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Using Watershed Pour-Point Elevations to Evaluate the Base of Fresh Groundwater in the Cumberland Plateau of Eastern Kentucky

Ethan S.L. Davis, T. Marty Parris, and Jerrad Grider

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For further information contact:
Technology Transfer Officer
Kentucky Geological Survey
228 Mining and Mineral Resources Building
University of Kentucky
Lexington, KY 40506-0107

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Statement of Benefit to Kentucky

Since the 1960s, the "Fresh-Saline Water Interface Map of Kentucky" by H.T. Hopkins has been a critical reference for assessing the maximum depth of fresh groundwater and provides important guidance for well operators and regulatory agencies. However, the map likely underestimates the depth of the interface. This study used new data and a new technique based on pour points in hydrologic units to refine those data and create a new map showing the deepest observed fresh water (more accurate terminology than "fresh-saline water interface").

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Abstract

Horizontal drilling with hydraulic fracturing at shallow depths (less than 2,200 ft) in the Devonian Berea Sandstone oil and gas play, along with the potential for high-volume hydraulic fracturing in the nascent Cambrian Rogersville Shale gas play, have generated a renewed interest in protecting groundwater quality in eastern Kentucky. A critical component of protection is an accurate understanding of the distribution of fresh water in the subsurface. The "Fresh-Saline Water Interface Map of Kentucky" by H.T. Hopkins, published by the U.S. Geological Survey and Kentucky Geological Survey in 1966, has been a critical reference for assessing the maximum depth of fresh groundwater and is an important guidance document for well operators and regulatory agencies. To create the map, Hopkins assumed that total depth of domestic water wells equaled the base of fresh groundwater (total dissolved solids less than 1,000 ppm). Most domestic wells fail to penetrate the deepest fresh groundwater, however, and consequently, Hopkins's map likely underestimates the depth of the fresh-saline water interface.

Our study also used total depths of wells to map the base of fresh groundwater, but increased the data density by adding data from domestic water wells drilled after 1966. In the 14-county study area, the number of wells increased from 50 used by Hopkins to 4,824 in this study. Total well depths were contour mapped using Petra software. Despite the increased data density, the inclusion of a greater number of shallow wells produced contour patterns that impeded resolution of deep fresh groundwater distribution (i.e., noise). To limit the influence of shallow wells, we eliminated wells with total depths above the elevations of watershed pour points in each watershed defined by 14- and 11-digit hydrologic unit codes. This excluded wells that did not penetrate the deepest fresh groundwater in low-order watersheds. We then created maps based on all wells with total depths below the elevations of their respective pour points in 14- and 11-digit hydrologic units ($n=3{,}203$ and 854, respectively), as well as maps based on the single deepest well in the 14- and 11-digit hydrologic units ($n=1{,}420$ and 74, respectively). The pour-point method improved the resolution of deep fresh groundwater distribution, and the map using the single deepest well depth in each 11-digit hydrologic unit provided the clearest illustration of deep fresh groundwater distribution.

Throughout most of the study area, the estimated depth of fresh groundwater derived from the 11-digit hydrologic unit deepest-well map is, on average, 147 ft deeper than the interface shown on the Hopkins map; in eastern Lawrence County, the difference exceeds 500 ft. Even though our study resulted in an improved estimate of maximum fresh groundwater depth, uncertainties remain in the data and methods. To reflect this uncertainty, the term "deepest observed fresh water" should be used as an alternative to "fresh-saline water interface."

Introduction

Since 2011, relatively shallow drilling depths and increased production have caused the Devonian Berea Sandstone in northeastern Kentucky to become a leading oil producer in the state. To date, more than 150 wells have been drilled and completed in the Berea Sandstone in a six-county area (Fig. 1). The Berea play has been developed using hydraulic fracturing and horizontal drilling at vertical depths of less than 2,000 ft, with some development as shallow as 800 ft. In addition, eastern Kentucky is home to a nascent oil and gas play in the Cambrian Rogersville Shale. So far, only six wells have tested the Rogersville, and, consequently, its development potential is unknown. Mapping by Harris and Hickman (2016) suggests that the play could develop over a 14-county area at reservoir depths of 5,000 to 10,000 ft (Fig. 1). Early tests suggest that, if successful, the Rogersville could be developed using high-volume hydraulic fracturing involving hundreds of thousands to millions of gallons of fluid and hundreds of thousands of pounds of sand. This would be the first widespread use of large-volume hydraulic fracturing in Kentucky.

The potential use of large-volume hydraulic fracturing in the Rogersville and the shallow drilling depths in the Berea have renewed interest in evaluating and protecting groundwater quality in eastern Kentucky. This requires an understanding of the subsurface distribution of potable groundwater, which, to a large extent, comes from the work of H.T. Hopkins, who mapped the fresh-saline water interface. Published in 1966, Hopkins's "Fresh-Saline Water Interface Map of Kentucky" is an important guidance document used by well operators and state officials evaluating groundwater depth and the depth of surface casing in oil and gas wells.

Using data from files at the U.S. Geological Survey and Kentucky Geological Survey, Hopkins (1966) defined the interface as the boundary between water having total dissolved solids less than 1,000 ppm (fresh water) and water having total dissolved solids equal to or greater than 1,000 ppm (saline water). Hopkins made the critical assumption that the total depth of domestic water wells equaled the base of fresh groundwater, and hence, the fresh-saline water interface. This assumption is likely incorrect, however, for the following reasons. First, there is no financial incentive to drill to deeper aquifers once an aquifer with sufficient freshwater yield has been penetrated. Consequently, most compilations of domestic-well TDs are skewed to shallow aquifers. Second, drillers want to avoid saline water that might degrade a potable water supply, because many do not have the ability to plug back a well. Third, fresh water directly in contact with saline water rarely occurs in eastern Kentucky, because the hydrogeology of the area is characterized by interstratified confining units and aquifers, with water quality in the latter being variable (Fig. 2a). Collectively, these reasons likely contribute to an underestimation of the depth of the fresh-saline water interface in the Hopkins map.

This report provides a new analysis of the estimated base of fresh groundwater in the area of the Berea and Rogersville plays. To reach a more accurate estimation, we added data from domestic water wells drilled after 1966. We analyzed those data in the context of watersheds defined by hydrologic unit codes of the National Hydrography Dataset and their associated pour points—the intersection of the HUC boundary and the lowest-elevation stream outlet from that HUC. This analysis deepens the estimated base of fresh groundwater—herein referred to as deepest observed fresh water—an average of 147 ft, compared to the Hopkins map.

Geologic and Hydrogeologic Setting

The study area covers Greenup, Boyd, Carter, Lawrence, Elliott, Johnson, Martin, Floyd, Magoffin, Breathitt, Morgan, Wolfe, Owsley, and Lee Counties, which are located in the Cumberland Plateau, a southern subregion of the greater Appalachian Plateau physiographic province (Fig. 1). The Cumberland Plateau is a dendritically dissected upland characterized by steep ridges and narrow valleys. Geologically, the study area is in the Appalachian Basin, a foreland basin that contains Cambrian–Permian strata, although the latter are not found in eastern Kentucky. Surface rocks are primarily sandstones, siltstones, and conglomerates of the Pennsylvanian Breathitt Group and Conemaugh Formation (Fig. 1). Locally, Mississippian limestones, siltstones, and shales are exposed

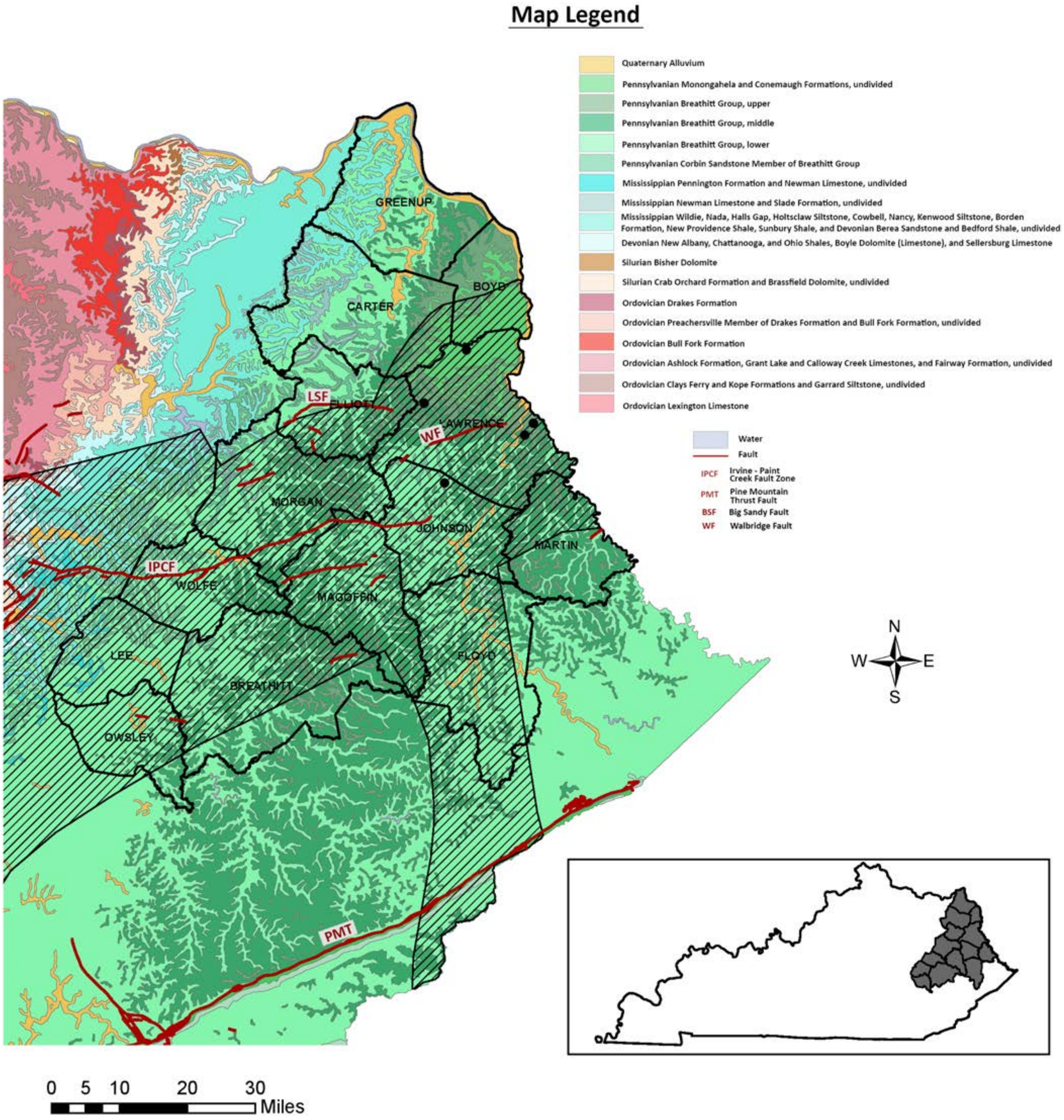

Figure 1. Geology of the study area (from Sparks, 2009). Diagonal line pattern represents locations of the Rome Trough and area of possible Rogersville Shale production. Test wells in the Rogersville are shown with black circles. The area of Berea Sandstone oil production includes Greenup, Carter, Boyd, Elliott, Lawrence, and Johnson Counties. Major fault abbreviations are used in subsequent figures.

in deeply cut valleys, particularly in the western margin of the study area. Major streams have deposited Quaternary alluvium in stream beds and stream valleys.

