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Hydrogeologic controls on springs in the Mukwonago River watershed, SE Wisconsin

Final Report to the Wisconsin Department of Natural Resources

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PROJECT SUMMARY

Title: Hydrogeologic controls on springs in the Mukwonago River watershed, SE Wisconsin.

Project ID: NMD00000239

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Period of Contract: July 1, 2003 to June 30, 2005

Background/Need: The health of wetlands is essential for maintaining overall environmental health as wetlands play an integral role in the storage of water after flood events, recharge and discharge to the local aquifer, balancing of baseflow and the regulation of water quality (Carter, 1986). The effects of urbanization on the natural environment, and on wetlands in particular, can be profound. By increasing the coverage of impervious surfaces as well as the demand for ground water, urbanization can result in long-term damage to wetland systems. As development of high capacity wells and surface construction in the Mukwonago River watershed continues, managers involved with conservation recognize that maintaining spring discharge and water levels in the wetland is essential to preserving the integrity of these aquatic habitats. There is a critical need to evaluate potential effects of increased pumping and decreased recharge that may accompany continued suburban development.

Objectives: The goals of this project were to asses the hydrogeologic controls on ground water discharge to the Mukwonago River watershed's springs and wetlands and to develop a numerical ground water flow model to assess development impacts.

Methods: In this study we used water level and stream flow measurements along with major ion and strontium isotope analyses to estimate sources and amounts of ground water from bedrock aquifers that may mix with shallow waters before discharging to springs and wetlands in the watershed. We developed a numerical ground water flow model that captures the essential interactions among subsurface hydrostratigraphic units and surface discharge features, which in turn allows assessment of the impact of ground water pumping to the system.

Results and Discussion: Field data and modeling were used to evaluate two conceptual models for spring flow in the Mukwonago River watershed, one in which springs are supported primarily by discharge from the shallow sand and gravel aquifer and another in which preferential flow zones in the bedrock are responsible for focused discharge at the springs. Evidence suggesting a bedrock preferential flow source includes the location of springs along the edge of a buried bedrock valley and the fact that one spring complex located east of Bluff Road supplies an estimated 70% of total baseflow to the reach upstream of Lulu Lake under low flow conditions. However, decreases in baseflow during a particularly dry period of August, 2003 that correlate with water level declines in a sand and gravel well indicate that at least 20% of the baseflow under average conditions is supplied by the shallow glacial deposits.

Major ion chemistry and strontium isotope data were interpreted to develop a revised conceptual model in which the springs are supplied by a combination of 1) water that has traveled rapidly through bedrock preferential flow zones and 2) water that has interacted only with the sand and gravel aquifer. In this mixing model, the bedrock water is assumed to have a bedrock $^{87}Sr/^{86}Sr$ ratio but a low total dissolved solids concentration due to limited contact time for dissolution.

The revised conceptual model was tested using numerical models with and without high conductivity bedrock layers that create preferential flow zones. The model with preferential flow zones provides an improved match to observed discharge patterns under recharge conditions for normal and drought periods. Reverse particle tracking from the Bluff Road springs in the calibrated model shows distinct paths and recharge areas for water discharging from bedrock preferential flow zones and water that has traveled only through glacial deposits. However, the overall lengths of the flow paths through bedrock and glacial deposits are similar.

Conclusions/Implications/Recommendations:

The combined data analysis and modeling support the conclusion that shallow bedrock is a significant source of water to the springs. Models that do not include a high conductivity layer in the Ordovician dolomite predict 17% less flow than models with a high conductivity layer. However, decreases in baseflow that were observed during dry periods and that correlate with declines in water levels in the sand and gravel aquifer indicate that at least 20% of the total discharge to the stream comes from the sand and gravel aquifer. Thus, managing ground water in both these aquifers is important to maintaining baseflow in the Mukwonago River.

Urbanization in the watershed threatens to increase runoff as well as decrease water levels in the upper sand and gravel aquifer. While the presence of preferential flow from the shallow bedrock to the springs may help to damp immediate impacts of pumping in the upper aquifer, decreased water levels still threaten the fragile ecosystem supported by the streams and wetlands in the watershed. Pumping in the glacial deposits that are along the flow paths through that aquifer is likely to have an impact on spring flow. Increased urbanization may also decrease recharge to the shallow bedrock. Maintaining local recharge is therefore important to maintaining spring flow.

While the initial particle tracking simulations suggest a local recharge source for water transported in bedrock preferential flow zones, it is also possible that some of the water captured by these flow zones originates from recharge areas to the west/northwest of the watershed, outside the boundaries of the inset model. Urbanization in these areas may also affect flow to the springs and the watershed.

Related Publications: Gittings, H.E., 2005. Hydrogeologic controls on springs in the Mukwonago River watershed, SE Wisconsin. M.S. thesis, University of Wisconsin –Madison, Department of Geology and Geophysics.

Key Words: wetland, Troy Valley, strontium, high conductivity, southeastern Wisconsin, ground water modeling, Mukwonago

Funding: Wisconsin Department of Natural Resources

INTRODUCTION

The series of wetlands, springs and lakes surrounding the Lulu Lake Preserve in the headwaters of the Mukwonago River in southeastern Wisconsin are identified as "outstanding and exceptional resource waters" by the Wisconsin state legislature (Figure 1).

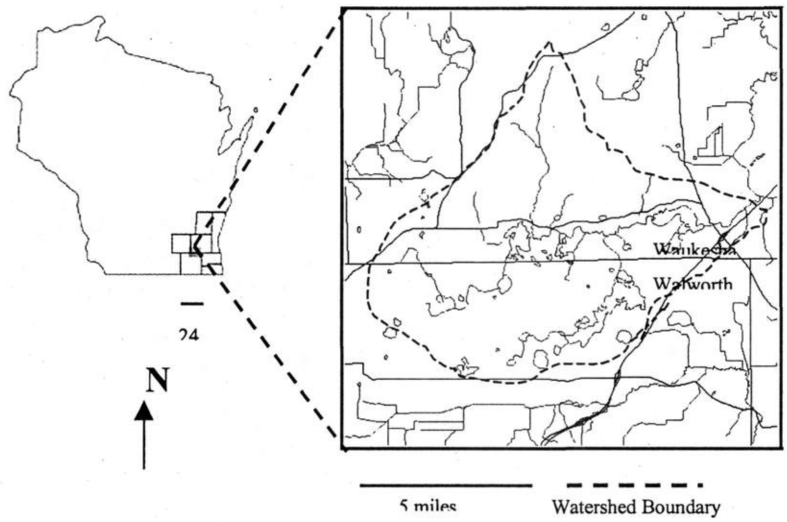

Figure 1. The State of Wisconsin and the location of the Mukwonago River watershed.

Despite extensive research and planning in the 1970's by the Southeastern Wisconsin Regional Planning Committee (SEWRPC, 2002), faster than expected suburban expansion from the City of Milwaukee and other areas has added stresses to the Mukwonago River system. The often-uncoordinated development, pollution, addition of impervious surfaces and increased demand for ground water are of concern to those responsible for the status of the river and the lakes and wetlands along its course.

The health of wetlands is essential for maintaining overall environmental health as wetlands play an integral role in the storage of water after flood events, recharge and discharge to the local aquifer, balancing of baseflow and the regulation of water quality (Carter, 1986).

The effects of urbanization on the natural environment, and on wetlands in particular, can be profound. By increasing the coverage of impervious surfaces as well as the demand for ground water, urbanization can result in long-term damage to wetland systems. These changes include increased stormwater peaks, increased water volumes and pollutants from runoff (Klein, 1979; Dingman, 1994; Wang et al., 2001) as well as potential decreases in baseflow to lakes and streams from reduced ground water contribution (Krohelski, 1986; Krohelski et al., 2000).

