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Hydrostratigraphy of west-central Wisconsin: A new approach to groundwater management

Final report to the University of Wisconsin Water Resources Institute

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Project Summary

Title	Hydrostratigraphy of West-Central Wisconsin: A new approach to groundwater management
Project I.D.	05-HDG-02
Investigators	Dr. David L. LePain, Stratigrapher/Assistant Professor, Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension Dr. Kenneth R. Bradbury, Hydrogeologist/ Professor, Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension Michael K. Cobb, Research Assistant, University of Wisconsin – Madison, Department of Geology and Geophysics
Period of Contract	July 1, 2004 through June 30, 2005

Background/ Need

The bedrock that provides the primary water supply for west-central Wisconsin is both lithologically and hydraulically diverse, forming a complex sequence of aquifers and confining units, variably interconnected, and each of unique hydrogeologic character. Though this heterogeneity is an accepted fact, documented in studies in neighboring areas, there has been no significant work to develop a hydrogeologic framework specific to the bedrock of the region. A detailed hydrostratigraphic model – giving the sequence and properties of bedrock based on distinct hydrogeologic character – is sorely needed. Such a model will be a synthesis of a wide assortment of data, ideally incorporating all parameters affecting groundwater occurrence and flow for each distinct interval in the bedrock section. At the commencement of this project, it was unclear what useful hydrostratigraphic data might already exist, and hence where additional study was most needed.

Objectives

This project takes the first step toward a comprehensive hydrostratigraphic model of west-central Wisconsin. The objectives were as follows:

- Identify and compile all of the relevant hydrostratigraphic data that exist;
- Review these available data resources with respect to relevance and data quality;
- Synthesize, to the degree feasible, the data that do exist; and
- Identify major data gaps remaining.

Methods

The project focused on the Cambrian-Ordovician strata within Pierce, St. Croix and Dunn Counties. We identified types of data that were needed for a hydrostratigraphic model, determined the most likely sources of those data and then sought to acquire them – generally from state agencies, and municipalities. Whenever feasible, we have compiled these data sources as scanned files on a data CD, available from the WGNHS. Limited data reduction, mostly of digital well log data and hydrogeologic parameters, was completed using standard electronic spreadsheet, database and GIS tools. Hydraulic conductivity values were estimated from specific capacity tests for more than 8000 well logs using a new spreadsheet version of TGuess (Bradbury and Rothschild, 1985), developed for this project. The updated TGuess program is included on the data CD.

Results and Discussion

Of a great many contaminated site investigations completed in the region, 16 were found that contain useful hydrostratigraphic data (e.g., hydraulic tests and other studies of bedrock hydrogeology). These investigations are geographically skewed toward populated areas, and generally focus on only the uppermost intervals of bedrock. Forty-five geotechnical reports by the Wisconsin and Minnesota departments of transportation provide some additional detail on bedrock lithology, but generally have little or no data of a hydraulic nature. Municipal water authorities have some of the only data for the deeper aquifers – most private and environmental test wells are comparatively shallow. A limited dataset of downhole geophysics and video logs are available for town water-supply wells.

Three statewide electronic databases of completed wells (maintained by the WDNR and WGNHS) are the most comprehensive data resource, with greater than 14,000 wells in the study area. The utility of these data is, however, limited by their frequent lack of detail and poor data quality. The well logs' specific capacity test data does permit a rough estimation of hydraulic conductivity, albeit subject to large uncertainties about data quality.

Evidence of karst in the region's carbonate rocks (particularly the Ordovician Prairie du Chien Group dolomite) is widespread but mostly observational. Various spring and sinkhole studies have been completed, but no data exist that provide a coherent model of modern karst processes. The WGNHS now maintains a karst features inventory, but the dataset is largely incomplete.

Conclusions and Recommendations

The data that currently exist are inadequate to develop a fully coherent hydrostratigraphic conceptual model. Sufficient data exist to suggest parallels with the better-constrained hydrostratigraphy of eastern Minnesota (Runkel et al, 2003), but not to independently verify it. The sequence, thickness, and lithologic character of the bedrock is the best constrained element of the hydrostratigraphy at this time. The intrinsic hydraulic properties of the rock are less well known. Hydraulic conductivity values (from consulting reports, municipal well tests, and specific capacity test analyses) exist for several broadly defined intervals, but are not adequately depth-precise and continuous to allow differentiation of aquifers and confining units. There is also a complete lack of vertical hydraulic conductivity values. The relative importance of intergranular porosity, fractures, and karst conduits is completely unknown. No porosity data exist, and only limited well video and downhole geophysical logs constrain the degree of fracturing. The function of karst in the carbonate units is especially uncertain. There are numerous examples of sinkholes, caves and solution-enlarged cavities, but no work has been done to identify integrated karst systems, patterns of karst development, or to describe the effect of karst on groundwater flow patterns.

Related Publications

Pending release as a WGNHS Open-File report.: Hydrostratigraphic Data Resources for West-Central Wisconsin, Open-File Report 2005-04.

Key Words

Hydrostratigraphy, west-central Wisconsin, Pierce County, St. Croix County, Dunn County, specific capacity tests, TGuess, well-constructor reports.

Funding

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1 Introduction

In west-central Wisconsin, the groundwater flowing through the sandstone and dolomite of the Paleozoic bedrock forms the area's most significant water resource. The stratigraphy of these rocks has been much studied, with the section parsed into eleven distinct formation-level units spanning the Cambrian and lower-Ordovician. The hydrostratigraphy – the sequence and properties of bedrock based on distinct hydrogeologic character – is, by comparison, only poorly understood. In an early and often-cited report on the hydrogeology of the area, *Ground-Water Resources and Geology of St. Croix County, Wisconsin* (Borman, 1976), the hydrogeologic properties of the entire bedrock section are characterized as a single undifferentiated unit, called the sandstone aquifer. This unit-lumping super-aquifer approach to hydrostratigraphy was an unfortunate necessity given the data available at the time, but it is now generally recognized as a major simplification. Statewide and regionally, the trend has long been toward unit differentiation, and a recognition of the importance of heterogeneities (e.g., Kammerer, 1984; Young, 1992; Eaton et al, 2000; Runkel et al, 2003). In west-central Wisconsin, there is now a general awareness that hydrogeologic heterogeneities pervade the bedrock, but there has not been adequate local study to demonstrate how they are actually significant – for instance, what implications hydrostratigraphic heterogeneity may have on water-resources protection and development.

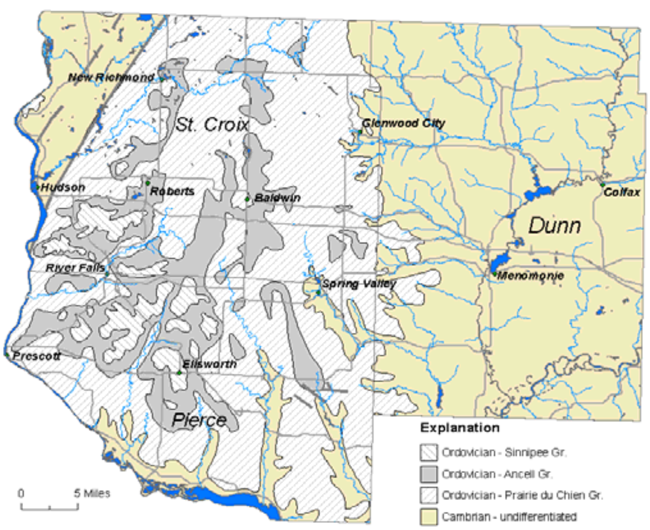

Figure 1. Project study area with simplified bedrock geology. Modified from Mudrey and others (1997) and Brown (1988).

This project is a first step toward a comprehensive hydrostratigraphic model of west-central Wisconsin. The project compiles existing data on the geology and hydraulic properties of the Cambrian-Ordovician strata within the west-central Wisconsin study area, defined as Pierce, St. Croix and Dunn Counties (Figure 1). We review the hydrostratigraphic data resources now available, with discussion of relevance and data quality. The principal product of this project is a data CD, for which this report serves as accompanying documentation. The data CD contains a variety of primary and secondary data resources which have been scanned and graphically indexed and placed, to the degree feasible, in a searchable format. The data CD is available from the Wisconsin Geological and Natural History Survey (WGNHS), and is intended as a data resource for groundwater professionals and researchers practicing in the region.