The majority of freshwater aquifers in eastern Kentucky are in the Lower to Middle Pennsylvanian Lee and Breathitt Formations (Minns, 1993). These formations were deposited in the central

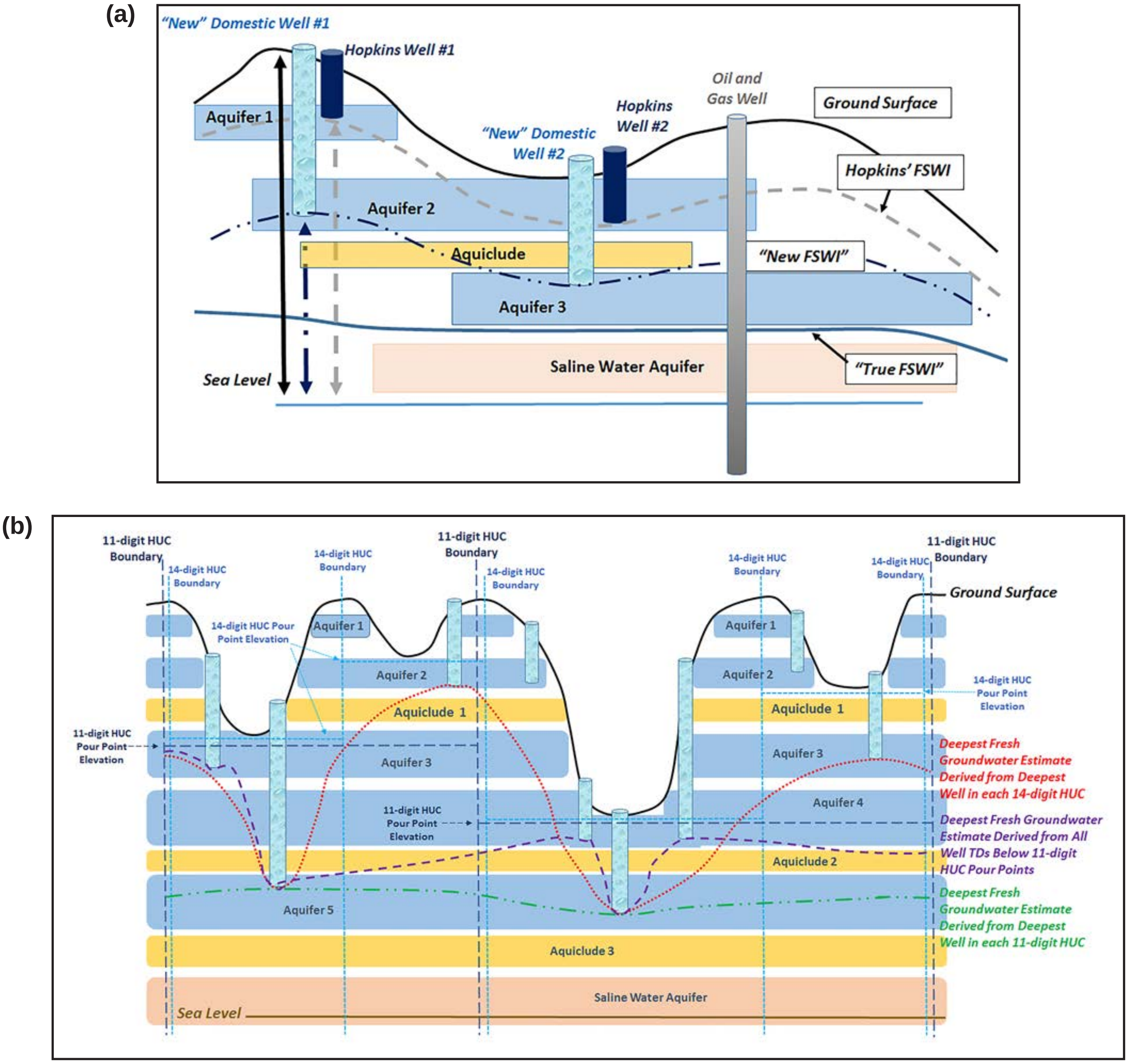

Figure 2. Conceptual cross sections illustrating the impact of: (a) studying additional post-1966 domestic water wells to more accurately estimate the depth of fresh water; vertical arrows show depths converted to elevations in relation to sea level and (b) using 14- and 11-digit HUC boundaries and their pour points to filter out shallower wells for improving the analysis of deep fresh groundwater distribution. Figures are not to scale.

Appalachian foreland basin in response to thrusting and basin downwarping associated with the Alleghenian Orogeny (Tankard, 1986; Shumaker, 1996). The Breathitt Formation primarily consists of interbedded feldspathic and micaceous sandstone, siltstone, shale, coal, underclay, and thin limestone, with sandstone composing half of the total thickness of the group (Lloyd and Lyke, 1995). The Breathitt Formation shows significant lateral heterogeneity typical of strata deposited in a deltaic environment (Rice and others, 1979). The Lee Formation, which underlies the Breathitt Formation, is predominantly composed of sandstone and conglomerate, with smaller amounts of interbedded siltstone, shale, and coal in the upper section. Rice and others (1979) postulated that sandstone in the

Lee Formation was deposited in distributary channels in a delta that prograded to the southwest.

Chesnut (1992) proposed a change in nomenclature that dropped the terms "Breathitt" and "Lee Formations" and combined the strata to form the Breathitt Group. Individual sandstones that were formerly members of the Breathitt and Lee Formations, such as the Corbin and Bee Rock Sandstone and Princess Formation, were elevated to formations in the Breathitt Group. We adopted the nomenclature of Chesnut (1992), except when citing previous studies.

Numerous conceptual models have been formulated to explain the movement of groundwater in the Valley and Ridge terrain of eastern Kentucky (Kipp and Dinger, 1991; Wunsch, 1993) and elsewhere in the Appalachian Basin (Stoner, 1983; Larson and Powell, 1986; Harlow and LeCain, 1991). Two geologic features play important roles in the movement of groundwater in this setting. First, interbeds of sandstone, siltstone, coal, and underclay with contrasting hydraulic conductivity influence downward and lateral groundwater flow. Aquifers largely occur in permeable sandstone and coals with well-developed cleat systems. Strata with low permeability, such as underclays, form an impediment to downward movement of groundwater and cause lateral movement toward the valley walls, where springs and diffuse seeps may develop. The contrast in hydraulic conductivity associated with the different strata may also produce perched aquifers.

The second important influence is fractures superimposed on the bedded strata. Vertical and near-vertical fractures facilitate downward movement of groundwater within beds, but fractures that are more continuous also provide paths for interaquifer flow across confining units. The influence of fractures on groundwater flow is mostly shallow, occurring within approximately 100 ft of the surface. Some flow in fractures may respond promptly to rainfall (Kipp and Dinger, 1991). The aggregate effect of the bedded strata and fractures is downward movement of groundwater in a stair-step fashion along the valley wall and toward the valley bottom. As depth increases, the abundance and interconnectedness of fractures decrease, and regional groundwater flow becomes restricted.

Though saturated, aquifers in the interior of ridges do not appear to respond to rainfall and likely contain groundwater having a longer residence time (Kipp and Dinger, 1991). The distribution of deeper aquifers at or below the valley bottoms in eastern Kentucky is uncertain. Several authors have noted that saline water is often encountered 100 to 150 ft below the valley surface (Price and others, 1962; Hopkins, 1966; Wunsch, 1993). Upper Mississippian shales and siltstones form a barrier to downward migration of groundwater, and consequently, the contact between Mississippian and Pennsylvania rocks is often marked by springs. In the western part of the study area, alluvial stream valleys overlying Mississippian limestones create recharge zones for local freshwater aquifers (Lloyd and Lyke, 1995). These aquifers are generally restricted to the limestone members of the Upper and Middle Mississippian Slade and Borden Formations. Overall, however, Mississippian strata are not common aquifers in the Cumberland Plateau.

Methods

Development of the Kentucky Groundwater Data Repository (kgs.uky.edu/kgsweb/DataSearching/watersearch.asp; last accessed 07/25/2018) in 1990 by the Kentucky Geological Survey has provided straightforward and up-to-date access to domestic water-well data. The repository provides, for example, information about well location, depth, and water yields, supplied by the Kentucky Division of Water. Hence, the first step in reassessing the distribution of deep, fresh groundwater was to query the repository to acquire "new" domestic water-well data, most of which post-dated Hopkins (1966) or were not readily available to Hopkins for his analysis. We extracted data for active domestic water wells (i.e., for residential use) with total depths of 1,000 ft or less below the ground surface. Although most domestic water wells are significantly shallower than 1,000 ft (an average depth of 132 ft in the study area), we used the deeper search criterion to ensure that deeper domestic wells would be included (Fig. 2a).

With a few exceptions, the search did not include water wells drilled for agriculture, mining, industry, commercial use, monitoring, uranium-resource evaluation, academic research, or unknown uses. A critical assumption in our search was that wells completed for domestic use produce fresh water (total dissolved solids less than 1,000 mg/L). This assumption allowed for a larger data set, because water-chemistry measurements were available for only 19 percent of domestic wells in the original query. This strategy contrasts with that of Hopkins, who only used well data that, at a minimum, had chloride measurements. Our expanded query yielded 4,824 wells, whereas Hopkins used data from 50 wells in the same area.