As development of high capacity wells and surface construction in the Mukwonago River watershed continues, managers involved with conservation recognize that maintaining spring discharge and water levels in the wetland is essential to preserving the integrity of these aquatic habitats. There is a critical need to evaluate potential effects of increased pumping and decreased recharge that may accompany continued suburban development.

Two conceptual models for spring flow were investigated as part of this research. Previous studies of ground water flow in this area focused on local scale flow patterns and geochemistry, producing a conceptual model in which spring flow and diffuse discharge to the wetlands are supported by shallow ground water flow through glacial deposits (TNC, 2004b).

Those studies interpreted lower hydraulic heads observed in the deep bedrock to infer that ground water flows from the upper aquifer to the lower bedrock aquifer. According to this conceptual model, there would be minimal contributions from, and sometimes ground water loss to, bedrock aquifers from surface water (Figure 2, I) (TNC, 2004b).

An alternative conceptual model, suggested by recent studies of springflow in nearby Dane County, WI, is that high volume springs may be supported by discharge from preferential flow zones in the shallow bedrock (Figure 2, II) (Swanson and Bahr, 2004; Swanson et al., 2006).

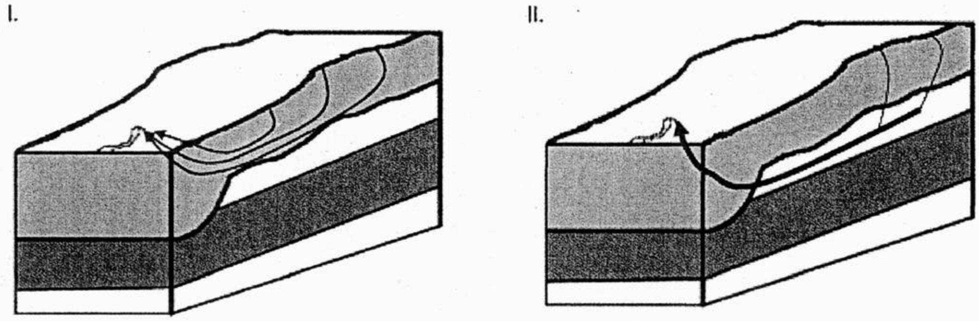

Figure 2. Conceptual models for spring flow in the Mukwonago River watershed.
I. Conceptual model one: springflow and diffuse discharge to the wetlands are supported by shallow ground water flow through glacial deposits.
II. Conceptual model two: high volume springs supported by discharge from preferential flow zones in the shallow bedrock (modified from Swanson, 2001).

These preferential flow zones could be associated with bedding plane partings or zones of coarse-grained material and are hydraulically continuous for tens of kilometers. Where these zones intersect the margins of the bedrock valley, the result is focused discharge to springs. In the Mukwonago River watershed, similar to conditions in Dane County, the locations of the springs appear to coincide with the steep wall of the buried bedrock Troy Valley (Figure 3).

The differences between the two conceptual models have significant implications for the management of ground water resources in the watershed. If spring flow is generated primarily by discharge from shallow glacial deposits, new and increased pumping from the shallow sand and gravel aquifer could have immediate effects on the wetlands and spring-fed lakes in the area. However, if springs are supported by discharge from bedrock flow systems, they may be buffered from some of the effects of pumping in the sand and gravel aquifer. We therefore attempted to identify such zones in order to provide additional constraints on the sources of baseflow to the Mukwonago River.

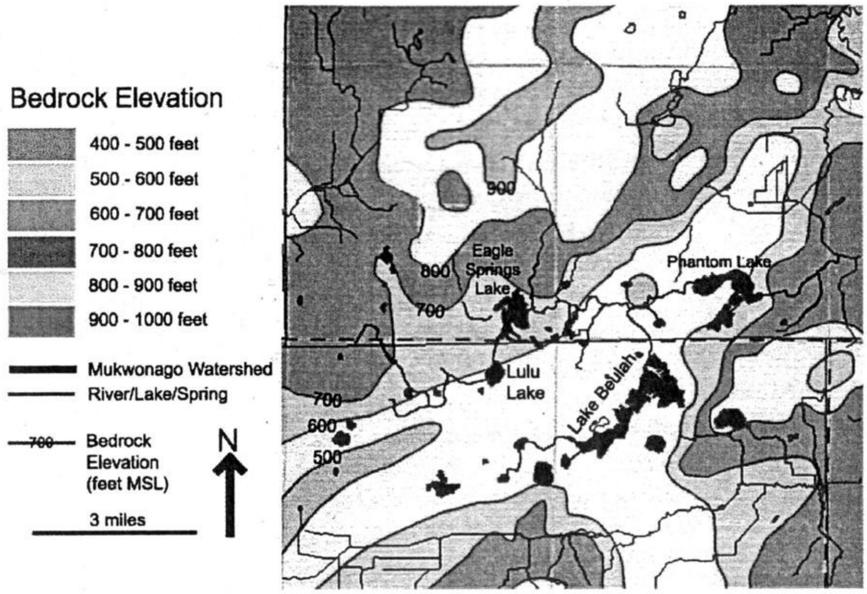

Figure3. Bedrock elevation above mean sea level. The buried bedrock Troy Valley directly underlies the Mukwonago River watershed. Many of the springs and lakes lie along the edges of the buried bedrock valley. The valley runs from Milwaukee County, WI into Lee County, IL. (modified from SEWRPC, 2002).

PROCEDURES AND METHODS

In order to improve understanding of hydrogeologic controls on ground water discharge to springs and wetlands in the Mukwonago River watershed we used physical, chemical and numerical modeling investigations to test the conceptual model for spring localization along the edge of pre-glacial, buried bedrock valleys.

Water level monitoring and stream discharge

In order to characterize the response of water levels in the wetlands near Lulu Lake to precipitation and streamflow, four shallow wells were dug using a hand-auger and constructed with PVC casing near the small bridge at the Lulu Lake Preserve in September, 2002.

Global Water pressure transducers measured water levels continuously at 30 minute intervals from September, 2002 through October, 2004. Additional, pre-existing private wells used for intermittent irrigation in the headwaters area were also monitored from January, 2003 through October, 2004 in order to capture water level data for the upper sand and gravel aquifer. Data from the loggers were downloaded periodically to a portable computer. Down-hole water level measurements via electronic tape (Solinst®) were made for comparison with data logger levels. Water level data for the USGS monitoring well 908 completed in the sand and gravel aquifer near Lulu Lake were obtained from the USGS monitoring well website (USGS, 2005).

To quantify variations in discharge along the stream, periodic synoptic stream flow surveys were made in portions of the watershed and nearby areas. A pygmy flow meter was used when water depths and flow rates in the channel were sufficient for this type of measurement. Where conditions precluded the use of a flow meter, temporary weirs and timed measurements of flow from a culvert into a bucket were used instead. All flow measurements are listed and locations shown in Appendix B Table 1. A stilling well was installed near a bridge upstream of Lulu Lake to collect continuous records of stream stage. A staff gage was also installed near this bridge and was read each time data were retrieved from the data logger for comparison with flow and stilling well measurements.

Major ion analysis

Sampling for laboratory chemical analyses was accompanied by field measurements of various chemical parameters using electrodes and colorimetric analysis. A total of 24 water samples were collected from various locations within the watershed in July, 2003 and July, 2004. Temperature and specific conductance were measured using an YSI 30 Salinity, Conductivity and Temperature probe. A Cole-Parmer® Chemcadet pH meter with an electrode was used for pH measurements. Measurements of dissolved oxygen, total iron, total alkalinity, and nitrate were also made in the field using colorimetric kits (CHEMetrics, Inc.). These field parameters were recorded for each sample. Wells were pumped for fifteen minutes prior to sample collection. Samples were filtered using Cole-Parmer® 0.45µm nylon filters. Samples for total dissolved mineral analysis were preserved with ~3 drops of 4.5 M HNO_3. All samples were capped and put on ice until delivery to the lab.