1.1 Background

The Pierce, St. Croix and Dunn County study area is distinctive as a broad upland flanked by three major rivers: the St. Croix, Mississippi and Chippewa. The bedrock geology of the region was mapped at 1:250,000 scale in two WGNHS maps (Brown, 1988; Mudrey et al., 1987).[1] Figure 1 shows a simplified version of the bedrock geology. The youngest bedrock present, capping hilltops in western Pierce and St. Croix counties, is the Upper Ordovician Sinnippee Group. The youngest water-bearing rocks are in the Upper Ordovician St. Peter Formation (Ancell Group). The Upper Cambrian Mt. Simon Formation is

[1] The WGNHS is currently in the middle of a multi-year State-Map project to update and refine the bedrock stratigraphy of the area.

everywhere the basal Paleozoic rock, overlying the Precambrian basement. Figure 2 shows the general stratigraphic column of the Paleozoic section.

System	Group	Formation	Principal Lithology
Ordovician	Sinnipee	Platteville	dolomite
	Ancell	Glenwood	shale
		St. Peter	sandstone
	Prairie du Chien	Shakopee	dolomite & sandstone
		Oneota	dolomite
Cambrian	Trempealeau	Jordan	sandstone
		St. Lawrence	dolomite
	Tunnel City	Mazomanie / Lone Rock	sandstone
	Elk Mound	Wonewoc	sandstone
		Eau Claire	shale & sandstone
		Mt. Simon	sandstone

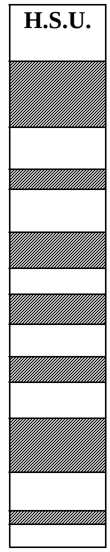

Figure 2.
Stratigraphic column of major units present in the project study area. Relative thicknesses are approximate. The hydrostratigraphic units (H.S.U.) refer to the intervals designated by Runkel et al (2003) for the respective units in southeastern Minnesota. Cross-hatched intervals are interpreted as aquitards, open intervals as aquifers.

Extensive work in neighboring portions of Minnesota has broken the coincident sequence of Paleozoic bedrock into 14 hydrostratigraphic units (Runkel et al., 2003; Figure 2). Rather than a single homogeneous groundwater mass in a uniform medium, this framework divides the section into seven aquifers and seven aquitards, variably interconnected, and each of unique hydrogeologic character. As will be discussed, this framework generally appears to hold in west-central Wisconsin. However, it is a correlation based on apparent uniformity in lithostratigraphy, tectonic setting, and erosional history – not on the sorts of direct hydrogeologic measures that would permit independent development of a hydrostratigraphy.

2 Methods

The principal tasks of the project were to identify and compile existing data. The methods employed, therefore, were quite straight forward. We identified types of data that were needed for a hydrostratigraphic model, determined the most likely sources of those data and then sought to acquire them (from state agencies, municipalities, etc.).

A hydrostratigraphic model depends on a synthesis of hydrogeologic and stratigraphic data. Useful data can be found in a variety of forms, but it all generally relates to one or more central questions that must be answered to fully develop a hydrostratigraphic model. Table 1 indicates four central questions, and the relevant data types sought to answer them.

Table 1. Hydrostratigraphic data types

Hydrostratigraphic Question	Relevant Data Types Sought
What is the stratigraphy – the physical sequence, thickness and continuity of the rock units?	• Well logs • Surface mapping • Geophysical studies
What are the intrinsic hydraulic properties of the rock – porosity, conductivity and storativity?	• Hydraulic testing (slug tests, pumping tests, specific capacity tests) • Rock porosity and permeability tests
What is the relative importance of intergranular, fracture and karst-conduit porosity in groundwater flow?	• Borehole geophysics, caliper, flow metering and well video • Discreet interval (packer) tests • Tracer tests • Spring and sinkhole studies
What are the lateral and vertical hydraulic relationships within and between units?	• Vertical gradient assessments • Potentiometric surface mapping

Data of the types described above are widely distributed and can be challenging to find, and not all data types exist for the study area. For this project, we have attempted to locate and compile as many relevant data sources as possible. Some minor sources were almost certainly missed. The data sources that were found fall into several categories:

- Contaminated site investigation reports,
- Electronic databases of completed wells,
- Karst features data,
- Wisconsin Department of Transportation (DOT) geotechnical reports,
- Municipal water authority studies, and
- Other studies, including groundwater modeling and overburden and bedrock mapping projects.

The contents, data quality and usability of these sources constitute the results of this project, and are discussed in Section 3 below.

Certain methods of data analysis relating to the digital well databases are described in Appendix A1. The most significant element of this work was updating TGuess (Bradbury and Rothschild, 1985), a program used to estimate hydraulic conductivity from specific capacity test data. Approximately 8,000 such tests were made for this project, using the new spread-sheet version of TGuess. TGuess is discussed in Appendix A2. The distribution of estimated values is presented in Section 4.

3 Results and Discussion

This section describes the hydrostratigraphic data resources now available for west-central Wisconsin, with discussion of their relevance and data quality.

3.1 Contaminated Site Investigation Reports

As in the rest of the country, much of the work on groundwater issues in west-central Wisconsin has been completed by environmental consulting firms investigating and remediating contaminated sites. This work is not always as thorough and rigorously completed as desirable, and is often very restricted in scope, but it does nonetheless form a viable hydrostratigraphic data resource. For this project, we identified hydrogeologic studies for numerous sites involved in investigation and clean-up programs of the Wisconsin Department of Natural Resources (WDNR) and the Wisconsin Department of Agriculture, Trade and Consumer Protection (DATCP). No USEPA-lead sites were identified in the three-county area.

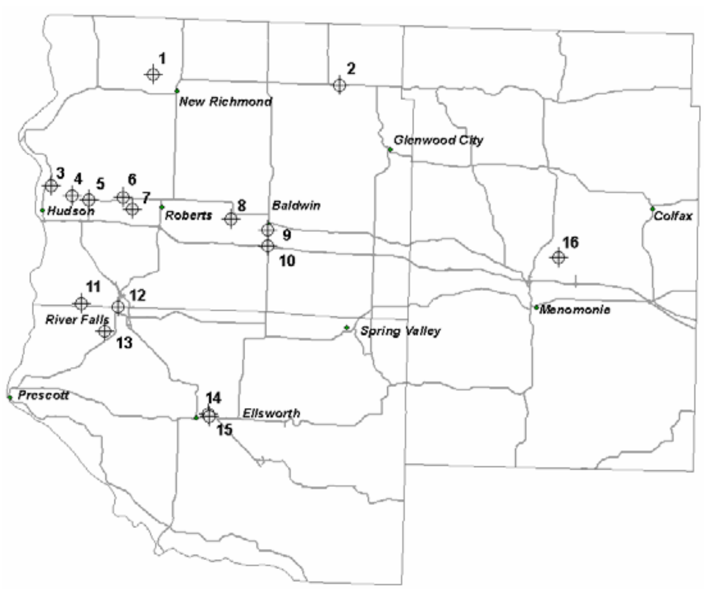

Figure 3.
Distribution of contaminated site investigations with bedrock hydrostratigraphic data

Site Index
1 New Richmond Landfill
2 Cenex Station
3 Hudson Landfill
4 Trout Brook Road
5 Nor-Lake
6 Junker Landfill
7 Warren TCE Site
8 Four Seasons Farm Supply
9 Fabritec
10 Craig Rasmussen Property
11 Nelson Farm Supply
12 Wilkens Towing
13 River Falls Landfill
14 Ellsworth Coop
15 Deiss & Nugent Feed Co.
16 Cedar Falls Store

While there are many contaminated sites and landfills in west-central Wisconsin registered in state regulatory programs, relatively few have generated useful hydrostratigraphic data. Most are small in scale, and deal only with shallow soil conditions, not bedrock. With assistance from WDNR and DATCP representatives we have identified 16 projects in the study area with bedrock components and varying levels of hydrostratigraphic data. Figure 3 shows the distribution of sites. Appendix A3 provides a table of the data resources available for each site, and stratigraphic units each evaluates. Excerpts of more than 30 reports and documents have been scanned and indexed as PDF files on the data CD.

For most of the projects, the files include at a minimum water-table maps, boring logs, and the consultant's interpretation of the hydrogeologic conditions of their site. Many include slug tests or more elaborate hydraulic testing, interpretive geologic cross-sections, and multiple rounds of water-level data. These resources are included as-is, with the primary data and test reductions included wherever possible. Values of hydraulic conductivity and storativity have been tabulated and are discussed in Section 4.

The majority of these projects have evaluated only the rock of the Ordovician Prairie du Chien group or, to a lesser degree, the Ordovician St. Peter sandstone – a bias reflecting the uppermost position of these units in the saturated section. It also suggests that the Ordovician section is the most at risk to contamination. In this respect, the available data are concentrated where they are most needed, but also leave the deeper portions of the bedrock section poorly constrained.