We imported the data for the extracted wells as XY coordinates into the GIS software Esri ArcMap and created a feature class of well sites. Although latitude-longitude locations of wells were not physically verified, surface elevations for wells were verified and corrected, where necessary, using the U.S. Geological Survey's 10-m Digital Elevation Model for Kentucky (kyraster.ky.gov/arcgis/rest/services/ElevationServices/Ky_DEM_USGS_10M/ImageServer; last accessed 07/17/2018). This DEM is a statewide, level 1 DEM with a root-mean-square error-based desired vertical accuracy of 7 m or less. We imported the DEM into ArcMap and extracted an elevation value for each data point via the Spatial Analyst extension. We then converted the depth of each well to feet above mean sea level by subtracting the total depth from the updated surface elevation. Total depths ranged from 61 to 2,196 ft AMSL, with an average of 701 ft AMSL.

Though the query provided a large data set with which to reassess the distribution of fresh groundwater, it still included many wells completed in shallow aquifers not representative of a deep aquifer system. To address the problem of oversampling wells in shallow aquifers, and to analyze the data by means of spatial distribution, we examined the data using 5-min Carter coordinate quadrants. Developed by the Carter Oil Co. and unique to Kentucky, the Carter coordinate system is a land grid that divides the state into a series of quadrants defined by 5 min of latitude and 5 min of longitude. We grouped the wells by 5-min Carter coordinate quadrants and selected the two deepest wells in the northern, central, and southern parts of each quadrant. Selecting the six deepest wells in each 5-min quadrant provided 966 wells for mapping.

Analyzing the well data by Carter grid provided a suitable spatial distribution, but it did not provide a basis for analyzing the distribution of groundwater based on hydrogeologic principles. In accordance with the recommendations of scientists in the Kentucky Geological Survey Water Resources Section, we made a strategic shift to analyze the data using the framework of watersheds as defined by hydrologic unit codes. HUCs are hierarchical polygons representing surface-water drainage basins in the National Watershed Boundary Dataset developed by the U.S. Geological Survey (nhd.usgs.gov/wbd.html; last accessed 07/17/2018). By convention, larger watersheds are defined by HUC numbers with fewer digits (e.g., two-digit HUCs) and encompass multiple smaller watersheds defined by HUC numbers with more digits. For example, part of the study area includes parts of the Kentucky River Basin, which corresponds to the six-digit HUC 051002. This HUC encompasses five eight-digit HUCs that feed the larger Kentucky River Basin (e.g., Middle Fork of the Kentucky River Basin, 05100202). Still smaller watersheds are designated as 11-digit, 12-digit, and 14-digit HUCs.

A significant feature of a HUC is the pour point, which is defined as the intersection of the HUC boundary and the lowest-elevation stream outlet from that HUC. From a hydrogeologic perspective, the deepest groundwater in a given HUC, by definition, must be deeper than that basin's pour point. We therefore restricted our analysis to wells having TDs below the pour-point elevation in the watershed in which the wells occur (Fig. 2b). We then verified the elevations of the pour points using a HUC overlay feature class and the USGS 10-m DEM of Kentucky in ArcMap by identifying the DEM elevation at the stream outlet along the HUC boundary for each 11- and 14-digit HUC.

To obtain a data set favorable for mapping, we examined the spatial distribution of well TD data in different HUC sizes and concluded that 11- and 14-digit HUCs were optimal. The study area contains 92 11-digit HUCs and 1,151 14-digit HUCs, and we present results from both sizes for comparison and analysis. Mapping was done using the software IHS Petra, and we initially contoured the TD elevation of all wells (n = 1,420) with TDs below the pour-point elevation of their respective 11-digit

HUCs. A second map, based on a smaller data set (n = 74), contoured the elevation of TD of the single deepest well in each 11-digit HUC. Similar maps based on well TDs below the pour points of 14-digit HUCs utilized more data points (n = 3,203 for all wells, n = 854 for single deepest well) because of the smaller size of the watersheds. In the study area, 1,621 wells (34 percent) did not penetrate depths below pour-point elevations in their respective 14-digit HUCs, and 3,404 wells (71 percent) did not penetrate below the pour-point elevations in their respective 11-digit HUCs. In addition, 279 of the 14-digit HUCs (26 percent) and 18 of the 11-digit HUCs (20 percent) did not contain any wells with TDs deeper than the pour-point elevations.

For the map based on the deepest well in each 11-digit HUC (see **Results,** below), contour lines were further edited to clean up spurious contours caused by an absence of data on the margins of maps, and to further develop trends not mapped by Petra. We made these edits in areas where isolated elevation highs and lows were spatially close enough that they were likely connected hydrogeologic features or reflections of regional trends. Isolated highs were connected by extending 600-ft contour lines in Breathitt, Wolfe, and Lee Counties. The low trough running from the Big Sandy River in Lawrence County to the Licking River in Magoffin County contains a 100-ft contour low that we extended to the eastern border of the map, as well as an extension of 200- and 300-ft contours corresponding to the regional trend.

Petra is primarily an oil and gas analysis software, and one of its principal functions is subsurface geologic mapping, an advantageous feature for this study. Moreover, Petra provides an isopach mapping function useful in comparing multiple digital maps. The Kentucky Geological Survey has significant in-house expertise that favored Petra over other digital mapping options. Our Petra-generated maps were created using an inverse-distance-weighted, squared interpolation method. Inverse-distance methods weigh data points during interpolation such that the influence of a data point on neighboring points decreases with increasing distance between the points. This interpolation method is ideal for irregularly spaced data in which the data values for each point are assumed to be related to the other points based on local variations.

We used Petra's isopach mapping function to create two "difference maps" representing differences in elevation (i.e., thickness) between two surfaces. Our first isopach map measured the elevation difference between the map based on the deepest well in each 11-digit HUC (11-digit HUC deepest-well map) and the Hopkins (1966) map. We used this isopach map to compare our results with those of Hopkins. A second isopach map measured the elevation difference between the 11-digit HUC deepest-well map and the USGS 10-m DEM, with the elevation difference representing the depth from ground surface to the estimated base of fresh groundwater.

To generate the isopach maps, we created contour feature classes of the Hopkins map and the USGS 10-m DEM map to import into Petra. To create these features, we imported a raster image of the Hopkins map into ArcMap and georeferenced the image to the study area. We then created a polylines feature class in ArcMap, manually traced the Hopkins contours, assigned polyline values matching the contours, and imported the polylines as a contour feature class into Petra. We also created a 10-ft-contour feature class of the USGS 10-m DEM in ArcMap using the 3D Analyst Contour tool and imported the contour feature class into Petra. Once the Hopkins and USGS 10-m DEM contours were imported into Petra, we created grids from each set of contours for use in the isopach measurement. We used a nearest-neighbor method to resample each grid in Petra to match the 1,500-ft cell size, rows, and columns originally used in the Petra-generated 11-digit HUC deepest-well map. From the resampled grids, we then produced the isopach maps using the Isopach From Grids function in Petra.

In addition to generating a map of deepest observed fresh water, we examined water quality in the context of multiple-scale watersheds and geochemical facies models for a subset of domestic water wells with chemistry data (n = 370). Specifically, we used Aqueous Solutions' The Geochemist's Workbench software to determine dominant cations and anions, total dissolved solids, ionic strength, and charge-balance error. A charge-balance error equal to or less than 10 percent was used as a threshold for selecting wells for further geochemical analysis (n = 40).

Results

At the onset, it was not clear which map(s) would provide the best resolution of deep fresh groundwater distribution, so, as described above, we generated contour maps using all wells with TDs below the pour-point elevation in each watershed and contour maps using the single deepest well below the pour-point elevation in each watershed. Contour maps of estimated fresh groundwater depth using all wells with TDs below the pour points in the 11- and 14-digit HUCs showed similar broad trends, but also numerous bullseye patterns and erratic contours (Figs. 3a, b). The latter effects were especially prominent on the 14-digit HUC map, which contains more data points distributed among more numerous smaller watersheds compared to the 11-digit HUC map. The erratic and bullseye patterns are an attempt by the mapping software to contour juxtaposed wells with TDs in aquifers of different depths. Although meeting the criteria of being below the pour point, the shallower TDs in both maps most certainly continue to underestimate the depth of deepest fresh groundwater (Fig. 2b). The underestimation is more significant with the 14-digit HUCs, which represent many watersheds in which first- and second-order streams originate, and are located at higher elevations within larger watersheds. Consequently, well TDs below the pour points in 14-digit HUCs are, on average, 92 ft shallower than those below the pour points in 11-digit HUCs (Fig. 4).

The maps using all wells with TDs below the pour point in effect portray the depth of target aquifers over a range of depths, but in doing so, the shallow wells insert significant noise into the signal of the distribution of deeper fresh groundwater. To mitigate this influence, we further restricted our analysis by creating a map based on the TDs of the single deepest well drilled below the pour-point elevation in each of the 14-digit HUCs. A similar map was created using the 11-digit HUCs. These two resulting single-deepest-well maps use fewer data points, which reduced the noisy patterns in the 14-digit HUC map and almost eliminated them in the 11-digit HUC map (Figs. 3c, d). The effect of using the single deepest well can be seen in the shift in data distribution shown in Figure 4. Persistence of the bullseye pattern in the 14-digit HUC map reflects the influence of variable well TDs in adjacent small watersheds. In contrast, using the single deepest well in each 11-digit HUC produced a map in which contours are smoothed and continuous over longer distances. Without the influence of shallower wells, the 11-digit HUC deepest-well map is the most representative of the distribution of deep fresh groundwater, and therefore most of our further analysis and discussion are based on this map.

The depth of deepest observed fresh water on the 11-digit HUC deepest-well map tends to be shallower on the west side of the study area and deeper to the east (Fig. 3d). Average elevation of the deepest observed fresh water across the study area is 453 ft AMSL, the highest elevation being 667 ft AMSL in Wolfe County and the lowest being 61 ft AMSL in Lawrence County. Contours show a regular southwest-northeast trend in the northern and northwestern parts of the study area. This trend and west-east deepening correspond with the regional attitude of Pennsylvanian and other Paleozoic strata that have an overall southwest-northeast strike and dip to the southeast in eastern Kentucky (Fig. 5). Farther to the south, a small trough of deeper fresh water is located in northwestern Breathitt County and is surrounded by shallower fresh water in southeastern Breathitt, Wolfe, Lee, and Owsley Counties. One of the most prominent features is the west–east-trending trough that extends from Magoffin County eastward into Johnson and Lawrence Counties, where the lowest TD elevations (61 and 84 ft AMSL, respectively) are found. Unlike in other parts of the study area, contours defining the trend of a trough in Lawrence and Johnson Counties are nearly orthogonal to contours defining the aforementioned regional southwest-northeast strike.

