detroleum Tank       15. Collector Sever:unitsin diameter       24. Ditch         8. Shoreline/Swimming Pool (circle one)       16. Clearwater Sump       20. Other NR 812 Waste Source         6. Dulliob Dimensions       Tom       Method of Construction       User         10. (n.)       (f.)       (f.)       S. Cable-tool Bitin. dia.       dpri ft         5. Satiface       85. Sotay: Foam       11       Statuse Source       11         6. Temp. Outer Casingin. dia.       dpri       ft       surface       82         5. Satif Acce       15. Cable-tool Bitin. dia.       dpri       ft       11       11         7. Casing, Liner, Streem	5. Is the w	ell located u	pslope or	sideslope and not do	wnslope from	n any conta	mination	sources, in	cluding the	ose on neighboring properties?	Yes No	on back sid	lin le.
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# **APPENDIX B**

Two-way Cluster Analysis of Geochemical Data to Constrain Spring Source Waters

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### Abstract

The magnitude and temporal variation of major ion concentrations in groundwater proved to be useful in distinguishing source waters for springs in the Nine Springs watershed. The use of summary statistics resulted in the identification of three "groups" of waters and two-way cluster analysis of the geochemical data further identified subtle geochemical characteristics of the three groups. One spring, which is representative of smaller springs and seeps found in the watershed, belongs to a group that is characterized by variable nitrate and chloride concentrations. Water discharging from this spring has a groundwater residence time of approximately 8 years based on the tritium/helium-3 dating method and is thought to be representative very local groundwater flow. Most of the springs in the watershed belong to a group that is characterized by elevated, but consistent nitrate, sodium, and chloride concentrations. Apparent groundwater ages for this group range from 10 to 15 years. The water discharging from the majority of the springs in the watershed is thought to travel through the unlithified glacial materials and the uppermost bedrock units before discharging into the former glacial lakebed wetland complex. Due to the relatively short groundwater residence times, spring water quality and flow are likely to be vulnerable to the rapid urban expansion occurring within the watershed.

Keywords: springs, cluster analysis, geochemistry, tritium, helium

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#### I. Introduction

The Nine Springs watershed, located in Dane County, Wisconsin, contains an unusual concentration of cold-water springs. The springs are representative of those sometimes associated with former lakebed wetlands in the glaciated Upper Midwest. These springs often provide an important and consistent source of high quality water needed to maintain diverse wetland systems, and they can contribute significantly to the hydrologic budgets of these systems.

The Nine Springs watershed is situated in an area of rapid urban expansion and it is faced with problems that are typical of urbanizing watersheds. Declines in wetland plant diversity, which are already visible, are likely due to increased surface water inputs in combination with decreased groundwater inputs resulting from past agricultural practices, loss of groundwater recharge, and increased municipal pumping.

Despite the hydrological and ecological importance of these springs, it is currently unclear what effects development is having on them and how springflow will be impacted by further development. The springs are poorly understood due to the inaccessible nature of the geologic features ultimately responsible for their formation. This study is the first step in the development and refinement of a conceptual model of the hydrogeologic system responsible for flow to the springs. Future work will include detailed hydrostratigraphic characterization and numerical modeling. In this paper we describe the use of two-way cluster analysis to test geochemical interpretations and further identify subtle geochemical characteristics of the groundwater discharging to the springs in the Nine Springs watershed. We also use apparent ages based on the tritium/helium-3 dating method to support and constrain groundwater residence time estimates.

#### II. Site Description

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The Nine Springs watershed is located in south-central Dane County, Wisconsin (Figure 1), and is a sub-basin of the Yahara-Monona watershed. The uplands in the watershed are composed primarily of sandy till belonging to the Horicon member of the Holy Hill formation (Clayton and Attig, 1997) overlying dolomitic sandstone bedrock of Cambrian age. The low-lying areas in the watershed occupy a preglacial erosional bedrock valley that was subsequently filled with glacio-lacustrine deposits and till (Bradbury et al., 1999). It is likely that the bedrock valley deepens and widens to the east where it joins a larger buried erosional valley system.

