various lengths of the top section of the carbonate-rock aquifer (table 6). Data from these deep bedrock wells were compared to data from nearby shallow bedrock wells to assist in understanding the ground-water chemistry at depths as great as 450 ft below the top of the carbonate-rock aquifer.

A comparison of the chemical and isotopic data and the estimated ground water ages (tables 7, 8, and 11) between the shallow bedrock wells and the deep bedrock wells that are open hole through the entire length of the well shows that the chemistry and the ground-water ages between these wells are generally similar. The differences in ground-water ages in all these wells ranges from several hundred to less than 3,000 years. Of the pairs of shallow and deep bedrock wells that have ages greater than 50 years, ground water in the deep bedrock well is older than in the shallow bedrock well in well groups 3, 5, and 15; whereas ground water in the shallow bedrock well is older than in the deep bedrock well in well groups 4 and 16. The similarity between ground water from wells that are open only to the shallow part of the carbonate-rock aquifer and ground water from wells that are open to a much greater part of the carbonate-rock aquifer indicates that either (1) the chemistry and age of the ground water is similar throughout the sampled thickness of the carbonate-rock aquifer or (2) if ground water at depth has a distinctly different chemistry or older age, then the carbonate rocks are not transmissive enough at the greater depths to contribute significantly to the overall chemistry of the sampled water, and most ground water is produced from the upper part of the carbonate-rock aquifer.

Data from a shallow interval (less than 50 ft below the top of the aquifer) and an isolated deeper interval (as great as 450 ft below the top of the aquifer) within the carbonate-rock aquifer are available for well groups 10, 13, 14, and 17. A comparison of ground-water chemistry and ages between the shallow and deep bedrock wells at well groups 13 and 14 shows a systematic change in chemistry with depth and a distinctly different ground water in the deeper part of the carbonate-rock aquifer than in the shallow part. The chemical and isotopic data from these two well groups indicate that, in this area of the aquifer system, some recharge water enters the glacial aquifers and the shallow zones of the carbonate-rock aquifer but does not penetrate deeply into the aquifer system. In contrast, a comparison of ground-water chemistry and ages at well groups 10 and 17 shows little difference between the shallow and deeper parts of the aquifer system. At well group 10, tritium concentrations indicative of post-1953 recharge are found throughout the entire sampled thickness of the carbonate-rock aquifer. These wells are located at the highest potentiometric level in the aquifer system, where recharge rates to the deepest parts of the aquifer system should be relatively high. The chemical and isotopic data for ground water from wells 17G and 17D, located near the Sandusky River and Lake Erie, is quite similar. The age of the water in the overlying glacial aquifer is slightly older than water from deeper within the carbonate-rock aquifer (13,500 years compared to 12,000 years, using the lower age limit as discussed in the previous section). This slight decrease in age with depth may reflect an upward flow of ground water as it discharges the aquifer system.

Chemical and isotopic data are also available for ground water that was sampled from specific intervals in three deep wells that penetrate the entire thickness of the carbonate-rock aquifer in northwestern Indiana (D.J. Schnoebelen, U.S. Geological Survey, written commun., 1993). Ground water was sampled from various 10-ft intervals of the carbonate-rock aquifer by use of an inflatable packer system. Hydrogeologic data for these three wells and a description of the packer technology are given in Arihood (1994). The chemical and isotopic data from all the sampled intervals in each well are very similar, an indication that there is no stratification of ground-water chemistry with depth in this part of the aquifer system; however, the samples do not represent water from the deepest part of the carbonate-rock aquifer because the rocks in the bottom 60 to 400 ft of the wells are not necessarily transmissive (Arihood, 1994).

SUMMARY AND CONCLUSIONS

Aquifers in Quaternary glacial deposits and underlying Silurian and Devonian carbonate rock in parts of Indiana, Ohio, Michigan, and Illinois compose an integrated regional-scale water-table aquifer system. This 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.

Glacial deposits within the study area are the result of multiple glacial advances and directly overlie the carbonate rocks along the axes of the structural arches in the central part of the study area. These glacial deposits mask the ancient bedrock topography and bury numerous valleys in the bedrock surface. The glacial deposits and the carbonate rocks are separated by a shale sequence along the margins of and within the surrounding structural basins.