The geographic distribution of sites is also heavily biased toward the most populous areas, principally the far west, nearest Minnesota, and along the I-94 corridor. The most heavily investigated part of the region is the area between Hudson and Roberts in St. Croix County, where there are three major contaminated sites: Nor Lake, Junker Landfill and the Town of Warren TCE site (index numbers 5, 6, and 7 on Figure 3). These three sites have combined to create a continuous plume of chlorinated solvents in the groundwater in the Prairie du Chien Group (and portions of the St. Peter sandstone). Groundwater in the underlying Jordan Formation appears to be unaffected.

3.2 Electronic Databases of Well Logs

There are three state-wide quasi-independent electronic databases of well logs: 1) WDNR's Well-Constructor Report (WCR) database, 2) WDNR's High-Capacity Well database, and 3) WGNHS's WiscLith database. Together, the databases contain records for more than 14,000 wells in the three-county study area. The vast majority are low-capacity water wells, described only in well-constructor reports. High-capacity water wells are often described in better detail. The best-described wells are those contained in the WiscLith database, some of which include detailed cuttings logs prepared by a WGNHS geologist. Table 2 compares the content of the three databases.

While their precise content and level of detail varies, all three databases include certain types of information: physical location, well construction details, geology, water-level, and some measure of well yield. The data quality and frequent incompleteness can be a serious limitation, but the sheer quantity and spatial density of these data make them one of the key resources of hydrostratigraphic data in the area.

Table 2. Digital well database contents

	WCR	High-Capacity	WiscLith
Number of wells listed in study area	14,169	489	1,305
Number of bedrock / overburden wells	9,681 / 2,648	307 / 92	797 / 235
Number with viable basic geologic descriptions	12,291	197	1,032
Number with detailed lithology descriptions	0	0	104
Number with viable specific-capacity data	8,114	151	13

There is tremendous redundancy between with three databases. In theory, the WCR database should be comprehensive, with the high-capacity and WiscLith databases forming subsets and providing a somewhat different data focus. In practice, not all wells are reliably coded with the Wisconsin Unique Well ID number, so cross-referencing can be non-trivial. Appendix A1 reviews the content and qualities of the databases in more detail.

For this project, we attempted to wrest what value could be had from each of the three digital databases. Appendix A1 describes the process and results of this work. The most intriguing aspect of the digital well records, from a hydrostratigraphic standpoint, is the specific capacity test data they include. These data are not ideal for determining hydraulic properties, but neither are they useless. For this project, we have estimating hydraulic conductivity from more than 8000 specific capacity tests. The results are discussed in Section 4.

3.3 Karst features data

The significance of karst is probably the greatest hydrostratigraphic uncertainty in west-central Wisconsin. The solution weathering of carbonate rocks, particularly the Ordovician Prairie du Chien group, is known to have created sinkholes, caves, and other significant cavities. But there is no real consensus on how the existence of these solution features effects groundwater flow in the carbonate units. The existing data regarding karst in the study area is unequivocally sparse and is generally not rigorously documented. These data reside in a variety of forms, described below.

<u>WGNHS Karst Features Inventory</u>
The WGNHS is attempting to document karst features throughout the state through a voluntary reporting program using a standard *Wisconsin Interagency Karst Feature Reporting Form* (available at www.uwex.edu/wgnhs/karst.htm). The program has only recently been implemented and is not yet widely used. At this stage, the file for Pierce, St. Croix and Dunn Counties contains only forms, memos and clippings relating to a handful of sinkholes. All of these files have been scanned and indexed as a PDF on the data CD.

<u>Wisconsin Speleological Society Records</u>
As the organization most dedicated to exploring and preserving the state's karst features, the Wisconsin Speleological Society is a viable resource of karst feature data. However, as a safeguard against inappropriate cave use, the society's data are not always easily accessible. The organization has identified and mapped numerous caves in St. Croix and Pierce Counties, most of them small. Limited cave descriptions can be found in the society's newsletter, the Wisconsin Speleologist (e.g., Olcott, 1970; Frater, 1970), which is on file at the Wisconsin Historical Society.

<u>County Spring Surveys</u>
The WGNHS maintains an archive of county spring surveys completed by the Wisconsin Conservation Department in the 1950s and 1960s (1959a, 1959b, 1960). These surveys attempted to be comprehensive for each county, and collected data on flow, physical setting and potential for economic development. In many cases, the data appear to be approximations, particularly with respect to flow. Many springs, particularly in Dunn County, are listed but described as dry. The surveys include many springs not identified on USGS 7.5 minute topographic maps, but also miss some that are. Despite some clear errors and omissions, these surveys are the most comprehensive spring surveys in existence for the study area. Scanned copies of the surveys are included on the data CD.

3.4 Wisconsin Department of Transportation geotechnical reports

The Wisconsin Department of Transportation maintains an electronic archive of geotechnical investigations completed for road construction projects. Of a great many investigations completed in the study area, 45 include some assessment of the bedrock and therefore have been included on the data CD. The value of the DOT files as a hydrostratigraphic data resource varies. Most of the geotechnical borings go no deeper than necessary to confirm competent rock (the median depth of rock penetration for the 45 investigations is only 7 feet). On the other hand, many of the borings are cored, and have been logged in greater detail than is typical of the boring completed by environmental consultants. The borings also tend to be precisely surveyed, adding a useful level of confidence and control to the water-well stratigraphic data. Some cored locations include rock-quality designations (RQD), a measure of fracturing. Unfortunately, since the vast majority of core is collected only in the very shallow rock surface, these data generally do not provide a useful measure of fracture density within the rock mass proper.

The Minnesota Department of Transportation completed the single most substantial DOT geotechnical investigation in the study area, for the new bridge crossing the St. Croix River at Stillwater. This investigation includes more than 100 borings, many exceeding 150 feet deep with described core. Appendix A4 lists the 45 investigations included on the data CD.

3.5 Municipal water authority studies

Towns with one or more high-capacity water wells often have engineering reports and other well testing data in their files. In the study area, the town of Hudson has completed by-far the most thorough study of their groundwater resources, and possess a library of video logs, several pumping tests, and limited down-hole geophysics. Less comprehensive data was obtained from River Falls and Menomonie. The data CD includes Hudson’s wellhead protection studies, and documentation for several pumping tests. The CD also includes geophysical logs for several municipal wells in Hudson and Menomonie.

In addition to independent municipal studies, the WDNR has delineated source water areas for the major municipalities in Pierce and St. Croix Counties. The project, which was completed as part of the Source Water Assessment Program (SWAP), included a 2D regional numerical flow model (GFLOW), downhole geophysical studies of several municipal wells in Hudson and River Falls, and other related tasks. These data have not yet been released.

The well videos acquired from Hudson and River Falls provide a unique view of the bedrock, through they have limited hydrostratigraphic value except to clarify other data, such as cuttings logs or geophysical data. At best, the significance of fractures in groundwater flow can be quite vividly seen. For instance, there is obvious turbulent flow entering the bottom of River Falls well 3. On the other hand, the town of Hudson’s use of dynamite to develop its wells likely accounts for the cavernous voids and fracturing visible in the videos. The original VHS videos obtained from the towns have been converted to a digital format, and are archived at the WGNHS in Madison. Appendix A6 provides an index of the video logs, with well depths and formations logged. Due to the video file sizes, only the video indices are included on the data CD; the files themselves are not.

3.6 Other studies

There are several additional studies completed and underway that are relevant to the hydrostratigraphy of the study area, but that were not compiled with this project. These include various mapping and groundwater modeling projects. Additionally, there area several as-yet unpublished sinkhole studies. Brief descriptions of this work and relevant contact information are included in Appendix A5.

4 Conclusions and Recommendations

The data that currently exist are inadequate to develop a fully coherent hydrostratigraphic conceptual model. Sufficient data exist to suggest parallels with the better-constrained hydrostratigraphy of eastern Minnesota (Runkel et al, 2003), but not to independently verify it. As outlined in Table 1, a hydrostratigraphic model may be divided into a series of questions relating to the hydraulic characteristics of the bedrock: stratigraphy, intrinsic hydraulic properties, relative importance of diffuse, fracture and conduit flow, and the hydraulic relationships of the units. The discussion below is organized accordingly.