Many of the low-lying areas within the watershed are occupied by groundwater-fed wetlands with peat accumulations of up to 3 meters. The wetlands historically consisted of shrub carr/sedge meadow dominated by *Carex spp.* and *Salix spp.* These wetlands were maintained by consistent, diffuse groundwater discharge and by numerous small seeps and several large springs or spring complexes. Due in part to past agricultural practices including tiling and introduction of exotic plant species, large portions of the wetlands are now dominated by a monoculture of reed canary grass (*Phalaris arundinacea L.*); however, pockets of high-quality sedge meadow remain primarily in the western and southern parts of the watershed, south of Nine Springs Creek. Nine Springs Creek, which was straightened and channelized in the 1930s, flows east through the wetland area and discharges to Mud Lake.

Two field sites, the Gunflint Trail site and the Syene Road site, were chosen on the basis of their proximity to major springs. Two large (>4.3E-03 m<sup>3</sup>/s) springs, hereafter referred to as the big spring and the nursery spring, are located near the Gunflint Trail site. Many smaller springs or seeps, including one referred to as the peat spring, are also present

in the vicinity of this site. One large spring, the Syene Road spring, is located in the vicinity of the Syene Road site. Each field site was instrumented with at least 10 monitoring wells installed in nests (Figure 2). Most of the well nests consist of a water table well, an intermediately-screened well installed in sandy till, and a well screened in a highly weathered zone at the top of the dolomitic sandstone bedrock. The uppermost bedrock unit in much of the study area is the Tunnel City Formation, which is described as a medium-grained, cross-bedded, dolomitic, and in some places glauconitic, sandstone (Ostrom et al., 1970).

Groundwater samples were collected quarterly from the springs and selected monitoring wells at the two field sites from November 1997 to March 2000. In order to sample groundwater that is representative of water flowing through the bedrock aquifers in the vicinity of the sites, several privately-owned wells within the watershed were included in the monitoring network. Private wells were chosen on the basis of their proximity to the field sites, the availability of a well construction report and driller's log on file at the Wisconsin Geologic and Natural History Survey, and the limited screened or open interval of the well (<15m) (Table 1).

#### III. Methods

#### **1.** Geochemical Analysis

The first groundwater samples were collected in November of 1997, and sample locations were added to the quarterly sampling program as new wells were installed. Private well sampling began in August of 1998 and was also conducted on a quarterly basis. Sampling continued through March of 2000. All samples were analyzed at the Wisconsin State Laboratory of Hygiene for major cations (Mg2+, Ca2+, K+, Na+) by ICP/atomic emission spectrometry and anions (NO<sub>3</sub>-, SO<sub>4</sub>2-, Cl-) by automated colorimetry. The

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laboratory also reported temperature, pH, conductivity (corrected to 25°C), and total alkalinity. However, temperature, pH, conductivity, and total alkalinity, as well as dissolved oxygen, were measured in the field at the time of sample collection. Alkalinity and dissolved oxygen were measured using Chemetrics® colorimetric ampoules, which use a hydrochloric acid titrant with a pH indicator and an indigo carmine method, respectively. Concentrations of total dissolved solids (TDS) were also calculated by summing the concentrations of cations and anions for each monitoring point from each sampling event.

#### 2. Summary Statistics

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Preliminary observations and conclusions were based on the use of simple summary statistics including the sample mean and coefficient of variation. The coefficient of variation was used to provide a measure of spread or dispersion about the mean concentration for each analyte at each monitoring point. The sample mean is computed by

$$\overline{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

where,  $x_1, x_2,...$  are the sample observations. The coefficient of variation is defined

$$CV = s_x / |\overline{x}|$$

where,  $s_r$  is the sample standard deviation, given by

$$s_x = \left[\frac{1}{n-1}\sum_{i=1}^n (x_i - \bar{x})^2\right]^{\frac{1}{2}}$$

### 3. Cluster Analysis

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Cluster analysis can be useful when abundant data are available and clear hydrogeologic models have not yet been developed (Colby, 1993; Suk and Lee, 1999). A two-way cluster analysis was performed on 22 monitoring points and 10 analytes to provide a check on the interpretation of the geochemistry results that were based on summary statistics and stratigraphy. While both analytes and monitoring points were clustered, the primary purpose of the exercise was to identify relationships among monitoring points. However, by also clustering analytes the characteristics of the monitoring point clusters are more apparent. Before performing the analyses, all analytical data were standardized using the global mean for each analyte. Standardization was necessary because concentrations vary over a wide range among the analytes (Colby, 1993; Everitt, 1993). Because each monitoring point also has multiple sampling events, a local mean for each analyte at each sampling location was then calculated. It is important to note that by choosing the mean as the representative summary statistic, these analyses do not consider within-group variation in analyte concentration at each sample location.

