Ground Water Salinity in the Cockfield Aquifer, Washington County, Mississippi

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INTRODUCTION

History

In the Mississippi River city of Greenville, and in a large portion of Washington County, salinities in waters from the Tertiary aquifers tend to be higher than normal, averaging 173 milligrams per liter in Cockfield wells sampled. High chlorides concentrations have been observed for several decades and have shown an erratic geographic and vertical distribution that has made determining the source and flow characteristics of these waters difficult.

Taylor & Thompson of the U.S. Geological Survey (USGS) (1971), documented and studied this phenomenon. Mississippi Office of Land and Water (OLWR) workers Bockelman (1987) and Carter (1991), continued to map and describe the problem and performed extensive water sampling in the area.

Scope

The current study focused on Washington County, Mississippi, (Figure 1) and undertook two objectives. The first was to compile and analyze existing data on the hydrogeology of the area in greater detail.

The second was to continue, and report results of, the OLWR sampling and well monitoring programs from 1995 through 2000, and to interpret the data in light of more complete hydrogeologic information.

Methods

Monitoring of chlorides concentrations consisted of analyzing, in Department of Environmental Quality (MDEQ) laboratories, biannual (1995-1997) and annual (1998-2000) pumped samples from a network of 20 Cockfield aquifer wells in the high-chlorides area. Field testing of conductivity was also undertaken, as well as some limited sampling for other parameters such as color and iron.

Water level monitoring was conducted on a network of 37 Cockfield aquifer wells. The wells were surveyed biannually in 1991-92, annually in 1993-97, and again in 2000, using steel tapes to measure depths to static water level from ground surface, corrected to elevations versus mean sea level. Continuous (hourly) water levels were obtained in three wells fitted with transducers in 1993-1997.

Existing geological and hydrological data was compiled, reviewed and entered into databases. Sources included borehole geophysical logs (electric resistivity/SP, etc.) from 74 water wells and 32 petroleum exploration wells, cuttings samples from 13 water wells, 367 water well data sheets (USG S), 146 water well driller's logs, 754 chemical analyses of water from 273 wells, daily river gauge data, processed aeromagnetic data, pertinent published literature and petroleum 'scout tickets'. In addition to data on file at MDEQ, The Yazoo-Mississippi Joint Water Management District (YMD) supplied recent water level and chlorides information, and other major data contributions came from the USGS and the Mississippi Office of Geology.

Data was linked with map coordinates for use in three-dimensional analyses. Kriging-type interpolation was used to project known contact depths from selected wells into locations of wells where formation data was unknown. Testing of interpolation methods was conducted to ensure interpolations remained close to original data.

FINDINGS

Hydrogeology

Structure

The Mississippi Embayment, an enormous indention in the continent, is the dominant structural feature in this area. (Figure 1). The mapped border of the Embayment represents the edge of the Coastal plain sediment wedge of Tertiary and Quaternary sediments. The wedge thickens tremendously gulfward south of the line of 'marginal faults' which wrap from Texas to Alabama. These are, from west to east, the Balcones, Mexia-Talco, South Arkansas, and Pickens-Gilbertown. The salt basins and salt dome areas lie gulfward of these marginal faults. The study area lies directly between the South Arkansas zone and the Pickens-Gilbertown zone, within a large gap where marginal faults have not been mapped by previous workers.

Figure 1 locates the two structural elements which dominate in the study area: the Desha Basin, a downwarp which stretches west into Desha County, Arkansas; and the Monroe Uplift (or Monroe-Sharkey Platform), a prominent structural high underlying parts of Louisiana, Arkansas, and Mississippi. Marked upward movement of the Monroe uplift occurred during the Jurassic and Cretaceous. Tertiary formations thin onto the uplift.

In Washington County, a slowing or cessation of relative upward movement during the Eocene is suggested by reduced influence of basin structure upon the uppermost beds. (Figure 3)

While major faults have not been mapped at the margin of the Monroe/Desha in this area, and well control is not adequate to describe any definite system of faults, correlations of Tertiary formations suggest there is adequate (on the order of 100') offset within the upper Tertiary section to justify postulating a NW-SE trending fault zone underlying the northern margin of the Monroe Uplift in the study area. Such a zone is likely to be high-angle with offset gradually increasing with depth.

In Louisiana, where more well control has been available, a fault zone has been mapped marking at least part of the south margin of the Monroe structure, (Schumm et al, 1982, p. 108).

In addition to a Monroe margin fault, a second fault, in the Wayside area, is suggested by several lines of evidence.

Processed magnetic data collected in a national aerial survey in 1980 (DOE, 1980) was filtered to include data points at about 1/4 mile density along east-west flight lines on 6-mile spacing, with north-south control lines on 18-mile spacing and 1/4 mile density. The anomaly data was contoured, without further processing (Figure 4). The immediate study area shows the expected broad positive anomaly under the Monroe structure. To the west, a much smaller, more intense, positive anomaly underlies an area of Chicot County Arkansas. Early oil exploration wells encountered volcanics at a depth of 3240' in this area (Spooner, 1934, p. 282), confirming the likelihood that the anomaly is related to a concentration of igneous materials at depth. The anomaly or 'bright spot' lies about ten miles northwest of the maximum area of high chlorides in Chicot County studied by Huff and Bronck (1993, p. 6).