The water table within the Midwestern Basins and Arches aquifer system generally is within the glacial deposits. Glacial aquifers typically consist of sands and gravels in outwash deposits or as discontinuous lenses within ground or end moraines. Because such lenses are not necessarily areally extensive, the glacial aquifers can supply large yields of ground water only locally.

An areally extensive aquifer is present in the carbonate rocks that underlie the glacial deposits. At the regional scale, the carbonate-rock aquifer is semiconfined by the finer grained glacial deposits where the aquifer directly underlies these deposits (subcrop area of the carbonate-rock aquifer) but is confined where the aquifer underlies the intervening shale sequence, called the upper confining unit, along the margins of the aquifer system. Most active freshwater flow in the carbonate-rock aquifer is limited to the subcrop area of the aquifer because the upper confining unit inhibits recharge to the carbonate-rock aquifer. This lack of freshwater flow beneath the upper confining unit results in a transition from freshwater to saltwater in the carbonate-rock aquifer within the surrounding structural basins. Saline water is present within 5 mi of the subcrop boundary along the Michigan and Appalachian Basins. Freshwater extends as far as 70 mi downdip from the western subcrop boundary along the Illinois Basin; however, ^{14}C data for one freshwater sample (1D) (fig. 32) collected from the aquifer just west of the subcrop boundary indicates that this water may be 23,000 to 31,000 years old. The fact that this water is older than most waters throughout the subcrop area may indicate that freshwater in the carbonate-rock aquifer in the Illinois Basin is not associated with active freshwater flow.

The hydraulic characteristics of the aquifers within the Midwestern Basins and Arches aquifer system are varied. On the basis of available aquifer-test data, transmissivities of the glacial deposits span four orders of magnitude, ranging from 1.5 to 69,700 ft^2/d, whereas transmissivities in the carbonate-rock aquifer span three orders of magnitude, ranging from 70 to 52,000 ft^2/d. Such variability in the carbonate-rock aquifer is attributed to the nonuniform distribution of fractures, joints, bedding planes, and solution channels in the rocks. The results of a numerical ground-water flow model, which simulates regional flow systems within the aquifer system, indicate that where the carbonate rocks are hundreds of feet thick, the entire thickness of the rocks may not contribute substantially to the transmissivity of the aquifer. Some of the available aquifer-test data support these model results. In addition, the local presence of anhydrite within the carbonate rocks at depths of only a few hundred feet near Sandusky Bay in the northeastern part of the aquifer system indicates that active freshwater flow may be restricted to the upper few hundred feet of the carbonate rocks in this area.

The types and distribution of hydrochemical facies of water within the glacial aquifers and the subcrop area of the carbonate-rock aquifer are similar. Water of a $Ca\text{-}Mg\text{-}HCO_3$ type is present throughout much of the area but is found only locally in the northeastern part of the study area, where $Ca\text{-}Mg\text{-}SO_4$ type water predominates. The dissolution of calcite and dolomite is responsible for the presence of the $Ca\text{-}Mg\text{-}HCO_3$ water, whereas dedolomitization driven by gypsum dissolution and the oxidation of pyrite are responsible for the $Ca\text{-}Mg\text{-}SO_4$ water. Multiple-water-type facies in the aquifer system, which are found near the margins of the Michigan and Illinois Basins, are characterized by the presence of $Ca\text{-}Mg\text{-}Na\text{-}HCO_3$ water or $Ca\text{-}Mg\text{-}Na\text{-}SO_4$ water, or both; cation exchange in shales within the aquifer system is responsible for the presence of these Na-enriched waters. The distribution of these multiple-water-type facies may be related to past patterns of ground-water flow associated with Pleistocene glaciation. Water in the carbonate-rock aquifer under the upper confining unit in the Appalachian and Michigan Basins is a Na-Ca-Cl type, whereas the water under the upper confining unit in the Illinois Basin is a Na-Cl type. In general, the distribution of hydrochemical facies observed within the aquifer system is controlled by the mineralogy of the aquifer material rather than the evolution of water chemistry along paths of regional ground-water flow, as is commonly observed in closed aquifer systems.

