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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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TABLE OF CONTENTS

Figures

Tables

Appendices

I. INTRODUCTION

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

- 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

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 air-rotary 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

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.

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

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 high-hydraulic 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 high-hydraulic 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

The geochemistry results are summarized in a paper recently submitted for publication in the journal Chemical Geology. 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

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

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

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^{-1}; and layer 4 is assigned a specific storage term of 2.8e-04 ft^{-1}.

E. Calibration

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

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

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

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

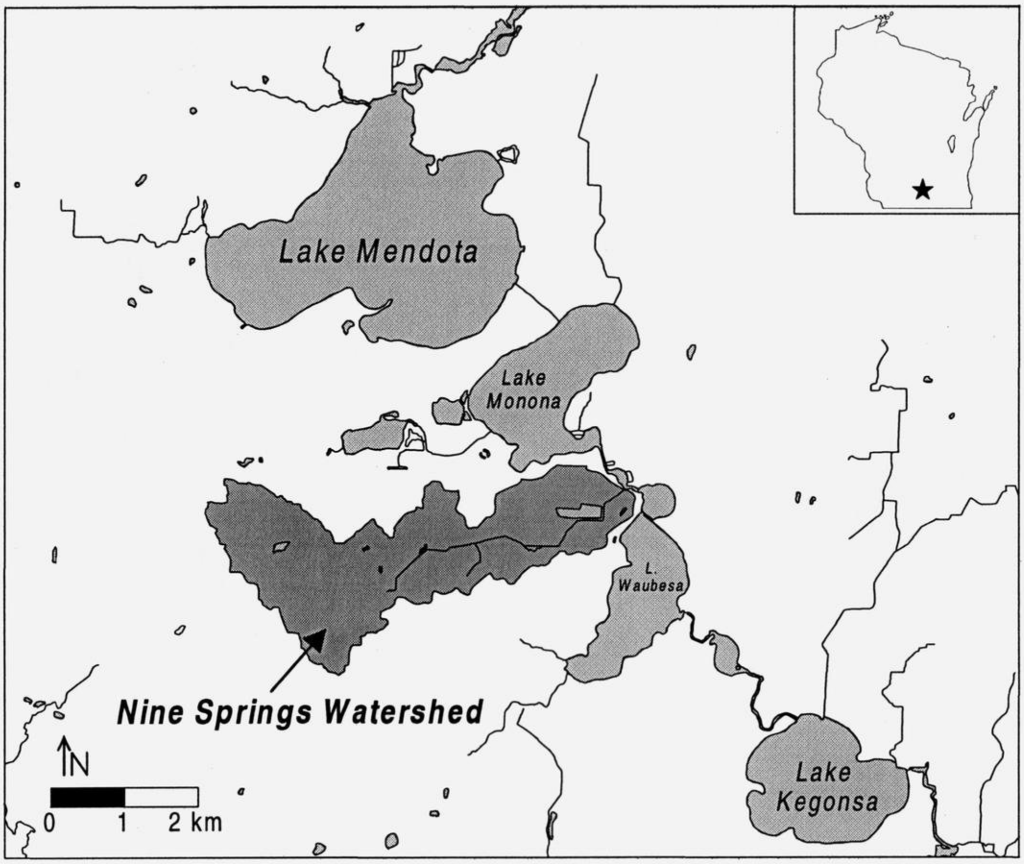


Figure 1. Nine Springs watershed

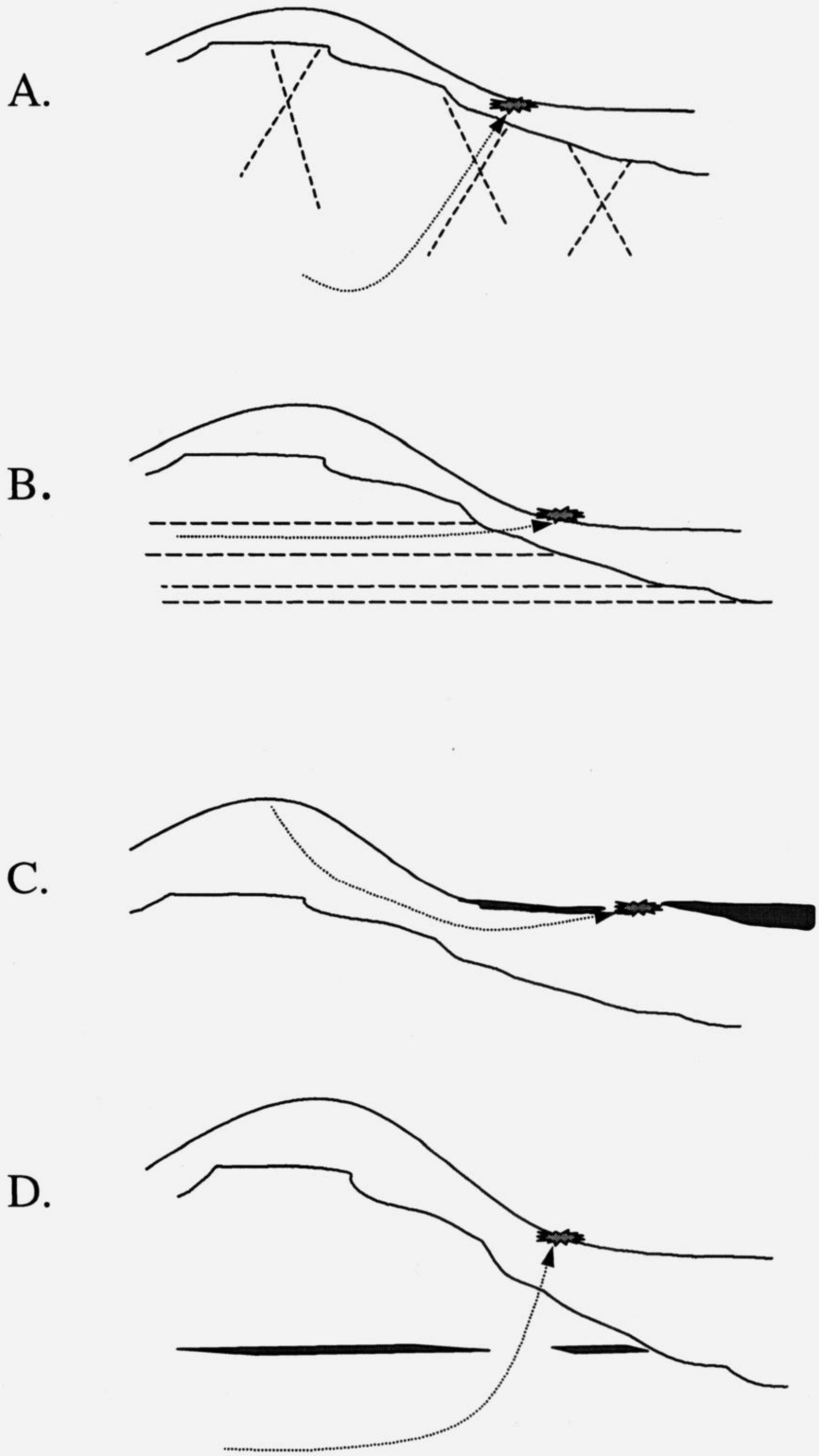
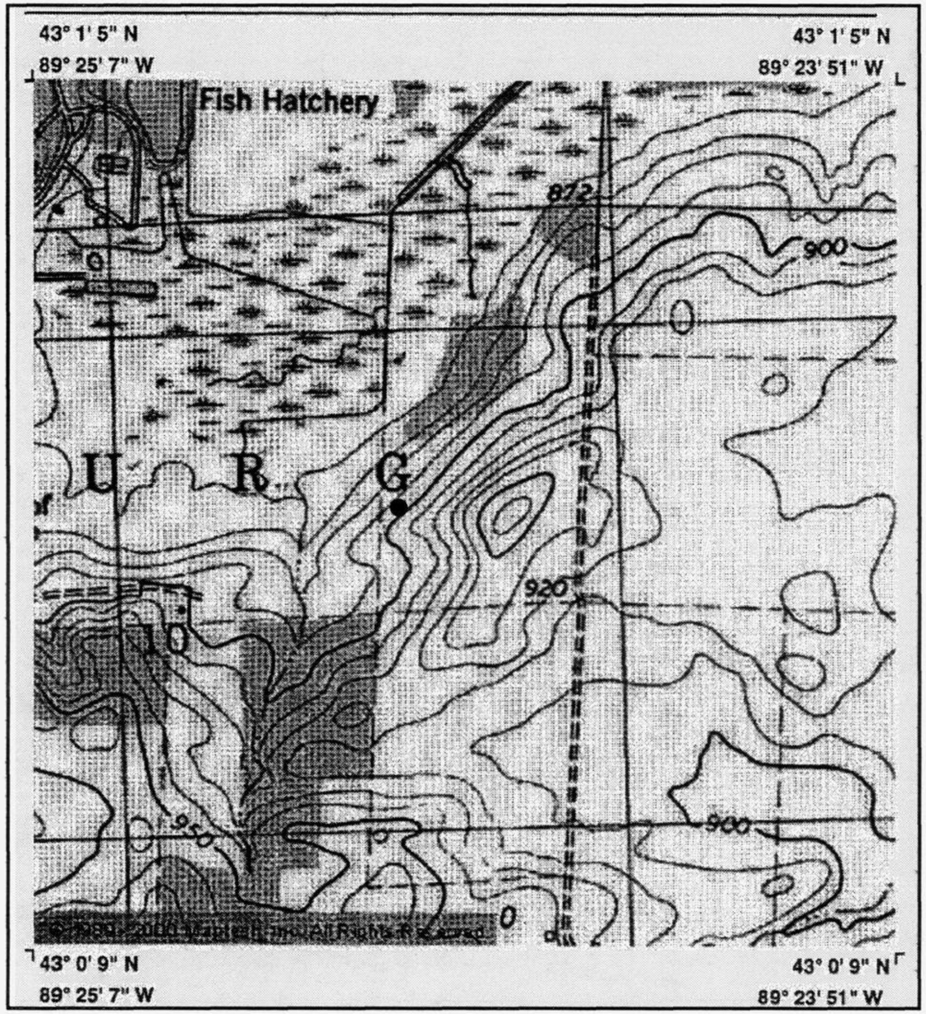


