REGIONAL AQUIFER-SYSTEM ANALYSIS—MIDWESTERN BASINS AND ARCHES

REGIONAL GROUND-WATER FLOW AND GEOCHEMISTRY IN THE MIDWESTERN BASINS AND ARCHES AQUIFER SYSTEM IN PARTS OF INDIANA, OHIO, MICHIGAN, AND ILLINOIS

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ABSTRACT

This report synthesizes information on the regional ground-water flow and geochemistry in the Midwestern Basins and Arches aquifer system in parts of Indiana, Ohio, Michigan, and Illinois. Aquifers that compose this water-table aquifer system include glacial aquifers and an underlying, areally extensive carbonate-rock aquifer.

Water within the aquifers is most commonly a Ca-Mg-HCO_3 type or a Ca-Mg-SO_4 type. In general, the distribution of hydrochemical facies within the aquifer system is controlled by the mineralogy of the aquifer material, rather than by a chemical evolution of water along general directions of regional ground-water flow.

Some ground-water flow systems within the aquifer system provide base flow to streams in response to ground-water recharge events. Other (often deeper) ground-water flow systems respond minimally to variations in ground-water recharge from precipitation and provide a fairly constant supply of water to streams. Streamflow hydrographs and base-flow duration curves were used to estimate such components of base flow in selected streams for long-term steady-state conditions in the aquifer system. Mean sustained ground-water discharge (discharge from fairly stable ground-water flow systems) ranges from 3 to 50 percent of mean ground-water discharge (discharge from all ground-water flow systems) to the selected stream reaches. These percentages indicate that 50 to 97 percent of base flow in the streams within the study area can be attributed to transient ground-water flow systems, which typically have a major component of local-scale flow. Because ground-water flow across the external boundaries of the aquifer system is minimal, such percentages indicate that most ground-water flow in the aquifer system is associated with seasonally transient local flow systems.

Results of a ground-water flow model that was calibrated by use of regression methods and that simulates regional flow systems within the aquifer system (approximately 10 percent of total ground-water flow in the aquifer system) indicate that most water (99 percent) in simulated regional flow systems is from recharge at the water table. Most water (78 percent) discharges from simulated regional flow systems to the principal streams. Less than 3 percent of water in simulated regional flow systems discharges to the Ohio River, Lake Erie, or downdip areas in the Illinois (structural) Basin.

Simulations also indicate that most of the Midwestern Basins and Arches aquifer system is characterized by alternating regional recharge and discharge areas at intervals of less than every 10 miles along the dominant regional trends of the potentiometric surfaces in the aquifers. Such alternating regional recharge and discharge areas result in the absence of long flow paths from the very highest regional potentiometric levels to the very lowest regional potentiometric levels. The presence of tritiated ground water (less than 50 years old) across most of the aquifer system also indicates that the aquifer system receives recharge across most of the study area.

The northeastern part of the aquifer system near Lake Erie differs from the rest of the system with respect to regional ground-water flow and chemistry. Specifically, part of the northeastern part of the aquifer system can be characterized as a broad area (tens of miles) of weak regional discharge (less than 0.5 inch per year). Results of the regional ground-water flow model indicate that regional flow systems have a limited ability to carry ground water away from this area; thus precipitation is prevented from recharging the regional flow systems in this part of the aquifer system. Some ground water recharged during Pleistocene glaciation was found in this area. Sulfide concentrations and sulfur isotope data, which indicate that extensive sulfate reduction has occurred in the aquifer system within this area, confirm that only minimal recharge of this part of the aquifer system has taken place over a long period of time.

The longest simulated ground-water flow paths within the aquifer system (nearly 50 miles) were also identified in the northeastern part of the aquifer system. These flow paths terminate at Lake Erie. On the basis of carbon-14 data, some of the oldest waters (approximately 13,000 years) were found at the downgradient end of these particularly long flow paths. The area near these flow paths is the only area within the aquifer system in which a systematic increase in ground-water ages was observed in the general direction of regional ground-water flow. Not all of the regional flow paths in the northeastern part of the aquifer system are particularly long. The very oldest waters that were found in the aquifer system (approximately 38,000-45,000 years) are associated with comparably short ground-water flow paths (approximately 10 miles). These waters are present beneath the Maumee River Basin and indicate that parts of the aquifer system beneath the Maumee River Basin are fairly stagnant.