Some ground-water flow systems within the Midwestern Basins and Arches aquifer system provide base flow to streams in response to ground-water recharge events, whereas other (often deeper) ground-water flow systems respond minimally to variations in ground-water recharge from precipitation. These latter, more stable flow systems have a more dominant influence of intermediate- and regional-scale flow than do the flow systems that readily respond to ground-water recharge, and they provide a fairly constant supply of water to streams over the course of a year and throughout long periods. Discharge to streams from such stable flow systems within the aquifer system is termed “sustained ground-water discharge” in this report.

Mean sustained ground-water discharge (discharge from fairly stable ground-water flow systems) to selected stream reaches within the study area ranges from 3 to 50 percent of mean ground-water discharge (discharge from all ground-water flow systems) to the stream reaches. These percentages indicate that the greatest amount of ground-water discharge to the streams (50 to 97 percent) is generally associated with transient flow systems, which typically have a major component of local-scale flow. Because results of the regional ground-water flow model indicate that most water in regional flow systems within the aquifer system discharges to streams within the study area, these percentages imply that seasonally transient local flow systems dominate flow in the Midwestern Basins and Arches aquifer system.

Values of mean sustained ground-water discharge as a percentage of mean ground-water discharge increase with distance downstream in nearly half of the principal surface-water drainage basins; this pattern indicates that streams at the bottoms of these drainage basins receive more base flow from stable flow systems within the aquifer system than streams in the upbasin areas. Percentages decrease with distance downstream along stream reaches in the south-central part of the study area, where the carbonate-rock aquifer is absent and the underlying bedrock is not an aquifer, and along stream reaches in the Maumee and Sandusky River Basins.

Differences in the relative amounts of base flow in the principal surface-water drainage basins that can be attributed to discharge from fairly stable ground-water flow systems are notable for long-term steady-state conditions in the aquifer system. On the basis of historic streamflow data, the Wabash River Basin has the greatest percentage (33 percent) of base flow that can be attributed to discharge from fairly stable flow systems. In contrast, less than 15 percent of the base flow in the principal surface-water drainage basins that drain into Lake Erie can be attributed to such stable flow systems.

The numerical model of regional flow systems within the aquifer system, which simulates approximately 10 percent of total ground-water flow in the system, indicates 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 within the area. Some water (19 percent) leaves simulated regional flow systems by means of evapotranspiration or discharge to seeps, springs, ditches, or small streams. Less than 3 percent of the water in simulated regional flow systems discharges to the Ohio River or Lake Erie or flows downdip into the Illinois Basin.

The Midwestern Basins and Arches aquifer system is generally characterized by alternating regional recharge and discharge areas, typically on a scale of less than 10 mi. Ground water does not follow long, continuous flow paths from recharge areas associated with the very highest potentiometric levels to discharge areas associated with the very lowest potentiometric levels while remaining isolated from additions of recharge. Rather, regional recharge areas exist all along the regional potentiometric gradient, except in the northeastern part of the aquifer system. Some of the highest regional recharge rates are associated with the Bellefontaine Outlier in Ohio.

The presence of tritiated water across most of the aquifer system can also be used to conclude that the aquifer system receives recharge across most of the study area. On the basis of tritium concentrations and modeled ^{14}C activities, ground-water ages throughout most of the aquifer system range from less than 50 years to several thousand years. Significant amounts of post-1953 water is found more than 100 ft beneath the surface of the bedrock in the area of the Bellefontaine Outlier.

High rates of simulated discharge from regional flow systems are typically associated with the principal streams that drain the area underlain by the aquifer system. Simulated regional discharge areas, however, are not limited to the vicinity of these streams. Specifically, a broad area (tens of miles) of weak regional discharge (less than 0.5 in/yr) exists within the northeastern part of the study area. This broad regional discharge area likely represents an area in which water that moves through regional flow systems leaves the aquifer system by means of ditches, small streams, or evapotranspiration. The Maumee and Sandusky River Basins in the northeastern part of the study area are the only principal river basins where simulated regional discharge areas are larger than simulated regional recharge areas.