Figure 2. Conceptual models of springs



● Approximate location of Mt. Simon and Upper Paleozoic wells

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. btoc
Casing: 82 ft. bgs

Well: DN1441
Sue Swanson Deep Mt Simon well

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

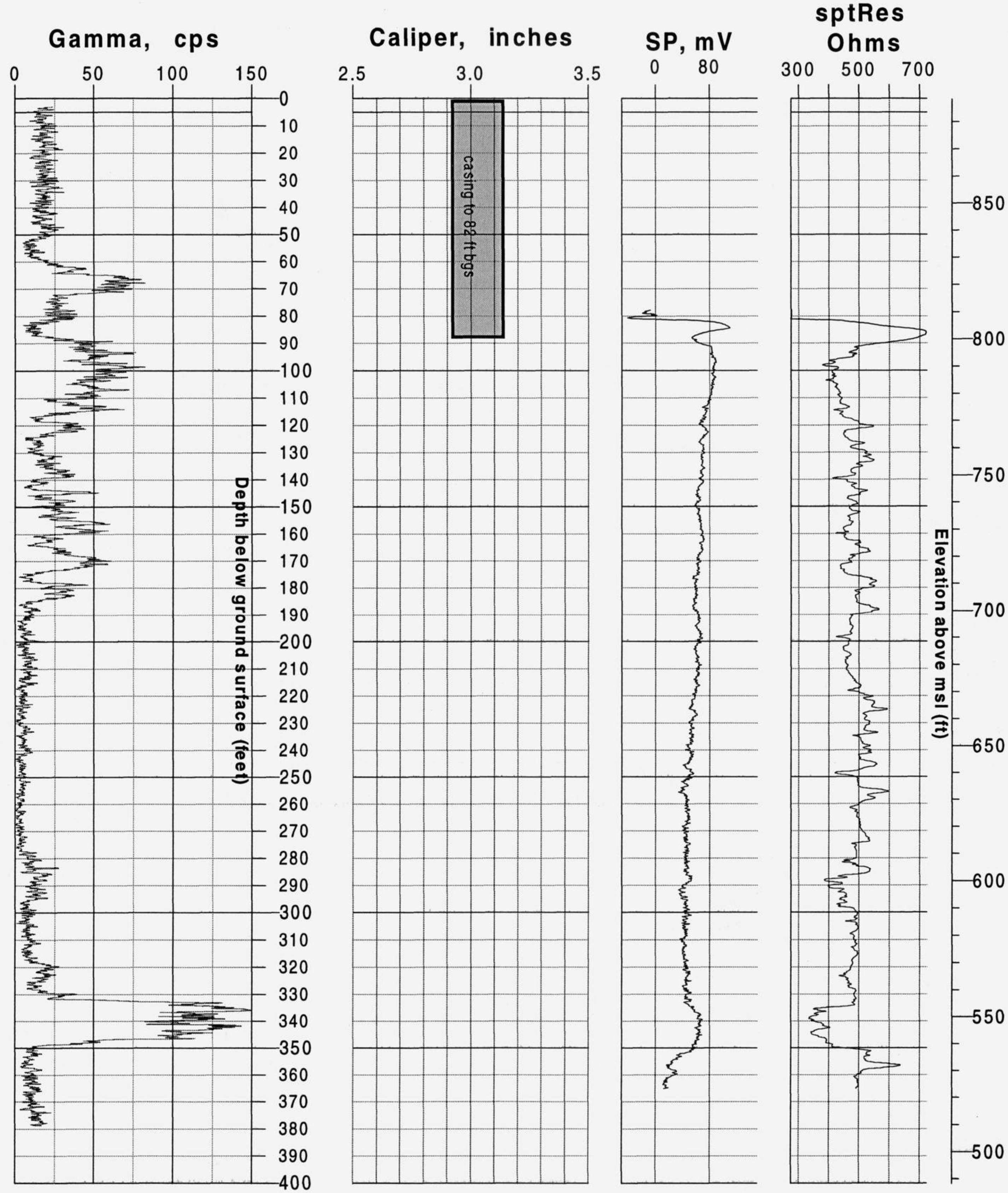


Figure 4. Geophysical logs for the Mt. Simon well

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

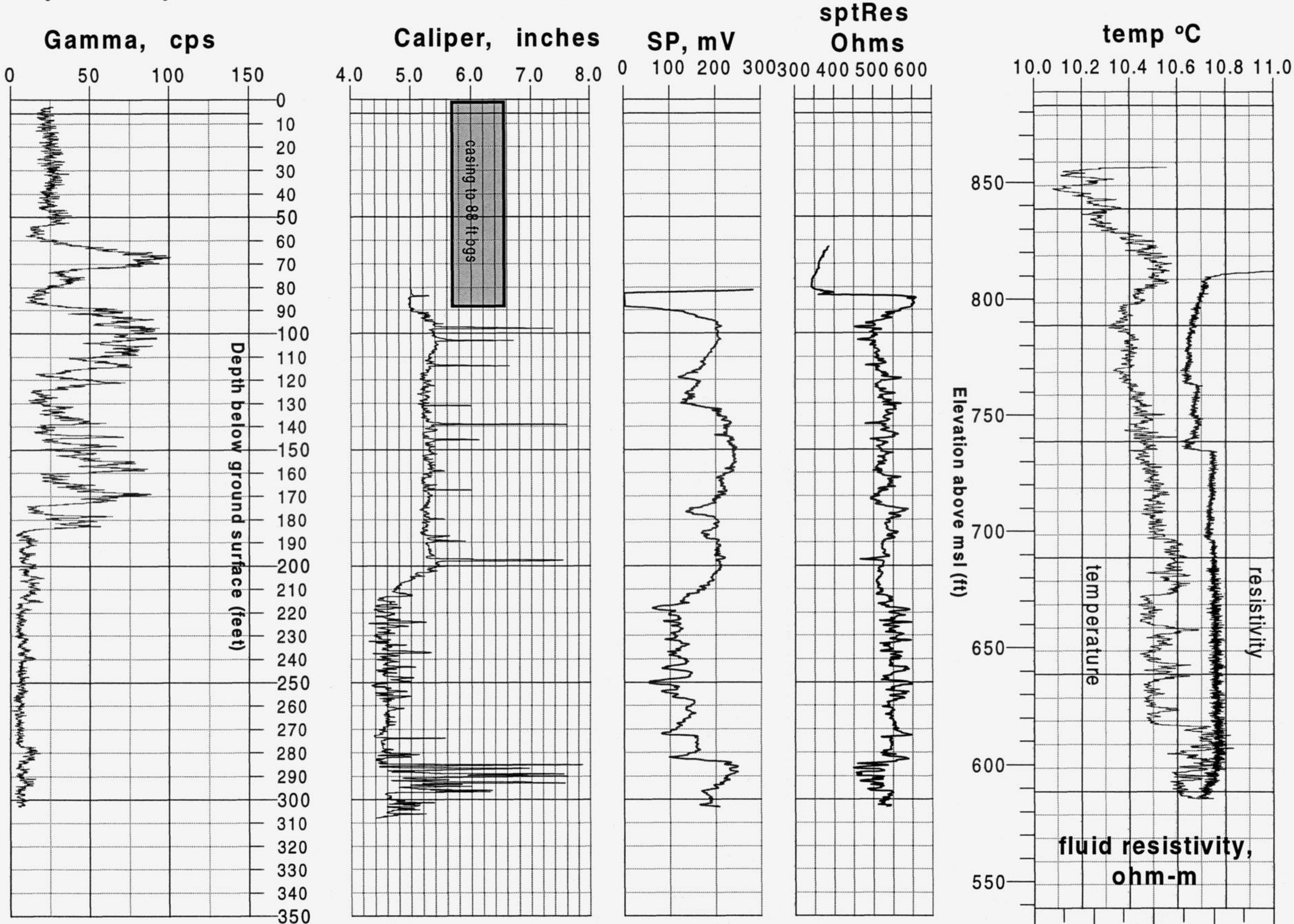


Figure 5. Geophysical logs for the Upper Paleozoic well

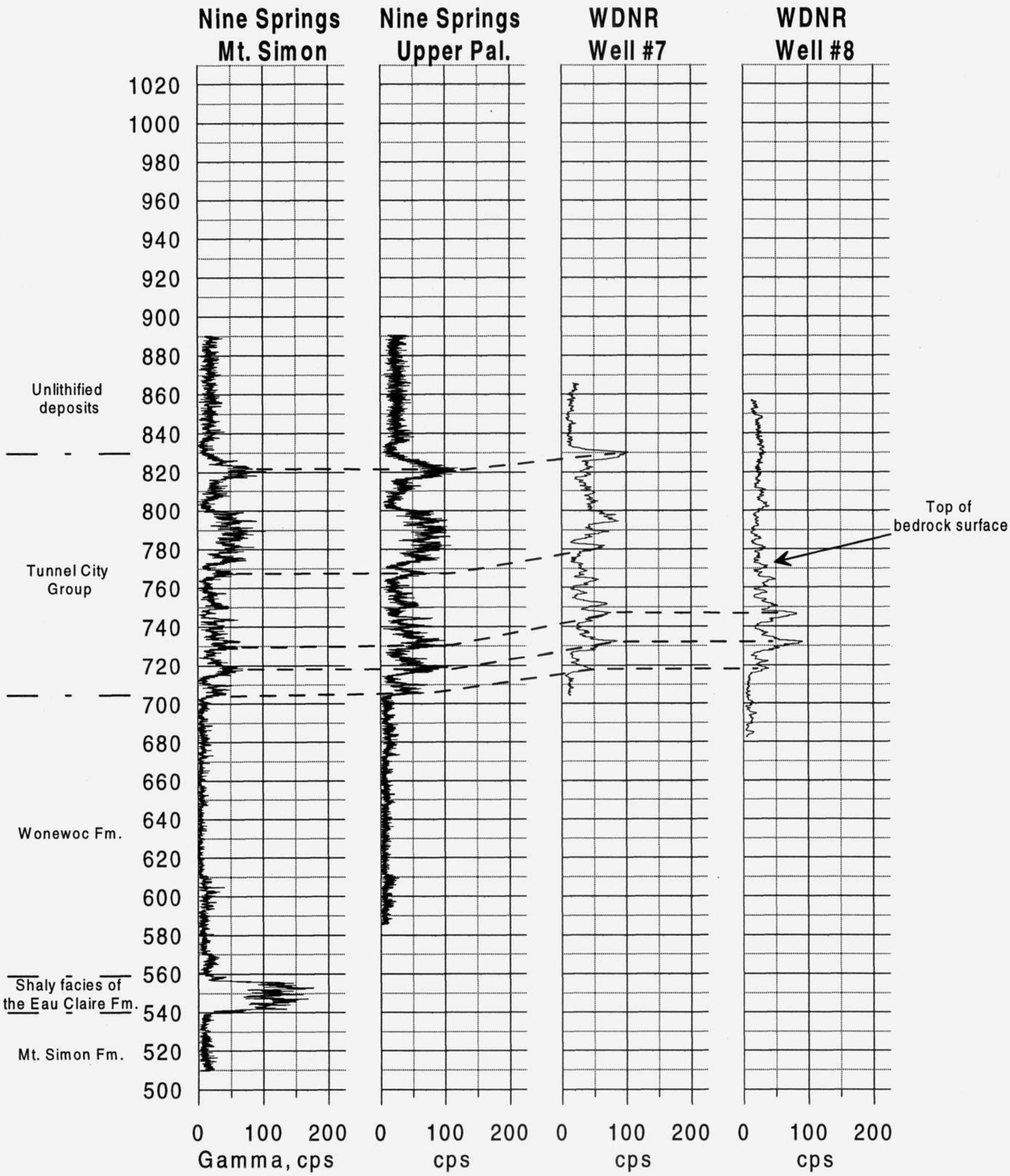


Figure 6. Natural gamma logs for the Mt. Simon well, the Upper Paleozoic well, WDNR#7, and WDNR#8