The two-way analysis was performed by (i) clustering the sample locations, (ii) clustering the analytes, and then (iii) creating a two-way dendrogram or tree diagram to illustrate the results. A Euclidean distance measure was used with Ward's hierarchical clustering method to perform the analyses in the statistical software Statistica (StatSoft, Inc., 1997). The Euclidean distance between any given pair of either monitoring points or analytes is equal to the geometric distance in multidimensional space (Everitt, 1993):

$$d_{AB} = \left\{ \sum_{i=1}^{p} (x_{Ai} - x_{Bi})^2 \right\}^{\frac{1}{2}}$$

d = the Euclidean distance,

;

where

A and B = any given pair of monitoring points or analytes,
x = local standardized mean concentration, and
p = number of variables (10, the number of analytes when clustering monitoring points; 22, the number of monitoring points when clustering analytes).

Calculating the distance between all possible pairs of monitoring points and analytes results in two matrices of Euclidean distances. The distance matrices are useful for initially determining similarity between variables and illustrating the relative similarity in the final dendrogram. However, once several variables are grouped together, a linkage rule or clustering method is necessary to determine clusters and evaluate distances between the new clusters. Ward's hierarchical clustering method aims to minimize the loss of information at each step in the clustering process. Information loss is defined in terms of an error sum-of-squares (ESS) criterion. Given g clusters, the procedure sequentially reduces the number of clusters to g-1 by considering the loss of information associated with the union of all possible (g\*(g-1)/2) sets. (Ward, 1963). The error sum-of-squares for each cluster is given by

$$ESS_{i} = \sum_{j=1}^{n_{i}} \sum_{k=1}^{q} (x_{ijk} - \bar{x}_{ik})^{2}$$

where

n = the number of objects grouped together in a cluster (2),
q = the number of variables (the number of analytes when clustering monitoring points, the number of monitoring points when clustering analytes),

 $x_{ijk}$  = local standardized mean analyte concentration,

 $\overline{x}_{ik}$  = mean analyte concentration of objects grouped together in

a cluster.

The total ESS can be evaluated as the sum of multiple separate sums of squares.

$$ESS_{total} = \sum_{i=1}^{g} ESS_i$$

where g = number of sets evaluated.

Finally, a dendrogram is created. The dendrogram illustrates the groupings made at each successive stage of the clustering process (Everitt, 1993); the branches of the dendrogram are scaled to represent the Euclidian distances between members of each cluster.

#### 4. Tritium/Helium-3 Analysis

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A selected number of monitoring points were sampled for analysis of tritium (3H) and its stable decay product helium 3 (3He) for purposes of groundwater age dating. The 3H/3He dating method extends the usefulness of the mid-1960's tritium groundwater inputs to cases where radioactive decay and dispersion have significantly reduced the amount of 3H in groundwater (Solomon et al., 1992). In this study, the apparent ages calculated by the 3H/3He method place constraints on our conceptual model of groundwater flow.

Groundwater samples were collected from ten monitoring points including MW3A, MW3B, MW4B, MW5A, MW5B, MW7A, MW7B, the big spring, the nursery spring, and the peat spring. In addition, a small spring on the north side of Nine Springs Creek was sampled. This spring was not included in the cluster analysis because the limited number of geochemical samples precluded the calculation of meaningful summary statistics.

Tritium samples were collected from the monitoring wells using a Waterra inertial pump, which consists of a footvalve connected to a length of polyethylene tubing. When oscillated up and down in the well, the pump produces a flow of water. Prior to collecting the samples, two to three well volumes of water were purged from the monitoring wells. Spring samples were collected by fully submerging sample bottles in the spring pool as close to the point of discharge as possible. Before filling and capping, bottles were rinsed with sample. Samples were collected in 250ml glass bottles with tight sealing caps, and were submitted to the University of Utah Noble Gas Laboratory for analysis of tritium by the tritium in-growth method.

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Dissolved gas samples were collected in copper tubes that were cold-welded using refrigeration clamps. After purging a monitoring well, a copper tube was attached to the discharge end of the plastic tubing. Water was then pumped through the plastic tubing and the in-line copper tube for several minutes to minimize bubble entrapment within the copper tube. Refrigeration clamps on either end of the copper tube were then tightened, and the ends of the copper tube capped. Samples were collected in a similar manner from the springs; however, water was drawn through the plastic tubing and in-line copper tube using a handheld vacuum pump. Samples were submitted to the University of Utah Noble Gas Laboratory for analysis of dissolved gases by mass spectrometry.