INTRODUCTION

Quaternary glacial deposits and underlying Devonian and Silurian carbonate rock in parts of Indiana, Ohio, Michigan, and Illinois compose the Midwestern Basins and Arches aquifer system investigated as part of the Regional Aquifer-System Analysis (RASA) program of the U.S. Geological Survey (USGS) (Sun and Johnston, 1994). Objectives of the Midwestern Basins and Arches RASA project were to describe the geohydrology, ground-water flow, and geochemistry in this aquifer system (Bugliosi, 1990). Large subregions of the Midwestern Basins and Arches aquifer system were previously investigated (Ohio Department of Natural Resources, Division of Water, 1970; Norris and Fidler, 1973; Bloyd, 1974; Weist, 1978; Indiana Department of Natural Resources, 1988, 1990); these investigations, however, were limited in areal extent by political boundaries (state lines) or surface-water drainage divides. The RASA program provided an opportunity to synthesize earlier work and to study the full areal extent of the aquifer system.

Principal results of the Midwestern Basins and Arches RASA project are presented in Professional Paper 1423. Chapter A is a summary of the aquifer system. Chapter B describes the geohydrologic framework of the aquifer system. Chapter C (this chapter) describes regional ground-water flow and geochemistry in the aquifer system.

PURPOSE AND SCOPE

This report presents information on the geohydrology of and regional flow and geochemistry in the Midwestern Basins and Arches aquifer system in parts of Indiana, Ohio, Michigan, and Illinois. Specific report objectives are to describe (1) physical and hydraulic boundaries of the aquifer system; (2) regional relations between surface water and ground water; (3) a numerical model used to compute a regional ground-water budget, regional recharge and discharge areas, and patterns of regional ground-water flow; and (4) ground-water chemistry in relation to these patterns of regional flow. In the "Summary and Conclusions" section of the report, the hydrological and geochemical information are integrated to present a comprehensive analysis of the occurrence and flow of water in the aquifer system.

Regional flow, as defined for this report, is ground-water flow associated with flow systems that are minimally affected by seasonal variations in ground-water recharge from precipitation. Although local-scale flow systems that readily respond to variations in ground-water recharge are numerous and important throughout the aquifer system, it was outside the scope of the RASA project to investigate such flow systems. Specifically, local flow systems are not explicitly simulated by the numerical ground-water flow model.

APPROACH

A steady-state quasi-three-dimensional finite-difference ground-water flow model (numerical model) was constructed, calibrated, and used to describe regional flow in the Midwestern Basins and Arches aquifer system. Before this regional ground-water flow model was constructed, calibration targets were established. These calibration targets are based on measured ground-water levels and estimated ground-water discharge from regional flow systems, as approximated from measured streamflows, and were used to judge how well the numerical model simulated field conditions in the aquifer system. The numerical model (a mathematical representation of regional flow in the aquifer system) was built from a conceptual model (a simplified description of the aquifer system). The conceptual model was developed by synthesizing information on the thickness and areal extent of the aquifers and confining units within the aquifer system, as well as information on hydraulic characteristics, boundary conditions, flow regimes, sources and sinks of water, and general directions of ground-water flow. A geographic information system (GIS) was used to prepare a geographically referenced data base of this information, which was then converted for input into the numerical model by use of an interface program (Van Metre, 1990). Available computer codes MODFLOW (McDonald and Harbaugh, 1988) and MODFLOWP (Hill, 1992) were used to construct and calibrate the numerical model on the basis of a nonlinear-regression method developed by Cooley and Naff (1990). Nonlinear regression was used to automatically adjust parameter values that represent hydraulic characteristics of the aquifers and confining units, as well as annual recharge, so that the calibration targets were matched as closely as possible. Aspects of the model other than the parameter values were calibrated by trial and error adjustment. A postprocessing routine (Harbaugh, 1990) was used to help quantify ground-water budgets. Output from the calibrated numerical model was also used in conjunction with the GIS to map regional recharge and discharge areas. The particle-tracking program MODPATH (Pollock, 1989) was used to determine and illustrate simulated advective regional ground-water flow patterns. An additional postprocessing routine was used to map discharge vectors (Scott, 1990).

Geochemistry data were used to describe the relations among ground-water chemistry, aquifer mineralogy, and present and past patterns of regional flow in the Midwestern Basins and Arches aquifer system. The spatial variability in the concentrations of major solutes in the ground water was evaluated and related to the source aquifers and general patterns of regional ground-water flow. Chemical and isotopic analyses of ground water and aquifer material along general directions of regional ground-water flow were used to evaluate the important hydrologic and geochemical processes controlling ground-water chemistry and to qualitatively estimate ground-water ages.

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GEOHYDROLOGY

The area of principal hydrologic interest of the Midwestern Basins and Arches RASA project encompasses approximately 44,000 mi^2, most of which is in the Midwestern Basins and Arches Region as defined in Shaver (1985). Boundaries of this study area (fig. 1) are coincident with the contact between Devonian limestones and younger Devonian shales (fig. 2) or surface-water bodies.