Comparison of the well TD elevations in Figure 3d with the base of Pennsylvanian structure shows that most wells reach total depth in the Pennsylvanian Breathitt Group (Fig. 5). Wells that reach total depth in Mississippian strata are mostly in the western part of the study area, and TDs range from 3 to 568 ft (average of 181 ft) below the base of the Pennsylvanian. Comparison with rock types making up the Pennsylvanian subcrop mapped by

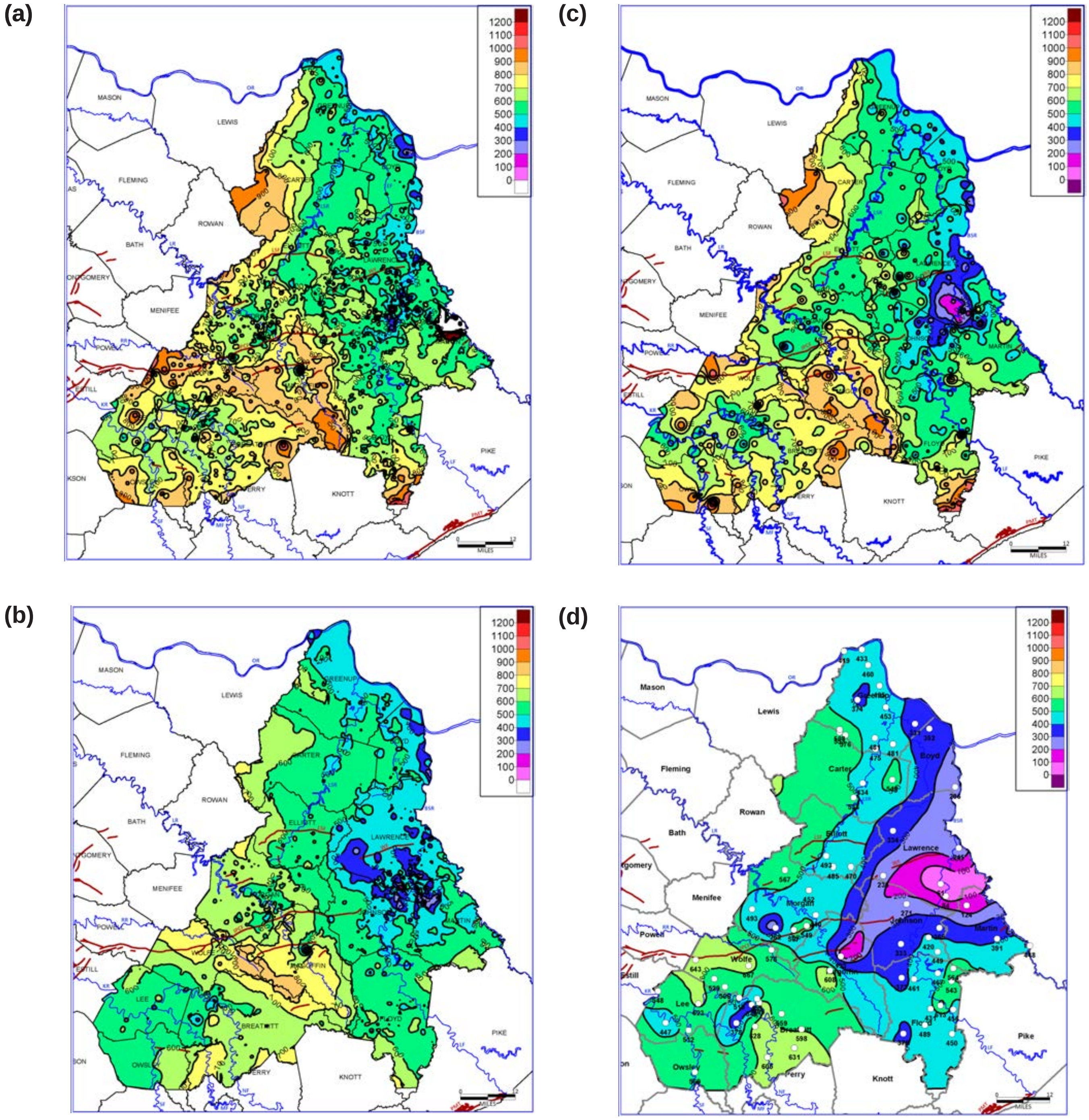

Figure 3. Elevation of deepest observed fresh water using (a) all domestic wells with TDs below the pour point in their respective 14-digit HUCs, (b) all domestic wells with TDs below the pour point in their respective 11-digit HUCs, (c) TDs of the single deepest domestic well in each 14-digit HUC, and (d) TDs of the single deepest domestic well (white circles) in each 11-digit HUC. Elevations are in feet AMSL. OR = Ohio River, TC = Tygarts Creek, LSR = Little Sandy River, EF = East Fork of the Little Sandy River, BSR = Big Sandy River, LR = Licking River, LF = Levisa Fork of the Big Sandy River, KR = Kentucky River, SF = South Fork of the Kentucky River, MF = Middle Fork of the Kentucky River, NF = North Fork of the Kentucky River. Stream abbreviations are used in subsequent figures.

Chesnut (1992) suggests that well TDs just below the base of the Pennsylvanian would primarily be in the Slade Formation to the west and the Borden Formation in Greenup County. Elsewhere, howev-

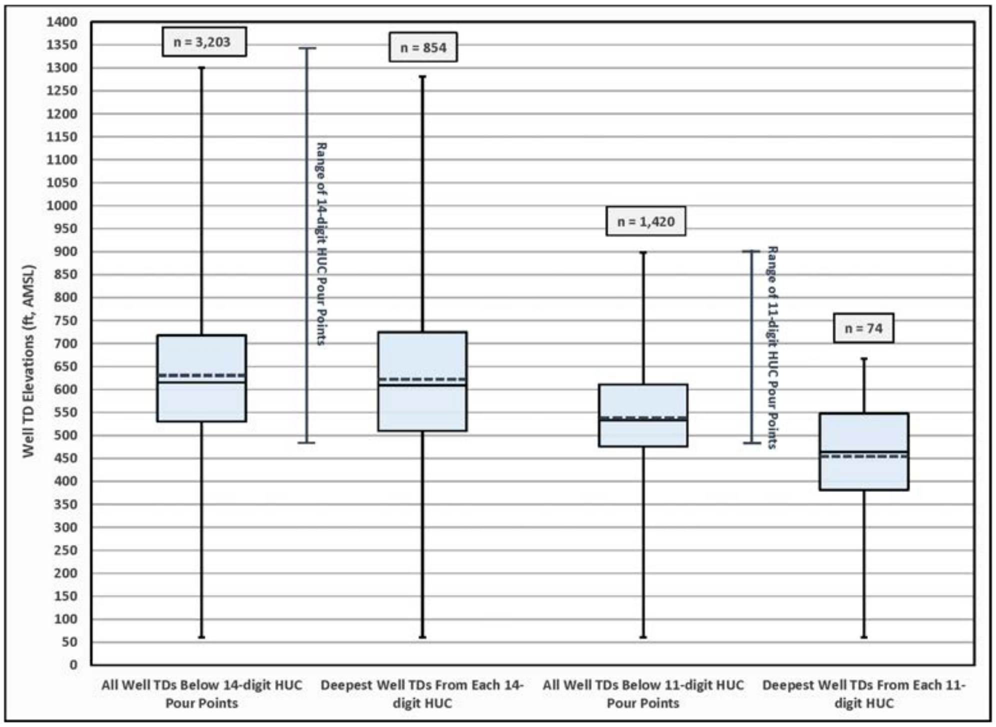

Figure 4. Box-and-whisker plots detailing the distribution of domestic-well TDs (feet AMSL) in each of the deep fresh-groundwater-elevation maps (Figs. 3a–d). The bottom and top of each box show the 25th and 75th percentiles, respectively, and the interior solid lines denote the median. The dotted lines show the mean. Whiskers represent total range of TDs.

er, well TDs just below the base of the Pennsylvanian would be in the lower Pennington Formation, though fewer wells penetrate it.

The analysis of deep fresh groundwater distribution in this study provided an opportunity to investigate how different water types vary with respect to pour points in watersheds. Coming from domestic wells in 12 counties, samples meeting the charge-balance criterion show a wide range of salinities, and $NaHCO_3$ and $CaHCO_3$ water types are most common (Table 1). Most of the samples are from the Pennsylvanian Breathitt Group (n = 28), with a smaller number from the Mississippian (n = 4) and Quaternary alluvium (n = 2) aquifers. Eleven wells (28 percent) had TDs shallower than the pour-point elevations in their respective 14-digit HUCs, whereas 17 wells (43 percent) had TDs deeper than the pour-point elevations in their respective 11-digit HUCs. The remaining 12 wells (29 percent) had TDs that fell between the pour-point elevations in the 14- and 11-digit HUCs.

The least-saline water types were associated with $CaHCO_3$- and $CaSO_4$-type waters, whereas the most-saline waters tended to be NaCl- and $NaHCO_3$-type. When considered in the context of pour-point elevation, water type does not appear to be distributed systematically, and correlation with total dissolved solids is weak (Fig. 6). Indeed, most wells have TDs that are 100 ft above or below the pour-point elevation in the watershed, and nearly all water types are represented within this 200-ft interval. In addition, most wells (n = 33) have TDs within 200 ft of the ground surface, and most water types are represented in this 200-ft interval. Wells located on hillslopes contained $NaHCO_3$-type water, whereas valley-bottom wells contained all water types. Stratigraphically, there does not appear to be any systematic variation in salinity (51 to 708 mg/L) or water type depending on whether samples come from aquifers in the lower or upper Breathitt Group.