The 3H/3He dating method was first proposed by Tolstikhin and Kamensky (1969) and has proved useful in many groundwater studies (e.g. Togersen et al., 1979; Solomon et al., 1992; Solomon et al., 1993). When measurements of tritiogenic 3He (3He\*), which results exclusively from the decay of 3H, are made in association with 3H, the measurements can be used to calculate the time since the water was isolated from the atmosphere. The 3H/3He age ( $t_{3H/3He}$ ) is calculated by

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$$t_{3H/3He} = \lambda_{3H}^{-1} \ln \left( \frac{3He^*}{3H} + 1 \right)$$

where,  $\lambda_{3H}$  is the decay constant for tritium.

Helium isotopes in groundwater, including both 3He and helium 4 (4He), come from several different sources. In order to compute 3He\*, these additional sources and the 3He/4He ratio in the atmosphere must be taken into account. The total dissolved 3He is the sum of atmospheric 3He, 3He\*, and nucleogenic 3He. The total dissolved 4He is the sum of atmospheric and radiogenic 4He. In this study, 3He\* was computed using the following equation derived by Solomon et al. (1992):

$$3He^{*} = \frac{R_{t=0} 4He_{m} - R_{sol} \left[ \alpha' \left( 4He_{m} - 4He_{sol} \right) + 4He_{sol} \right]}{1 + \alpha' \left( \frac{4He_{m}}{4He_{sol}} - 1 \right)}$$
(1)

where

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 $R_{t=0} = 3$ He/4He ratio at the time of sampling,

 $R_{sol} = 3$ He/4He ratio of water is isotopic equilibrium with the atmosphere,

 $4He_m$  = measured 4He,

 $4He_{sol} = 4He$  resulting from equilibrium solubility with the

atmosphere,

 $\alpha' = air/water fractionation factor (\alpha'=1.012 at 10°C,$ 

#### Weiss, 1970)

This equation assumes that samples are supersaturated with respect to atmospheric nitrogen and helium, resulting from bubble entrapment inside the copper sampling tubes. In addition, one sample was analyzed by a different equation, also derived by Solomon et al.

(1992), which assumes samples are undersaturated with respect to atmospheric nitrogen and helium:

$$3He^* = R_{t=0} 4He_m - \frac{(R_{sol} 4He_{sol})}{(4He_{sol} - 4He_m)/4He_m} + 1$$
(2)

Equation (2) assumes that gas stripping by  $CH_4$  and/or  $CO_2$  occurs at the water table and that no radiogenic 4He is present in the groundwater sample (Solomon et al., 1992).

#### IV. Results and Interpretation

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#### 1. Geochemical Results and Summary Statistics

The geochemical results show that waters sampled cannot be distinguished on the basis of their major ion facies alone. Due to the high carbonate content of both the unconsolidated glacial deposits and the sedimentary bedrock units in the area, all waters sampled are a calcium-magnesium bicarbonate type. A Piper diagram of the March 1999 analytical results, which is representative of all the sampling events, is shown in Figure 3.

The magnitude and temporal variation of individual ions, primarily nitrate ( $NO_3$ -) and chloride (Cl-), proved to be more useful in distinguishing between possible source waters, groundwater flow paths, and residence times. On the basis of the geochemical analytical results, three "groups" of waters were identified. Table 2 presents the geochemical characteristics of the groups and identifies the sampling locations that define each group. The distinguishing geochemical characteristics of each group (defined relative to the other two groups of waters) are also discussed below.

#### i. Group I

Group I consists of monitoring wells MW2A, MW2B, and MW3A, and a small spring or seep called the peat spring. This group shows temporal variability in nitrate

concentrations (CV= 0.13-0.62) and, relative to the other groups, somewhat higher variation in chloride concentrations (CV > 0.17). In some cases (MW2A and MW2B), potassium concentrations are elevated (8.8-78mg/L) and variable ( $CV_{(MW2A)}=0.50$ ,  $CV_{(MW2B)}=0.20$ ). Sodium concentrations tend to be low (1.7-7.7 mg/L) and somewhat more variable (CV=0.08-0.41) than at other sampling locations. TDS concentrations range from 400 to 740mg/L.