The stratigraphy

The majority of data that exist, as well logs, as bedrock maps, and as geophysical studies, address the question of stratigraphy. Though there is still significant uncertainty in the faulted blocks in western St. Croix County, the sequence, thickness, and lithologic character of the bedrock is the best constrained element of the hydrostratigraphy at this time. It is beyond the scope of this report to describe the lithostratigraphy of the study area in any detail. As a generality, there appears to be strong continuity in unit properties and inter-unit relationships between the study area and the proximal portions of Minnesota described in Runkel et al (2003). The present geologic mapping work of the WGNHS in west-central Wisconsin is expected to be the area's best stratigraphic resource once completed.

The intrinsic hydraulic properties of the rock

If, as in Minnesota, we conceive a framework of ten or more hydrostratigraphic units in the bedrock section, it would be ideal to have characteristic values of porosity, hydraulic conductivity and storage for each. In reality, no porosity data were found. And the data for hydraulic conductivity and storativity that do exist are not ideal for this sort of parsing, since they are often of inadequate detail to link to a precise hydrostratigraphic interval.

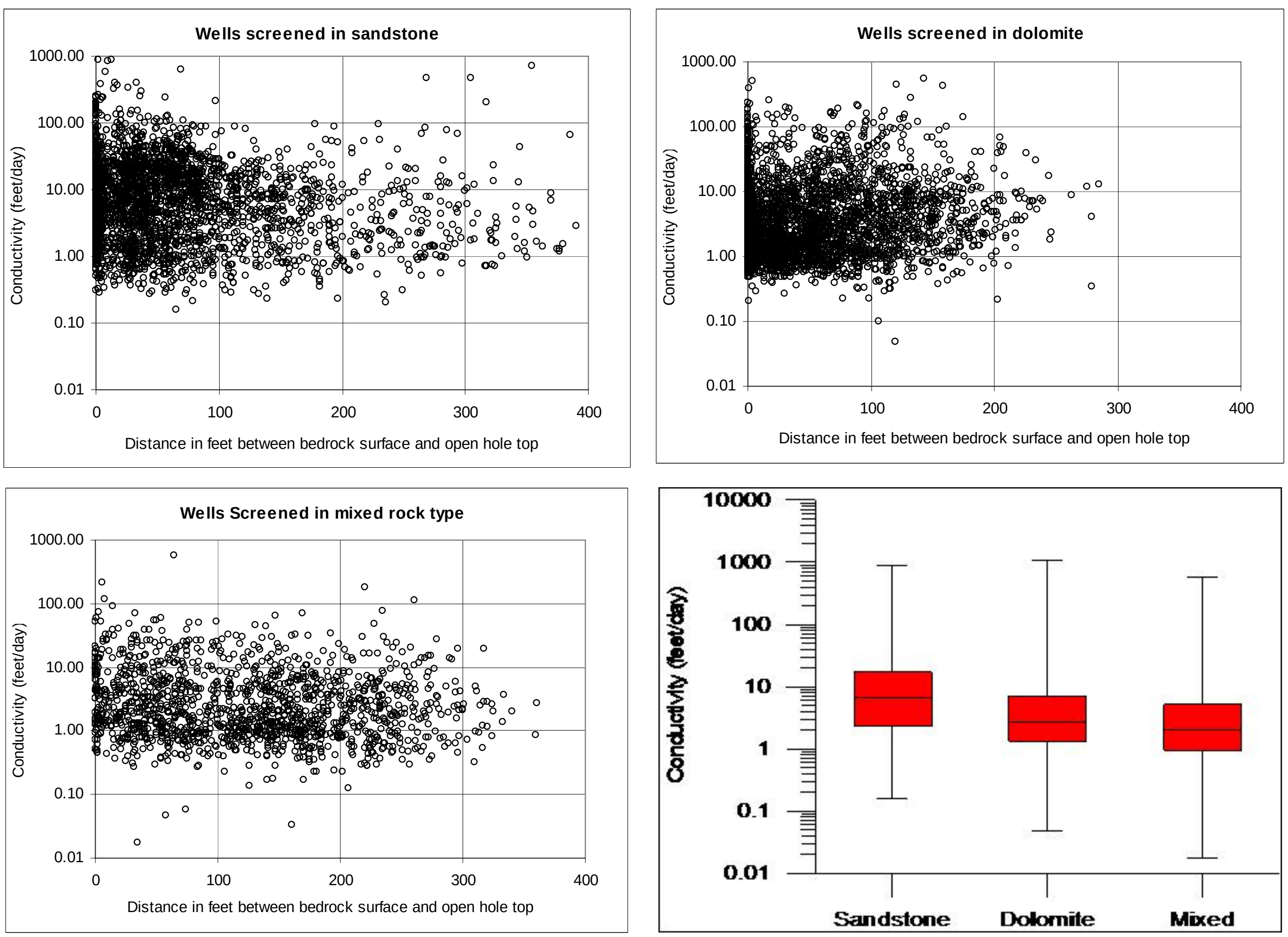

Figure 4. Results of hydraulic conductivity estimation from specific capacity test data for a) 2797 wells reported to screen a sandstone unit, b) 3737 wells reported to screen a dolomite unit, c) 1460 wells reported to screen a combination of sandstone, dolomite and/or shale; d) Box plot of all data.

The specific capacity data from more than 8000 wells listed in the WCR, High-Capacity Well and WiscLith databases were used to estimate hydraulic conductivity. The results are shown in Figure 4, sorted by the geology of the screened interval and the depth of the screened interval below the bedrock surface. It is important, again, to emphasize that this estimation technique (described in Appendix A2) is only a crude tool. Though it was not feasible to precisely correlate rock type with unit, it is likely that nearly all of the dolomite unit wells represent the Prairie du Chien. The sandstone and mixed (sandstone, dolomite and shale) groups, unfortunately, may represent nearly any interval of the pre-Sinnipee Paleozoic section.

The plots of hydraulic conductivity data in Figure 4 show very little that can be recognized as systematic trends, with either depth or lithology. There is roughly a three order-of magnitude spread in the hydraulic conductivity values for all depths and lithologies, centered between 1 and 10 feet per day.

The municipal and contaminated site reports included a number of hydraulic conductivity values, usually derived from slug tests. Only seven multi-well pumping tests have been completed (for the City of Hudson, the Nor-Lake site, and Cedar Falls store site). Where pumping tests occurred, values of storativity were also reported. Table 3 summarizes these reported values, organized by geologic unit.

Table 3. Values of hydraulic conductivity and storativity reported in reviewed sources.

	Oa St. Peter Fm.	Op Prairie du Chien Gr.		Cj Jordan Fm.	Cm Mt. Simon Fm.	
Test Type	Slug	Slug	Pumping	Pumping	Slug	Pumping
Hydraulic Conductivity						
Number of tests	4	25	1	2	6	4
Median (ft/day)	2.1	3.2	0.4	125.5	2.2	78.6
Geometric Mean (ft/day)	1.5	4.2	na	125.5	1.8	77.1
Maximum (ft/day)	9.6	47.2	na	126.0	86.4	97.3
Minimum (ft/day)	0.1	0.3	na	125.0	0.04	59.6
Storativity						
Number of tests	na	na	1	2	na	4
Mean	na	na	0.25*	.00066	na	.0090*

*reflects unconfined condition

The values given in Table 3 should be considered with respect to their source. In general, slug tests evaluate smaller volumes of aquifer than do specific capacity tests or pumping tests , and neither test is ideal in heterogeneous media, such as fractured or karsted rock. Both slug test and pumping test data reduction techniques assume homogeneity and isotropy, neither of which hold for the bedrock section except at a highly focused scale. Also, all of the reported values of hydraulic conductivity are for horizontal flow. For hydrostratigraphic parsing, it is important to understand vertical hydraulic conductivity, particularly in confining units.

<u>Relative importance of intergranular porosity, fractures, and karst conduits</u>
Very little data exist to quantify or even qualitatively assess the relationship between flow in pore spaces, fractures and karst conduits. Though no porosity data were identified, it is more likely that fractures are the dominant control on groundwater flow in most aquifers (Runkel et al, 2003). Conduit flow in the carbonate units may locally dwarf both fracture flow and diffuse flow through pore spaces.

The existence of sinkholes, springs, caves, solution cavities, dry streams and a depressed water table are the current best evidence that conduit flow is significant in the Prairie du Chien group. The Wisconsin Conservation Department county spring surveys (1959a, 1959b, 1960) list springs by volume of discharge. The many large springs erupting from sandstone in the incised valleys of southern Pierce

County and western Dunn County suggest that efficient flow has developed along fractures in portions of Jordan formation and Tunnel City Group and Wonewoc formation.