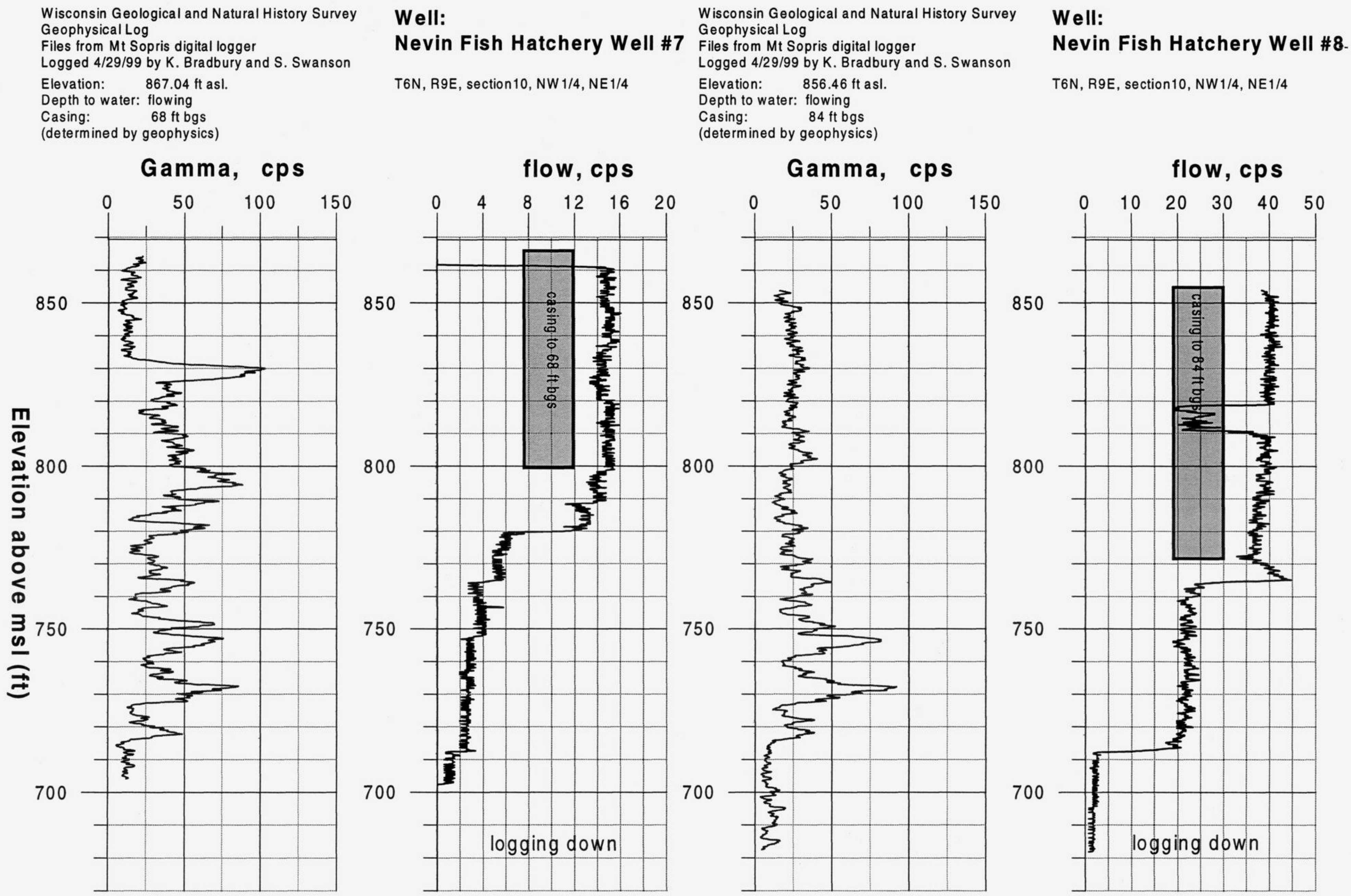


Figure 7. Natural gamma and flow logs for WDNR#7 and WDNR#8

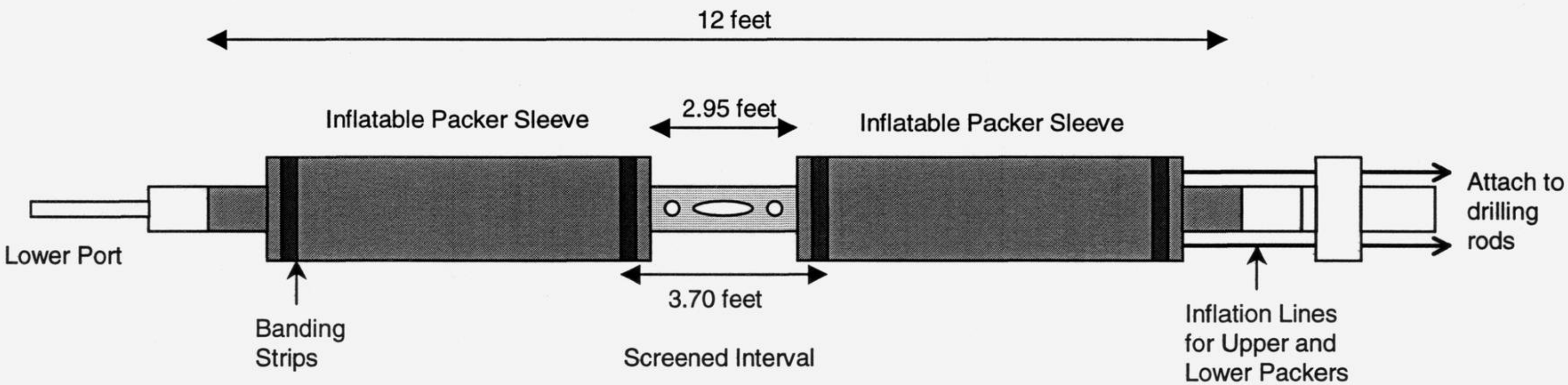
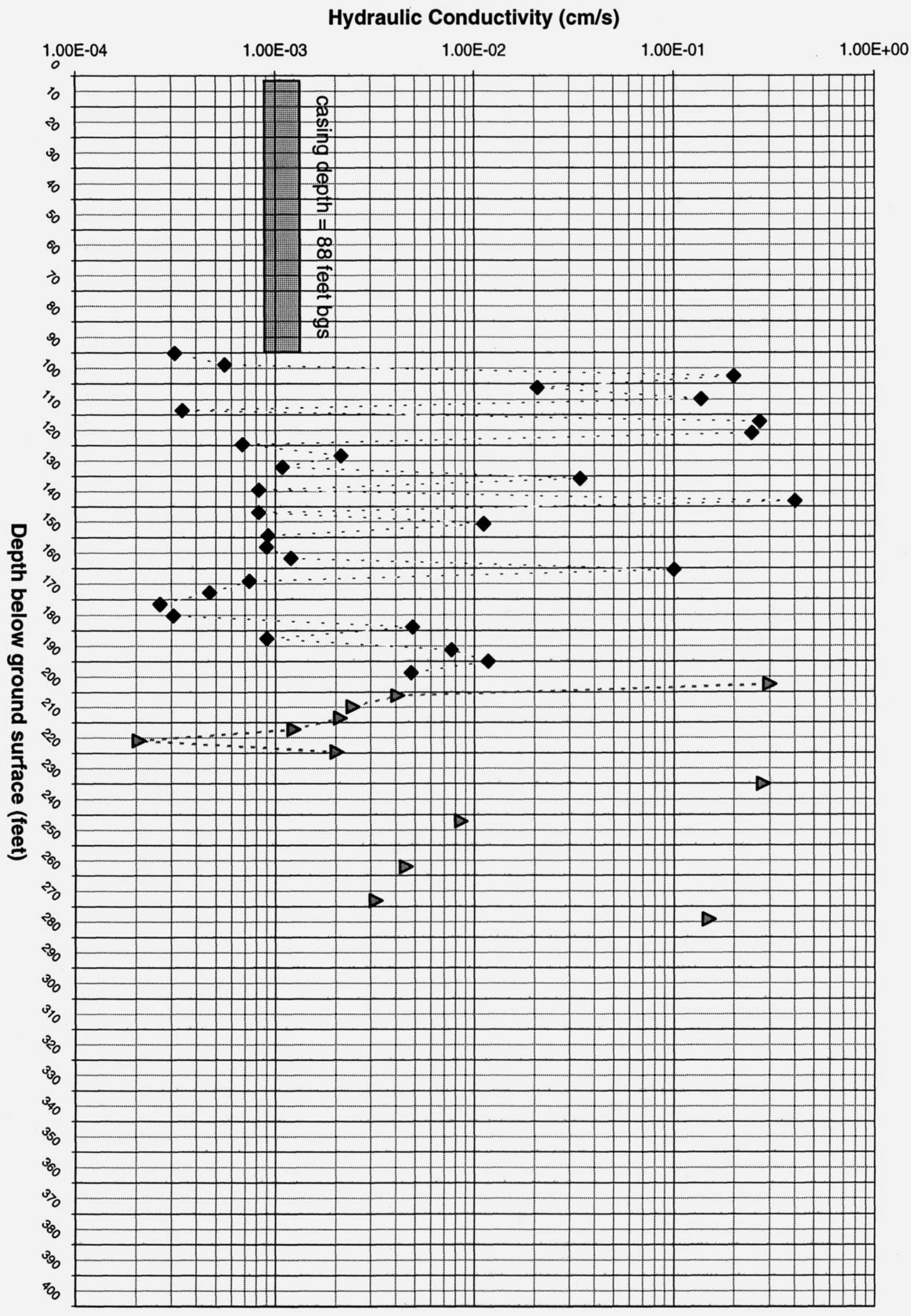


Figure 8. Straddle-packer assemblage

Figure 9. Slug test results



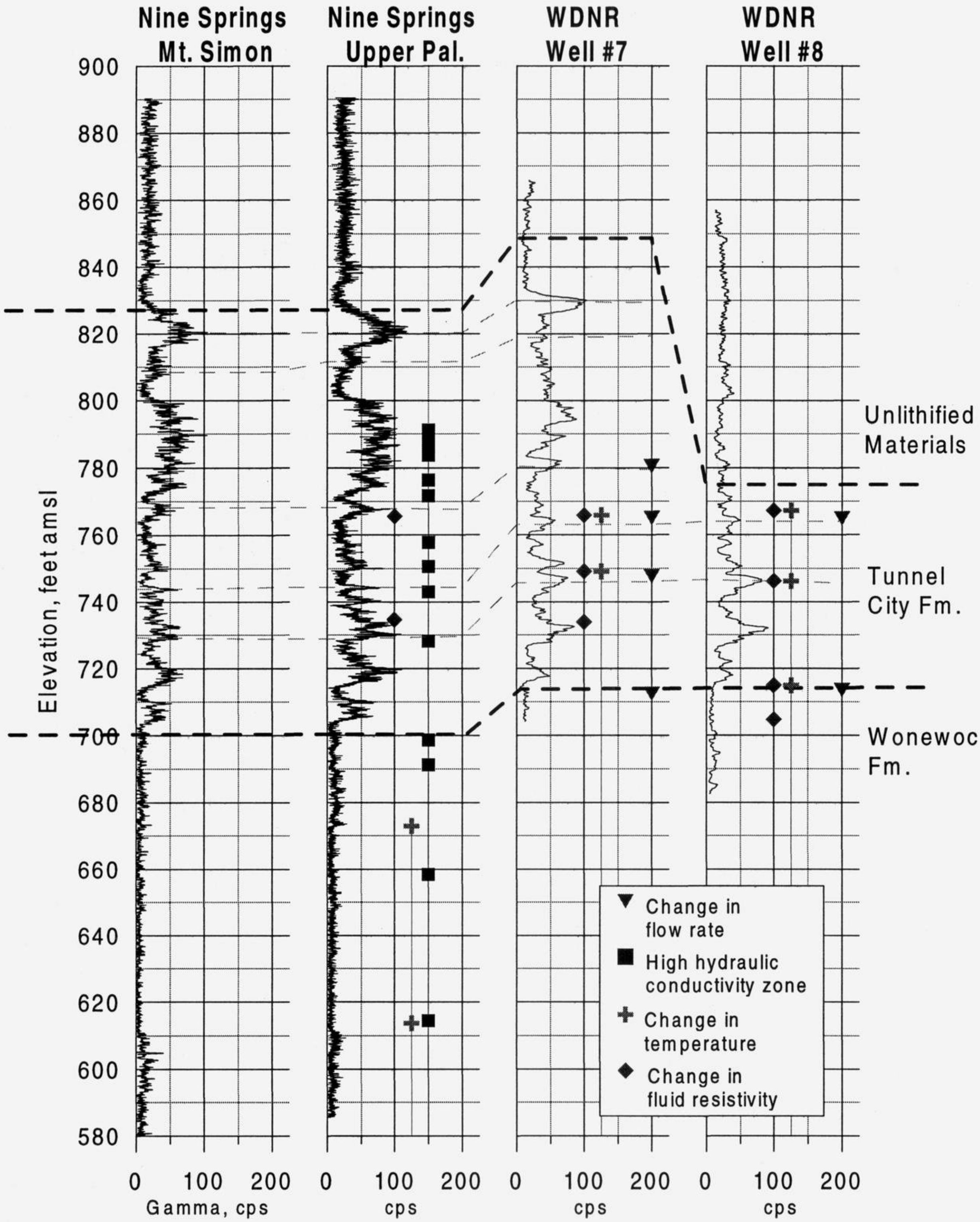


Figure 10. Correlation of geophysical logs and hydraulic conductivity data for the Mt. Simon well, the Upper Paleozoic well, WDNR#7, and WDNR#8