MW2A and MW2B are located in a recharge area and are screened in till. MW2A is screened across the water table. MW3A is also screened in till, and it is located in an area that, depending on the time of the year and individual storm events, can be either a recharge or discharge area. MW2A and MW2B are located in a field that was farmed through the 1997 agricultural season, and an actively farmed field is located less than 150 meters to the south. MW3A and the peat spring are located down-gradient of MW2A and MW2B, approximately 60 and 90 meters to the north, respectively. The high and temporally variable nitrate and potassium concentrations observed in these wells are probably a result of seasonal fertilizer application, while the variable chloride concentrations may be a remnant of seasonal road salt application. The high nitrate and chloride concentrations in conjunction with the general variability in analyte concentrations observed in MW2A, MW2B, and MW3A suggest that groundwater travels along short flow paths, has short residence times, and is part of a local flow system. Therefore, the water discharging to the peat spring is probably also locally-derived.

#### ii. Group II

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Group II consists of monitoring wells MW4B, MW1C, MW5A, MW5B, MW6A, and MW6B; private wells P-3, P-4, and P-5; and three large springs (>3.40E-03 m<sup>3</sup>/s): the big

spring, the nursery spring, and the Syene Road spring. The geochemical characteristics of this group include elevated (generally >10 mg/L), but relatively consistent (generally CV<0.05) nitrate concentrations and high (generally >20mg/L) and consistent (generally CV<0.06) chloride concentrations. In addition, sodium concentrations tend to be higher (7.1-14 mg/L) than concentrations detected at other monitoring points and consistent (CV<0.07) throughout the sampling period. TDS concentrations range from 460 to 580 mg/L.

All of the monitoring wells in this group are in discharge areas. MW5A and MW6A are screened in till; however, all other monitoring wells are screened at the top of the dolomitic sandstone bedrock surface. MW5A and MW6A are located in areas where upward vertical gradients range from 0.10 to 0.24. The privately-owned wells (P-3, P-4, and P-5) are drilled to various depths in the bedrock. From the well construction reports, it appears that P-3 is open to the Tunnel City Fm. and P-4 and P-5 are open to the overlying Jordan Fm., which is described as fine to medium grained, thick-bedded quartzarenite (Ostrom et al., 1970). The high nitrate and chloride concentrations at these locations are probably due to the application of agricultural fertilizers and road salt, but it is likely that flow paths and residence times are longer than those for Group I because temporal variations in nitrate and chloride groundwater flow system. Therefore, the characteristics of the water discharging to the big spring, the nursery spring, and the Syene spring may also be a result of an intermediate groundwater flow system.

#### iii. Group III

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Group III consists of monitoring wells MW7A, MW7B, and private well P-1. None of the springs that were monitored had characteristics that were similar to this group. The

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geochemical characteristics of this group include very low (<2.4 mg/L) and consistent (CV<0.09) nitrate concentrations throughout the sampling period and low (<3.1mg/L) chloride concentrations. In addition, sulfate concentrations were somewhat lower (<8 mg/L) throughout the sampling period at these locations. Sodium concentrations are consistently (CV<0.05) less than 3.3 mg/L throughout the sampling period, and TDS concentrations are consistently (CV<0.05) less than 460 mg/L. The lowest conductivity measurements recorded in groundwater samples were also collected from MW7A, MW7B and P-1 and MW7B has low dissolved oxygen concentrations (2-4 mg/L) compared to 5-7 mg/L at other sampling locations.

MW7B and P-1 are screened in fine sandy lacustrine material that fills the preglacial bedrock valley below Nine Springs Creek. MW7A is screened in the overlying till. The upward vertical gradient between MW7B and MW7A ranges from 0.001 to 0.005. The low nitrate and chloride concentrations probably represent background levels of these constituents in regional groundwater. It is likely that either (i) fertilizer or road salt sources do not exist in the recharge area or (ii) elevated concentrations of nitrate and chloride, resulting from heavy use of fertilizers and road salt beginning in the 1930's, have not yet reached these locations due to long flow paths and residence times.

#### iv. Exceptions

Exceptions to the groups defined above include monitoring well MW3B and private wells P-2 and WDNR #9. Monitoring well MW3B is screened in till, near the top of the bedrock surface at the Gunflint Trail site. It is located in an area where vertical groundwater gradients alternate between upward and downward, depending on the season and/or individual storm events. Therefore, it is not surprising that the groundwater shows some characteristics that are consistent with Group I (temporally variable nitrate concentrations) and some that are consistent with Group II (elevated, but consistent chloride concentrations).