Lateral and vertical hydraulic relationships
A principal aim of developing a hydrostratigraphic model is to understand how flow moves between units, and the degree to which confining units segregate the bedrock into distinct water masses. Very little data exists now to evaluate these questions. The water table maps generated for Dunn, St. Croix and Pierce Counties (Lippelt, 1988, 1990a, 1990b) provide a rough approximation of the regional trends in groundwater flow, but do not capture any of the subtlety of flow in and between the many aquifers and aquitards lying beneath.

4.1 Data Needs

This section outlines the major data needs remaining to develop a fully coherent, usable hydrostratigraphic conceptual model. With ongoing development pressure in the region, and a near-total reliance on groundwater as a resource, the need to better understand how groundwater moves through the bedrock has become critical. This is especially so in the most densely developed areas, in western St. Croix and Pierce counties, where the heterogeneities of the Prairie du Chien group have left grave uncertainties about how to concurrently use and protect the groundwater resource.

Karst
The foremost need is for data constraining the occurrence and function of karst in the Prairie du Chien Group. At this stage the data are entirely observational, and generally fail to describe the active function of the aquifer. In any carbonate aquifer where solution weathering has occurred, there will be a balance of flow through pore spaces, through unweathered fractures, and through open conduits. The nature of that balance is now entirely a matter of speculation, but it has great importance for managing the Prairie du Chien as an aquifer. Though some of the initial steps to characterize the karst aspects of the Prairie du Chien have already been taken, many areas for further work remain: characterizing the transience of springs and groundwater levels; identifying correlations between solution features, structural features and lithostratigraphy; characterizing the hydraulic relationships between the Prairie du Chien and adjacent units; and completing karst-appropriate studies of groundwater flow (e.g., using tracers to confirm point-to-point flow paths).

Fracture systems, fracture density and their importance for flow
A second and not unrelated need is for more comprehensive data on fractures throughout the bedrock. Very few assessments of this sort have been completed in the study area. Fracture orientation and density data have been collected from outcrops of the Sinnipee Group (Williams and others, 1989), Prairie du Chien Group, and Jordan Formation (Pace and others, 2005) at scattered locations in St. Croix and Pierce counties, but no systematic study of fracture orientations has been made throughout the three county area. Two areas for further work are apparent: development of a comprehensive dataset of geophysical logs characterizing fracture density as a function of depth and stratigraphic interval, and detailed packer-testing to assess the relative importance of individual fractures and discreet porous zones.

Aquitards
Perhaps the most useful data for developing a hydrostratigraphic model are those describing the effectiveness of aquitards. However, almost no data of this sort currently exist in the study area. Similar to assessing fracture systems, the best tools to evaluate bedrock aquitards are multi-level head measurements, downhole geophysics, and packer testing (Cherry and others, in press). There is also a need for multiple time-series datasets of water-levels in well pairs straddling the aquitards.

Other topics

Though not given much attention in this report, there are several faults in the Paleozoic rocks which may have profound hydrostratigraphic effects. In particular, the Hastings Fault in western St. Croix County may have several important hydraulic implications that have not yet been studied: hydraulic damming behind the uplifted Precambrian basement and preferential vertical and lateral flow along the fault.

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Appendix A

Supplemental Materials

Table of Contents

Appendix A1 Review of Digital Well Databases

1 Introduction

The WNDR and WGNHS maintain three state-wide quasi-independent electronic databases of well logs:

- WDNR's Well-Constructor Report (WCR) database
- WDNR's High-Capacity Well database
- WGNHS's WiscLith database

This appendix describes the hydrostratigraphic data each database contains for west-central Wisconsin, and outlines some basic data reduction techniques that were applied to each.

2 Scope and content of the databases

Though their precise content and level of detail can vary, all three databases include certain types of information: physical location, well construction details, geology, water-level, and some measure of well yield. The data quality and frequent incompleteness of the databases can be a serious limitation, but the sheer quantity and spatial density of these data make them one of the key resources of hydrostratigraphic data in the area.

2.1 WCR Database

The single largest source of subsurface information in west-central Wisconsin is the monstrous database of well-constructor reports that the WDNR maintains online and on their regularly updated Water Well Data Disc. The January 2005 release of the database includes approximately 14,000 records of water wells constructed in the three counties since 1988. Logs of older wells exist, but mainly as paper copies and scanned PDFs on file at the WGNHS, and so are a more cumbersome resource.

Figure B-1. WCR database coverage and statistics

Number of wells in study area	14,169
Number of bedrock / overburden wells	9,681 / 2,648
Number with viable geologic descriptions	12,291
Number with viable water-levels	10,845
Number with viable specific-capacity data	8,114

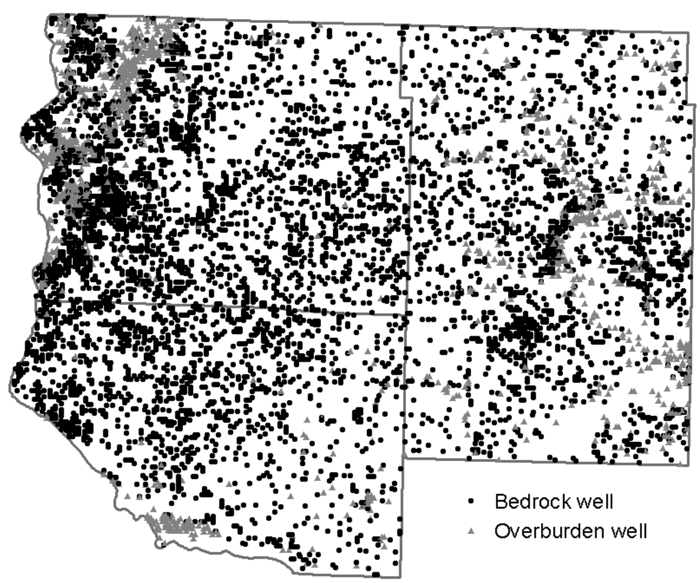


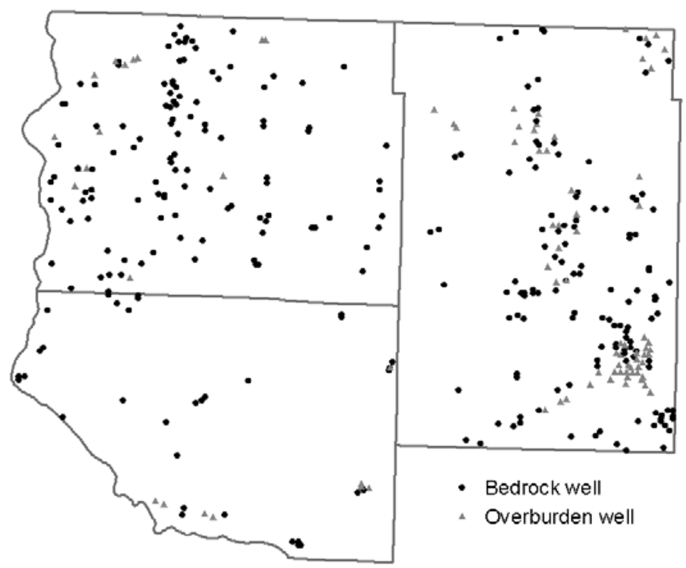
Figure B-1 shows the spatial distribution of WCR database wells in the study area, with statistics summarizing the data set. The saving virtue of WCRs is that there are so very many of them. Individually, their data quality is highly suspect, and can occasionally appear to be outright fiction. And often, important gradations in lithology are too subtle to be easily seen in a stream of air-rotary cuttings. Locations are given only as Public Land Survey System (PLSS) coordinates, and surface elevations are not listed. Combining potential data inaccuracy with uncertainty in position and elevation leaves a very strong chance for significant error in any derived value made from the dataset – for instance, elevations of the water-table, bedrock surface or a formation contact. Such data must therefore be viewed with a strong dose of skepticism, and only given credence where many independent points indicate a trend.

2.2 High-Capacity Well Database

Along with the WCR database, the WDNR maintains online and on their regularly updated Water Well Data Disc a database of high-capacity wells. The January 2005 release of the database includes approximately 490 records of high capacity water wells in the three counties. Figure B-2 shows the spatial distribution of high-capacity database wells in the study area, with statistics summarizing the data set.