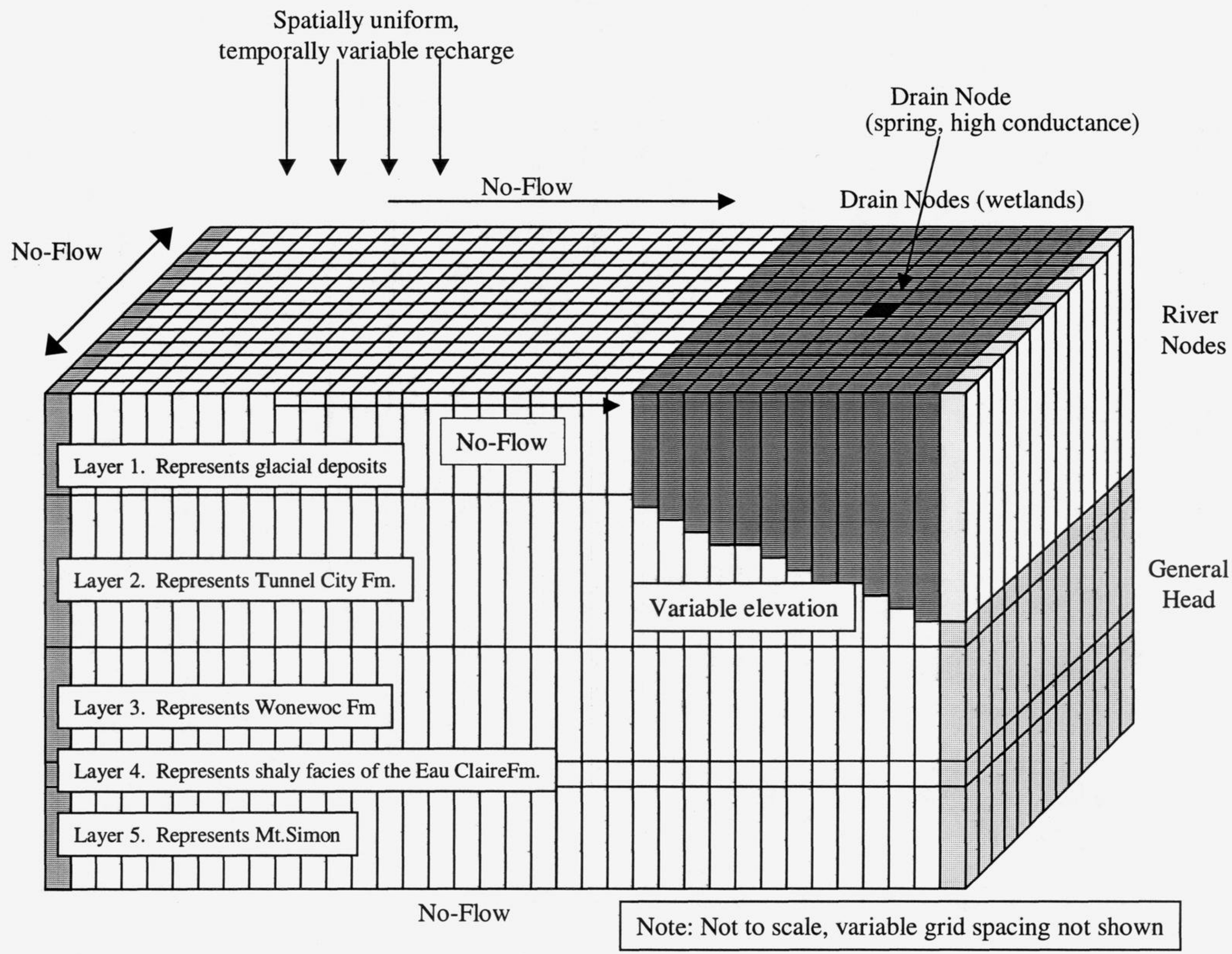


Figure 11. Generic model grid

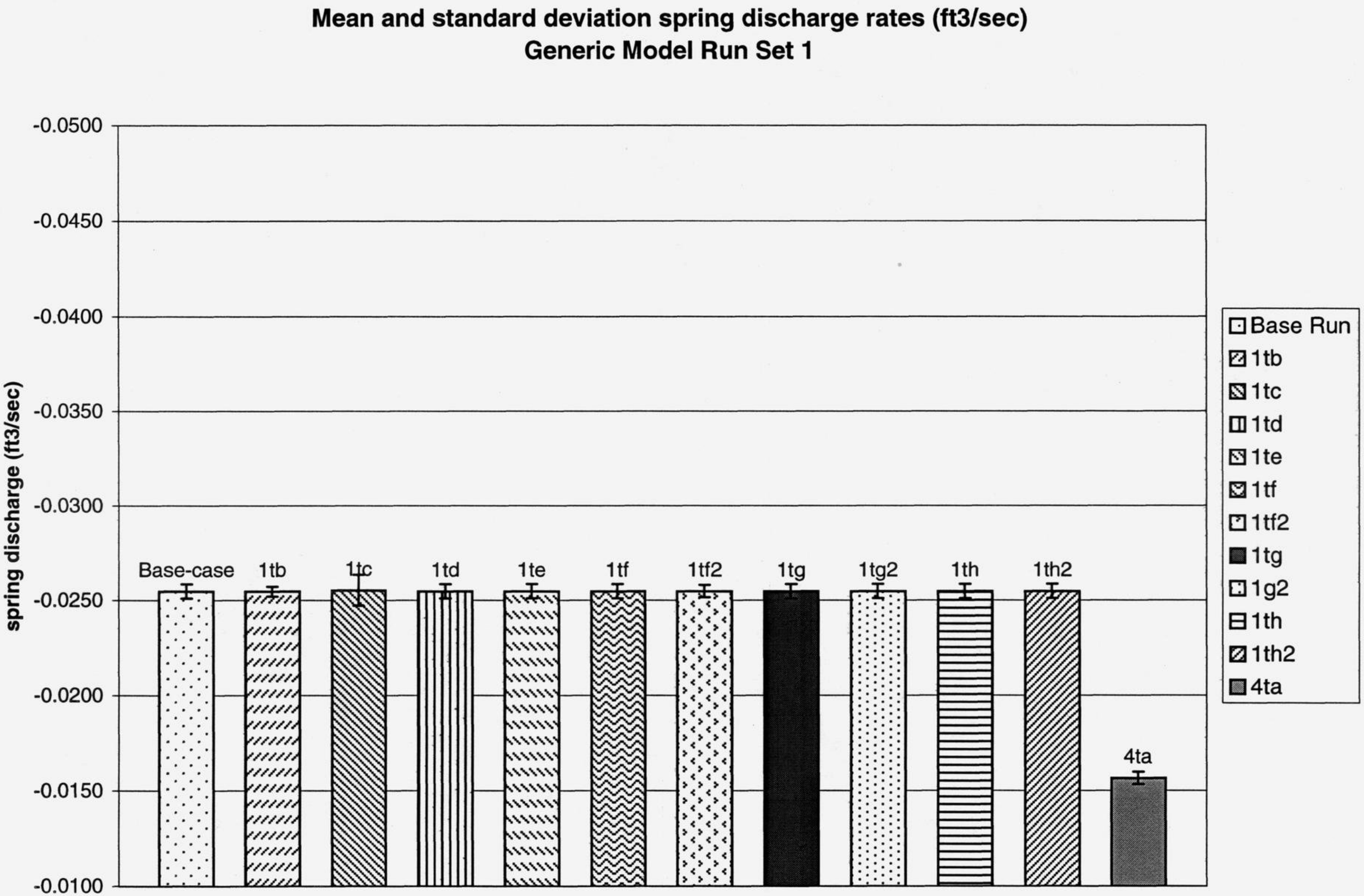


Figure 12. Spring flow and variation, set 1

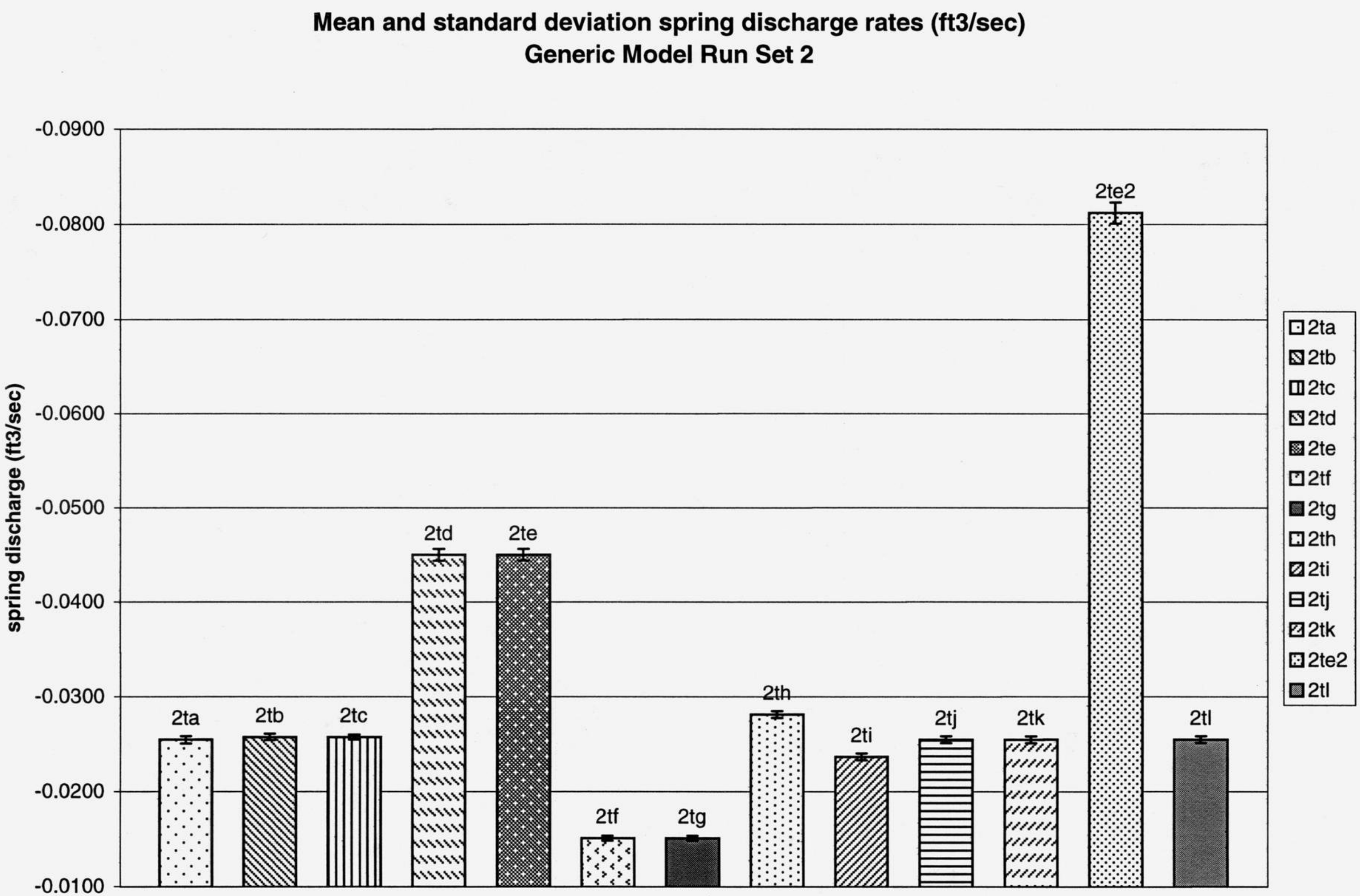


Figure 13. Spring flow ans variation, set 2

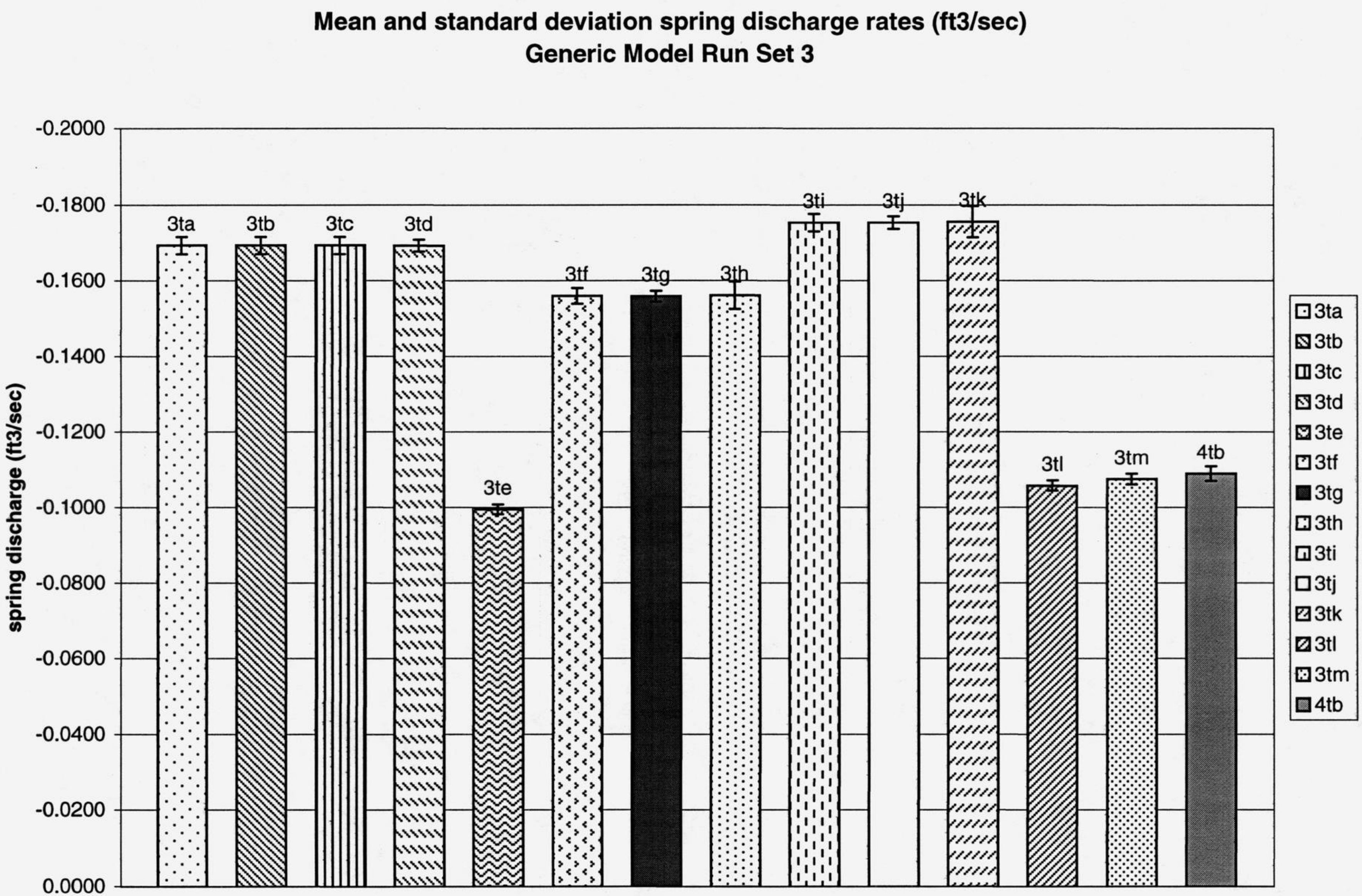


Figure 14. Spring flow and variation, set 3

TABLES

Table 1. Summary of set 1 and 2 simulations

Simulation number		Description	Number of layers	Input																			
				Layer 1				Layer 2					Layer 3				Layer 4			Layer 5			
				K (ft/day)				K (ft/day)					K (ft/day)				K (ft/day)			K (ft/day)			
				1.53	15.30	0.153	S_y	5	10	20	2.5	S_s	10	15	5	S_s	3.0E-07	3.0E-06	S_s	10	15	5	S_s
1	base	base run:layer 1 two isotropic zones, layers 2-5 homogeneous and isotropic	5	x			0.2	x				2.10E-05	x			2.10E-05	x		2.80E-04	x			2.10E-05
	b	vary storage, L1(increase)		x			0.3	x				2.10E-05	x			2.10E-05	x		2.80E-04	x			2.10E-05
	c	vary storage, L1 (decrease)		x			0.07	x				2.10E-05	x			2.10E-05	x		2.80E-04	x			2.10E-05
	d	vary storage, L2 (decrease)		x			0.2	x				1.05E-05	x			2.10E-05	x		2.80E-04	x			2.10E-05
	e	vary storage, L2 (increase)		x			0.2	x				3.15E-05	x			2.10E-05	x		2.80E-04	x			2.10E-05
	f	vary storage, L3 (decrease)		x			0.2	x				2.10E-05	x			2.10E-06	x		2.80E-04	x			2.10E-05
vary storage	f2	vary storage, L3 (increase)		x			0.2	x				2.10E-05	x			2.10E-04	x		2.80E-04	x			2.10E-05
	g	vary storage, L4 (decrease)		x			0.2	x				2.10E-05	x			2.10E-05	x		2.80E-05	x			2.10E-05
	g2	vary storage, L4 (increase)		x			0.2	x				2.10E-05	x			2.10E-05	x		2.80E-03	x			2.10E-05
	h	vary storage, L5 (decrease)		x			0.2	x				2.10E-05	x			2.10E-05	x		2.80E-04	x			2.10E-06
	h2	vary storage, L5 (increase)		x			0.2	x				2.10E-05	x			2.10E-05	x		2.80E-04	x			2.10E-04
2	a	increase K, L1	5		x		0.2	x				2.10E-05	x			2.10E-05	x		2.80E-04	x			2.10E-05
	b	decrease K, L1				x	0.2	x				2.10E-05	x			2.10E-05	x		2.80E-04	x			2.10E-05
	c	decrease K and increase storage L1				x	0.3	x				2.10E-05	x			2.10E-05	x		2.80E-04	x			2.10E-05
	d	increase K, L2		x			0.2		x			2.10E-05	x			2.10E-05	x		2.80E-04	x			2.10E-05
	e	increase K and increase storage L2		x			0.2		x			3.15E-05	x			2.10E-05	x		2.80E-04	x			2.10E-05
	e2	increase K, L2		x			0.2			x		2.10E-05	x			2.10E-05	x		2.80E-04	x			2.10E-05
vary conductivity	f	decrease K, L2		x			0.2				x	2.10E-05	x			2.10E-05	x		2.80E-04	x			2.10E-05
	g	decrease K and increase storage L2		x			0.2				x	3.15E-05	x			2.10E-05	x		2.80E-04	x			2.10E-05
	h	decrease K, L3		x			0.2	x				2.10E-05			x	2.10E-05	x		2.80E-04	x			2.10E-05
	i	increase K, L3		x			0.2	x				2.10E-05		x		2.10E-05	x		2.80E-04	x			2.10E-05
	l	increase K, L4		x			0.2	x				2.10E-05	x			2.10E-05		x	2.80E-04	x			2.10E-05
	j	increase K, L5		x			0.2	x				2.10E-05	x			2.10E-05	x		2.80E-04		x		2.10E-05
	k	decrease K, L5		x			0.2	x				2.10E-05	x			2.10E-05	x		2.80E-04			x	2.10E-05