Discussion

The distribution of deepest observed fresh water, as shown by contours on the 11-digit HUC deepest-well map, likely reflects multiple influences (Fig. 3d). First is the aforementioned regional southwest-northeast strike and southeast dip of Pennsylvanian and other Paleozoic strata. Though regional folds and faults deform Pennsylvanian strata, their impact on the distribution of deep fresh water in Pennsylvanian aquifers is not obvious. For example, high-angle faults with down-to-the-south normal slip, such as the Walbridge, Irvine–Paint Creek, and Little Sandy, offset Pennsylvanian strata about 100 ft or less (Fig. 5). In some areas, Pennsylvanian strata are slightly thicker on the south side of the faults, indicating contemporaneous sedimentation and fault movement (Ettensohn, 1979; Chesnut, 1992). These faults do

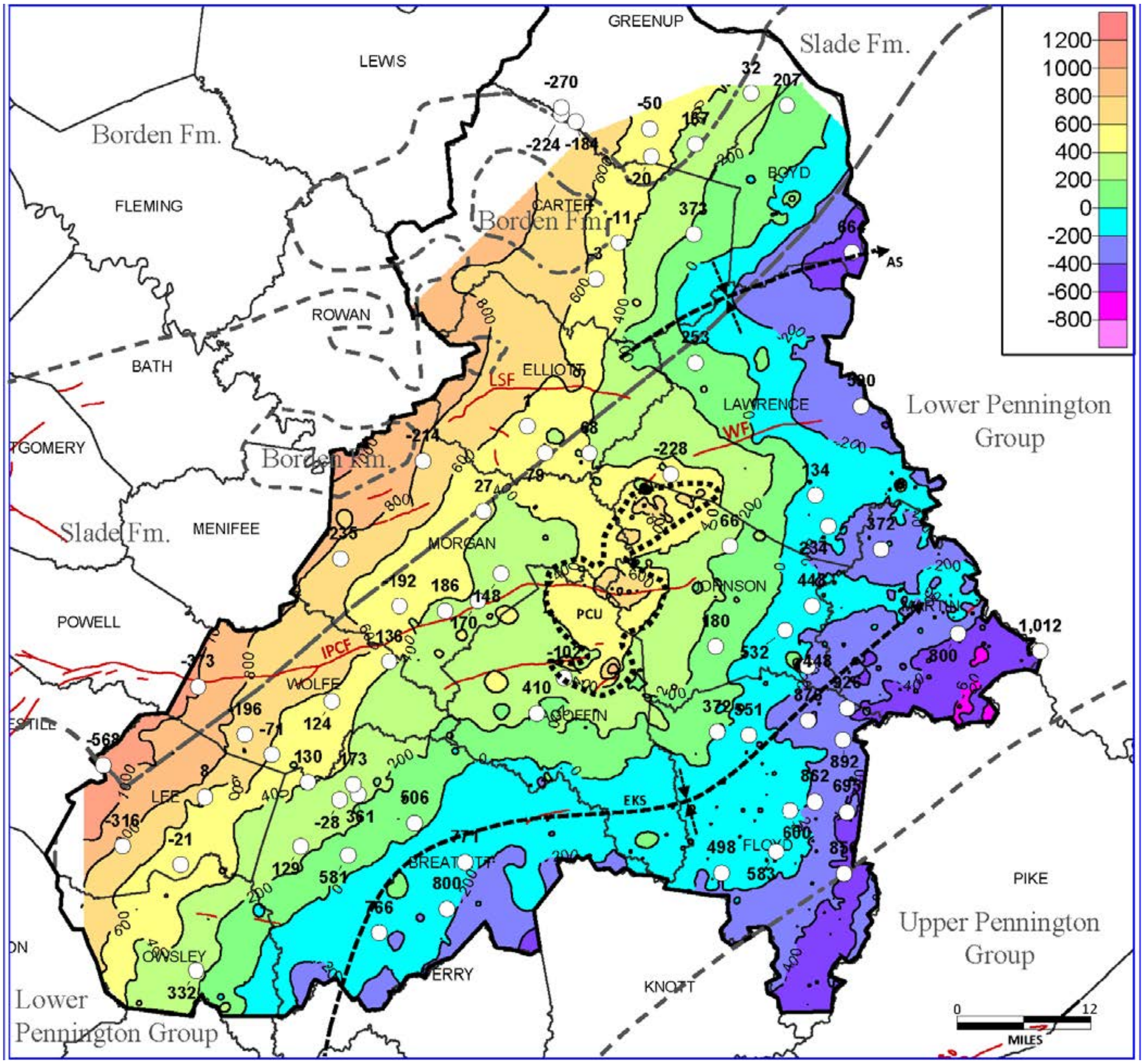

Figure 5. Base of Pennsylvanian strata; positive and negative values represent elevation (feet) above and below sea level, respectively. Heavy gray dashed lines show boundaries of different Mississippian strata that form the Pennsylvanian subcrop (from Chesnut, 1992). White circles represent locations of wells used as control points in the 11-digit HUC deepest-well map (Fig. 3d). Numbers adjacent to well locations represent the distance (feet) of the well TD above (positive) or below (negative) the base of the Pennsylvanian. Short dashed lines show the Allegheny Synclinorium (AS), Paint Creek Uplift (PCU), and Eastern Kentucky Syncline (EKS).

not appear to offset contours in either of the deepest-well maps (Figs. 3a–d). The lack of offset may result from small amounts of dip-slip displacement combined with widely spaced data points. Similarly, contours in the deepest-well maps do not appear to be influenced by broad folds, such as the northeast–southwest-trending Allegheny Synclinorium and Eastern Kentucky Syncline (Huddle and others, 1963; Chesnut, 1992) (Fig. 5).

A possible exception to the lack of structural influence occurs south of the Walbridge Fault, where a prominent west-east hydrogeologic trough

Table 1. Location, elevation, and geochemistry summary for domestic water wells having charge-balance errors equal to or less than 10 percent (n = 40). All depths and elevations are in feet. TD Penn represents elevation of well total depth above (positive) or below (negative) the base of the Pennsylvanian. Geologic formations are the best estimate of the stratigraphic unit at the well TD; the unit at TD is ambiguous for two wells, and the first unit listed is the most likely. In ascending order, the stratigraphic units are the Mississippian Borden (Mb) and Pennington Formations (Mpg); Pennsylvanian lower Breathitt Group (Pbl), middle Breathitt Group (Pbm), upper Breathitt Group (Pbu), and Conemaugh Formation (Pc); and Quaternary alluvium (Qal). AKGWA = Assembled Kentucky Ground WAter, an identification number assigned by the Kentucky Division of Water.

AKGWA Number	*County*	*Surface Elevation*	*Total Depth (from surface)*	*Total Depth (AMSL)*	*Formation at Well TD*	*TD Penn*	*14-Digit HUC Pour-Point Elevation*	*11-Digit HUC Pour-Point Elevation*	*Charge Imbalance Error (%)*	*Water Type*	*Total Dissolved Solids (mg/L)*
00054662	Johnson	625	15	610	Qal/Pbm	739	547	524	–0.1734	NaCl	536
00060922	Wolfe	952	25	927	Qal/Pbm	193	886	640	5.59	$CaHCO_3$	230
00018618	Lawrence	701	180	521	Pc	896	651	507	2.61	$NaHCO_3$	568
00009029	Carter	691	152	539	Pbu	594	653	575	–2.79	$NaHCO_3$	582
00016517	Boyd	641	165	476	Pbu	604	620	507	–1.89	$NaHCO_3$	628
00047554	Boyd	692	75	617	Pbu	623	603	507	1.70	$NaHCO_3$	492
00029505	Greenup	546	75	471	Pbm/Qal	121	505	505	–5.418	$CaHCO_3$	484
00029508	Greenup	548	75	473	Pbm/Qal	158	505	505	7.759	$CaHCO_3$	326
00053129	Magoffin	978	12	966	Pbm/Qal	480	809	722	1.46	$CaHCO_3$	496
40000127	Martin	668	61	607	Pbm/Qal	1,205	595	546	–0.67	NaCl	512
40003805	Martin	657	48	609	Pbm/Qal	1,010	640	546	0.65	NaCl	521
00012311	Johnson	724	75	649	Pbm	596	626	590	3.05	$NaHCO_3$	708
00019669	Elliott	688	135	553	Pbm	304	639	505	1.081	$NaHCO_3$	238
00032501	Greenup	581	100	481	Pbm	176	575	540	–1.17	$NaHCO_3$	496
00032510	Floyd	747	60	687	Pbm	1,032	653	653	6.55	$CaHCO_3$	164
00032515	Johnson	640	103	537	Pbm	420	625	590	2.88	$NaHCO_3$	164
00036344	Lawrence	679	150	529	Pbm	227	647	505	–2.046	$NaHCO_3$	422
00042492	Magoffin	608	470	138	Pbm	319	555	524	6.266	$NaHCO_3$	551
00042832	Boyd	584	150	434	Pbm	339	559	507	–1.40	$NaHCO_3$	457
00048656	Lee	853	90	763	Pbm	384	645	624	–2.06	$NaHCO_3$	254
00050406	Martin	716	90	626	Pbm	849	640	546	6.76	$CaHCO_3$	178
00051638	Magoffin	995	85	910	Pbm	953	936	807	–6.56	$NaHCO_3$	450
00062468	Johnson	886	100	786	Pbm	574	716	505	–0.83	$NaHCO_3$	320
00062485	Johnson	856	270	586	Pbm	316	716	505	2.90	$CaHCO_3$	218
00064916	Magoffin	884	88	796	Pbm	603	671	616	3.59	$CaSO_4$	130
40002219	Martin	688	86	602	Pbm	786	622	590	–0.93	$NaHCO_3$	213

Table 1. Location, elevation, and geochemistry summary for domestic water wells having charge-balance errors equal to or less than 10 percent (n = 40). All depths and elevations are in feet. TD Penn represents elevation of well total depth above (positive) or below (negative) the base of the Pennsylvanian. Geologic formations are the best estimate of the stratigraphic unit at the well TD; the unit at TD is ambiguous for two wells, and the first unit listed is the most likely. In ascending order, the stratigraphic units are the Mississippian Borden (Mb) and Pennington Formations (Mpg); Pennsylvanian lower Breathitt Group (Pbl), middle Breathitt Group (Pbm), upper Breathitt Group (Pbu), and Conemaugh Formation (Pc); and Quaternary alluvium (Qal). AKGWA = Assembled Kentucky Ground WAter, an identification number assigned by the Kentucky Division of Water.