The privately-owned wells (P-2 and WDNR #9) are open to bedrock at somewhat lower elevations than the other private wells. While detailed geologic logs are unavailable for the privately-owned wells, P-2 is probably completed in the Tunnel City Fm. based on the elevation of the open interval. The sampling results from this well are very similar to the characteristics of Group II, with a few exceptions; groundwater shows lower, but still consistent, sodium and chloride concentrations.

WDNR #9, which is a flowing well, is open to the Tunnel City Fm. and the underlying Wonewoc Fm., which is described as fine to medium grained, thick-bedded quartzarenite (Ostrom et al., 1970). The groundwater discharging from this well has lower nitrate, chloride, and sodium concentrations than those detected for Group II; however, the concentrations are higher than those detected for Group III. The water discharging from WDNR #9 may be a mixture of these two groups of waters.

#### 2. Cluster Analysis

The two-way tree diagram, or dendrogram, that was generated by the cluster analysis is shown in Figure 4. The linkage distances shown on the tree diagram are arbitrary Euclidian distances that represent the relative similarity between the clusters of sampling locations and analytes. The cluster analysis resulted in four monitoring point clusters with linkage distances of less than 7. By also clustering analytes, the characteristics of each of the four monitoring point clusters are more easily identified. The monitoring point clusters are labeled A, B, C, and D on Figure 4, which also shows the characteristics of each cluster in terms of mean standardized analyte concentrations. Table 3 summarizes the characteristics of each monitoring point cluster.

#### i. Cluster A

Cluster A is composed of monitoring wells MW2A, MW2B, MW5A, and MW3B and is characterized by nitrate, calcium, and magnesium concentrations that tend to be greater than the mean. All of the wells are screened in till. MW2A and MW2B are located in a recharge area, MW5A is located in a discharge area, and MW3B is located in an area where vertical gradients fluctuate depending on the season and individual storm events. Of the four wells in Cluster A, MW2A and MW2B are members of Group 1, discussed earlier. MW5A belongs to Group 2 and MW3B was considered an exception, with characteristics of both Groups 1 and 2.

#### ii. Cluster B

Cluster B comprises the majority of the monitoring points and three major springs, the big spring, the nursery spring and the Syene Road spring. Analyte concentrations tend to be within one standard deviation of the mean. Only potassium and alkalinity are consistently less than the mean, while nitrate is greater than the mean. All of the monitoring points in Cluster B are members of Group 2, discussed above.

#### iii. Cluster C

Cluster C groups MW7A, MW7B, and P-1 together. Within this cluster, chloride, calcium, magnesium, conductivity, total dissolved solids, sulfate, and nitrate are all less than the mean minus one standard deviation. Potassium and sodium are also less than the mean, but are within one standard deviation of the mean. MW7A, MW7B, and P-1 were all members of Group 3, discussed above.

#### iv. Cluster D

Cluster D consists of MW3A, WDNR#9, and the peat spring. In general, analyte concentrations are less than the mean; however fewer distinctive characteristics are apparent. MW3A and the peat spring are both members of Group I, and WDNR#9 was considered an exception. A distinguishing characteristic of Group I is the variability of nitrate, chloride, potassium, and sodium concentrations. As previously mentioned, the mean was chosen as the representative summary statistic for each analyte at each monitoring point. Therefore, the cluster analysis does not consider within-group variation in analyte concentration at each sample location. On average the analyte concentrations may be somewhat higher at these locations; however, the variability in analyte concentrations is thought to be a more distinguishing characteristic of the geochemical results. In addition, MW3A is a shallow water table well screened in till whereas WDNR#9 is a flowing well open to sandstone bedrock, and is approximately 52 meters deep. For these reasons, we believe that Cluster D is an artifact of the cluster analysis method, but that it cannot be justified hydrogeologically.

#### 3. Tritium and Helium 3 Results

The apparent ages calculated by the 3H/3He method are shown in Table 4. Seven of the ages were calculated using equation (1), because the samples were supersaturated with respect to atmospheric nitrogen and helium. The age for the nursery spring was calculated using equation (2) because the sample was undersaturated with respect to atmospheric nitrogen and helium. Ages could not be calculated for MW7A and MW7B because very little or no tritium was present in the samples.