A number of factors help explain the existence of the broad, weak regional discharge area. The streams in this area are incised only a few feet, which limits their ability to intercept regional ground-water flow. In addition, the area has a very low hydraulic gradient, which results in the presence of regional discharge areas that are broader than the streams themselves. Results of the regional ground-water flow model indicate that the magnitude of regional-scale horizontal ground-water flow in the poorly permeable glaciolacustrine deposits within the area is lower than elsewhere in the aquifer system. In general, model results indicate that the regional flow systems have a limited ability to carry ground water away from the area, which prevents precipitation from recharging the regional flow systems. Previous researchers have noted that much of this area was swampland before being ditched in the early 1900’s and that the historic Black Swamp resulted from poor surface drainage in addition to ground-water discharge from regional flow into what was a relatively stagnant area. Conclusions based on results of simulations are consistent with the low percentages of mean sustained ground-water discharge to streams relative to mean ground-water discharge to the streams in the area; much of the precipitation that is prevented from recharging the regional flow systems in the area is likely to be forced to discharge locally by means of drainage tile or shallow, transient local flow systems.

Chemical data also indicate that the aquifer system receives limited recharge in the northeastern part of the study area. Water with isotopically light $\delta^{18}O$ values (-10.05, -14.35) is found in the aquifer system near the Maumee River; these values indicate that the water may have entered the aquifer system beneath Wisconsinan ice sheets. On the basis of ^{14}C ages, these are the oldest waters in the aquifer system. These data indicate minimal flushing of ground water since the last glaciation at depths greater than 100 ft below land surface in this part of the aquifer system. The occurrence of extensive sulfate reduction in this area, as indicated by sulfide concentrations and sulfur isotope data, confirms that only minimal recharge has taken place in this area over a long period of time.

A three-dimensional flow field exists within the aquifer system at the regional scale because regional recharge is available to the regional flow systems across most of the study area, as previously discussed. As a result, individual regional ground-water flow paths cannot be determined from two-dimensional potentiometric-surface maps of the aquifer system. They can be determined, however, by use of the three-dimensional regional ground-water flow model. Results of the model indicate that the longest regional ground-water flow paths within the aquifer system (at nearly 50 mi) terminate at Lake Erie.

Chemical data also indicate that water in the regional flow systems generally does not follow long flow paths (tens of miles). On the basis of dissolved-solids and sulfate concentrations in the ground water, there is a general absence of chemical evolution of ground water from the highest regional potentiometric levels to the lowest regional potentiometric levels. There also is no systematic increase in ground-water ages along the dominant regional trends of the potentiometric surfaces. An exception to this apparent absence of systematic increase in ground-water ages was identified along a geochemical section that terminates near Lake Erie.

Ground water at the downgradient end of the flow paths that terminate at Lake Erie is some of the oldest in the aquifer system (approximately 13,000 years). The very oldest ground water (approximately 38,000-45,000 years) was identified further west, beneath the Maumee River Basin. The $\Delta^{34}S$ values (69.1 per mil, 68.4 per mil) for ground water sampled near Lake Erie and the Maumee River also indicate relatively long residence times in these parts of the aquifer system. Because the very oldest ground water, which is present beneath the Maumee River Basin, is associated with short (typically less than 10 mi) regional ground-water flow paths as compared to the flow paths that terminate at Lake Erie, it is likely that this part of the aquifer system is fairly stagnant. The old ground water near Lake Erie, however, is more likely to be associated with position along regional flow paths rather than with a stagnation point in the aquifer system. Results of the regional ground-water flow model indicate that flow in the aquifer system near Lake Erie at the end of relatively long flow paths may be predominantly vertical and may be associated with discharge from the deep parts of the aquifer system. Ground-water ages from ^{14}C data for selected wells near Lake Erie increase slightly with decreasing depth, a pattern that is consistent with the modeled upward flow of ground water in this area.

No effects of future pumping on the aquifer system were investigated as part of the Midwestern Basins and Arches Regional Aquifer-System Analysis project. Nearly 433 Mgal/d of ground water was reported to have been withdrawn from the aquifer system by users capable of pumping 100,000 gal/d or greater during the 1990 calendar year. Only 15 percent of this water was reported to have been withdrawn from the carbonate-rock aquifer. Of the remaining 85 percent, most of the water was reported to have been withdrawn from outwash deposits that underlie principal streams. Estimates of mean ground-water discharge to streams for long-term steady-state conditions in the aquifer system indicate that more than 13,000 Mgal/d of water discharges from the aquifer system to streams within the study area. Current pumpage, therefore, is only a small percentage of the total amount of water that moves through the aquifer system. No regional-scale cones of depression are present within the aquifer system; the aquifer system is not heavily stressed at the regional scale, and much more of the water in the Midwestern Basins and Arches aquifer system could be used.

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