Table 2. Summary of set 3 simulations

Simulation number		Description	Number of layers	Input: Layer 1 K (ft/day) 1.53	Layer 1 K (ft/day) 15.30	Layer 1 K (ft/day) 0.153	Layer 1 S_y	Layer 2 K (ft/day) 5	Layer 2 K (ft/day) 10	Layer 2 K (ft/day) 2.5	Layer 2 S_s	Layer 3 {Layers 3 and 5 of 9 layer model} K (ft/day) 28	Layer 3 K (ft/day) 10	Layer 3 S_s	Layer 4 {Layers 4 and 6 of 9 layer model} K (ft/day) 5	Layer 4 K (ft/day) 10	Layer 4 K (ft/day) 2.5	Layer 4 S_s	Layer 5 {Layers 5 and 7 of 9 layer model} K (ft/day) 10	Layer 5 K (ft/day) 5	Layer 5 K (ft/day) 15	Layer 5 S_s	Layer 6 {Layer 8 of 9 layer model} K 3.0E-07	Layer 6 S_s	Layer 7 {Layer 9 of 9 layer model} K (ft/day) 10	Layer 7 K (ft/day) 5	Layer 7 S_s
3	a	add 5-foot high K layer, Layer 3	7	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
add high K layer	b	3a, vary storage of high K layer (increase)		x			0.2	x			2.10E-05	x		3.15E-05	x			2.10E-05	x			2.10E-05	x	2.80E-04	x		2.10E-05
	c	3a, vary storage of layers 2 and 4 (increase)		x			0.2	x			3.15E-05	x		2.10E-05	x			3.15E-05	x			2.10E-05	x	2.80E-04	x		2.10E-05
	d	3a, vary specific yield of layer 1 (increase)		x			0.3	x			2.10E-05	x		2.10E-05	x			2.10E-05	x			2.10E-05	x	2.80E-04	x		2.10E-05
	e	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
	f	use 3-foot high K layer, Layer 3		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
	g	3f, vary specific yield of layer 1 (increase)		x			0.3	x			2.10E-05	x		2.10E-05	x			2.10E-05	x			2.10E-05	x	2.80E-04	x		2.10E-05
	h	3f, vary specific yield of layer 1 (decrease)		x			0.1	x			2.10E-05	x		2.10E-05	x			2.10E-05	x			2.10E-05	x	2.80E-04	x		2.10E-05
	l	add anisotropy to high K layer in model 3a, Kx=Ky=28, Kz=5		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
add high K layers	i	use two 3-foot high K layers, Layers 3 and 5	9	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
	j	3i, vary specific yield of layer 1 (increase)		x			0.3	x			2.10E-05	x		2.10E-05	x			2.10E-05	x			2.10E-05	x	2.80E-04	x		2.10E-05
	k	3i, vary specific yield of layer 1 (decrease)		x			0.1	x			2.10E-05	x		2.10E-05	x			2.10E-05	x			2.10E-05	x	2.80E-04	x		2.10E-05
	m	add anisotropy to high K layers in model 3i, Kx=Ky=28, Kz=5		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

Table 3. Summary of set 4 simulations

Simulation number		**Description**	**Number of layers**	**Input**																	
				Layer 1				Layer 2				Layer 3				Layer 4			Layer 5		
				K (ft/day)				K (ft/day)				K (ft/day)				K (ft/day)			K (ft/day)		
				1.53	15.30	0.153	S_y	5	10	2.5	S_s	10	5	15	S_s	3.0E-07	10	S_s	10	5	S_s
4	a	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	b	use 3a model; window in Layer 6	7	x			0.2	(see Table 2)				x			2.10E-05	x	x	2.80E-04 & 2.10E-05	x		2.10E-05

APPENDIX A

State of Wisconsin
Department of Natural Resources

Route to: Solid Waste ☐ Haz. Waste ☐ Wastewater ☐
Env. Response & Repair ☐ Underground Tanks ☐ Other ☐ ________

MONITORING WELL CONSTRUCTION
Form 4400-113A Rev. 4-90

Facility/Project Name: 9 Springs	Local Grid Location of Well: ______ ft. ☐ N. ☐ S. ______ ft. ☐ E. ☐ W.	Well Name: Nine Springs Mt. Simon Monitoring Well
Facility License, Permit or Monitoring Number: ________	Grid Origin Location: Lat. ______ Long. ______ or	Wis. Unique Well Number: JQ702 ~~DNR Well Number~~ DN-1441 County ID
Type of Well: Water Table Observation Well ☐ 11; Piezometer ☒ 12	St. Plane ______ ft. N, ______ ft. E.	Date Well Installed: 11 / 10-12 / 99 (m m / d d / y y) (NP417)
Distance Well Is From Waste/Source Boundary: N.A. ft.	Section Location of Waste/Source: SE 1/4 of NE 1/4 of Sec. 10, T. 6 N, R. 9 ☒ E. ☐ W.	Well Installed By: (Person's Name and Firm) Water Wells, Inc. Micheal + Kevin
Is Well A Point of Enforcement Std. Application? ☐ Yes ☒ No	Location of Well Relative to Waste/Source: u ☐ Upgradient; s ☐ Sidegradient; d ☐ Downgradient; n ☐ Not Known	

A. Protective pipe, top elevation ___.__ ft. MSL
B. Well casing, top elevation 890.40 ft. MSL
C. Land surface elevation 888.40 ft. MSL
D. Surface seal, bottom ___.__ ft. MSL or ___.__ ft.

12. USCS classification of soil near screen:
GP ☐ GM ☐ GC ☐ GW ☐ SW ☐ SP ☐
SM ☐ SC ☐ ML ☐ MH ☐ CL ☐ CH ☐
Bedrock ☒ Mt. Simon Sandstone

13. Sieve analysis attached? ☐ Yes ☒ No

14. Drilling method used: Mud Rotary ☒ 50
Hollow Stem Auger ☐ 41
Air hammer Other ☒

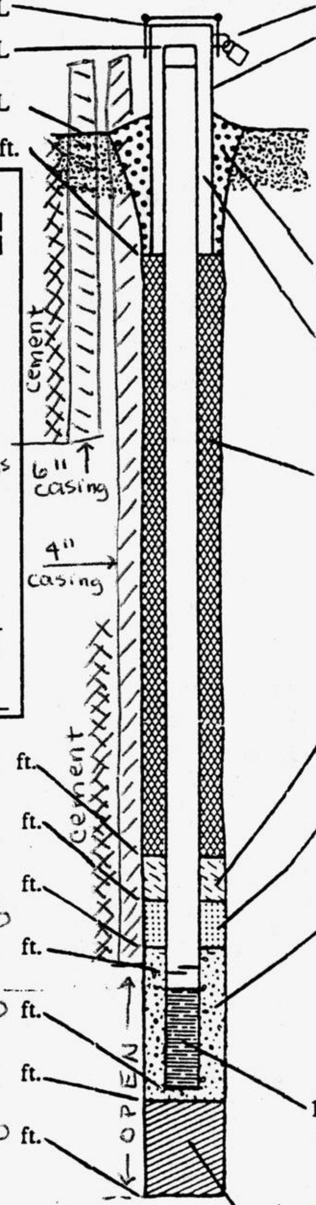
15. Drilling fluid used: Water ☒ 02 Air ☒ 01
Drilling Mud ☒ 03 None ☐ 99

16. Drilling additives used? ☐ Yes ☒ No

Describe ________

17. Source of water (attach analysis):
Potable water source

E. Bentonite seal, top ___.__ ft. MSL or 0.0 ft.
F. Fine sand, top ___.__ ft. MSL or — ft.
G. Filter pack, top ___.__ ft. MSL or — ft.
H. Casing Bottom ~~Screen joint, top~~ ___.__ ft. MSL or 365.0 ft.
I. Well bottom ___.__ ft. MSL or 385.0 ft.
J. Filter pack, bottom ___.__ ft. MSL or — ft.
K. Borehole, bottom ___.__ ft. MSL or 385.0 ft.
L. Borehole, diameter 8.75" to 82 ft. 6" to 365 ft 4" to 385 ft. ~~in.~~
M. O.D. well casing __.__ in.
N. I.D. well casing 4.00 in.



1. Cap and lock? ☒ Yes ☐ No
2. Protective cover pipe:
a. Inside diameter: 6.0 in.
b. Length: 85.0 ft.
c. Material: Steel ☒ 04; Other ☐
d. Additional protection? ☐ Yes ☒ No
If yes, describe: ________
3. Surface seal: Bentonite ☐ 30; Concrete ☒ 01; Other ☐
4. Material between well casing and protective pipe:
Bentonite ☐ 30
Bentonite-cement Annular space seal ☐
Other ☒
5. Annular space seal: a. Granular Bentonite ☐ 33
b. ____ Lbs/gal mud weight . . . Bentonite-sand slurry ☐ 35
c. ____ Lbs/gal mud weight . . . . . Bentonite slurry ☐ 31
d. ____ % Bentonite . . . . . . Bentonite-cement grout ☒ 50
e. ______ Ft^3 volume added for any of the above
f. How installed: Tremie ☐ 01; Tremie pumped ☒ 02; Gravity ☐ 08
6. Bentonite seal: a. Bentonite granules ☐ 33
b. ☐ 1/4 in. ☐ 3/8 in. ☐ 1/2 in. Bentonite pellets ☐ 32
c. Not applicable Other ☐
7. Fine sand material: Manufacturer, product name & mesh size
a. Not applicable
b. Volume added — ft^3
8. Filter pack material: Manufacturer, product name and mesh size
a. Not applicable
b. Volume added — ft^3
9. Well casing: Flush threaded PVC schedule 40 ☐ 23
ASTM 853 Grd. B Flush threaded PVC schedule 80 ☐ 24
Flush-beveled steel casing Other ☒
10. Screen material: open borehole
a. Screen type: Factory cut ☐ 11; Continuous slot ☐ 01
Not applicable Other ☐
b. Manufacturer —
c. Slot size: 0. ___ in.
d. ~~Slotted~~ length: open interval 20.0 ft.
11. Backfill material (below filter pack): None ☐ 14
Not applicable Other ☐

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm
Susan Swanson	UW - 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.

Well Construction Report For WISCONSIN UNIQUE WELL NUMBER NP 417

State of Wisconsin
Private Water Systems-DG/2
Department of Natural Resources
Box 7921
Madison, WI 53707

(Please type or print using a black pen.)

Please use decimals instead of fractions.

Property Owner	Dept. of Geology University of Wis.
Telephone Number	608 262-9467
Mailing Address	1215 W. Dayton Street
City	Madison, W
State	WI.
Zip Code	53706
County of Well Location	Dane
Co. Well Permit No.	W
Well Completion Date (mm-dd-yy)	11 - 15 - 99
Well Constructor (Business Name)	WATER WELLS INC.
License #	6
Address	6400 Lake Road
City	Windsor
State	WI
Zip Code	53598

1. Well Location [X] Town [ ] City [ ] Village of Fitchburg. Fire # (If avail.)

Grid or Street Address or Road Name and Number

Subdivision Name / Lot # / Block #

2. Mark well location with a dot in correct 40-acre parcel of section. N / S / E / W

Gov't Lot # ____ or NW 1/4 of NE 1/4 of Section 10, T 6 N; R 9 [X] E [ ] W

3. Well Type [X] New [ ] Replacement [ ] Reconstruction (see item 13 below) of previous unique well # ____ constructed in 19____

Reason for replaced or reconstructed well? monitor well

[X] Drilled [ ] Driven Point [ ] Jetted [ ] Other

4. Well serves - # of homes and or ____ (Eg: barn, restaurant, church, school, industry, etc.)

High Capacity: Well? [ ] Yes [X] No; Property? [ ] Yes [X] No

5. Is the well located upslope or sideslope and not downslope from any contamination sources, including those on neighboring properties? [X] Yes [ ] No If no, explain on back side.

Well located in floodplain? [X] Yes [ ] No

Distance in Feet From Well To Nearest: (include proposed)

vacant land

1. Landfill
2. Building Overhang
3. Septic or Holding Tank (circle one)
4. Sewage Absorption Unit
5. Nonconforming Pit
6. Buried Home Heating Oil Tank
7. Buried Petroleum Tank
8. Shoreline/Swimming Pool (circle one)
9. Downspout/Yard Hydrant
10. Privy
11. Foundation Drain to Clearwater
12. Foundation Drain to Sewer
13. Building Drain [ ] Cast Iron or Plastic [ ] Other
14. Building Sewer [ ] Gravity [ ] Pressure [ ] Cast Iron or Plastic [ ] Other
15. Collector Sewer: ___units ___in. diameter
16. Clearwater Sump
17. Wastewater Sump
18. Paved Animal Barn Pen
19. Animal Yard or Shelter
20. Silo
21. Barn Gutter
22. Manure Pipe [ ] Gravity [ ] Pressure [ ] Cast Iron or Plastic [ ] Other
23. Other Manure Storage
24. Ditch
25. Other NR 812 Waste Source

6. Drillhole Dimensions

Dia. (in.)	From (ft.)	To (ft.)
8.75	surface	80
6	80	365
4	365	385

Upper Enlarged Drillhole: Method of Construction

- [X] 1. Rotary - Mud Circulation
- [ ] 2. Rotary - Air
- [ ] 3. Rotary - Foam
- [ ] 4. Reverse Rotary
- [ ] 5. Cable-tool Bit ____ in. dia.
- [ ] 6. Temp. Outer Casing ____ in. dia. ____ depth. Removed? [ ] Yes [ ] No. If no, explain why not
- [ ] 7. Other

9. Geology

DNR USE ONLY	Type, Caving/Noncaving, Color, Hardness, Etc.	From (ft.)	To (ft.)
	drift	surface	60
	limestone	60	100
	limestone w/green layers	100	120
	tan sandtsone	120	198
	white sandstone	198	260
	tan & white sandstone	260	335
	shale	335	350
	pink and white sandstone	350	385

7. Casing, Liner, Screen

Dia. (in.)	Material, Weight, Specification Manufacturer & Method of Assembly	From (ft.)	To (ft.)
6	std. steel PE	surface	80
	18.97 lbs ASTMA053 -Saw-hill		
4	std. steel PE		
	10.79 lbs. Saw-hill		
Dia. (in.)	screen type, material & slot size	From	To

10. Static Water Level ____ ft. above ground surface; WELL HAD ft. below ground surface NO RECOVERED

11. Pump Test: Pumping Level 300 ft. below surface. Pumping at 1 GPM for 50 hours

12. Well Is: 25 in. [X] Above [ ] Below Grade. Developed? [X] Yes [ ] No. Disinfected? [X] Yes [ ] No. Capped? [X] Yes [ ] No

8. Grout or Other Sealing Material Braiden head-bentonite
Method circulated before setting pipe

Kind of Sealing Material	From (ft.)	To (ft.)	# Sacks Cement
6" neat cement	surface	80	20
4" neat cement	0	365	35

13. Did you notify the owner of the need to permanently abandon and fill all unused wells on this property? [ ] Yes [X] No If no, explain none

14. Signature of Point Driver or Licensed Supervisory Driller: Richard Barkholt. Date Signed 11/30/99

Signature of Drill Rig Operator (Mandatory unless same as above): Michael A B arkholt. Date Signed 11/30/99