Figure B-2. High-capacity well database coverage and statistics

Number of wells in study area	489
Number of bedrock / overburden wells	307 / 92
Number with formation picks	197
Number with viable water-levels	216
Number with viable specific-capacity data	151



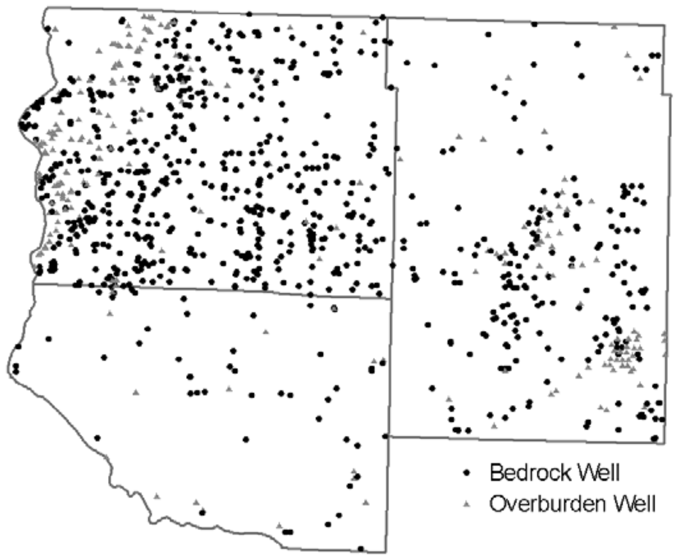
There is a lot of redundancy between the WCR, high-capacity well and WiscLith databases. Roughly 85% of the high-capacity wells are listed with the Wisconsin Unique well ID number, which makes it possible to cross-reference with the WCR database. Though most high-capacity wells appear in both of the other databases, the data themselves are not always precisely the same. Geologic descriptions, for instance, are given as formation picks (not driller-observed lithology) which are based on WGNHS geologist descriptions of cuttings (and are identical for cross-listed wells in the WiscLith database). The high-capacity well database, however, contains specific capacity test data that are frequently omitted in WiscLith, and are occasionally different from those given in the WCR database.

2.3 WiscLith Database

The WiscLith database is yet another digital compendium of well data and geologic descriptions. WiscLith is maintained by the WGNHS and is regularly updated and reissued as a CD Open-File Report. Of the three databases reviewed, WiscLith has the most detailed and highest-quality geologic characterizations, generally based on observation of cuttings submitted by the driller. The database does not, however, contain many records with specific capacity tests. Figure B-3 shows the spatial distribution of WiscLith-described wells in the study area, with statistics summarizing the data set.

Figure B-3. WiscLith well database coverage and statistics

Number of wells in study area	1,305
Number of bedrock / overburden wells	797 / 235
Number with formation picks	1,032
Number with detailed lithology descriptions	104
Number with viable specific-capacity data	13



Again, there is persistent redundancy between WiscLith, the high-capacity and the WCR databases. Unfortunately, only 87 of the 1305 WiscLith wells in the study area are listed with Wisconsin Unique well ID numbers, so cross-referencing the databases is non-trivial.

The WiscLith database includes WTM-coordinates (rather than PLSS coordinates) and surface elevations, greatly improving the confidence of position data. Many of the wells located in St. Croix County included in WiscLith were used by Borman (1976) and their locations have been field checked.

2.4 Other digital databases

As part of this project, we looked for other databases that may have value as hydrostratigraphic resources, but found the three above most relevant. Other somewhat relevant databases certainly exist, notably several with geochemical data (e.g., WDNR's Groundwater Retrieval Network and the Central Wisconsin Groundwater Center's Private Wells Database). While groundwater chemistry is a viable approach for differentiating hydrostratigraphic units, it fell outside the scope of this project.

3 Digital Well Log Data Reduction

For this project, we attempted to extract usable hydrostratigraphic data from the digital databases. This effort is described below.

With their terrific abundance and spatial distribution, digital well logs would appear to be the ultimate data trove. In reality, they are fraught with errors and omissions. Most logs are dependent on driller descriptions of cuttings, and their notes of time, water-level and pumping rates. Thus some records are of impeccable quality, while others are decidedly not, with no clear way of distinguishing the two.

The databases can be manipulated using the standard tools of Microsoft Excel™, Access™, and ArcGIS™ to create mapable datasets, such as the following:

- The depth and elevation of the bedrock surface, where applicable, and nature of the first rock encountered.
- The depth and elevation of the measured static water-level in the well.
- The formation type of the screened or open interval of each well.

To extract such data as a bulk process (i.e., without reviewing each individual record), however, requires multiple steps in the which built-in uncertainties accumulate and compound:

- Converting, where necessary, the Public Land Survey System coordinates (PLSS, i.e., township, range, section, quarter, quarter-quarter) to the Wisconsin Transverse Mercator (WTM) coordinates for the centroid of the quarter-quarter parcel. This process was a matter of querying the WDNR's 24K Landnet database (1996) within Microsoft Access.

- Determining approximate surface elevations for each point using ArcGIS and extracting elevations from a 30-meter grid digital elevation model (DEM).

- Reducing, where necessary, inconsistent geologic descriptions to a uniform, simplified code. The original WCR descriptions are, for instance, remarkably haphazard, making bulk sorting and statistical comparisons impossible until replaced by a standardized code.

Many records, particularly in the WCR database, can be parsed out because they are clearly erroneous. Over 1,800 WCR records, for instance, were not sufficiently detailed to determine if the wells they described screened the bedrock or the overburden. Many specific capacity tests were too short, or too weakly pumped. Many simply omitted necessary data fields, or contained implausible values.

With initially poor data quality compounded by data processing uncertainties, the resulting datasets have dubious value except as crude indicators. Most mapping applications still require individual review of records. As part of a federally funded STATEMAP project, the WGNHS is in the process of manually checking and revising many bedrock well locations, well by well, in Pierce and St. Croix counties, then making stratigraphic picks based on review and judgment of individual records. While vastly more tedious, this level of effort is likely necessary to make any technically viable use of the data.

The specific capacity data included in most digital well records offers, at least in theory, an opportunity to characterize the hydrogeologic character of the rock. These data are not ideal for determining hydraulic properties, but neither are they useless. Specific capacity is, itself, a more-or-less meaningless number: a pumping rate divided by the drawdown at some given moment. However, using those parameters, along with certain well details, it is possible to estimate aquifer transmissivity and hydraulic conductivity using the Cooper-Jacob approximation of the Theis equation. This method is documented in Bradbury and Rothschild (1985), which introduced TGuess, a simple DOS-based computer program for solving the equation.

With many thousand specific capacity tests to process, the 20 year-old TGuess would have been cumbersome to use. We have, therefore, updated the program and transformed it into a Microsoft Excel™ workbook, using Visual Basic modules to automatically run through the iterations necessary to solve the Cooper-Jacob equation. This update makes it possible to process thousands of tests at once using only standard spreadsheet tools. Appendix A2 describes the math behind TGuess, and the use of a spreadsheet update created for this project.

Appendix A2   An update of TGuess

TGuess is a simple DOS-based computer program developed by Bradbury and Rothschild (1985) that estimates transmissivity from specific capacity data. For this project, we have updated the program so that the same method may be applied more simply, in a Microsoft Excel table running the code as a series of Visual Basic for Applications (VBA) user-defined functions. This update makes processing large batches of specific capacity tests simpler, and requires only standard spreadsheet tools to run. A template file is included on the data CD accompanying this report.

The TGuess solution applies the Cooper-Jacob approximation of the Theis equation, with corrections for partial penetration and well loss. as indicated in equations 1-4.

Eq. 1 $$T = \frac{Q}{4\pi(s_m - s_w)}\left[\ln\left(\frac{2.25Tt}{r_w^{\,2}S}\right) + 2s_p\right]$$

Eq. 2 $$s_w = CQ^2$$

Eq. 3 $$s_p = \frac{1-L/b}{L/b}\left(\ln\frac{b}{r_w} - G(L/b)\right)$$

Eq. 4 $$G(L/b) = 2.948 - 7.363(L/b) + 11.447(L/b)^2 - 4.675(L/b)^3$$

b - aquifer thickness	s_m - measured drawdown
C - well loss coefficient	s_w - well loss
L - screen length	s_p - partial penetration parameter
Q - mean pumping rate	S - storativity
r_w - effective radius	T - transmissivity
	t - pumping duration

Equation 1 is the modified Cooper-Jacob approximation of the Theis equation for transient radial flow to a well in a confined aquifer. Equation 2 calculates well loss, based on a correction factor (C), which must be estimated or determined by alternate test methods. Equation 3 calculates a unitless partial penetration correction factor (see assumptions below), employing the function G(L/b), approximated in Equation 4 with a polynomial best-fit.