Samples from various locations in the Mukwonago River watershed were sent to the University of Wisconsin-Madison Soil & Plant Analysis Lab for analysis. (These analyses were supported with funds separate from those supplied by this WI DNR grant. Results are included in Gittings, 2005.) Analyses included concentrations of total dissolved minerals and anions. Anions were analyzed by ion chromatography using a DIONEX DX 500. The total dissolved minerals were analyzed using inductively coupled plasma optical emission spectrometry (Jarrell Ash IRIS High Resolution ICP-OES) (UWSPL, 2004).

Strontium isotope analysis

Strontium isotope analyses were conducted in the Radiogenic Isotope Laboratory at the University of Wisconsin-Madison Department of Geology and Geophysics.

Prior to Sr sample collection, wells were pumped for fifteen minutes. Samples were filtered using Cole-Parmer® 0.45µm nylon filters. All wells were sampled prior to contact with any water softeners.

Strontium isotope analyses were conducted using a 7-collector Micromass Sector 54 thermal ionization mass spectrometer using zone refined Ta filaments. Mass analysis was done using a 3-jump multi-collector dynamic analysis routine with exponential mass bias normalization to $^{86}Sr/^{88}Sr = 0.1194$. Each reported analysis represents the average of 120 ratios. The ion intensity at ^{88}Sr was maintained at 3×10^{-11} amps during the analysis. All $^{87}Sr/^{86}Sr$ ratios were corrected for Rb isobars at mass 87 by monitoring at ^{85}Rb; corrections were less than 0.0019%. The reported error for each analysis is 2 standard errors of the mean. These internal errors agree well with the external error (2-standard deviations) of Sr isotope analyses. For example, during the course of this study the NIST SRM-987 was analyzed 27 times with an average $^{87}Sr/^{86}Sr$ of 0.710266 ± 0.000017 (2-standard deviations). Moreover, two samples (12 and 13) were analyzed on the mass spectrometer using the same chemically processed sample. The spread in $^{87}Sr/^{86}Sr$ analyses for these were 0.000006 (sample 12) and 0.000012 (sample 13). Based on the replicate analyses of the water samples and the NIST Sr isotope reference material SRM-987, we conclude that $^{87}Sr/^{86}Sr$ ratios different by 0.000034 are analytically resolvable at the 95% confidence interval.

Strontium concentrations determined by IDMS were made for 15 samples collected in 2004 using the same mass spectrometry conditions except that the ^{88}Sr signal was typically 3×10^{-11} amps and the measured $^{84}Sr/^{86}Sr$ ratio was based on the average of 10 ratios. Measured $^{84}Sr/^{86}Sr$ ratios were between 0.040678 and 1.0880866.

Pumping-test of new Eagle wells

During the course of the study two new municipal wells were installed by the town of Eagle approximately 2.3 miles from the Lulu Lake bridge site. Both wells are completed in the upper sand and gravel aquifer. A 24-hour constant rate pumping test was conducted for the new Eagle municipal wells TW-3 (MW3) and TW-4 by the Aquifer Science and Technology division of Ruekert Mielke, Inc. The tests were conducted on February 25-26, 2003 and March 10-11, 2003 for TW-4 and TW-3, respectively, using equipment provided by the Layne Northwest Co.

Ground water flow modeling

We created a ground water flow model to test the conceptual models by attempting to calibrate to the observed head and discharge patterns using models with and without bedrock preferential flow paths. The resulting calibrated model is ultimately intended for use by resource managers in the Mukwonago River watershed to assess potential the impacts of urban development.

The Mukwonago River inset model (MRIM) was created from the SEWRPC regional model (Feinstein et al., 2004) using the telescopic mesh refinement (TMR) approach (Ward et al., 1987), which is part of the user interface software Groundwater Vistas 4.19 (Rumbaugh and Rumbaugh, 2004). We assigned fluxes from the SEWRPC model to the boundaries of the MRIM in order to maintain connection with the regional flow system (Ward et al., 1987) (Figure 4a).

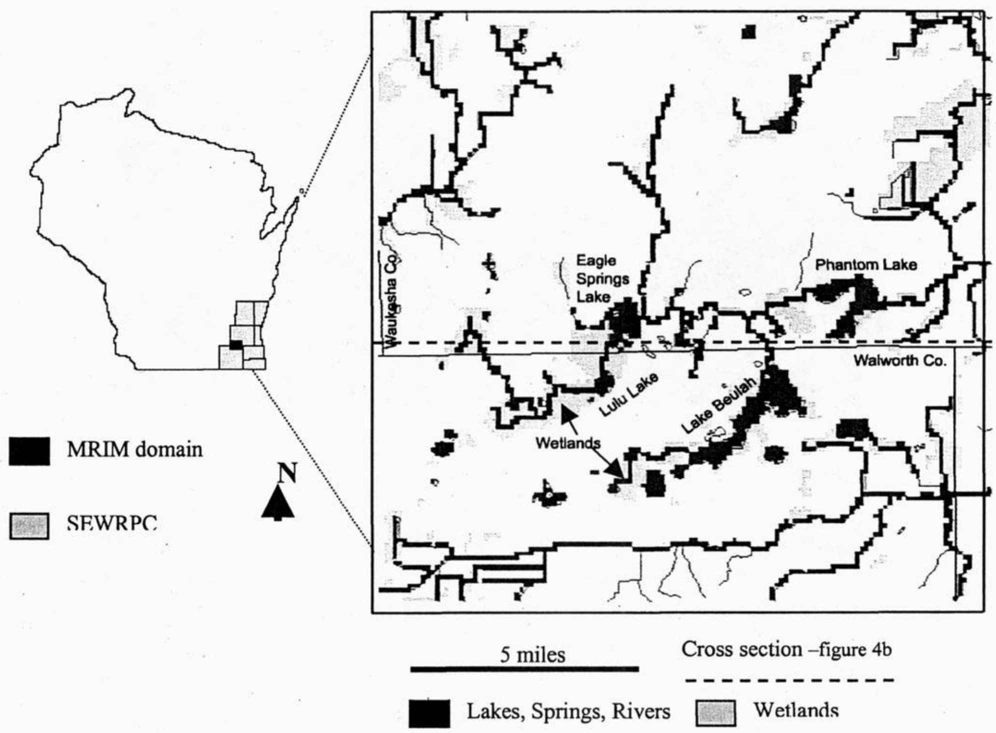

Figure 4a. The Mukwonago River Inset Model (MRIM) domain relative to the South Eastern Wisconsin Regional Model (SEWRPC regional model).

In order to assess the importance of the buried Troy Valley on the localization of springs, special attention was paid during construction of the MRIM to the interface between the buried bedrock valley and adjacent glacial material. Gittings (2005) used a simplified cross-sectional MODFLOW model to assess the effects of model layer structure on simulation of flow across this interface. Based on these results, we concluded that adequate representation of flow from preferential flow zones into a buried bedrock valley requires an approximately horizontal layer structure, with multiple layers spanning the bedrock and adjacent valley sediments. This layer structure differs significantly from that of the regional SEWRPC model, which represents the unlithified aquifer as a single layer of varying thickness (actually varying transmissivity) overlying bedrock layers that are also of varying thickness. Converting the initial TMR model to one with a horizontal layer structure involved addition of many new layers and adjusting hydraulic conductivity (K) zones to correspond to bedrock and sediment properties within a given layer. The final model includes 36 layers with thicknesses grading from 25 ft at the top to 500 ft at the bottom of the model. Three layers with high conductivity represent preferential flow paths (Figure 4b).