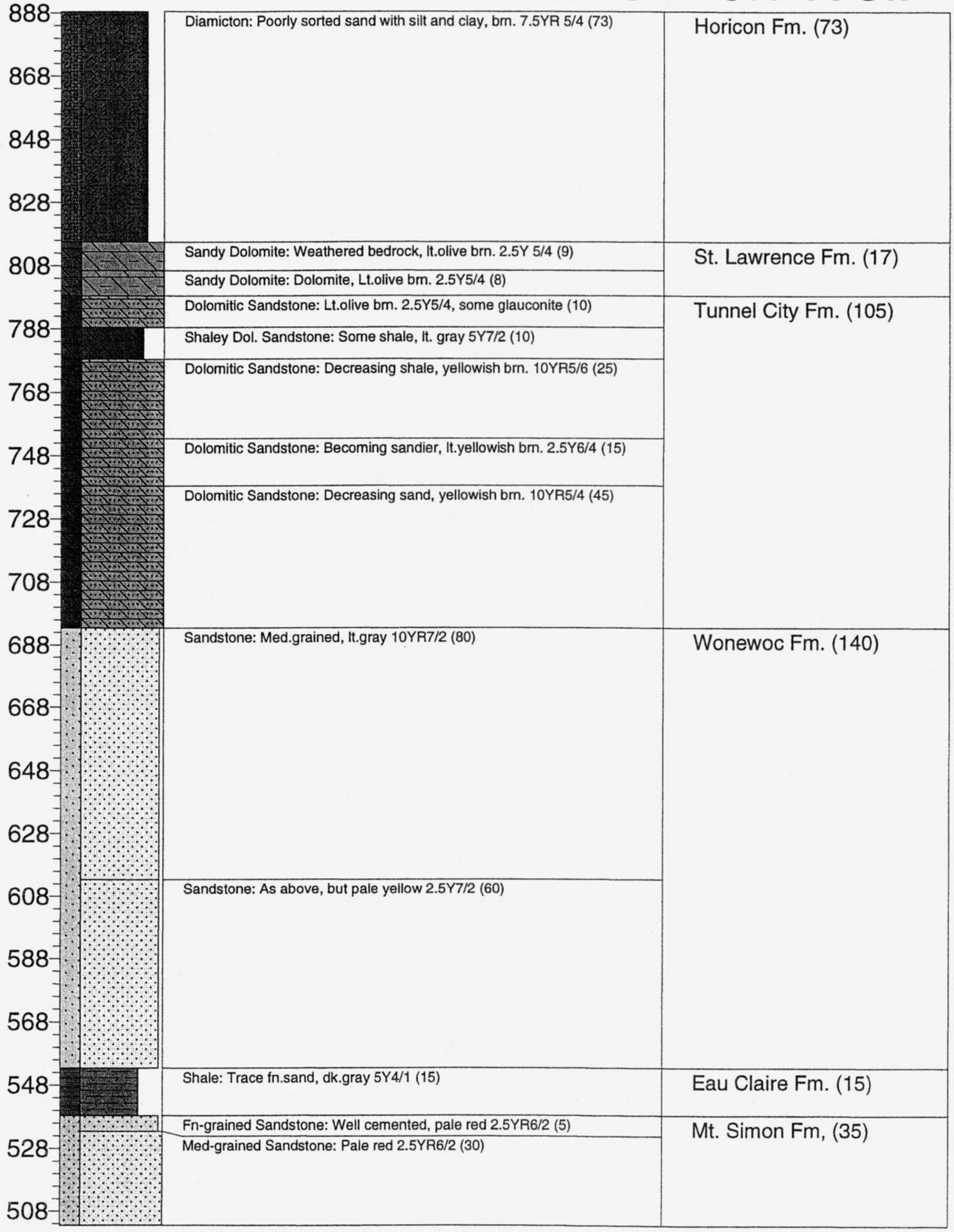
Make additional comments on reverse side about geology, additional screens, water quality, etc.

Comments on reverse side ____ (CHECK √, IF YES)

WELL CONSTRUCTION REPORT Form 3300-77A Rev. 8-98

WELL OWNER

Mt.Simon Well



Field Soil Boring Log Information

Project Name	Start Date	End Date	Boring Number
9 Springs	11/10/99	11/14/99	—

Boring Drilled By	Drilling Method
Water Wells, Inc.	Mud Rotary, Air hammer, Air rotary

Drill Rig	Common Well Name	Initial Water Level	Surface Elevation	Borehole Diameter
	Mt. Simon Well		888.4 ft amsl	Variable Inches

Boring Location State Plane	Easting	Northing	Local Grid Location (If applicable)
SE 1/4 of NE 1/4 of Section 10 T 6 N,R 9E			☐ N Feet ☐ S ☐ E Feet ☐ W

County	State	DNR County Code	Civil Town/City/ or Village
Dane	WI	13	fitchburg

Number	Length (In) Recovered	Blow Counts	Depth In Feet	Group Name, Percent & Range of Particle Sizes, Plasticity, Color, Odor, Moisture, Density/Consistency, Additional Comments, Geologic Origin (Stratigraphic Unit)	Sample Type	PID/FID	Standard Penetration	Well Diagram	RQD/ Comments
				Mud rotary through unconsolidated deposits; poor sample recovery. Top of bedrock surface at ~70-73 feet bgs. Set casing to 82 feet bgs.					
			82	Dolomite, 2.5Y 5/4 light olive brown		St.	Lawrence		Fm.
			85	As above					
			90	Dolomitic Sandstone, fine-grained, some glauconite					
			95	increasing glauconite 95-100'		Tunnel	City	Fm.	
			100	some shale 5Y 7/2, light gray					
			105	As above					
			110	decreasing shale, becoming sandier 10YR 5/6 yellowish brown					
			115	as above, fine-med. grained dolomitic sandstone, high plag. feldspar content, some					
			120	glauconite, 10YR 5/4 yellowish brown					

Logged By:	Checked By:
Susan Swanson	

F-204A (R 12-94)

Field Soil Boring Log Information

Project Name	Start Date	End Date	Boring Number

Boring Drilled By	Drilling Method

Drill Rig	Common Well Name	Initial Water Level	Surface Elevation	Borehole Diameter Inches

Boring Location State Plane Easting Northing 1/4 of 1/4 of Section T N,R

Local Grid Location (If applicable) Feet ☐ N ☐ S Feet ☐ E ☐ W

County	State	DNR County Code	Civil Town/City/ or Village

Number	Length (In) Recovered	Blow Counts	Depth In Feet	Group Name, Percent & Range of Particle Sizes, Plasticity, Color, Odor, Moisture, Density/Consistency, Additional Comments, Geologic Origin (Stratigraphic Unit)	Sample Type	PID/FID	Standard Penetration	Well Diagram	RQD/ Comments
			120	As above					
			125	As above					
			130	As above					
			135	becoming lighter, 2.5Y 6/4 light yellowish brown, becoming medium-grained sandstone					
			140	As above, med.-grained, less clay					
			145	As above					
			150	Becoming finer-grained, some shale					
			155	As above, fine-grained dolomitic sandstone					
			160	As above, some shale - 5Y 6/2 light olive gray					
			165	As above, fine-grained dolomitic sandstone					
			170	Shale, 5Y 6/2 light olive gray					
			175	Fine-grained dolomitic sandstone as above 10YR 5/4 yellowish brown					
			180	As above					

Logged By:	Checked By:
Susan Swanson	

Field Soil Boring Log Information

Project Name	Start Date	End Date	Boring Number

Boring Drilled By	Drilling Method

Drill Rig	Common Well Name	Initial Water Level	Surface Elevation	Borehole Diameter
				Inches

Boring Location
State Plane Easting Northing
1/4 of 1/4 of Section T N,R

Local Grid Location (If applicable)
☐ N ☐ E
Feet ☐ S Feet ☐ W

County	State	DNR County Code	Civil Town/City/ or Village

Number	Length (In) Recovered	Blow Counts	Depth In Feet	Group Name, Percent & Range of Particle Sizes, Plasticity, Color, Odor, Moisture, Density/Consistency, Additional Comments, Geologic Origin (Stratigraphic Unit)	Sample Type	PID/FID	Standard Penetration	Well Diagram	RQD/ Comments
			180	As above			Tunnel City Fm.		
			185	As above					
			190	increasing glauconite and shale					
(no sample)			195	Fine - med grained quartz arenite, very well sorted, rounded grains, 10 YR 8/1 white to 7/2 light gray			Wonewoc Fm.		
			200						
			205	As above					
			210	As above					
			215	As above					
			220	As above, trace glauconitic sandstone					
			225	As above, but med.- coarse sand, 10 YR 7/3					
			230	As above					
			235	As above, but med.-grained, 10 YR 7/2 light gray					
			240	As above					

Logged By:	Checked By:
Susan Swanson	

Field Soil Boring Log Information

Project Name	Start Date	End Date	Boring Number

Boring Drilled By	Drilling Method

Drill Rig	Common Well Name	Initial Water Level	Surface Elevation	Borehole Diameter Inches

Boring Location State Plane Easting Northing; 1/4 of 1/4 of Section T N,R

Local Grid Location (If applicable) ☐ N ☐ S Feet ☐ E ☐ W Feet

County	State	DNR County Code	Civil Town/City/ or Village

Number	Length (In) Recovered	Blow Counts	Depth In Feet	Group Name, Percent & Range of Particle Sizes, Plasticity, Color, Odor, Moisture, Density/Consistency, Additional Comments, Geologic Origin (Stratigraphic Unit)	Sample Type	PID/FID	Standard Penetration	Well Diagram	RQD/ Comments
			240						
			245	As above					
			250	As above					
			255	As above, but dolomitic, 10YR 7/4 to 10YR 7/6					
			260	As above,					
			265	As above					
			270	As above					
			275	As above, but 2.5Y 7/2, little to no dolomite					
			280	As above					
			285	As above, but 2.5Y 7/4					
			290	As above					
			295	As above, but fine-med. grained					
			300	As above					

Logged By:	Checked By:
Susan Swanson	

Field Soil Boring Log Information

Project Name	Start Date	End Date	Boring Number
Boring Drilled By	Drilling Method		
Drill Rig / Common Well Name	Initial Water Level	Surface Elevation	Borehole Diameter Inches
Boring Location State Plane Easting Northing 1/4 of 1/4 of Section T N,R		Local Grid Location (If applicable) ☐ N ☐ E Feet ☐ S Feet ☐ W	
County / State	DNR County Code	Civil Town/City/ or Village	

Number	Length (In) Recovered	Blow Counts	Depth In Feet	*Group Name, Percent & Range of Particle Sizes, Plasticity, Color, Odor, Moisture, Density/Consistency, Additional Comments, Geologic Origin (Stratigraphic Unit)*	Sample Type	PID/FID	Standard Penetration	Well Diagram	RQD/ Comments
			300						
			305	As above					
			310	As above					
			315	As above				Wonewoc	
			320	As above, but trace chips of shale 5Y 6/2				Fm.	
			325	As above, but increasing shaly chips					
			330	As above, but increasing shaley chips (Note: color change in drilling fluid at 335ft.)					
			335	Shale, some very fine sand + silt 5Y 4/1 dark gray				Eau Claire Fm.	
			340	As above, some glauconite					
			345	As above, but increasing well-cemented very fine sandstone					
			350	grades to... Medium-grained, well sorted quartz arenite, 5Y 5/1 gray, with 2.5 YR 4/2 weak red and 2.5 YR 2.5/0 black				Mt. Simon	
			355					Fm.	
			360	becoming fn-med. grained, quartz arenite 2.5YR 6/2 pale red and 5YR 6/2 pinkish gray					

Logged By: Susan Swanson

Checked By:

F-204A (R 12-94)

Field Soil Boring Log Information

Project Name	Start Date	End Date	Boring Number

Boring Drilled By	Drilling Method

Drill Rig	Common Well Name	Initial Water Level	Surface Elevation	Borehole Diameter
				Inches

Boring Location State Plane — Easting — Northing — 1/4 of — 1/4 of Section — T — N,R

Local Grid Location (If applicable) ☐ N ☐ S Feet ☐ E ☐ W Feet

County	State	DNR County Code	Civil Town/City/ or Village

Number	Length (In) Recovered	Blow Counts	Depth In Feet	Group Name, Percent & Range of Particle Sizes, Plasticity, Color, Odor, Moisture, Density/Consistency, Additional Comments, Geologic Origin (Stratigraphic Unit)	Sample Type	PID/FID	Standard Penetration	Well Diagram	RQD/ Comments
			360	As above, becoming 5YR 8/1 white			Casing set to 365' bgs		
(no sample)			365						
			370	As above, 5YR 7/2 pinkish gray					
			375	As above					
			380	As Above					
			385	- - - - - - End of Boring - - - - - - Total Depth = 385 ft. bgs					

Logged By:	Checked By:
Susan Swanson	

State of Wisconsin
Department of Natural Resources

Route to: Solid Waste ☐ Haz. Waste ☐ Wastewater ☐
Env. Response & Repair ☐ Underground Tanks ☐ Other ☐ ________

MONITORING WELL CONSTRUCTION

Form 4400-113A Rev. 4-90

Facility/Project Name: 9 Springs	Local Grid Location of Well: ________ ft. ☐N. ☐S. ________ ft. ☐E. ☐W.	Well Name: Nine Springs Upper Paleozoic Mon. Well
Facility License, Permit or Monitoring Number: _ _ _ _ _ _ _ _	Grid Origin Location: Lat. ________ Long. ________ or	Wis. Unique Well Number: JQ 703; ~~DNR Well Number~~: DN-1442 County ID
Type of Well: Water Table Observation Well ☐ 11; Piezometer ☒ 12	St. Plane ________ ft. N, ________ ft. E.	Date Well Installed (NP425): 12/8-10/99 (mm/dd/yy)
Distance Well Is From Waste/Source Boundary: NA ft.	Section Location of Waste/Source: SE 1/4 of NE 1/4 of Sec. 10, T. 6 N, R. 9 ☒E. ☐W.	Well Installed By: (Person's Name and Firm) Water Wells, Inc. Richard + Kevin
Is Well A Point of Enforcement Std. Application? ☐ Yes ☒ No	Location of Well Relative to Waste/Source: N.A. u ☐ Upgradient; s ☐ Sidegradient; d ☐ Downgradient; n ☐ Not Known	