The benefit of this method is that it requires very few parameters to solve: a value of drawdown after a specified duration of pumping at a specified rate, and basic details of well construction. However, with only one point defining the time-drawdown curve, the results yielded by this method are only rough estimates. If slug tests, time/drawdown or distance/drawdown tests are available, they should be considered vastly preferable. The TGuess solution method includes several assumptions that further limit the confidence placed in its estimates:

a) the tested aquifer is confined, non-leaky, homogeneous and isotropic;
b) the storage coefficient of the aquifer is known;
c) the well loss is known;
d) the effective aquifer thickness is known.

In most cases, the storage coefficient, well loss, and aquifer thickness can only be estimated. The error introduced is non-negligible, but can be loosely bracketed. The diagnostic section of the worksheet includes a limited sensitivity analysis.

If the user has little control on well loss, or aquifer thickness, the well loss and partial penetration correction terms may be removed, respectively, by setting the well loss coefficient (C) equal to zero, and the aquifer thickness (b) equal to the saturated screen interval. Note that the partial penetration correction factor assumes isotropic conditions (Kh = Kz), and gives a value of T extrapolated from the screened interval to the full aquifer thickness. If the aquifer is anisotropic, this correction is inappropriate.

Usage Notes

Units

The user may chose any combination of units for field data, estimated parameters and calculated results by changing the units shown in the column headers. Each of these cells has an embedded pull down list from which to chose. Only the listed options will work, because the embedded functions look for specific text strings. The units of the diagnostic columns are linked to the calculated results, and shouldn't be manually changed.

Input

Field data may be pasted in or entered directly. The units header should be changed to agree with the data. All depth values are assumed to be from a common reference point (e.g., ground surface).

Calculated Results

The calculated results cells all make use of user-defined functions written in Visual Basic for Applications. The functions and their arguments are listed in the "Notes" tab of the TGuess template. The code may be viewed by opening Excel's Visual Basic Editor. Cells containing these functions may be drag-filled or copied down their respective columns to extend the table. Changing the units in the column header will automatically change the output units.

Diagnostics

The difference between calculated drawdown the measured drawdown is a metric for assessing the convergence of the solution. If the error is unacceptably high, the maximum iterations and error tolerance may be adjusted in the fields above the table. The well bore storage test checks that the specific capacity test rate and duration were adequate to negate the influence of water removed from the well casing on the measured drawdown. The test applies criterion that the test duration be longer than 25*rw2/T (ASTM, 2004). Note that this check assumes well radius and riser radius are equal.

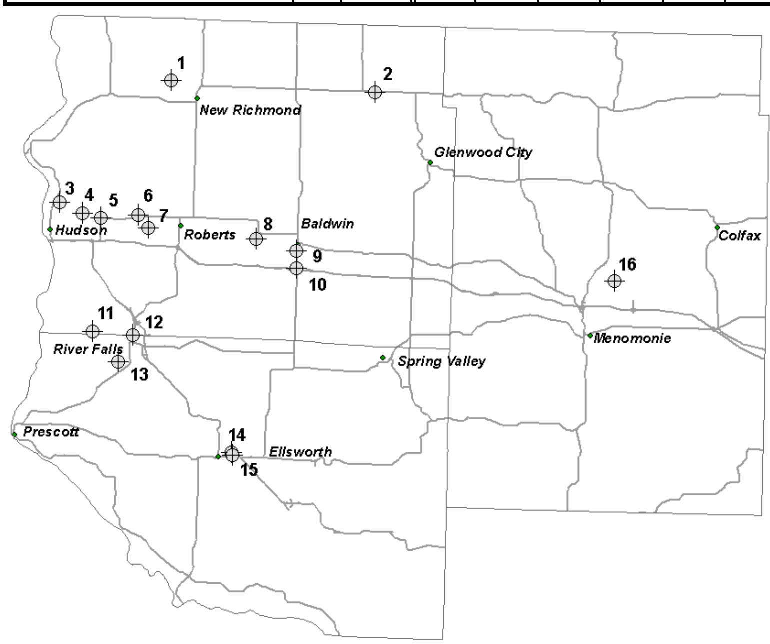
References

Bradbury, K.B., and E.R. Rothschild, 1985. A computerized technique for estimating the hydraulic conductivity of aquifer from specific capacity data: Ground Water vol. 23, No. 2, pp. 240-246.

ASTM International, 2004. Standard Test Method for Determining Specific Capacity and Estimating Transmissivity at the Control Well, Standard D 5472-93, in Annual Book of ASTM Standards, Vol. 04.08 pp. 1279-1282.

Appendix A3 Scope of Contaminated Site Investigations

Site Name	Map Index No.	County	Data Resources: Hydrogeology Discussion	Water Table Maps	Cross Sections	Boring Logs	Described Core	Hydraulic Testing	Surveyed Water-Level Data	Groundwater Modeling	Karst Features Noted	Geophysics, Video, or Packer Testing	Units Evaluated
New Richmond Landfill	1	SC	x	x	x	x			x		x	x	Op
Cenex Station	2	SC	x	x		x					x		Op
Hudson Landfill	3	SC	x	x	x	x							Ct / Cw
Trout Brook Road	4	SC	x	x	x			x	x			x	Op
Nor-Lake	5	SC	x	x	x	x		x	x	x			Op
Junker Landfill	6	SC	x	x	x	x	x	x	x			x	Os / Op
Warren TCE Site	7	SC	x	x	x	x	x	x	x				Os / Op
Four Seasons Farm Supply	8	SC	x	x		x		x	x				Os / Op
Fabritec	9	SC		x		x					x		Os / Op
Craig Rasmussen Property	10	SC	x	x	x	x			x		x		Op
Nelson Farm Supply	11	SC	x	x	x	x		x			x		Op
Wilkens Towing	12	PI	x	x	x			x	x				Op
River Falls Landfill	13	PI	x	x	x	x	x	x	x		x		Op / Cj
Ellsworth Coop	14	PI	x	x	x	x			x				Os / Op
Deiss & Nugent Feed Co.	15	PI	x			x					x	x	Op
Cedar Falls Store	16	DU	x	x	x	x		X	x				Cm



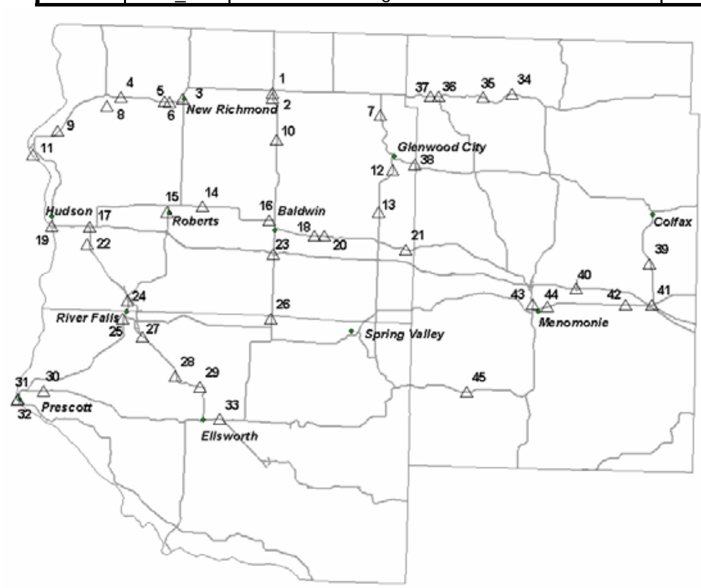
Notes:

1) Unit picks made per consultant and/or with reference to Mudrey et al. (1987) and Brown (1988). Abbreviations are as follows:
- Os - Ord. Sinnipee Gr.
- Op - Ord. Prairie du Chien Gr.
- Cj - Cambrian Trempealeau Gr.
- Ct - Cambrian Tunnel City Gr.
- Cw - Cambrian Wonewoc Fm.
- Cm - Cambrian Mt. Simon Fm.

2) Additional detail on site location and scope of contents is included for each site on the cover sheet accompanying the digital files on the data CD.
3) Described core includes conventional diamond core and roto-sonic core. "Described" does not necessarily imply substantial detail.
4) Surveyed water-level data refers to use of a sea-level datum; unchecked projects generally used a site-specific datum.

