# III. PROJECT SUMMARY

The Maquoketa Formation, a dolomitic shale, is an important regional confining unit between the Silurian dolomite aquifer and the deep Cambrian-Ordovician aquifer system in southeastern Wisconsin. Rapidly growing communities in the region rely on pumping municipal water supplies primarily from the deep aquifer system, which has caused the formerly upward vertical gradient across the Maquoketa Formation to be reversed. In addition, significant quantities of water are pumped from the Silurian dolomite aquifer which is the upper bedrock formation. Hence, the role that the Maquoketa confining unit plays in the regional multi-aquifer hydrogeologic system needs to be better understood for the purpose of long-term groundwater management and protection.

Two separate but related research projects were initiated in 1997 and 1998. The first project, entitled **Evaluation of the confining properties of the Maquoketa Formation in the SEWRPC region of southeastern Wisconsin** (P.I.s Eaton and Bradbury, 1998), focused on hydraulic and geochemical fieldwork at an observation well at one of two field sites (Minooka Park, Waukesha). The other project, entitled **Hydraulic Conductivity and Specific Storage of the Maquoketa Shale** (P.I. Wang and research assistant Hart, 1997) concentrated on laboratory measurements on core samples and computer modeling of poroelastic properties. The former project was planned for only one year, while the latter included a second-year budget component (FY99/00) to test some modeling hypotheses by installing a pumping well. We submitted a revised second year budget request to the second project (Wang, Eaton and Bradbury, 1998) in order to combine efforts and build on existing results with a slightly expanded joint fieldwork proposal. This report therefore summarizes early work by Wang and Hart, and presents the results of joint research conducted by all parties using the improved multiple-well design in the two years since.

The main objective of this research is to obtain hydrogeologic properties of the Maquoketa Formation in Waukesha County, Wisconsin. Due to the generally low conductivity of this confining unit, which is a lithologically diverse dolomitic shale (Eaton and Bradbury, 1998), hydrogeologic testing is considerably more difficult than for a conventional aquifer. We therefore employed two complementary approaches in our research. One is based on laboratory rock core tests and modeling, and subsequent field verification, using Biot's (1941) theory of poroelasticity, which accounts for coupled deformation of the rock mass with fluid pressure changes. Recent reviews are presented by Hsieh (1996) and Wang (2000).

The other approach is more conventional, relying on field hydraulic testing using multiple wells. One of the problems with single-well testing, particularly in low-conductivity formations, is that the volume of rock tested is limited to the immediate vicinity of the well. With a multiple-well configuration, a much larger and potentially more representative rock volume can be tested, and scaling effects can be evaluated. The major goal of the conventional approach was to conduct a pumping test in the underlying Sinnipee Group dolomite, and analyze resulting head change at multiple observation points in the Maquoketa Formation using the

■leaky aquifer• method of Hantush (1956) and Neuman and Witherspoon (1972) to estimate vertical hydraulic conductivity in the confining unit. The pumping was anticipated to provide the stress needed to induce the reverse water level fluctuations predicted by poroelastic theory. This was not the case, but we observed possible reverse water-level fluctuations due to drawdown from water sampling in a much closer well.

This study has investigated the hydraulic properties of the Maquoketa shale confining unit using a novel laboratory and poroelastic modeling approach as well as a more conventional field-based hydrogeological approach. Laboratory pulse-decay testing of rock core has established that hydraulic conductivity ranges between 6.2x10$^{-14}$ and 4.3x10$^{-12}$ ft/s, and specific storage ranges between 3.7x10$^{-9}$ and 8.5x10$^{-7}$ ft$^{-1}$, which we consider representative of unfractured rock matrix at small scales. Poroelastic modeling predicts a small reverse water-level fluctuation in response to pumping, and some of our field data may reflect such a coupled poroelastic response to our field testing.

However, prior field hydrogeologic testing (Eaton & Bradbury, 1998) resulted in considerably higher hydraulic conductivity values ranging between 1x10$^{-9}$ ft/s and 1x10$^{-4}$ ft/s. Multiple-well geophysical logging and hydraulic testing reported here indicate that significant bedding plane fractures occur in the upper 100 ft of the Maquoketa Formation, and that these conductive fractures are well connected vertically to the overlying Silurian dolomite aquifer. “Leaky aquifer” testing by pumping the adjacent formations failed to provide bulk hydraulic conductivity values for the Maquoketa Formation, in part because of the fractures but also because the underlying Sinnipee Group dolomite has a very low hydraulic conductivity of 2x10$^{-9}$ ft/s at this site.

We suggest a new conceptual model of the hydrogeology of this important regional confining unit, consisting of a relatively high transmissivity, interconnected, but sparse fracture network embedded in a low conductivity rock matrix. Bulk hydraulic conductivity of the rock mass is therefore a complex function of matrix conductivity, fracture density and transmissivity, and fracture network interconnectedness. Areas of relatively low fracture density and interconnectedness, such as the shale-rich base of the formation, do not readily transmit head changes, and may account for the regional confining properties of the Maquoketa Formation. In contrast, the upper fractured 100 ft of the Maquoketa Formation have a good hydraulic connection to the overlying Silurian aquifer via this fracture network.

These results have significant implications for the role of the Maquoketa confining unit in the regional groundwater flow system. Although at large scales, the shale-rich base of the formation provides an effective confining unit, the upper part is hydraulically coupled to the overlying Silurian aquifer. This suggests that it is not a good assumption that the top of the Maquoketa Formation is an effectively “impermeable” or no-flow boundary to the Silurian aquifer. These findings also indicate that groundwater contamination (particularly DNAPLs) could migrate into the fractured top of the Maquoketa Formation.