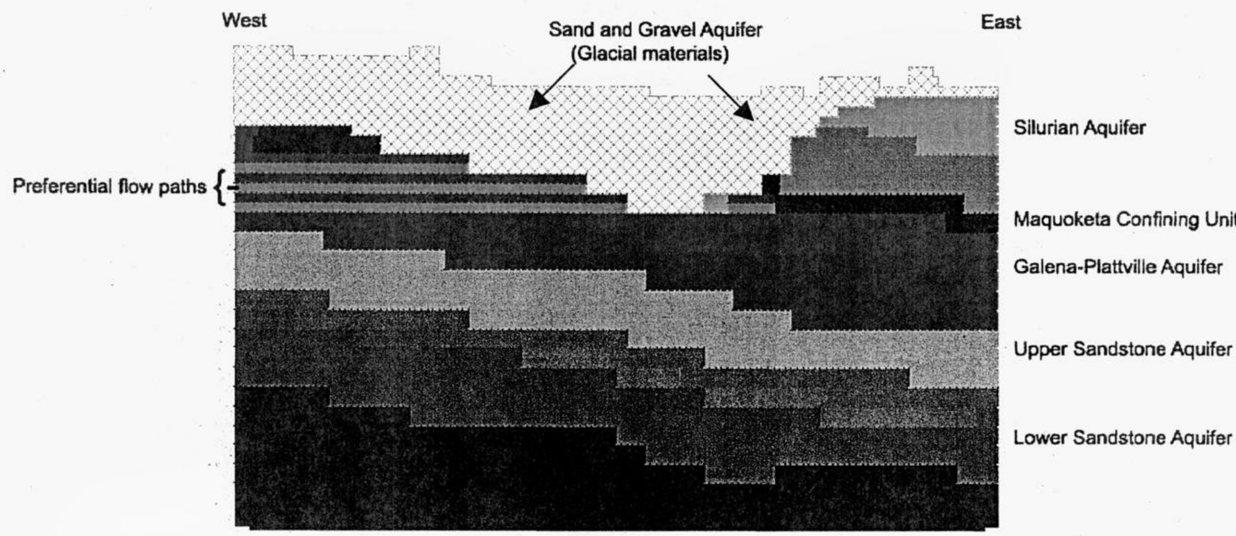

Figure 4b. Representative cross section of the Mukwonago River watershed inset model.

We used a uniform grid spacing to reduce cell dimensions in the horizontal direction from 2500 ft by 2500 ft in the SEWRPC model to 519 ft by 519 ft. Streamflow Package nodes were used to represent the Mukwonago River while River Package nodes represent lakes within the watershed and rivers and lakes outside of the watershed (Prudic, 1989; McDonald and Harbaugh, 1988). Wetlands were represented using the Drain Package (McDonald and Harbaugh, 1988). In general, starting heads were assigned using previous estimates of the water table (SEWRPC, 2002). We calibrated the model to flux targets based on field measurements and head distributions derived from the water table maps prepared by SEWRPC, 2002. Calibration was accomplished through the trial and error procedure as outlined by Anderson and Woessner (1992). Several distributions of recharge were tested during the calibration process including the recharge zonation used in the SEWRPC model and modifications to values within the SEWRPC zones designed to improve calibration to flux and head targets. We found that simulations employing a uniform distribution of recharge over the model area provided as good a match to fluxes as those with zoned recharge. Recharge was applied uniformly across the watershed and was calibrated to match target heads and fluxes for both "drought" conditions as well as more average conditions. The program MODPATH (Pollock, 1989) was used to identify recharge areas for the spring complex upstream of Lulu Lake.

RESULTS AND DISCUSSION

Water level monitoring and stream discharge

During the two year period of this study, precipitation in the Mukwonago River watershed followed its typical pattern of a wet June-July with approximately 3 to 4 inches of rain and a dry February with an average of only 1 inch of precipitation. Overall, 2003 had less precipitation than 2004. However, a particularly dry August, 2003 and an anomalously wet May, 2004 greatly influenced yearly totals and provided extreme conditions within the system during the study. These extremes helped to accentuate the interactions among precipitation, water levels and discharge. Hydrographs for wells in the upper headwaters area and in the Lulu Lake Preserve, show a relatively strong response to recharge from rain events.

Figure 5 shows flow rate measurements taken over short periods of time during June, 2003, August, 2003 and early September, 2004 at various locations along the upper reach of the Mukwonago River near Lulu Lake. In none of these synoptic gaging records does the baseflow increase linearly along the reach of the river as would be expected if there were uniform discharge from the sand and gravel aquifer. Instead, all synoptic gaging records show a dramatic increase in baseflow between sites 6 and 9. Flow measurements in August, 2003 show that approximately 70% of the water that flows into Lulu Lake enters the stream from wetlands and a tributary that originates at single large spring complex located east of Bluff Road and upstream of station 8 shown on Figure 5.

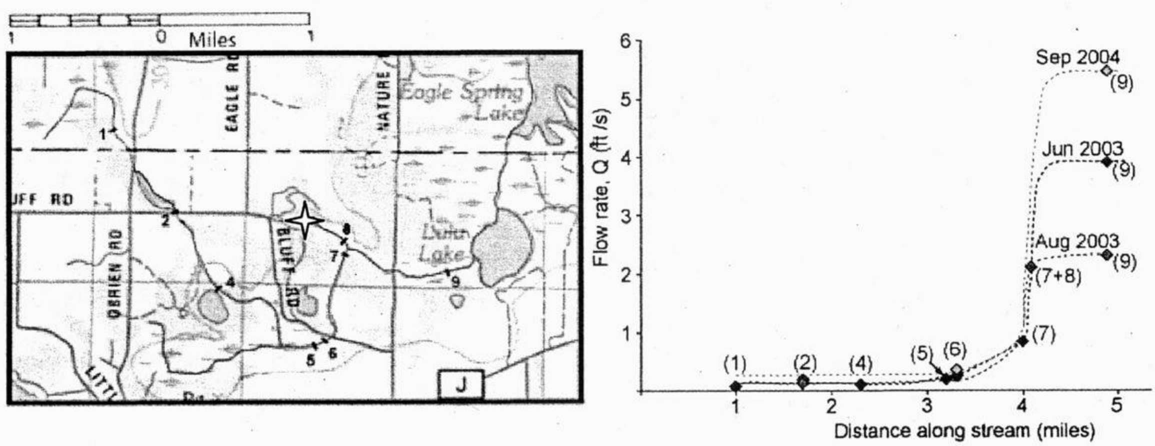

Figure 5. Flow rate measurements and locations taken during June, 2003, August, 2003 and early September, 2004 along the upper reach of the Mukwonago River watershed. The spring location is shown by a star.

Measurements in 2004 in the Lake Beulah area also showed a dramatic increase of flow relative to 2003. In 2003 the lake level was low enough in Lake Beulah that no flow went over the dam at its outlet. However, in early September, 2004 approximately 8.7 ft^3/s was flowing over the dam. A large percentage of the flow into Lake Beulah comes from a section of the stream upstream from the lake but downstream from Pickerel Lake Road. No discharge measurements were taken at this site in 2003 for comparison. However these results suggest that, like the area near Lulu Lake, the flow in this section of the stream may be indicative of preferential flow to this area.

In addition to showing variability over space, discharge to the stream near Lulu Lake Preserve also shows variability over time. Discharge measurements at the bridge upstream of Lulu Lake show a decrease in flow from 3.9 ft^3/s in June, 2003 to 3.5 ft^3/s in early August, 2003 and a minimum of 2.3 ft^3/s in mid-August, 2003, for a total decline of 1.6 ft^3/s during the summer. During the same period, flow measured at the small culvert off of Bluff Road (site 6) upstream of the spring complex also declined from 0.28 ft^3/s in early June to 0.17 ft^3/s.