AKGWA Number	*County*	*Surface Elevation*	*Total Depth (from surface)*	*Total Depth (AMSL)*	*Formation at Well TD*	*TD Penn*	*14-Digit HUC Pour-Point Elevation*	*11-Digit HUC Pour-Point Elevation*	*Charge Imbalance Error (%)*	*Water Type*	*Total Dissolved Solids (mg/L)*
40002588	Martin	779	90	689	Pbm	802	672	546	1.12	$CaHCO_3$	292
40003042	Martin	690	62	628	Pbm	1,045	672	546	2.74	NaCl	393
40003255	Martin	647	60	587	Pbm	781	615	590	8.86	$CaSO_4$	51
40003801	Martin	656	73	583	Pbm	796	635	546	1.53	$CaHCO_3$	222
40005164	Martin	680	71	609	Pbm	21	615	590	1.16	$NaHCO_3$	240
00032518	Johnson	690	123	567	Pbl/Qal	381	620	550	–3.01	$NaHCO_3$	188
00029638	Wolfe	837	300	537	Pbl	86	753	672	3.15	$NaHCO_3$	322
00032517	Johnson	754	170	584	Pbl	187	616	590	7.15	$CaHCO_3$	235
00043781	Elliott	758	265	493	Pbl	1	679	627	–2.12	$CaHCO_3$	164
00069529	Elliott	709	262	447	Pbl	876	679	627	2.88	$CaHCO_3$	100
00038804	Lawrence	720	435	285	Mpg	–228	653	505	1.14	$MgSO_4$	288
40005856	Wolfe	971	325	646	Mpg	–102	895	895	–10.40	$CaHCO_3$	154
50000109	Magoffin	853	660	193	Mpg	–85	827	805	–1.91	NaCl	707
00032516	Greenup	594	65	529	Mb	–271	539	487	–8.38	NaCl	732

representing deeper groundwater coincides with a west–east-trending anticline and syncline in Lawrence County. The trough continues southwest into Johnson and Magoffin Counties, where it coincides with the Paint Creek Uplift (Fig. 5). Proximity of the deeper groundwater to these structural features may reflect infiltration of fresh water along fractures.

The study area includes three major drainage watersheds—Kentucky River, Licking River, and Big Sandy River—that move surface water in an overall north direction, where it discharges into the Ohio River. These rivers and their tributaries also provide some local recharge to shallower, alluvial aquifers (Lloyd and Lyke, 1995). This influence can be seen in the 14-digit HUC maps, in which many of the deepest-well bullseye contours coincide with major tributaries (Fig. 3a, c). This coincidence reflects homes tending to be built on flatter ground in the floodplain alluvium and the easier access to shallow groundwater associated with the tributaries. In contrast, contours on the 11-digit HUC deepest-well map appear to have been negligibly influenced by rivers and tributaries (Fig. 3d). The lack of correlation supports the hypothesis that most of these wells have TDs in deeper aquifers and are part of a deeper groundwater flow system little influenced by surface recharge near any given well.

In comparison, the influence of surface drainage is evident in the Hopkins map (1966). This influence is especially visible north of the Irvine–Paint Creek Fault System, where soluble Mississippian limestone is exposed in the

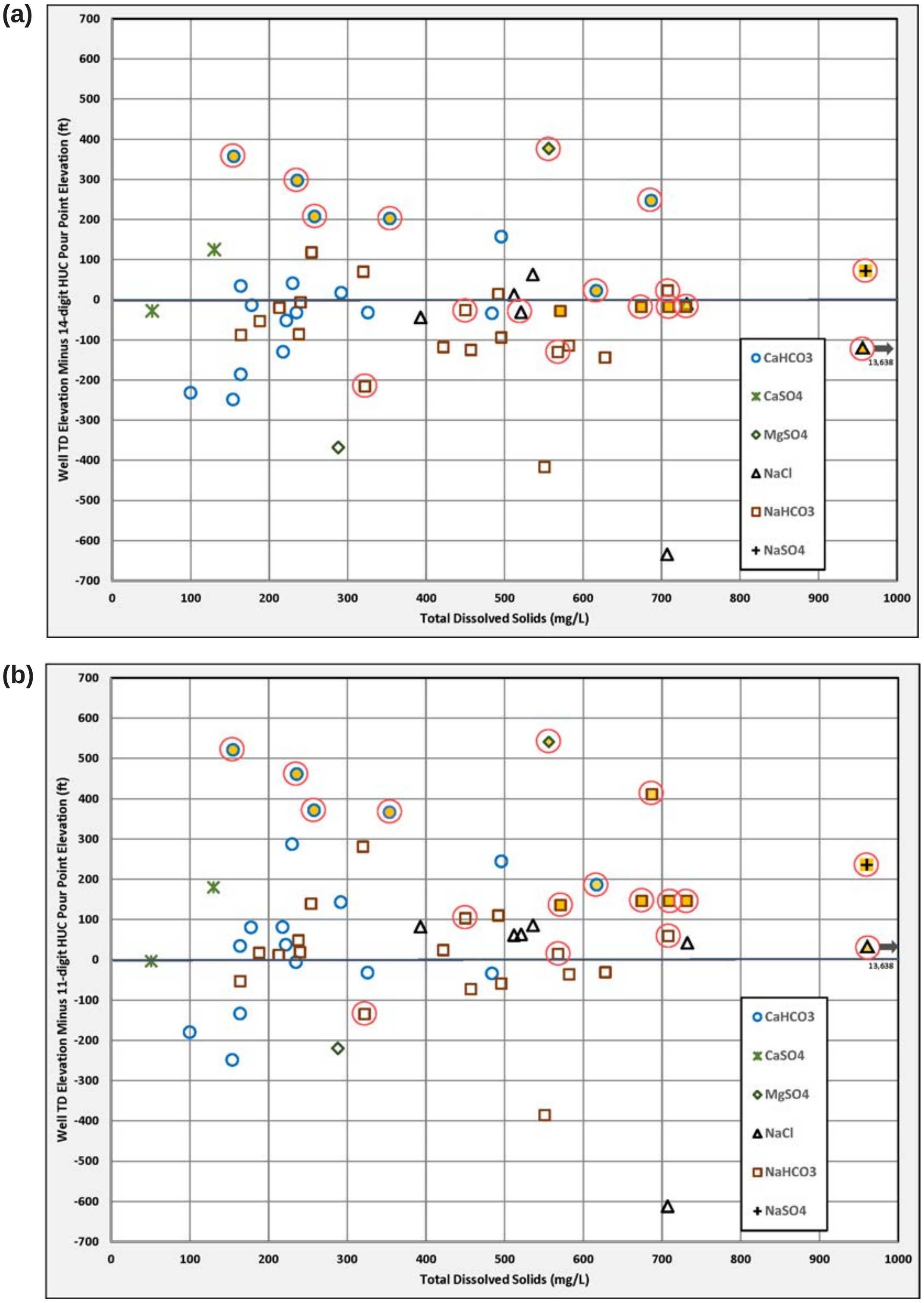

Figure 6. Scatter plots showing relation of salinity and water type relative to pour-point elevation in (a) 14-digit HUCs and (b) 11-digit HUCs. The pour-point elevation for each well is normalized to zero (bold horizontal line) by subtracting the pour-point elevation from the well TD elevation. Filled symbols are from Wunsch (1993) (n = 13) and open symbols are data retrieved in this study (n = 40). Red-circled wells are located on hillslopes or ridges, whereas other wells are in valley bottoms. For samples retrieved in this study, correlation coefficients (r) for salinity versus pour-point elevation in the 14- and 11-digit HUCs are –0.17 and –0.16, respectively.

drainages of the Little Sandy River and Tygarts Creek (Fig. 7). Dissolution in the limestone provides pathways for deeper freshwater infiltration.

Hopkins (1966) stated that the major influence on the fresh-saline water interface south of the Irvine–Paint Creek Fault System is the Eastern Kentucky Syncline. He mapped two "hydraulic lows" along the northwest limb of the syncline in our study area, in Johnson-Magoffin and Breathitt-Owsley Counties (Fig. 7). He suggested no mechanisms to account for the hydraulic lows, however. The hydraulic low in Johnson and Magoffin Counties partly coincides with the trough of deeper fresh water mapped in this study (Fig. 3d). As we postulated earlier, coincidence of deeper fresh water over the Paint Creek Uplift may represent infiltration along fractures, and the mechanism may likewise account for the hydraulic low in the Hopkins (1966) map.

The deepest observed fresh water in the 11-digit HUC deepest-well map is deeper in most areas than the fresh-saline water interface of the Hopkins (1966) map (Fig. 8). The average increase in depth is 147 ft, and it ranges up to more than 500 ft in eastern Lawrence County. The increased depth can be attributed to our use of a larger data set from which to select deeper wells, and the use of pour points to filter out shallower wells. The Hopkins (1966) fresh-saline water interface was deeper than the deepest fresh water in this study for some areas, however. A closer look shows that this opposite finding occurred when Hopkins (1966) projected deeper contours into areas, such as along the Little Sandy drainage in Elliott, Carter, and Greenup Counties, with few or no control points. Moreover, in some areas Hopkins (1966) generated contours deeper than his deepest control point.

Differences between the Hopkins map (1966) and the 11-digit HUC deepest-well map illustrate important differences in strategies. First, since we used wells with total depths below the 11-digit HUC pour points, our map is not as influenced by shallow wells—and hence shallow aquifers—as the Hopkins (1966) map was. Some studies suggest that the depth of the shallow groundwater table correlates to and mimics topography, at least on a local basis (Toth, 1963; Desbarats and others, 2002). It is clear that Hopkins, who used the TDs of shallow wells, was aware of the influence of topography on groundwater depth, and he appears to have projected contours accordingly to reflect this influence. In contrast, our 11-digit HUC deepest-well map was less influenced by topography, because total depths of mapped wells were deeper.

Although the use of deep wells with TDs below the pour points in large watersheds (11-digit HUCs) diminished the influence of topography on our evaluation of deep freshwater distribution as referenced to sea level, when viewed from the ground surface, the depth to deepest observed fresh water shows significant relief (Fig. 9). The relief shown in Figure 9 reflects variation in the depth of deepest observed fresh water (Fig. 3d), but also the relief associated with topography in the study area. As a practical matter, a map showing the depth to the estimated base of fresh groundwater from the ground surface is more intuitive and useful than a map referenced to sea level for most users, such as companies drilling water or oil and gas wells.

Oil and gas wells targeting deep reservoirs provide one of the few opportunities to document the distribution of fresh and saline water in the subsurface, either indirectly using geophysical logs, as in Davis and others (1974), or by direct observation during drilling. Observations of fresh versus saline water during drilling are based on taste, however, and are therefore subjective. Cordiviola and others (1981) used oil and gas well logs and other data to identify potential zones for injection and the distribution of fresh water in western Kentucky. A later analysis by Cordiviola and others (1983) used cross sections—including nine for the current study area—to show the main stratigraphic units and occurrences of water by unit and depth. One of their cross sections includes two wells in Boyd and Carter Counties in which fresh water has been documented deeper than the deepest observed fresh water in the 11-digit HUC deepest-well map. In contrast, another cross section from Cordiviola and others (1983) for Carter and Lawrence Counties references three wells in which saline water has been documented shallower than the deepest observed fresh water (Fig. 9).