A. Protective pipe, top elevation _ _ _ _ . _ _ ft. MSL

B. Well casing, top elevation 890.55 ft. MSL

C. Land surface elevation 888.55 ft. MSL

D. Surface seal, bottom _ _ _ _ . _ _ ft. MSL or _ _ . _ ft.

12. USCS classification of soil near screen:
GP ☐ GM ☐ GC ☐ GW ☐ SW ☐ SP ☐
SM ☐ SC ☐ ML ☐ MH ☐ CL ☐ CH ☐
Bedrock ☒ Tunnel City + Wonewoc Fm.s

13. Sieve analysis attached? ☐ Yes ☒ No

14. Drilling method used: Mud Rotary ☒ 50; Hollow Stem Auger ☐ 41; Air hammer, tri-cone Other ☒

15. Drilling fluid used: Water ☒ 02; Air ☒ 01; Drilling Mud ☒ 03; None ☐ 99

16. Drilling additives used? ☐ Yes ☒ No

Describe ________

17. Source of water (attach analysis): Potable water source

E. Bentonite seal, top _ _ _ _ . _ _ ft. MSL or 0.0 ft.

F. Fine sand, top _ _ _ _ . _ _ ft. MSL or — ft.

G. Filter pack, top _ _ _ _ . _ _ ft. MSL or — ft.

H. Casing bottom ~~Screen joint, top~~ _ _ _ _ . _ _ ft. MSL or 88.0 ft.

I. Well bottom _ _ _ _ . _ _ ft. MSL or 315.0 ft.

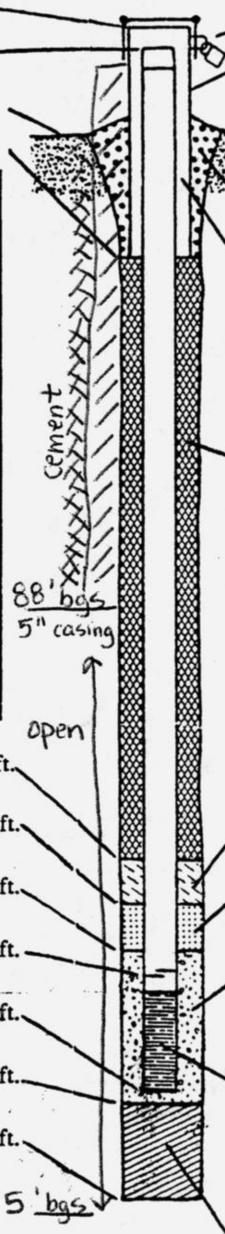
J. Filter pack, bottom _ _ _ _ . _ _ ft. MSL or — ft.

K. Borehole, bottom _ _ _ _ . _ _ ft. MSL or 315.0 ft.

L. Borehole, diameter 8.0 in. to 88'; 5.0 in. to 315'

M. O.D. well casing _ _ . _ _ in.

N. I.D. well casing 5.00 in.



1. Cap and lock? ☒ Yes ☐ No
2. Protective cover pipe:
   a. Inside diameter: 6.0 in.
   b. Length: 88.0 ft.
   c. Material: Steel ☒ 04; Other ☐
   d. Additional protection? ☐ Yes ☒ No. If yes, describe: ________
3. Surface seal: Bentonite ☐ 30; Concrete ☒ 01; Other ☐
4. Material between well casing and ~~protective pipe:~~ well bore: Bentonite ☐ 30; Annular space seal ☐; Bentonite - Cement Other ☒
5. Annular space seal: a. Granular Bentonite ☐ 33
   b. ____ Lbs/gal mud weight . . . Bentonite-sand slurry ☐ 35
   c. ____ Lbs/gal mud weight . . . . . Bentonite slurry ☐ 31
   d. ____ % Bentonite . . . . . . Bentonite-cement grout ☒ 50
   e. ________ Ft^3 volume added for any of the above
   f. How installed: Tremie ☐ 01; Tremie pumped ☐ 02; Gravity ☐ 08
6. Bentonite seal: a. Bentonite granules ☐ 33
   b. ☐1/4 in. ☐3/8 in. ☐1/2 in. Bentonite pellets ☐ 32
   c. Not applicable Other ☐
7. Fine sand material: Manufacturer, product name & mesh size
   a. Not applicable
   b. Volume added — ft^3
8. Filter pack material: Manufacturer, product name and mesh size
   a. Not applicable
   b. Volume added — ft^3
9. Well casing: Flush threaded PVC schedule 40 ☐ 23; ASTM 853 Grd. B Flush threaded PVC schedule 80 ☐ 24; Flush-beveled steel casing Other ☒
10. Screen material: open borehole
   a. Screen type: Factory cut ☐ 11; Continuous slot ☐ 01; Not applicable Other ☐
   b. Manufacturer —
   c. Slot size: 0. _ _ in.
   d. ~~Slotted~~ length: Open Interval 235.0 ft.
11. Backfill material (below filter pack): None ☐ 14; Not applicable Other ☐

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm
Susan Swanson	UW-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.

Well Construction Report For
WISCONSIN UNIQUE WELL NUMBER NP 425

State of Wisconsin
Private Water Systems-DG/2
Department of Natural Resources
Box 7921
Madison, WI 53707 **(Please type or print using a black pen.)**

Property Owner: Dept. of Geology University of Wis.	Telephone Number: 608 262-9467
Mailing Address: 1215 W. Dayton Stseet	
City: Madison	State: WI. Zip Code: 53706
County of Well Location: Dane	Co. Well Permit No. W____ Well Completion Date (mm-dd-yy): 12-10-99

Well Constructor (Business Name): WATER WELLS INC.	License #: 3
Address: 6400 Lake Road	
City: Windsor	State: WI Zip Code: 53598

2. Mark well location with a dot in correct 40-acre parcel of section. N / W / E / S — XX

1. Well Location **Please use decimals instead of fractions.**
[X] Town [ ] City [ ] Village of Fitchburg Fire # (If avail.)
Grid or Street Address or Road Name and Number: N. of Lacy Road
Subdivision Name: ESU CLSIRE WELL Lot # Block #
Gov't Lot #____ or NW 1/4 of NE 1/4 of Section 10, T 6 N; R 9 [X] E [ ] W

3. Well Type [X] New [ ] Replacement (see item 13 below) [ ] Reconstruction
of previous unique well # ____ constructed in 19____
Reason for replaced or reconstructed well? monitor well
[X] Drilled [ ] Driven Point [ ] Jetted [ ] Other ____

4. Well serves — # of homes and or —
(Eg: barn, restaurant, church, school, industry, etc.)
High Capacity: Well? [ ] Yes [X] No Property? [ ] Yes [X] No

5. Is the well located upslope or sideslope and not downslope from any contamination sources, including those on neighboring properties? [X] Yes [ ] No If no, explain on back side.
Well located in floodplain? [ ] Yes [X] No
Distance in Feet From Well To Nearest: (include proposed)

open field

____ 1. Landfill
____ 2. Building Overhang
____ 3. Septic or Holding Tank (circle one)
____ 4. Sewage Absorption Unit
____ 5. Nonconforming Pit
____ 6. Buried Home Heating Oil Tank
____ 7. Buried Petroleum Tank
____ 8. Shoreline/Swimming Pool (circle one)
____ 9. Downspout/Yard Hydrant
____ 10. Privy
____ 11. Foundation Drain to Clearwater
____ 12. Foundation Drain to Sewer
____ 13. Building Drain [ ] Cast Iron or Plastic [ ] Other
____ 14. Building Sewer [ ] Gravity [ ] Pressure [ ] Cast Iron or Plastic [ ] Other
____ 15. Collector Sewer: ___units ____in. diameter
____ 16. Clearwater Sump
____ 17. Wastewater Sump
____ 18. Paved Animal Barn Pen
____ 19. Animal Yard or Shelter
____ 20. Silo
____ 21. Barn Gutter
____ 22. Manure Pipe [ ] Gravity [ ] Pressure [ ] Cast Iron or Plastic [ ] Other
____ 23. Other Manure Storage ____
____ 24. Ditch
____ 25. Other NR 812 Waste Source

6. Drillhole Dimensions

Dia. (in.)	From (ft.)	To (ft.)
8.75	surface	85
5	85	315

Upper Enlarged Drillhole: Method of Construction
[X] 1. Rotary - Mud Circulation
[ ] 2. Rotary - Air
[ ] 3. Rotary - Foam
[ ] 4. Reverse Rotary
[ ] 5. Cable-tool Bit ____ in. dia.
[ ] 6. Temp. Outer Casing ____ in. dia. ____ depth
Removed? [ ] Yes [ ] No
If no, explain why not ____
[ ] 7. Other ____

9. Geology

DNR USE ONLY	Type, Caving/Noncaving, Color, Hardness, Etc.	From (ft.)	To (ft.)
	drift	surface	59
	limestone w/clay layers	59	82
	limestone	82	117
	tan sandstone	117	197
	tan & whhite sandstone	197	315

7. Casing, Liner, Screen

Dia. (in.)	Material, Weight, Specification Manufacturer & Method of Assembly	From (ft.)	To (ft.)
5	std. steel pe	surface	85
5	14.62 lbs Saw-Hill		

Dia. (in.)	screen type, material & slot size	From	To

10. Static Water Level
____ ft. above ground surface
39 ft. below ground surface

11. Pump Test
Pumping Level 315 ft. below surface
Pumping at 100 GPM for .25 hours

12. Well Is: 18 in. [X] Above [ ] Below Grade
Developed? [X] Yes [ ] No
Disinfected? [X] Yes [ ] No
Capped? [X] Yes [ ] No

8. Grout or Other Sealing Material Method: tremie line-pumped

Kind of Sealing Material	From (ft.)	To (ft.)	# Sacks Cement
neat cement	surface	85	19

13. Did you notify the owner of the need to permanently abandon and fill all unused wells on this property? [ ] Yes [X] No If no, explain: none

14. Signature of Point Driver or Licensed Supervisory Driller: Richard Berkholtz Date Signed: 12/27/99
Signature of Drill Rig Operator (Mandatory unless same as above): (Richard) C. Berkholtz Date Signed: 12-28-99

Make additional comments on reverse side about geology, additional screens, water quality, etc.
Comments on reverse side ____ **(CHECK √, IF YES)**

WELL CONSTRUCTION REPORT
Form 3300-77A Rev. 8-98

WELL OWNER

APPENDIX B

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

Swanson, Susan, K.[1], Bahr, Jean, M.[2],

University of Wisconsin, Department of Geology and Geophysics

Schwar, Michael, T.[3], Potter, Kenneth, W.[4],

University of Wisconsin, Department of Civil and Environmental Engineering

[1] FAX: (608)262-0693, EMAIL: skswanso@geology.wisc.edu, Please address all correspondence to Ms. Swanson.
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[4] FAX: (608)262-5199, EMAIL: kwpotter@facstaff.wisc.edu

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

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

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^3/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_3-, SO_42-, $Cl-$) by automated colorimetry. The 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

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

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

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

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

where, s_x 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

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):

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

where d = the Euclidean distance,

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

$$ESS_i = \sum_{j=1}^{n_i} \sum_{k=1}^{q} \left(x_{ijk} - \bar{x}_{ik} \right)^2$$

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,

$\bar{x}_{ik}$ = 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

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.

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 hand-held 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

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

where, λ_{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):

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

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

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

$4He_m$ = measured 4He,

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

α' = air/water fractionation factor (α'=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:

$$3He^* = R_{t=0}4He_m - \frac{(R_{sol}4He_{sol})}{\{\alpha'(4He_{sol} - 4He_m)/4He_m\} + 1} \qquad (2)$$

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

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

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^3/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 concentrations are not apparent in these quarterly samples. We conclude that Group II is representative of an intermediate 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

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 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 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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Table 1. Summary of privately-owned wells

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

Group	1	2	3	Exceptions
Monitoring Points	MW2A, MW2B, MW3A, peat spring	MW4B, MW1C, MW5A, MW5B, MW6A, MW6B, P-3, P-4, P-5, big spring, nursery spring, Syene Road spring	MW7A, MW7B, P-1	P-2, WDNR#9, MW3B
Characteristics	•Variable NO_3-and Cl- •Low and somewhat variable Na+	•Elevated, but consistent NO_3- •High and consistent Cl- •High and consistent Na+	•Low and consistent NO_3-, $SO_4$2-, and Na+ •Low Cl- •Low TDS and conductivity	

Table 3. Characteristics of monitoring point clusters

Cluster	**A**	**B**	**C**	**D**
Monitoring Points	MW2A, MW2B, MW5A, MW3B	MW4B, MW1C, MW5B, MW6A, MW6B, P-3, P-4, P-5, big spring, nursery spring, Syene Road spring	MW7A, MW7B, P-1	P-2, WDNR#9, MW3A, peat spring
Characteristics	• NO_3-, $SO_4$2-, Ca2+, Mg2+, conductivity, and total dissolved solids are greater than the mean	• Alkalinity and K+ are slightly less than the mean • Most other analytes are close to the mean	• NO_3-, Cl-, Ca2+, Mg2+, $SO_4$2-, conductivity, and total dissolved solids are less than the mean • Na+ and K+ are slightly less than the mean	• Na+, Cl-, $SO_4$2-, K+, and alkalinity are slightly less than the mean

Table 4

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

Location	Tritium samples				4He	3He	$R_{t=0}$	3He*	$t_{3H/3He}$	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