While an attempt was made to take flow measurements at baseflow, analysis of stilling well records for each year revealed that this was not achieved at all times. However, the stilling well record and flow measurements suggest a scaling between water level and flow changes in the stream allowing for an investigation into the amount of daily decreases in flow due to evapotranspiration as well as seasonal changes in discharge to the stream in 2003 and 2004.

The ratio of change in discharge (ft^3/s) to change in water level (ft) over two days in June 2003 when flow was gaged several times is 6.5, meaning that each 0.01 ft of water level change equals a change of 0.065 ft^3/s in discharge. The same scaling results from comparing discharge and water level measurements over a span of months in 2002.

This scaling can be used to estimate the magnitude of daily flow decreases due to evapotranspiration (assuming that it applies near baseflow conditions). By using the total daily declines in water level measured by the stilling well around June 4-5, 2003 of 0.07 to 0.08 ft, we calculate a loss of about 0.5 ft^3/s due to evapotranspiration over the contributing watershed during a 24 hour period.

The scaling factor can also be used to evaluate seasonal and interannual variations in baseflow. Comparison of an estimated flow record constructed using this scaling to changes in water levels in the sand and gravel aquifer suggests that they respond similarly to seasonal variations in precipitation. The best match was obtained using a time lag of 15 days for the stilling well. Using the relationship between the USGS well hydrograph and the estimated flows at the bridge, it appears that the "average" baseflow is on the order of 3.5 ft^3/s.

The 0.7 ft^3/s difference between baseflow in early June, 2003 and early September, 2003 represents approximately 20% of the total baseflow (3.7 ft^3/s) estimated for June, 2003. This decrease in baseflow is the result of the abnormally dry summer weather, indicating that the source of at least some of the baseflow is an aquifer (such as the sand and gravel tapped by the USGS well) that responds to short term variations in precipitation with a lag of less than a month.

For 2004, baseflow in early October was essentially equivalent to baseflow in April (both approximately 3.5 ft^3/s). During the unusually wet summer of 2004, discharge at the Lulu bridge increased to over 4 ft^3/s, with the increase in flow preceding the seasonal increase in water levels in the USGS well. The lag in the USGS well is the result of a delay in recharge reaching the water table compared to the rapid response of the stream to runoff and drainage from flooded wetland areas. At the end of 2004, baseflow likely returned to its "normal" value of approximately 3.5 ft^3/s.

The pumping tests of the new Eagle municipal wells conducted by Ruekert Mielke Inc. Consulting showed very little drawdown in any of the observation wells. This reveals a highly transmissive (41,500 ft^2/d) and unconfined sand and gravel aquifer. Negligible drawdown was observed in the residential monitoring wells during the time of the pumping tests (Jansen, personal communication). No response to the pumping-test was seen in any of our monitoring wells either in the upper headwaters area or further downstream near Lulu Lake.

Major ion analysis

Field measurements including temperature, pH, conductivity as well as colorimetric analyses from the date of sampling are listed in Table 2 in Appendix B. These measurements, along with major ion chemistry analysis, reveal that water samples within the watershed are predominantly calcium-bicarbonate. Some samples show elevated concentrations of Na^+ and Cl^-. However, these samples are all located close to roads and may be influenced by the presence of road salt. Overall, the samples show little variation in major ion facies. Thus, major ion facies cannot be used in this system to identify the source of water to the springs, river and wetlands.

A plot of Ca versus Sr reveals no correlation between these elements. Were this system controlled by a simple- two component mixing in which both Ca and Sr behave conservatively, a linear correlation would be expected. Because no trend exists it can be concluded that the system includes waters that originate from more than two distinct sources. A plot of Sr concentrations versus $^{87}Sr/^{86}Sr$ ratio also reveals no obvious correlation. This is not surprising as the effects of water-rock interactions on element concentrations are different from those on isotopic ratios (Johnson et al., 2000).

Strontium isotope analysis

The results of Sr isotope analysis are in Appendix B Table 3. Simple mixing calculations were conducted based on the assumption that water equilibrated with the bedrock mixes with water similar to that produced from a new well completed in the sand and gravel aquifer to provide municipal supply to Eagle. These assumptions, which correspond to the conceptual model without preferential flow paths, indicate that small amounts of high Sr concentration water from the bedrock would be sufficient to explain the shift observed in $^{87}Sr/^{86}Sr$ ratios of spring water from that of the sand and gravel. According to these calculations and using the Ordovician dolomite and the Silurian-Ordovician dolomites as bedrock aquifer end members, a maximum of 5% of the water to the Lulu Lake principal springs would originate in a deeper aquifer unit, consistent with spring discharge being controlled primarily by water flow and storage in the sand and gravel aquifer. However, these mixing calculations do not reproduce the observed $^{87}Sr/^{86}Sr$ ratios exactly and the major ion ground water chemistry does not reflect simple two component mixing. Furthermore, stream baseflow supported primarily by the sand and gravel aquifer does not explain the focused discharge at the springs.

The second conceptual model, in which spring flow is dominated by bedrock preferential flow zones, would be consistent with the observed $^{87}Sr/^{86}Sr$ ratios of the springs if dissolution rates are slow and the residence time in the bedrock is short, both of which are reasonable assumptions in the presence of preferential flow paths such as those identified in bedrock of Dane County. However, discharge supported entirely by bedrock preferential flow paths is not consistent with the observed decrease in baseflow that accompanies seasonal water level declines in the sand and gravel aquifer in the Mukwonago River watershed. As demonstrated by analytical models described in Swanson and Bahr (2004), spring discharge dominated by bedrock preferential flow paths is likely to be steady over time even in the case of significant seasonality of recharge.

Revised conceptual model based on mixing and preferential flow paths

A revised conceptual model that includes both preferential flow zones and mixing of water from the bedrock with water from the sand and gravel overcomes the limitations of the two original conceptual models. The revised conceptual model involves water moving through preferential flow paths in the Silurian or Ordovician carbonate and mixing with water from the sand and gravel aquifer before discharging at the surface (Figure 6).

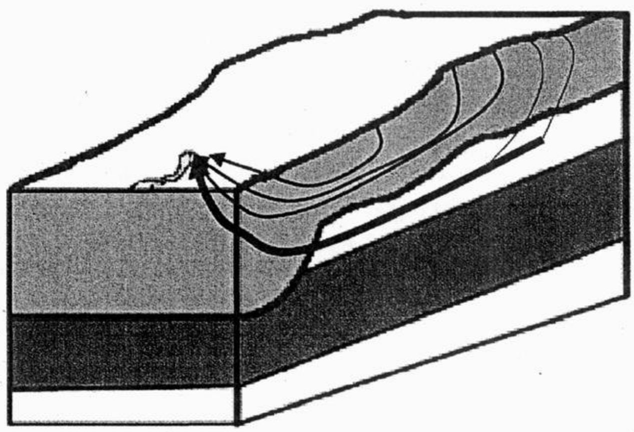

Figure 6. The revised conceptual model including preferential flow paths in the underlying bedrock. Focused discharge results where the high conductivity flow path intersects the edge of the bedrock valley. The resulting spring is a mixture of water from the bedrock preferential flow zone and the upper sand and gravel aquifer.

The $^{87}Sr/^{86}Sr$ isotopic ratio and mixing calculations of water discharging at boils in the spring complex west of Lulu Lake indicates that 15-100% of the water could originate from a bedrock source. Preferential flow paths in the bedrock would provide a conduit for rapid flow, resulting in limited contact time to dissolve Sr bearing minerals and, hence, significantly lower Sr concentrations in spring water relative to water equilibrated with the bedrock during longer contact times, represented by points C2 (Ordovician dolomite) and B2 (Silurian and Ordovician carbonates) on Figure 7.