The shortest residence times were calculated for the nursery spring (1.5 years), MW3A (3.3 years) and the peat spring (8.5 years). However, we believe that the age

calculated for the nursery spring is probably unreliable. The high level of  $CO_2$  detected in the sample in association with its undersaturation with respect to atmospheric nitrogen and helium suggest that gas stripping probably occurred. The spring pool at the nursery spring is shallow (<0.3m), and the points of discharge are relatively small. Therefore, it is likely that the sample that was collected is not representative of water discharging directly from the spring.

MW3A is a water table well that is located in a recharge area and is screened in till. Both MW3A and the peat spring are members of Group I, which we concluded are representative of groundwater that travels along short flow paths, has short residence times, and is part of a local flow system. The 3H/3He ages support these conclusions. The residence time associated with the peat spring is higher because it is a point of discharge whereas MW3A is in a recharge area.

Residence times for MW3B, MW4B, MW5A, MW5B, the big spring, and the nursery spring range from 9.8 to 14.5 years. With the exception of MW3B, all of these monitoring points are members of Group II, and all of the monitoring points except for MW3B and MW5A are members of Cluster B. We concluded that Group II is representative of an intermediate flow system, and the 3H/3He ages suggest that groundwater ages for these monitoring points are indeed greater than those for MW3A and the peat spring.

Very little or no tritium was detected in the samples collected from MW7A and MW7B. These wells are members of Group III and Cluster C, which are considered to be representative of regional groundwater with long flow paths and residence times. The apparent groundwater ages support this conclusion. It is likely that the groundwater at these

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monitoring points represent water that entered the system prior to, or only shortly after, the initiation of nuclear weapons testing in the 1950's and 1960's.

## V. Conclusions

We believe that our conceptual model of the monitoring points in Group I being representative of locally-derived water with short flow paths and residence times is valid. The monitoring wells in Group I are mostly shallow wells located in recharge areas. The variability in analyte concentrations was a important factor in grouping the sampling locations in Group I together. Because the cluster analysis was based on mean analyte concentrations, it was unable to capture this within-group variability. While Cluster A contains some of the monitoring points in Group I, it did not identify MW3A and the peat spring, which on the basis of the 3H/3He ages represent young water.

The majority of the sampling points and springs were grouped and linked together in Group II and Cluster B. The high, but consistent concentrations of nitrate and chloride suggest flow paths that are longer than those for Group I because the temporal variability in analyte concentrations is not apparent. 3H/3He ages support this conclusion, as ages range from approximately 10 to 15 years.

Group III and Cluster C contain monitoring wells MW7A, MW7B, and P-1. We conclude that these monitoring points are representative of more regional groundwater with longer residence times, or groundwater that has traveled along longer flow paths. The apparent lack of tritium in the samples collected from MW7A and MW7B supports these conclusions.

Relatively short groundwater residence times (<15 years) and the apparent lack of significant regional groundwater input to the springs suggest that the springs are particularly

vulnerable to reduced discharges caused by the reduction in groundwater recharge that is expected to accompany urbanization. As seen in the elevated nitrate and chloride concentrations, spring water quality has already been compromised due to past agricultural practices and maintenance of roads. Further development is likely to exacerbate water quality degradation, thereby hampering wetland restoration and preservation efforts.

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Well Identification	Well Depth (meters)	Approximate Ground Surface Elevation (meters amsl)	Screened or Open	Screened or Open Interval (meters)	Minimum and Maximum Elevation of Open Interval (meters amsl)	Inferred Geologic Unit at Screened or Open Interval
P-1	65	262-265	screened	1	197-201	Horicon Fm.
P-2	44	265-268	open	8	221-232	Tunnel City
						Fm.
P-3	42	268-271	open	10	226-226	Tunnel City
						Fm.
P-4	31	274-277	open	11	244-258	Jordan Fm.
P-5	75	308-311	open	13	233-249	Jordan Fm.
WDNR#9	52	259-265	open	11	207-224	Wonewoc and
						Tunnel City
						Fm.s