The larger data set and methodology used in the current study likely improve our understanding of deep fresh groundwater distribution. Nevertheless, comparison with oil and gas data suggests that the deepest observed fresh water depicted in

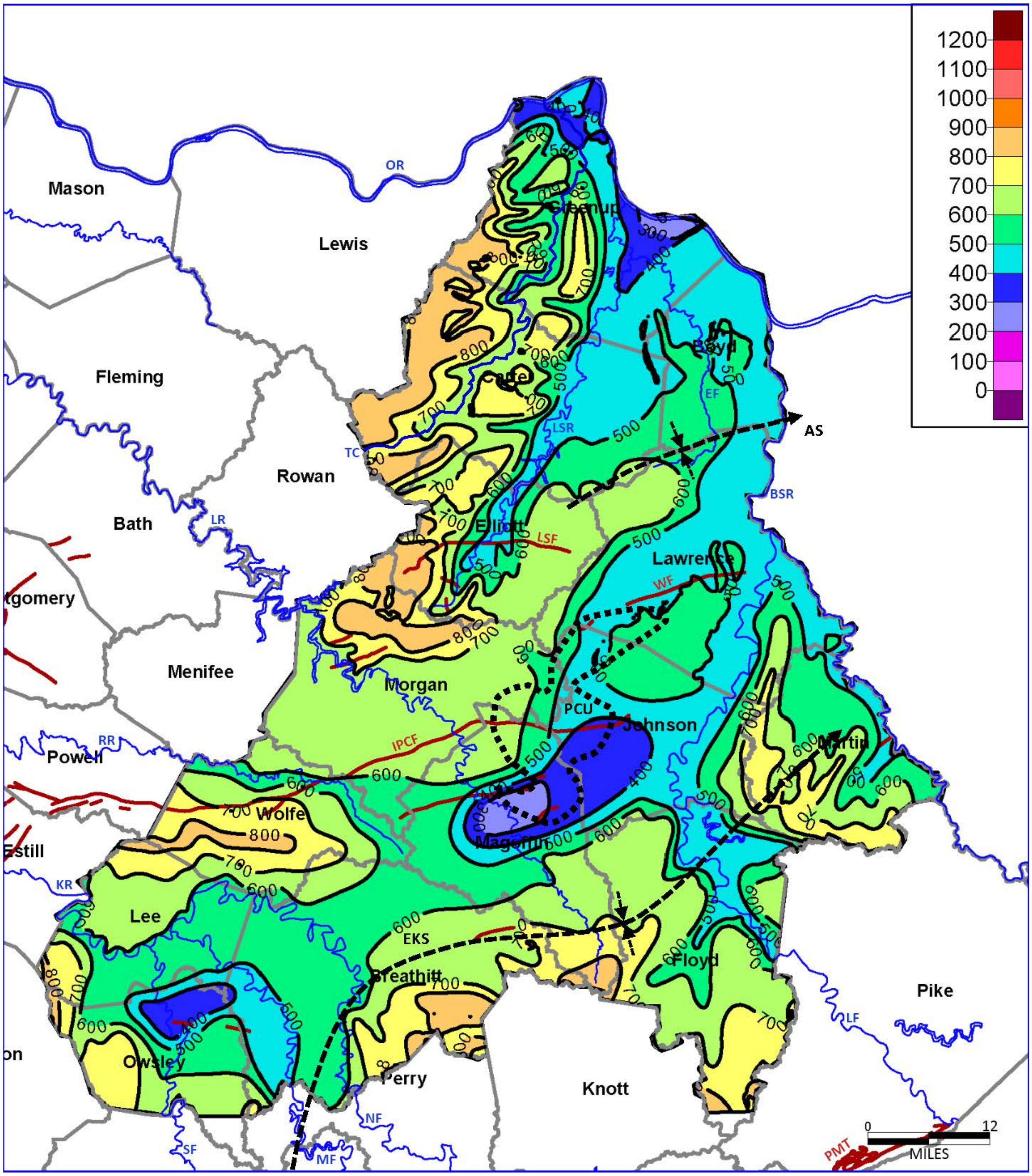

Figure 7. Digitized reproduction of the “Fresh-Saline Water Interface Map of Kentucky” (Hopkins, 1966) centered on the current study area. Contour interval is 100 ft and values indicate elevation of the interface.

the 11-digit HUC deepest-well map might be deeper in some areas, whereas the possible occurrence of saline water shallower than the deepest observed fresh water suggests a possible upward revision elsewhere. Defining the base of fresh groundwater, in this and previous studies thus is influenced by

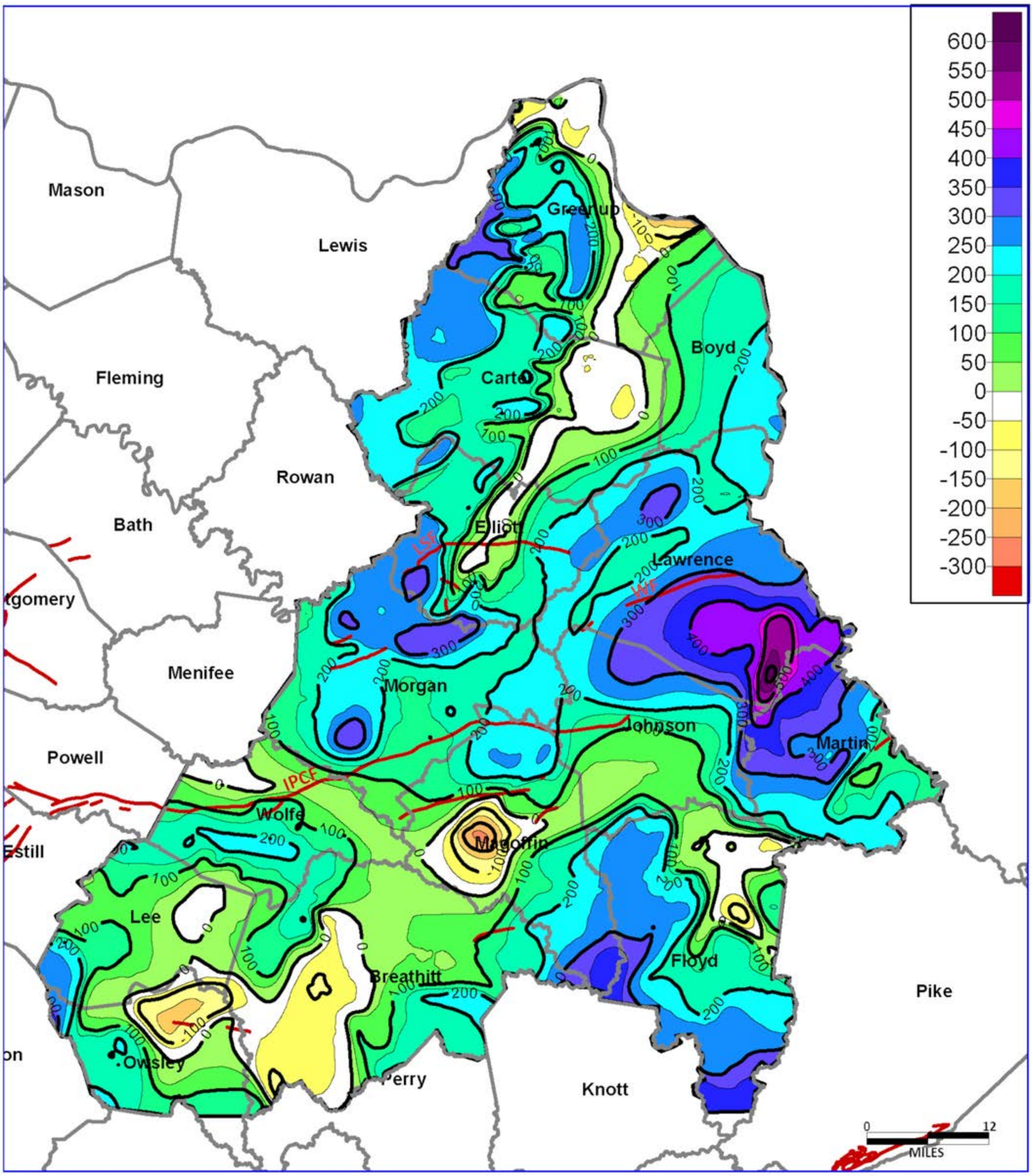

Figure 8. Isopach difference showing the vertical distance (feet) between the 11-digit HUC deepest-well map (Fig. 3d) and the Hopkins (1966) map (Fig. 7). Positive values correspond to areas where the Hopkins (1966) map elevations are higher than the 11-digit HUC deepest-well map, and negative values show a reverse relationship. White shading corresponds to areas where elevations in the two maps are nearly equal.