Because the Ordovician dolomite has the lowest $^{87}Sr/^{86}Sr$ ratio of the various bedrock units (point C2 on Figure 7), 15% represents the lower limit of the total amount of water contributed to the springs from the bedrock under this scenario. Larger percentages of bedrock preferential flow path water discharging to the springs would be estimated using a combined Silurian and Ordovician carbonate signature such as B2, with an upper bound of 100% if the preferential flow path water corresponds to a mixture of Cambrian and Ordovician water, represented by D2.

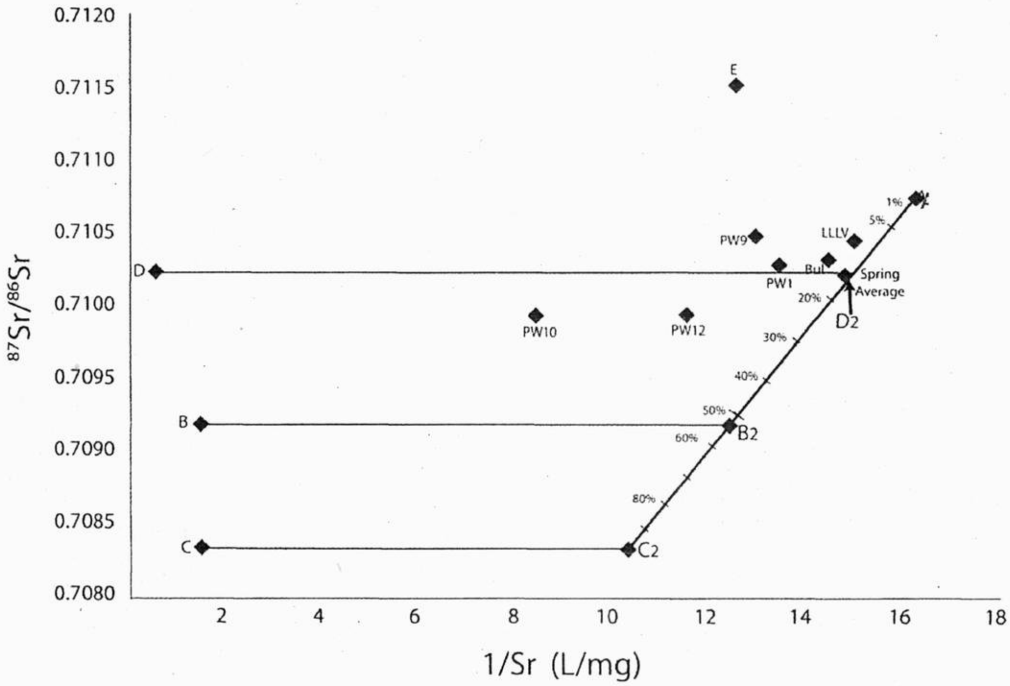

Figure 7. Samples plotted relative to mixing line for a new end member C2, representing waters from a preferential flow path. B2 and D2 represent the location of their preferential flow path end members. End members are for waters in the sand and gravel aquifer (A), Silurian-Ordovician dolomite mix (B), Ordovician dolomite (C), and a well pumping a mixture of Cambrian and Ordovician waters (D).

The observed correlation between seasonal variations in flow downstream of the springs west of Lulu Lake and water level variations in the sand and gravel aquifer suggests that the shallow aquifer does contribute water to the springs. Assuming that all baseflow loss can be attributed to decreased discharge from the glacial deposits, a lower limit of 20% is placed on total discharge from the sand and gravel aquifer to the stream with a corresponding upper limit of approximately 80% placed on discharge from a bedrock source.

Discharge measurements at the Lulu Lake bridge show greater changes over time than discharge upstream of the spring complex (Figure 5). Thus, some of the "concentrated" discharge must be coming from an aquifer that responds to seasonal variations in recharge. This suggests that changes in spring discharge (or of discharge in the area around the springs) are related to water level changes in the sand and gravel aquifer associated with temporal variations in recharge.

The spatial distribution of $^{87}Sr/^{86}Sr$ ratios within the upper Mukwonago River watershed provides the basis for an interpretation of discharge sources upstream of Lulu Lake and in portions of the Lake Beulah area. The Sr isotope data suggest that discharge from bedrock preferential flow paths is an important source of baseflow to the large spring complex west of Lulu Lake. Samples taken from other sites upstream of this spring complex indicate that groundwater discharging to the stream is principally from the shallow sand and gravel aquifer. It should be noted that groundwater discharge between the headwaters and the spring complex during low flow conditions totals less than 0.85 ft^3/s, or less than 37% of the flow measured at the bridge upstream of Lulu Lake.

$^{87}Sr/^{86}Sr$ ratios from the Lake Beulah area in the southeastern portion of the watershed suggest that a fraction of these waters also originate from a bedrock source. These samples show slightly elevated $^{87}Sr/^{86}Sr$ ratios compared to those from the western portion of the valley, indicating that they may be, in part, mixing with water from the Silurian bedrock. Strontium isotope measurements of a spring flowing into Lake Beulah show similar values to those of the spring complex upstream of Lulu Lake, suggesting the presence of a similar preferential flow path from a bedrock source in the area.

Ground water modeling

The calibrated ground water model of the Mukwonago River watershed (MRIM) simulated fluxes of 2.3 ft^3/s Lulu Lake Preserve and 14.5 ft^3/s at the Mukwonago site under drought conditions and 2.8 ft^3/s within the Lulu Lake Preserve and 17.6 ft^3/s in downstream areas during more average conditions.

Model calibration and sensitivity tests indicate that high conductivity zones play an important role in sustaining baseflow to the springs and wetlands in the watershed. Removal of the high conductivity zones in the Sinnipee dolomite (Ordovician) under low recharge conditions resulted in a 17% reduction of discharge to the springs near Lulu Lake and at the bridge upstream of Lulu Lake. Compared to the model incorporating high conductivity layers, a model without these simulated 14% less flow over the dam at Lake Beulah as well as 27% less flow in the Mukwonago River just upstream of the confluence with the Lake Beulah Branch. Overall the simulated Mukwonago River flow decreases by 23% with the removal of bedrock high conductivity zones. Removal of high conductivity bedrock zones for conditions with higher recharge resulted in similar percentage decreases in flow.

When modeled with high conductivity zones present, baseflow in reaches of the Mukwonago River upstream of Lulu Lake does not increase uniformly with distance along the stream, consistent with observed field measurements showing distinct areas where baseflow increases significantly over a short distance. Removal of the high conductivity paths from the simulation results in a more linear increase in discharge, although there is still an increase in flow at locations directly above the edge of the valley.

The program MODPATH (Pollock, 1989) was used to identify recharge areas for the spring complex upstream of Lulu Lake. Reverse particle tracking from these springs indicates that while the overall lengths of the flow paths through bedrock and glacial deposits are similar, the recharge areas are quite distinct (Figure 8).