Appendix A4 DOT Investigations

Index No.	File ID	Location	Surface Elev. (ft AMSL)	Max. Depth (ft)	Depth to Rock (ft)	Rock Surface Type	Cored	Max. Length of Core
1	SC_16	USH 63 over S. Fork Willow	1024	32	28	DM	N	na
2	SC_15	USH 63 over SOO Line Railroad	1069	88	77	DM	Y	4
3	SC_07	STH 64 over Willow River-Knowles Ave.	981	30	20	DM	Y	5.5
5	SC_10	CTH K over WCL RR and STH 64	1038	55	48	DM, SH	N	na
6	SC_06	STH 64 over Willow River	957	42	35	DM	Y	5
7	SC_19	STH 128 over Sandy Creek	1178	42	25	SS, SH	N	na
8	SC_08	STH 64 under WCL Railroad	928	81	67	SS	Y	4
9	SC_05	STH 35 & STH 64 over 150th ST	896	73	61	SS	N	na
10	SC_17	USH 63 over Dry River Creek	1090	24	18	DM	N	na
11	SC_11	Stillwater Bridge, St. Croix River	678	175	variable	SS	Y	78
12	SC_20	STH 128 over S. Branch Tiffany Creek	1014	60	50	SH	N	na
13	SC_18	STH 128 over Branch Beaver Creek	1122	10	9	DM	N	na
14	SC_25	USH 12 over Kinnickinnic	993	20	16	DM	N	na
15	SC_04	STH 65 over C&NW RR	1039	23	12	SS	Y	5
16	SC_22	USH 12 over Rush River	na	60	53	DM	Y	5
17	SC_03	I-94 over STH 35	888	90	82	DM	Y	5
18	SC_24	USH 12 over branch of Carr Creek	1151	79	72	SS, DM	Y	5
19	SC_01	I-94 over St. Croix River	na	120	108	SS	N	na
20	SC_23	USH 12 over Carr Creek	1148	59	54	DM	Y	5
21	SC_21	USH 12 over Wilson Creek	1020	26	16	SS	N	na
22	SC_12	STH 35 and Tower Rd	912	94	85	SS	Y	5
23	SC_02	STH 63 over I-94	1116	30	24	DM	Y	5
24	SC_13	STH 35 over Kinnickinnic	931	11	9	SS	N	na
25	SC_14	S. Main St. over S. Fork Kinnickinnic River	900	25	11	DM	Y	5
26	PI_08	STH 63 over Branch of Rush Creek	1062	26	18	DM	Y	6.5
27	PI_06	STH 65 over S. Branch Kinnickinnic	945	45		SS	N	na
28	PI_07	STH 65 over Trimbelle River	969	25	18	DM	Y	5
29	PI_05	STH 65 over Goose Creek	994	34	30	DM	Y	5
30	PI_03	USH 10 Over Oak Grove Creek	822	46	40	DM	Y	5
31	PI_02	USH 10 & Front Street	710	31	21	DM	Y	10
32	PI_01	USH 10 over St. Croix	na	172	161	SS, SH	Y	10
33	PI_04	USH 10/63 over Isabelle Creek	1034	21	17	SS	N	na
34	DU_10	STH 64 over Little Beaver Creek	985	78	76	SS	N	na
35	DU_09	STH 64 over Big Beaver Creek	999	39	33	SS, SH	N	na
36	DU_11	STH 64 over S. Fork Hay Creek	986	46	43	SS	Y	5
37	DU_08	STH 64 over Bolen Creek	983	60	53	SS	N	na
38	DU_13	STH 170 over Tiffany Creek	987	99	93	SS	N	na
39	DU_12	STH 40 over Muddy Creek	963	30	22	SS, SH	N	na
40	DU_01	CTH B & I-94	902	90	73	SS, SH	Y	5
41	DU_02	STH 29 over C&NWRR	947	17	10	SS, SH	Y	5.5
42	DU_05	USH 12/STH 29 over Muddy Creek	882	19	14	SS	N	na
43	DU_04	USH 12/STH 29 over Red Cedar River	813	55	34	SH, SS	Y	20
44	DU_07	USH 12/STH 29 & 22nd St	881	105	102	SS, SH	N	na
45	DU_03	STH 72 over Knights Creek	806	63	62	SS	N	na



Notes:
1) File ID refers to PDF file name on the data CD.
2) Surface elevations and rock depths are approximate for the site based on multiple borings.
3) In “Rock Surface Type” column, SS = sandstone, DM = dolomite, SH = shale.
4) “Cored” column reports whether rock core was collected and described, yes or no.
5) “Max length of core” reports maximum length of core penetration into rock of all site borings.
6) DOT = Department of Transportation

Appendix A5   Overview of Related Studies

Several additional studies – either completed, underway or completed but unpublished – are relevant to the hydrostratigraphy of the study area, and so deserve brief mention.

Bedrock mapping of Dunn, St. Croix and Pierce Counties
The WGNHS is now in the midst of three year federally funded STATEMAP project to revise and refine the bedrock map and stratigraphy of west-central Wisconsin (contact Dave LePain, WGNHS, Madison).

Spring mapping of St. Croix County
A project of UW-Eau Claire now underway will map and generate a water chemistry database for springs in St. Croix County (contact Katherine Grote, UW-Eau Claire Department of Geology).

Quaternary Geologic Mapping of St. Croix County
The Quaternary geology of St. Croix County was recently mapped in a two part effort by graduate students at UW-Madison. The first part, covering the western half of the county has been published as a thesis.

- Hinke, H.J., 2003, The Quaternary Geology of Western St. Croix County [MS thesis], University of Wisconsin-Madison, 105 p.

The eastern half of St. Croix county has been mapped but is not yet published (contact Steven J. Kostka, UW-Madison Department of Geology and Geophysics).

Regional Groundwater Modeling
The WDNR sponsored a 2D regional numerical flow model (GFLOW) for Pierce and St. Croix Counties as part of the source water assessment program. The project was led by Dr. Maureen Muldoon (University of Wisconsin-Oshkosh) and Dr. Kerry Keene (University of Wisconsin-River Falls), but has not yet been released.

The USGS is in the midst of a project to generate a 3D numerical (MODFLOW) model of groundwater flow in Polk, St. Croix and Pierce Counties (contact Paul Juckem, USGS-Madison).

Unpublished sinkhole mapping of Pierce and St. Croix Counties
Several sinkhole and closed-depression mapping projects have occurred in the study area, however none have been officially published. The most significant projects were two topographic map and air-photo studies to identify sinkholes led by Dr. Robert Baker of UW-River Falls. The studies resulted in two maps:

- Baker, R.W., Hughes, M., Huffman, S.F., Nelson, A., 1991, Closed Depression Map of St. Croix County Wisconsin.
- Baker, R.W., Bauer, E.J., Huffman, S.F., Hass, E. undated, Karst Map of Pierce County Wisconsin.

More recently, an undergraduate at UW-Eau Claire developed a field-checked map of sinkholes in St. Croix County. Her findings have been presented as a poster but have not been published as a map.

- Pace-Graczyk, K.J., 2005, Fracture orientations and closed depressions in St. Croix County, Wisconsin: effects of karst landscapes in hydrology, Geological Society of America Abstracts with Programs, v. 37, n. 5.

Appendix A6 Index of Well Video Logs

Video-logged Municipal Wells in Hudson and River Falls

Well	Casing Diam. (in)	Bottom Casing (ft.)	Total Depth (ft.)	Static Water (ft.)	Formations Logged
Hudson No. 3	16	258	538	152	Jordan fm.
Hudson No. 5	15	127	504	106	Cambrian undiff.
Hudson No. 7	23	381	501	86	Mt. Simon fm.
Hudson No. 8 (2 logs)	18	298	365	93	Jordan fm.
Hudson No. 9	18	303	394	94	Jordan fm.
River Falls No. 2	12	132	401	27	Prairie du Chien / Jordan fm.
River Falls No. 3	16	165	382	39	Prairie du Chien / Jordan fm.
River Falls No. 4	16	319	415	47	Jordan and St. Lawrence fms.
River Falls No. 5	16	318	386	73	Jordan fm.

Note:
Individual video log indices are included on the data CD. Window's Media format videos are archived at the WGNHS,

Appendix A7 Bibliography of Environmental Site Documents

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Cedar Corporation, 1993, Proposed Groundwater and Soil Remediation at the Former Wilkens Towing, River Falls, Wisconsin, on file at Wisconsin Department of Natural Resources.

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Cedar Corporation, 2003, Site Investigation Report, Town of Warren TCE Investigation, Town of Warren, St. Croix County, Wisconsin, on file at Wisconsin Department of Natural Resources.

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Soil Exploration Company, 1985, Phase II Remedial Investigation Report, Nor-Lake Inc. Facility, Hudson, Wisconsin, on file at Wisconsin Department of Natural Resources.

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