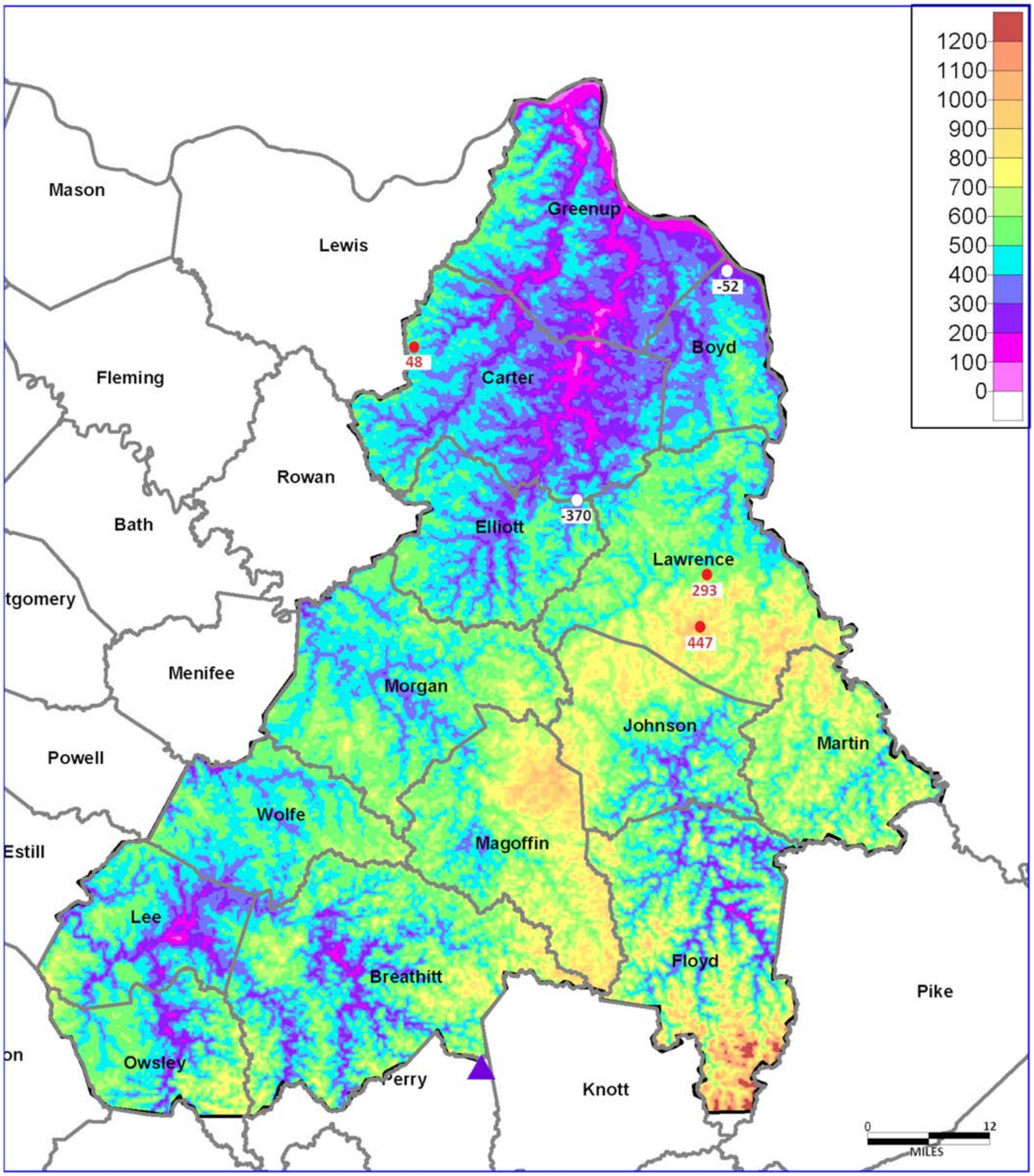

Figure 9. Estimated depth (feet) from the ground surface to the deepest observed fresh water as derived from the 11-digit HUC deepest-well map (Fig. 3d). Based on observations from oil and gas well records (Cordiviola and others, 1983), white circles mark locations of oil and gas wells where fresh water is observed below the deepest observed fresh water (n = 2) and red circles mark locations of oil and gas wells where saline groundwater is observed above the deepest observed fresh water (n = 3). Negative and positive numbers show the magnitude of the difference below or above the deepest observed fresh water, respectively. The purple triangle in the southern part of the map shows the study area of Wunsch (1993).

uncertainties inherent to the methods and data for both groundwater wells and oil and gas wells. This uncertainty underscores our use of the term "deepest observed fresh water" to describe the estimated maximum depth of fresh groundwater. One important caveat regarding estimates of deep fresh groundwater in this study is that a maximum of one well—the deepest well—from each HUC was used to represent the base of fresh groundwater laterally for large areas. Though the use of the single deepest well in each HUC minimized the influence of shallow wells, we recognize that using the depth from a single well in a HUC may extrapolate the data too much.

Incision into Pennsylvanian strata that produced the hills and valleys of the Cumberland Plateau of eastern Kentucky exerts an important influence on the mechanisms of recharge and groundwater flow. In turn, these mechanisms influence salinity distribution and hydrogeochemical facies in the aquifers. Previous investigators recognized this interrelationship and showed that different types of water tended to characterize the ridge, slope, and valley bottoms (Hopkins, 1966; Sprinkle and others, 1983; Minns, 1993; Wunsch, 1993). For example, Hopkins (1966) recognized that groundwater composition above the fresh-saline water interface ranged from Ca-MgHCO_3 to NaHCO_3, whereas below the interface, NaHCO_3- to NaCl-type waters were dominant. Even more detailed hydrogeochemical facies models were developed by Minns (1993) and Wunsch (1993).

We further examined the interrelationship between hydrogeochemical facies and pour points using data from Wunsch (1993) and well data in this study (Table 1). Wunsch (1993) sampled wells at discrete intervals to examine the variation in groundwater chemistry in relation to groundwater flow. Wells cited in the Wunsch (1993) study were located along the boundary of two 14-digit HUCs that extend from near a valley bottom to the top of a ridge and share a pour point (Fig. 9). All wells had TDs in strata of the Pennsylvanian Breathitt Group. Wunsch's (1993) geochemistry and head measurements formed the basis of a four-zone hydrogeochemical facies model based on the position of groundwater in relation to the surface and low-order drainages. Above local drainage elevations (i.e., pour points), near-surface and ridge-interior water types were Ca-MgHCO_3+SO_4 and NaHCO_3+SO4, respectively. Mixing of the two types with deeper water in valleys and below local drainage produced a Na-CaHCO_3+SO_4+Cl-type water. Finally, a saline NaCl-type water was predicted beneath the Na-CaHCO_3+SO_4+Cl-type water. Wunsch (1993) suggested that this connate, NaCl-type water might be encountered within 100 ft of valley bottoms of first- and second-order streams and at even shallower depths below higher-order streams.

Plotted versus the pour-point elevation, the data from the Wunsch (1993) wells show a systematic variation in chemistry, with a predominance of CaHCO_3-type waters at shallow depths and higher elevations in the 14-digit HUCs (Fig. 6). Downgradient, closer to and below the pour point, NaHCO_3- and NaCl-type waters become more prevalent. The deepest well in the Wunsch (1993) study was the most saline (total dissolved solids of 13,638 mg/L) and contained NaCl-type water. Viewed in the context of larger watersheds defined by 11-digit HUCs, which would include higher-order streams, all of Wunsch's (1993) wells are located above the pour point, and therefore do not provide insight into water chemistry in deeper aquifers.

Though our data set is relatively small, all samples used in our chemical analysis are defined as fresh water (Table 1), and therefore occur at or above the deepest observed fresh water as shown in Figure 3d. The varied water types and range of salinities by depth and stratigraphic unit make clear, however, that the simple distinction between fresh and saline water does not fully illustrate the hydrogeochemical complexity of the Pennsylvanian aquifers. The complexity makes hydrogeochemical characterization over large geographic areas difficult. For example, mapping by Sprinkle and others (1983, Plate 6) predicts that Lower Pennsylvanian aquifers throughout much of eastern Kentucky will contain saline water. In the data reported here, however, all five samples from the lower Breathitt Group contain fresh water (Table 1) and come from areas predicted to have saline water by Sprinkle and others (1983).

Broader extrapolation of local models may also be problematic. For example, the water types characterized by Wunsch (1993) clearly transition from Ca-rich to Na-rich waters with increasing depth and well TDs approaching the 14-digit HUC pour-point elevation. In contrast, data retrieved in this study show little to no correlation of water type or salinity with depth or with respect to pour-point elevation (Fig. 6). Differences in the data sets could result from sampling methods or local hydrogeologic differences. For example, the protocol in Wunsch (1993) was to sample aquifers at isolated intervals, which allows greater specificity in attribution of water source and composition. Domestic water wells, in contrast, are typically open-hole below the surface casing, and the water may come from multiple aquifers. Consequently, water composition may be a composite. Most samples retrieved in this study are from valley bottoms, whereas the Wunsch (1993) wells were located along a hillslope and ridge, which may result in hydrogeologically different aquifer types. Finally, data retrieved from wells in this study come from more diverse sites, each potentially having specific features (e.g., fractures, permeable coals) that influence local hydrogeochemistry, distinct from the Wunsch (1993) study site.

Summary

Eastern Kentucky has a long history of conventional oil and gas well development in which thousands of vertical wells have been drilled and completed. More recently, hydraulic fracturing in horizontal wells has been used to develop oil and gas resources, sometimes at depths of less than 2,000 ft. This history, along with the potential for future high-volume hydraulic fracturing, have generated new interest in evaluating and protecting potable groundwater resources. Fundamental to the evaluation is an understanding of fresh groundwater distribution in the subsurface.

Using methods similar to an earlier assessment of the fresh-saline water interface by Hopkins (1966), we estimated the depth of the base of fresh groundwater—i.e., deepest observed fresh water—using TDs of domestic water wells. In contrast to the Hopkins (1966) map, which used 50 wells in the 14-county study area, we mapped the deepest observed fresh water using wells with TDs deeper than the pour points of watersheds defined by 14- and 11-digit HUCs. The 14- and 11-digit HUCs provided the best spatial distribution and density of wells (n = 3,203 and 1,420, respectively) for mapping. The pour-point cut-off improved our resolution of deepest observed fresh water by reducing the noise generated by wells with TDs in shallow aquifers. Further improvement was obtained by mapping the single deepest well TD in each of the 14- and 11-digit HUCs (n = 854 and 74, respectively), with the map based on 11-digit HUCs providing the best resolution of deepest observed fresh water.

Contours in parts of the 11-digit HUC deepest-well map reflect the regional dip of Pennsylvanian aquifers; however, the influence of faults and folds is not obvious. A prominent east-west trough of deep fresh groundwater extends from Lawrence to Magoffin County and may be related to freshwater infiltration along fractures. Compared to the Hopkins (1966) map, the deepest observed fresh water represented in the 11-digit HUC deepest-well map is, on average, 147 ft deeper, and up to 500 ft deeper in Lawrence County.

From a hydrogeologic perspective, and as noted by Hopkins (1966), the so-called interface between fresh and saline water is most certainly a simplification. The depositional setting of Pennsylvanian strata has produced laterally discontinuous aquifers and confining zones that have variable porosity and permeability. Recharge and flow patterns have been further influenced by topographic dissection in the Cumberland Plateau region. Acknowledging this complexity, we use the term "deepest observed fresh water" to define the estimated maximum depth of fresh groundwater. The terminology implies that saline water is expected below the level of the deepest observed fresh groundwater, although the actual depth of saline water is a function of local geologic and hydrologic conditions.

Future work should attempt to reduce the uncertainty by using subpopulations—for example, the deepest percentile—of wells for mapping so that a single well TD is not the sole basis for estimating the maximum depth of fresh groundwater over a large area. Because some uncertainty will almost certainly persist in this type of analysis, conveying the uncertainty in spatial data will also be important (Bauer and Rose, 2015).

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