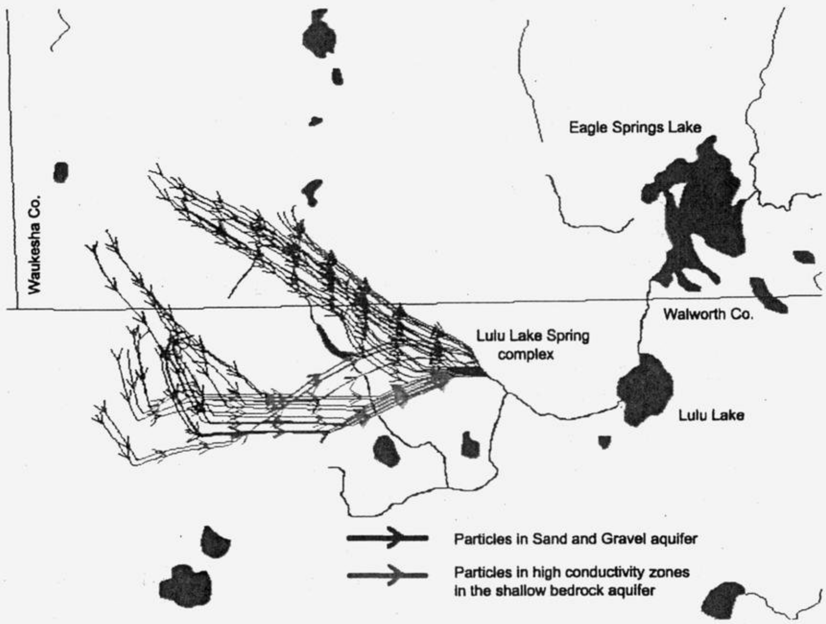

Figure 8. MODPATH (Pollock, 1989) reverse particle tracking is used to identify recharge areas for the spring complex upstream of Lulu Lake. Red paths indicate particles within high conductivity zones in the shallow bedrock. The overall lengths of the flow paths through bedrock and glacial deposits are similar, while the recharge areas are quite distinct.

Swanson and Bahr (2004), found that recharge flowing through bedrock preferential flow paths, even when recharge areas originate in relatively nearby areas, experiences a damping of seasonally influenced flow variations. Thus, one would expect to see less temporal variability in baseflow from reaches of the Mukwonago River watershed that are supported, at least in part, by bedrock aquifers compared to reaches along which baseflow is generated nearly exclusively by discharge from the sand and gravel aquifer. As discussed earlier, during the dry summer of 2003 baseflow conditions at Lulu Lake remained relatively constant while water levels in areas supported primarily by discharge from the sand and gravel declined rapidly. In contrast to the sustained flow observed upstream of Lulu Lake, during this time period discharge levels to Lake Beulah were low enough that no water was seen flowing over the small dam at its outlet. These observations suggest that total baseflow in reaches upstream of Lake Beulah is more dependent on the sand and gravel aquifer than is baseflow upstream of Lulu Lake.

CONCLUSIONS AND RECOMMENDATIONS

The goal of this research was to identify controls on ground water discharge into the Mukwonago River in order to allow assessment of the impacts of increased urban expansion including increased pumping from the sand and gravel aquifer as well as increased runoff from impervious surfaces.

The results of the investigations above indicate that flow in the Mukwonago River is dependent on ground water discharge from multiple aquifers. These observations suggest, contrary to previous studies, that a significant amount of water in the river may be contributed not only by the upper sand and gravel aquifer, but also from the bedrock units. Low total Sr concentrations for spring waters in the area indicate that flow through the bedrock aquifer is relatively fast, possibly due to highly conductive, preferential flow zones. Other researchers (Bradbury et al., 1998; Muldoon, 1999; Swanson et al., 2006) have identified thin laterally extensive, high permeability zones that affect ground water flow patterns at a regional scale. These zones could be the result of bedding plane partings, solution features and/or fractures. In the Mukwonago River watershed, water flowing from recharge areas through such preferential flow zones in the bedrock appears to mix with water from the sand and gravel aquifer before it is discharged at the surface.

In the springs west of Lulu Lake the estimated contribution from the shallow bedrock ranges from approximately 15%-80% of the total discharge. Calibration and sensitivity analyses of a numerical ground water flow model support the conclusion that shallow bedrock is a significant source of water to the springs. Models that do not include a high conductivity layer in the Ordovician dolomite predict 17% less flow than models with a high conductivity layer. Decreases in baseflow that were observed during dry periods and that correlate with declines in water levels in the sand and gravel aquifer indicate that at least 20% of the total discharge to the stream comes from the sand and gravel aquifer. Most of the baseflow flow in the extreme upper-most reaches of the Mukwonago River is supplied nearly exclusively by discharge from the sand and gravel upper aquifer. Sr isotope signatures indicate that bedrock aquifer discharge to the spring at Lake Beulah is primarily from the Silurian dolomite rather than from the Ordovician units that are inferred as sources for springs on the northwestern side of the buried Troy Valley.

Urbanization in this area threatens to increase runoff as well as decrease water levels in the upper sand and gravel aquifer. Increased impervious surfaces, as noted in the introduction, will decrease the amount of recharge to the upper sand and gravel aquifer. While the presence of preferential flow from the shallow bedrock to the springs may help to damp immediate impacts of pumping in the upper aquifer, decreased water levels still threaten the fragile ecosystem supported by the streams and wetlands in the watershed. Pumping in the glacial deposits that are along the flow paths through that aquifer is likely to have an impact on spring flow. However, increased urbanization may also decrease recharge to the shallow bedrock. Ground water modeling indicates that the recharge area for both the bedrock and sand and gravel aquifers discharging to the spring complex near Lulu Lake lie relatively close to the springs themselves. Therefore, maintaining local recharge is important to maintaining spring flow. While the initial particle tracking simulations suggest a local recharge source for water transported in bedrock preferential flow zones, it is also possible that some of the water captured by these flow zones originates from recharge areas to the west/northwest of the watershed, outside the boundaries of the inset model. Urbanization in these areas may also affect flow to the springs and the watershed within the Troy Valley.

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Appendix A. Publications and Presentations

Publications

Gittings, H.E., 2005. Hydrogeologic controls on springs in the Mukwonago River watershed, SE Wisconsin. M.S. thesis, University of Wisconsin –Madison, Department of Geology and Geophysics.

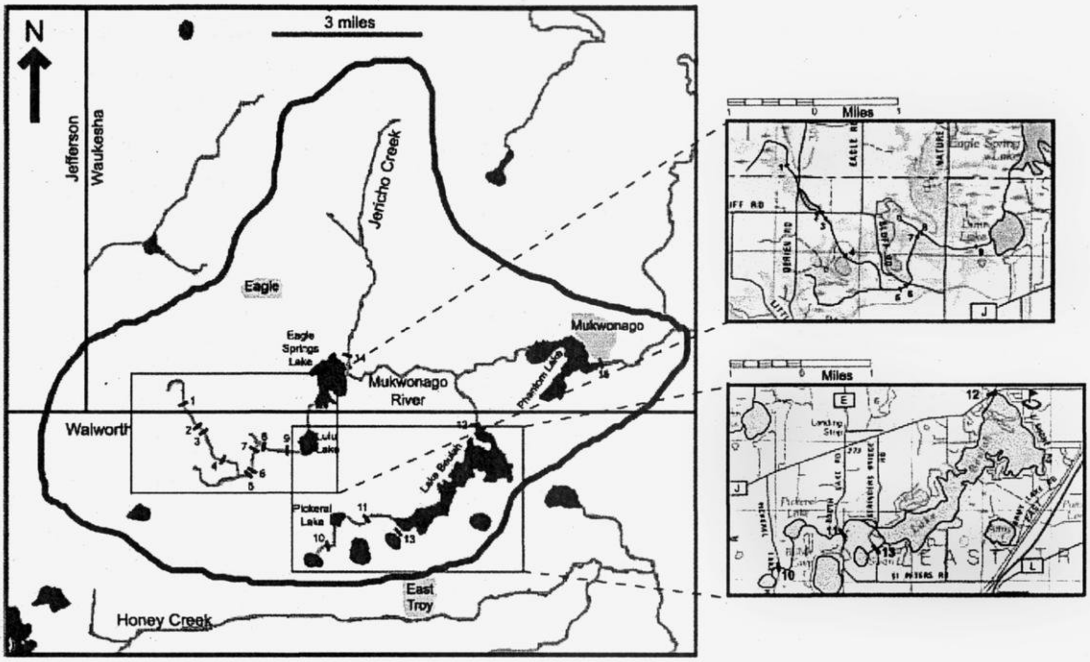
Presentations

Gittings, Hilary E and Bahr, Jean M, 2003. Hydrogeologic controls on springs in the Mukwonago River watershed, SE Wisconsin GSA Annual Meeting Abstracts with Programs, vol. 35.