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

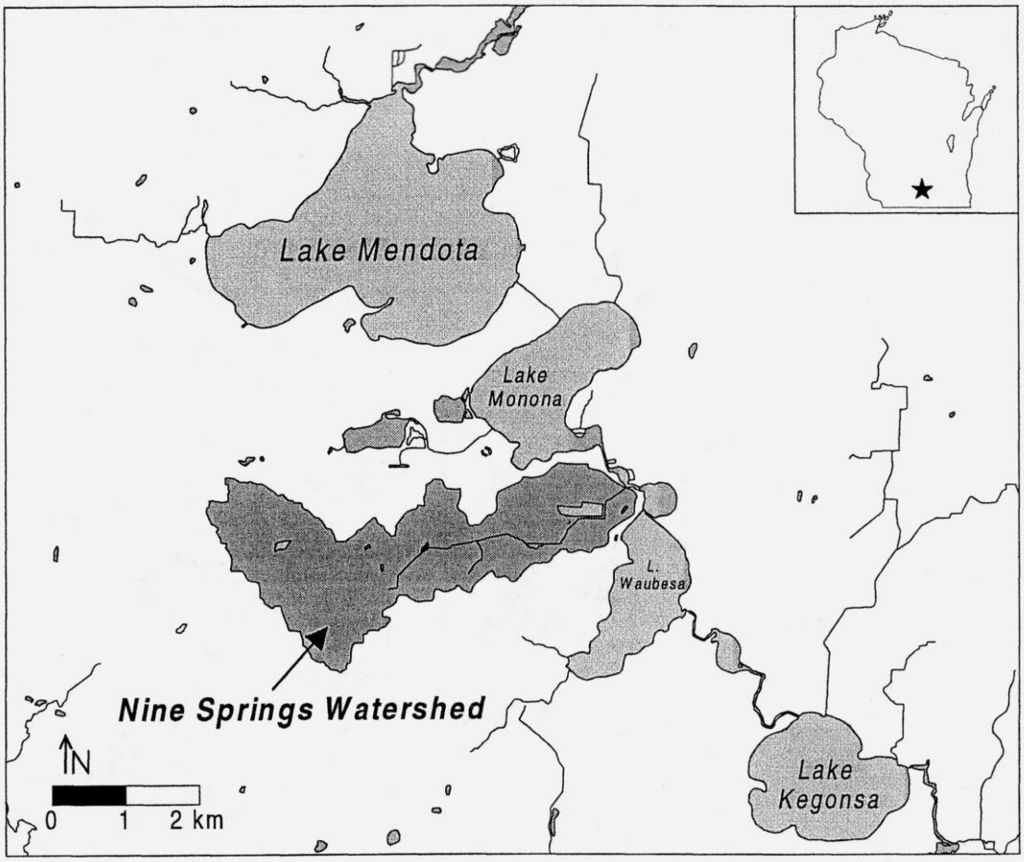

Lake Mendota
Lake Monona
L. Waubesa
Lake Kegonsa
Nine Springs Watershed
N
0
1
2 km

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

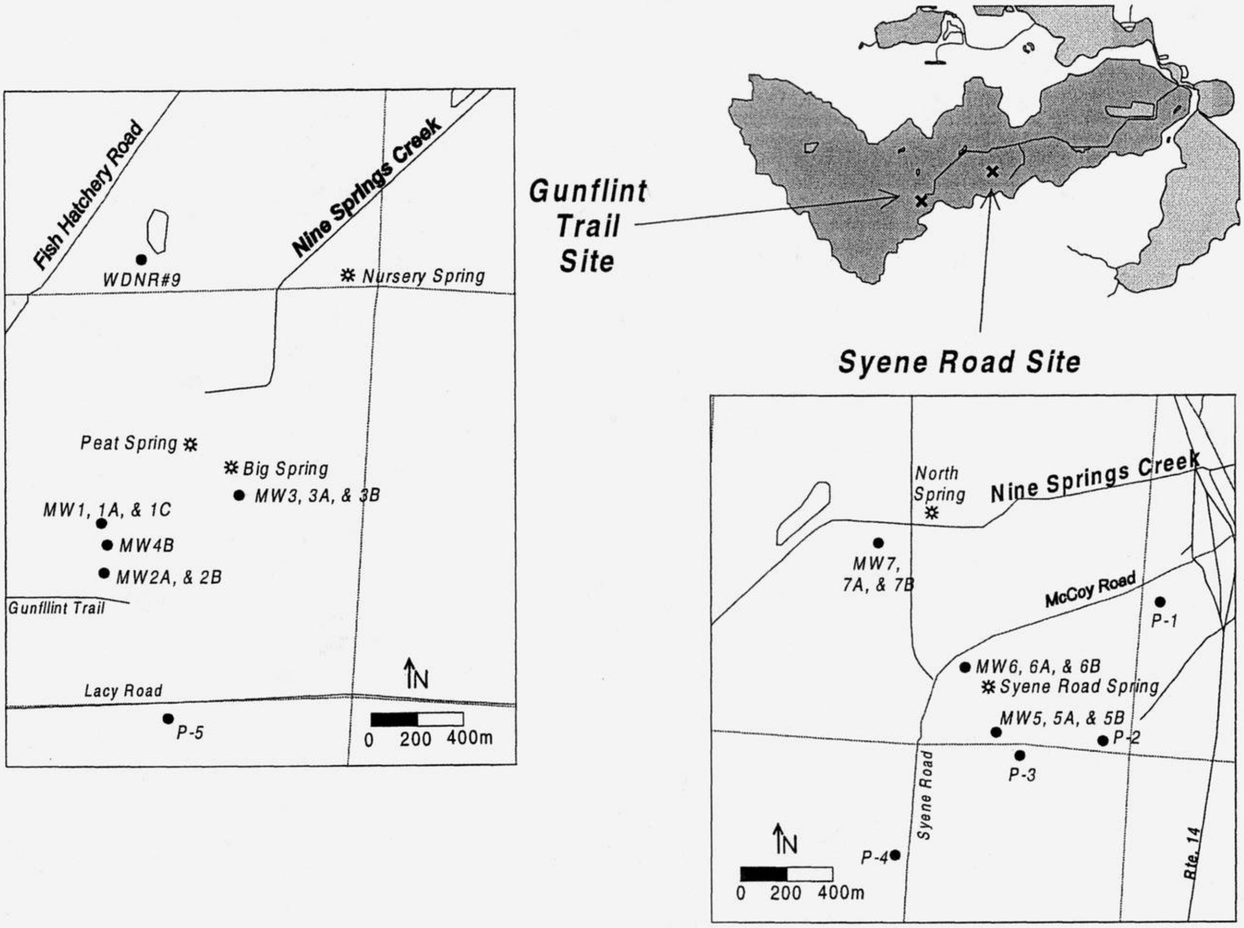
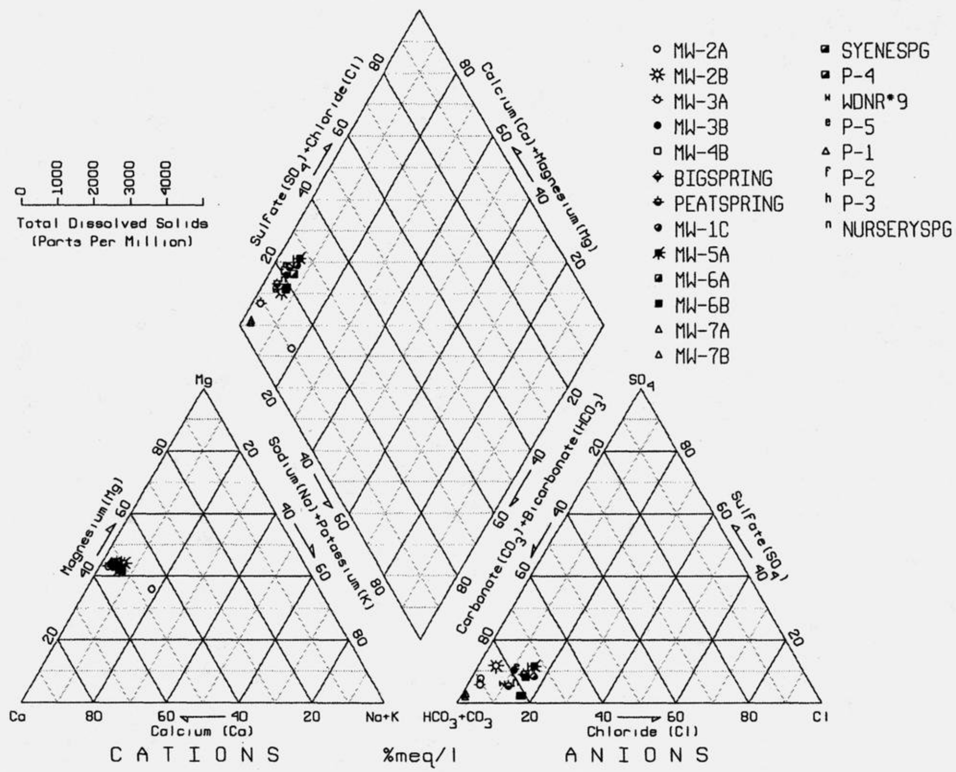
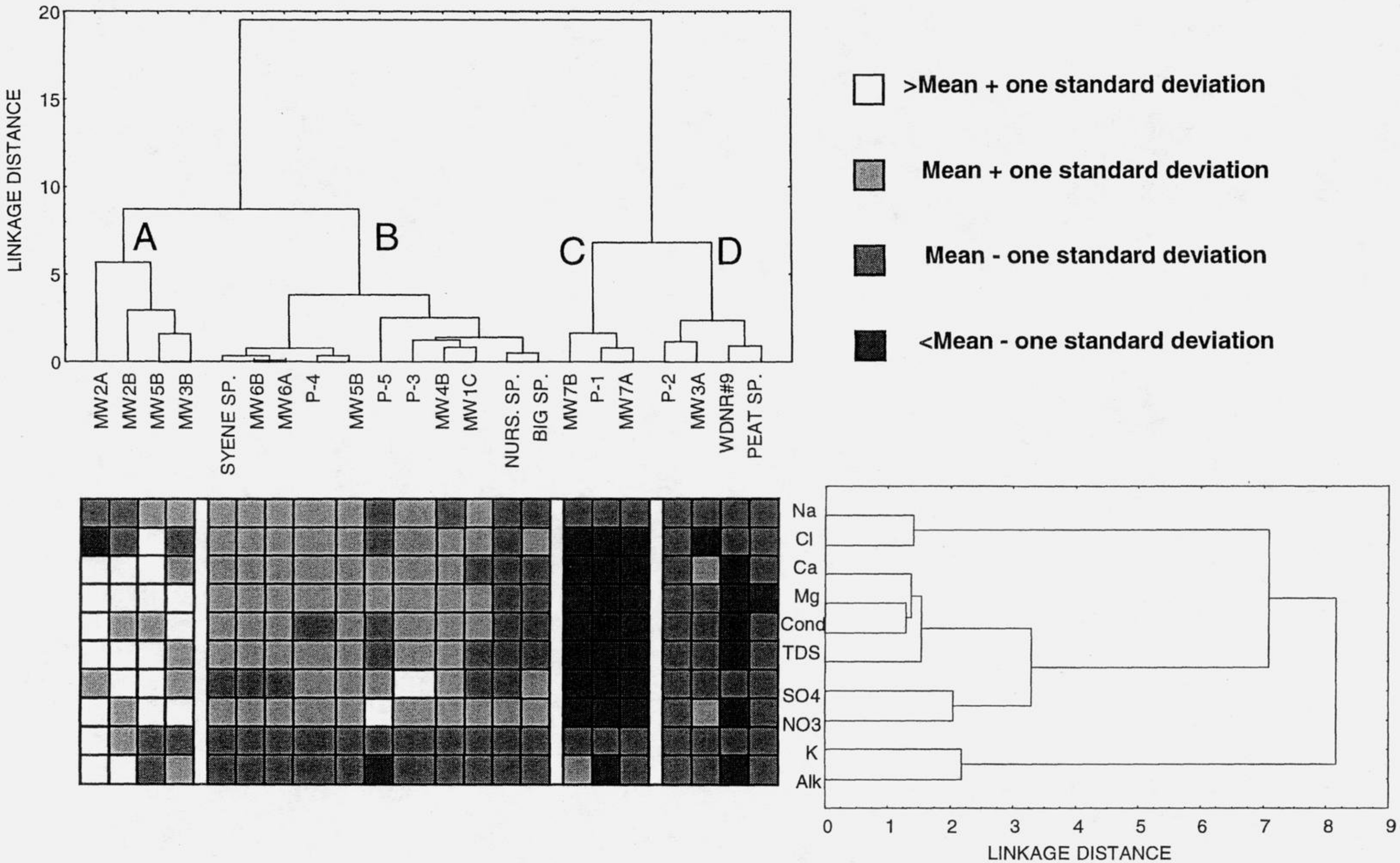

Gunflint Trail Site
Syene Road Site
Fish Hatchery Road
Nine Springs Creek
WDNR#9
Nursery Spring
Peat Spring
Big Spring
MW3, 3A, & 3B
MW1, 1A, & 1C
MW4B
MW2A, & 2B
Gunfllint Trail
Lacy Road
P-5
N
0 200 400m
North Spring
Nine Springs Creek
MW7, 7A, & 7B
McCoy Road
P-1
MW6, 6A, & 6B
Syene Road Spring
MW5, 5A, & 5B
P-2
P-3
Syene Road
P-4
Rte. 14
N
0 200 400m

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



Total Dissolved Solids (Parts Per Million)
0
1000
2000
3000
4000
MW-2A
MW-2B
MW-3A
MW-3B
MW-4B
BIGSPRING
PEATSPRING
MW-1C
MW-5A
MW-6A
MW-6B
MW-7A
MW-7B
SYENESPG
P-4
WDNR*9
P-5
P-1
P-2
P-3
NURSERYSPG
Sulfate(SO4)+Chloride(Cl)
Calcium(Ca)+Magnesium(Mg)
Sodium(Na)+Potassium(K)
Carbonate(CO3)+Bicarbonate(HCO3)
Magnesium(Mg)
Sulfate(SO4)
Mg
SO4
Ca
Na+K
HCO3+CO3
Cl
Calcium (Ca)
Chloride (Cl)
CATIONS
%meq/l
ANIONS

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



LINKAGE DISTANCE
A
B
C
D
MW2A
MW2B
MW5B
MW3B
SYENE SP.
MW6B
MW6A
P-4
MW5B
P-5
P-3
MW4B
MW1C
NURS. SP.
BIG SP.
MW7B
P-1
MW7A
P-2
MW3A
WDNR#9
PEAT SP.
>Mean + one standard deviation
Mean + one standard deviation
Mean - one standard deviation
<Mean - one standard deviation
Na
Cl
Ca
Mg
Cond
TDS
SO4
NO3
K
Alk
LINKAGE DISTANCE