GEOLOGIC SETTING

The Midwestern Basins and Arches aquifer system generally lies between the Appalachian, the Illinois, and the Michigan (structural) Basins and is located along the axes of the Cincinnati, the Findlay, and the Kankakee Arches in parts of Indiana, Ohio, Michigan, and Illinois (fig. 2). The sedimentary rocks within the area range in age from Precambrian through Mississippian; however, bedrock units of primary interest range in age from Ordovician (Cincinnatian) through Lower Mississippian (table 1). The oldest bedrock units exposed at the bedrock surface are generally found along the axis of the Cincinnati Arch in the south-central part of the study area, owing to several periods of erosion (figs. 2 and 3). In general, units exposed at the bedrock surface are progressively younger with distance from the axes of the arches. Four faults or fault zones partially dissect these sedimentary rocks within the region (fig. 2).

The bedrock units of Ordovician age (Cincinnatian) consist of interbedded shales and limestones. Shales predominate in these units; less than one-quarter of the sequence is made up of limestones (Gray, 1972). This sequence of interbedded shales and limestones thickens eastward from the western border of Indiana toward Ohio and is overlain by carbonate rocks (limestones and dolomites) of Silurian and Devonian age. These carbonate rocks locally contain some evaporite deposits in northwestern Ohio and northern Indiana (French and Rooney, 1969; Janssens, 1977); they contain sulfide minerals in an area associated with the Findlay Arch (Botoman and Stieglitz, 1978). The carbonate rocks of Silurian and Devonian age range in thickness from 0 ft at the contact with the rocks of Ordovician age to 2,500 ft in southeastern Michigan (Casey, 1994) (fig. 4). Erosion has resulted in the loss of hundreds of feet of carbonate rock from across the central part of the study area. The carbonate-rock sequence has been completely eroded in places by the ancient Teays-Mahomet River system, described in Melhorn and Kempton (1991). As a result of this erosion, the older shales and limestones of Ordovician age are present at bedrock surface in sinuous exposures north of their principal area of exposure (fig. 2). The carbonate rocks are overlain by shales of Devonian and Mississippian age along the margins of the structural basins. Erosion has resulted in the loss of the shale sequence throughout the central part of the study area except for an area approximately 50 mi northwest of Columbus, Ohio (fig. 2). This shale outlier is referred to herein as the “Bellefontaine Outlier.”

The bedrock is overlain by Quaternary glacial deposits throughout most of the study area (fig. 5 and table 1). These deposits directly overlie the carbonate rocks in the central part of the area (subcrop area of the carbonate rocks) and overlie the younger shales along the margins of the structural basins. Glacial deposits mask the ancient bedrock topography and bury numerous valleys in the bedrock surface.

The Quaternary glacial deposits—the result of multiple glacial advances—range in age from Kansan (oldest) to Wisconsinan (youngest) (Bennison, 1978). The deposits of Kansan and Illinoian age are not widespread within the study area and typically are present beyond the limit of the Wisconsinan ice sheet (fig. 5). The Kansan and Illinoian deposits are also thinner than the more widespread deposits of Wisconsinan age (Goldthwait and others, 1965; Geosciences Research Associates, 1982; Soller, 1986). The Wisconsinan ice sheet eroded much of these earlier glacial deposits; this resulted in landforms that contain material from multiple glacial advances. The resultant geomorphology is illustrated in figure 6; a photograph of a shaded relief generated from digital topographic data for every 30 seconds of latitude and longitude (U.S. Geological Survey, 1987).

The glacial deposits include ground- and end-moraine deposits, glaciolacustrine deposits, and outwash deposits (fig. 5); ice-contact stratified drift is present within the moraine deposits. The glacial deposits range in thickness from 0 to approximately 400 ft (fig. 7) (Mozola, 1969, 1970; Fleck, 1980; Gray, 1983; Soller, 1986). The areas dominated by ground- and end-moraine deposits are characterized by broad, low ridges with smooth, gentle slopes separated by flat, gently undulating plains (Mickelson and others, 1983). End moraines are close together where they abut highlands, such as the Bellefontaine Outlier (Young and others, 1985). The mineral composition of the moraines reflects local bedrock; about 4 percent of the material in Ohio was transported from the Canadian Shield north of the study area (Strobel and Faure, 1987).

Surficial glaciolacustrine deposits are present in the lowlands adjacent to Lake Michigan and Lake Erie and are the result of glacial lakes that formed along the margins of the retreating Wisconsinan ice (Young and others, 1985) (figs. 5 and 6). These glaciolacustrine deposits are dominated by lake bottom silts and clays. Minor sands and gravels mark the beaches of ancient shorelines (Goldthwait and others, 1965); some lakebed sands in Michigan just west of Lake Erie have been mapped (Western Michigan University, Department of Geology, 1981).