Gittings, Hilary E and Bahr, Jean M, 2004. American Water Resources Association - Wisconsin Section 28th Annual Meeting Program and Abstracts.

Appendix B.

Table 1. Locations and results of stream discharge measurements in the Mukwonago River watershed.



Stream Discharge Measurements				
Location	* unless noted all measurements used the pygmy meter			
Q (ft^3/sec)	Date	Time	Staff Gage (ft)	Site number
Upper Reaches Mukwonago				1
0.08	6/4/2003	3:00 PM		
Culvert on Bluff Road 1				2
0.24	6/4/2003	4:00 PM		
0.28	6/4/2003			
0.08	7/2/2003	4:00 PM		
0.08	7/2/2003			
0.17	8/5/2003	1:30 PM		
South of Culvert on Bluff Road		Bucket method		4
0.14	6/4/2003			
Bluff Road		orange method		5
0.19	6/4/2003			
0.2	6/4/2003			
Culvert on Bluff Road 2				6
0.32	6/5/2003	9:30 AM		
0.33	9/4/2004	8:30 AM		
Down stream of Bluff Road Springs				7
0.85	6/5/2003	3:45 PM		
Branch 1 of Spring Complex				8
1.07	8/13/2003			
Lulu Lake Bridge				9
3.90	9/24/2002	3:30 PM	0.41	
2.92	11/23/2002	12:30 PM	0.38	
3.90	6/4/2003	11:55 AM	0.36	
3.64	6/5/2003	8:30 AM	0.35	
3.50	8/5/2003	10:45 AM	0.31	
2.30	8/13/2003	3:15 PM	0.28	
2.55	8/20/2003	12:00 PM	0.26	
3.36	9/6/2003	6:00 PM	0.28	
5.46	9/4/2004	10:00 AM	0.34	

Stream Discharge Measurements			
Location	* unless noted all measurements used the pygmy meter		
Q (ft^3/sec)	Date	Time	Site number
Pickeral Lake Road			10
not enough to measure	7/1/2003		
not enough to measure	9/4/2004		
Booth Lake Rd- circular culvert			11
8.56	9/4/2004	11:45 AM	
Dam outlet from Beulah			12
0.00	8/5/2003		
0.00	8/13/2003		
8.68	9/4/2004	12:40 PM	
Stringers Bridge Rd- circular culvert			
0.01	9/4/2004	12:15 PM	13
Jericho Creek			14
0.72	7/1/2003	1:30 PM	
0.81	9/4/2004	3:47 PM	
Under bridge east of mukwonago			15
33.0	9/4/2004	2:40 PM	
Route N near Wilton Road			
1.65	7/2/2003	9:15 AM	
Route N near Wilton Road (main channel just upstream of confluence)			
1.56	7/2/2003	11:30 AM	
Paradise Springs			
0.96	7/2/2003	10:45 AM	
Route Z on upper springs Lake River (west side of river)			
3.87	7/2/2003	1:15 PM	
Route 59 near crossroads of 59 and Z (north of road and culvert)			
1.33	7/2/2003	2:30 PM	

Table 2. Field Chemistry Data

Field Chemistry									
Name	Type	Date	pH	Conductivity (us/cm)	Temp (C)	D.O. ppm	Iron ppm	Total Alk ppm	Nitrate-N ppm
LLBr	open stream	7/17/2003	8	536	-	10-12	<0.1	270	-
LL2a	hand augered well	7/17/2003	7.5	497	-	3-4	<1	250	-
LL2b	hand augered well	7/17/2003	7.4	-	16	1-2	<1	250	-
LLB1	spring boil	5/17/2004	6	672	11.3	10	0	286.5	-
LLB2	spring boil	5/17/2004	5.9	681	9.2	8-10	0	268.2	2.5-3
LLB3	spring boil	5/17/2004	7.4	673	10.2	8-10	0	286.5	2.5-3
LLB4	spring boil	7/16/2003	7.2	645	9.6	5-6	<0.1	200	1.5-2.0
LLB5	spring boil	7/16/2003	7.1	538	-	2-3	0.4	225	0
LLPR	spring boil	7/16/2003	8	441	-	6	<0.1	220	-
LLLV	shallow well	6/1/2004	7.2	606	13.1	3-4	0-0.1	225.5	0
PW1	shallow well	7/7/2004	7	463	10.9	10-12	0.8-1.0	243.8	0.2-0.3
PW2	shallow well	7/7/2004	7.3	575	10.2	6-8	0.2-0.3	243.8	0.8-1.0
PW4	shallow well	6/1/2004	7.4	600	11.4	<1	1-2	292.6	0-0.1
PW5	shallow well	7/16/2003	6.9	592	11.4	0.4	10	320	-
PW6	hand augered well	7/16/2003	7.6	600	13.7	6	1-2	320	-
PW7	open stream	6/22/2004	7.8	727	17.8	8-10	0	243.8	1
PW8	open stream	7/17/2003	7.8	533	-	8-10	0.2-0.3	170	-
PW9	shallow well	6/22/2004	7	842	12.5	1-2	0-0.1	243.8	1.5-2.0
PW10	shallow well	1/31/2004	7.6	-	1.6	5-6	1-2	268.2	-
PW11	deep well	1/31/2004	7.7	-	2.6	4-5	2-3	268.2	-
PW12	shallow well	6/22/2004	7	582	12.9	1-3	1-2	243.8	0-0.1
MW2	deep Eagle well	6/1/2004	7.4	483	13.6	2-3	0.2-0.3	243.8	0
MW3	shallow Eagle well	6/1/2004	7.1	910	11	5-6	0	317	4-5
Bul	spring	7/1/2004	-	130	12.2	4-5	0	243.8	-

Table 3. Strontium Data

Strontium Analysis				
Name	Type	Date	87Sr/86 Sr	Sr mg/L
LLBr	open stream	7/17/2003	0.7103	-
LL2a	hand augered well	7/17/2003	0.71018	-
LL2b	hand augered well	7/17/2003	0.71022	-
LLB1	spring boil	5/17/2004	0.71018	0.0662
LLB2	spring boil	5/17/2004	0.71021	0.0653
LLB3	spring boil	5/17/2004	0.71023	0.07
LLB6	spring boil	5/17/2004	0.71017	-
LLB4	spring boil	7/16/2003	0.71044	-
LLB5	spring boil	7/16/2003	0.71018	-
LLPR	spring boil	7/16/2003	0.71031	-
LLLV	shallow well	6/1/2004	0.71044	0.0663
PW1	shallow well	7/7/2004	0.71028	0.0738
PW2	shallow well	7/7/2004	-	0.0764
PW4	shallow well	6/1/2004	0.71152	0.0789
PW5	shallow well	7/16/2003	0.71027	-
PW6	hand augered well	7/16/2003	0.71118	-
PW7	open stream	6/22/2004	0.71083	-
PW8	open stream	7/17/2003	0.71068	-
PW9	shallow well	6/22/2004	0.71048	0.0766
PW10	shallow well	1/31/2004	0.70993	0.1178
PW11	deep well	1/31/2004	0.70919	0.6821
PW12	shallow well	6/22/2004	0.70994	0.086
MW2	deep Eagle well	6/1/2004	0.71024	1.9757
MW3	shallow Eagle well	6/1/2004	0.71074	0.0616
Bul	spring	7/1/2004	0.71032	0.0686