Table 1. Summary of privately-owned wells

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Group	1	2	3	Exceptions
Monitoring	MW2A,	MW4B, MW1C, MW5A,	MW7A, MW7B, P-1	P-2,
Points	MW2B,	MW5B, MW6A, MW6B,		WDNR#9,
	MW3A, peat	P-3, P-4, P-5, big spring,		MW3B
	spring	nursery spring, Syene		
		Road spring		
Characteristics	• Variable	•Elevated, but consistent	•Low and consistent	
	NO <sub>3</sub> -and Cl-	NO <sub>3</sub> -	$NO_3$ -, $SO_42$ -, and	
	•Low and	•High and consistent Cl-	Na+	
	somewhat	•High and consistent Na+	•Low Cl-	
	variable Na+		•Low TDS and	
			conductivity	

Table 2. Characteristics of geochemical groups based on the use of summary statistics

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Cluster		В	С	D
Monitoring Points	MW2A,	MW4B, MW1C,	MW7A,	P-2, WDNR#9,
	MW2B,	MW5B, MW6A,	MW7B, P-1	MW3A, peat
	MW5A, MW3B	MW6B, P-3, P-4, P-5,		spring
		big spring, nursery		
		spring, Syene Road		
		spring		
Characteristics	• NO <sub>3</sub> -, SO <sub>4</sub> 2-,	• Alkalinity and K+ are	• NO <sub>3</sub> -, Cl-,	• Na+, Cl-,
	Ca2+, Mg2+,	slightly less than the	Ca2+, Mg2+,	SO <sub>4</sub> 2-, K+,
	conductivity,	mean	SO₄2-,	and alkalinity
	and total	• Most other analytes	conductivity,	are slightly
	dissolved	are close to the mean	and total	less than the
	solids are		dissolved	mean
	greater than		solids are less	
	the mean		than the mean	
			• Na+ and K+	
			are slightly	
			less than the	
			mean	

Table 3. Characteristics of monitoring point clusters

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Table 4

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Location	Tritium samples			4He	3He	R <sub>t=0</sub>	3He*	t <sub>3H/3He</sub>	N2	CO2	
	TU	+	-	sample date	(cc/kg)	(TU)		(TU)	(years)	cc/kg	cc/kg
MW3A	8.54	0.43	0.43	8/20/99 16:00	6.64E-05	3.93E+01	1.47E-06	1.75E+00	3.3	21.27	0.0248
MW3B	10.29	0.51	0.51	8/20/99 15:30	5.83E-05	4.71E+01	2.00E-06	1.17E+01	13.4	18.15	0.0439
MW4B	12.90	0.65	0.65	8/20/99 14:20	6.25E-05	4.78E+01	1.89E-06	9.66E+00	9.8	20.90	0.0189
MW5A	12.78	0.64	0.64	8/21/99 13:00	7.16E-05	6.51E+01	2.26E-06	1.64E+01	14.5	22.82	0.1009
MW5B	10.42	0.52	0.52	8/21/99 12:30	6.59E-05	5.24E+01	1.98E-06	1.12E+01	12.8	21.58	0.0107
MW7A	1.02	0.06	0.13	8/21/99 11:00	NA	NA	NA	NA	NA	NA	NA
MW7B	0.00	0.14	0.27	8/21/99 11:15	6.46E-05	2.60E+07	NA	NA	NA	20.38	0.0075
big spring	10.99	0.55	0.55	8/19/99 14:30	6.01E-05	4.56E+01	1.88E-06	9.36E+00	10.7	18.85	0.0206
north spring	9.99	0.50	0.50	8/19/99 11:30	6.74E-05	5.53E+01	2.04E-06	1.23E+01	14.1	13.92	0.0392
nursery spring	11.60	0.58	0.58	8/19/99 17:00	2.72E-05	1.61E+01	1.46E-06	1.05E+00	1.5	13.01	1.0656
peat spring	11.42	0.57	0.57	8/19/99 16:00	9.75E-05	6.92E+01	1.76E-06	7.14E+00	8.5	32.01	0.0144

Table 4. Results of 3H, He, CO2, and N2 analyses and calculation of 3H/3He ages

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NA = not available

Equation (2) was used to calculate ages for MW3A, MW3B, MW4B, MW5A, MW5B, big spring, north spring, and peat spring. Equation (2) was used to calculate ages for the nursery spring.

Figure 1. The Nine Springs watershed, Dane County, Wisconsin

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Figure 2. Location of the field sites and sampling locations within the Nine Springs watershed.

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Figure 3. Piper diagram showing the results of the March 1999 groundwater sampling event. All waters sampled are a calcium-magnesium-bicarbonate type.



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Figure 4. Dendrogram resulting from the two-way cluster analysis.

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