No such intense 'bright' spot occurs in the study area, but there is a disruption to the Monroe broad anomaly, suggesting similar deep structure and lateral offset, along a N 10° W line in the Wayside area. An even stronger amount of offset, along a N-S line, appears associated with the Chicot feature.

A detailed structural analysis is not within the scope of this study, but it is important to note there is much still being discovered about this area, and that it lies in a key structural location. Burke and Dewey (1973) postulated the area as being underlain by a triple-junction separating crustal plates. Zimmerman (1992) interpreted major regional wrench faults passing through the area, with large scale motion being responsible for the offset course of the Mississippi between Greenville and Vicksburg. He postulated the intersection of the major faults beneath the area of chlorides concentration maximum in Chicot County.

Structural activity is not unknown today. At the north end of the embayment, the Reelfoot Rift is still an active (New Madrid) earthquake zone, which strikes southwest towards the Ouachita Mountains of Arkansas. Scattered occasional minor earthquakes occur in northern Mississippi, between the Reelfoot zone and the subject area. Schumm, Watson and Burnett (1982) considered the Monroe structure to be still actively moving upward.

Mississippi River Valley Alluvium

A Quaternary formation and aquifer, the Mississippi River Valley Alluvium (MRVA), blankets Washington County to depths of from 75 to 210 feet. Its base dips gently eastward across the county towards the center of the Delta, where it is thickest. It is thinnest near the Mississippi River. Beneath a 10-30' surficial clay, the formation is largely sand and gravel with coarsest materials tending to occupy the lowest beds. It is not, however, homogenous or well-stratified, and these fluvial deposits include lithologies ranging from boulders to silts to clay plugs and lignites.

This formation, being the only unit exposed at the surface in flat-lying country, has limited the amount of information available about the geology of Washington County. There are no surface exposures of older units available for study.

This aquifer is considered saturated and semi-confined. In YMD's fall 2000 survey, water levels in MRVA wells in this area ranged 67 to 118 feet above mean sea level. Ground elevations at wells in the county range 96 to 146 feet, and average 117 feet above mean sea level (MSL).

Jackson Group

Subcropping beneath the base of the MRVA are three formations. While in most of the county the Cockfield, a thick Claiborne Group sand formation and aquifer, directly underlies the MRVA, in a smaller area in western Washington County including much of the Greenville area, remnants of two overlying formations of the Jackson Group are present. The lower unit is the Moody's Branch Formation, a thin marl deposit containing shell, glauconite, fine clays, sands, and some gravel, and the upper unit contains the lowest beds of the Yazoo Formation, elsewhere a clay interval several hundred feet thick. Here, only basal sediments, averaging 34 feet in thickness, remain. The normal hydrogeologic role of the Yazoo is as an important confining unit, but in the study area the thinness and limited extent of the formation limits its effectiveness as an aquiclude.

Claiborne Group

The Cockfield is the primary aquifer for the area. From 153 to 466 feet of thickness has been drilled in county wells. Its base (Figure 2) illustrates the influence of the Desha Basin. The Monroe Uplift underlies the dip reversal in the southwest portion of the study area.

The formation is highly variable. Fine sand is the most common constituent, followed by silt. Coarser sands, clays, and shales, are common and minor sulfides, lignite, marl, and gravels also occur. Sorting varies in a wide range, with silty fine sands the most common mixture. Cementation varies from loose to very hard, with hard zones tending to occur most often in Mississippi River margin and Greenville locations.

Lithologies are discontinuous and heterogenous. Some general division can be observed in the Cockfield beds: a lower, sand-rich section, a middle shalier section, and an upper, partly marine section. The marine materials likely correlate with the Creola Sand Member described from Texas. From the limited samples available, the areal distribution of sediments appears to echo the structural basinal shape of the Desha, with marine materials restricted to the Greenville (basin center) area. Fine-grained sediments are most dominant to the northwest and northeast around the north basin rim, and also in the far southeast. The coarsest materials are found in the south, above the Monroe structure.

Figure 3 illustrates the relationship of other formations to the Cockfield. Directly underlying the Cockfield is the Cook Mountain Formation. In other locales this formation constitutes a significant confining unit separating the major Cockfield and Sparta aquifers, but in this area it can act as a minor aquifer. In type sections in central Mississippi, it consists of two shale members over a basal marl. In the study area, the formation and its log signature reflect higher sand content. A few water wells considered to be in the Cockfield aquifer were found in this study to be screened in Cook Mountain. This formation's thickness in the study area averages 145 feet.

The Sparta Formation and aquifer underlies the Cook Mountain. Like the Cockfield, the Sparta is a thick, variable formation, largely sand and sandstone but with significant intervals of shales, silts, and some minor sulfides, lignites, and rarely marls. It is thicker than the Cockfield, averaging 595 feet thick in the study area. Where strongly developed, the upper sands in the underlying marine Zilpha clay are included in the Sparta aquifer.

Only a few wells in the study area draw from two deeper aquifers, the Tallahatta and Meridian-upper Wilcox. These are separated from the overlying Sparta by the Zilpha clay and the Winona greensand (Figure 3).

Pre-Claiborne

Thick Lower Wilcox clastics, including the Midway confining unit, underlie the aquifers. Below the Tertiary section is a thick sequence of Cretaceous and Jurassic carbonates, which farther northwest on the Monroe Uplift structure hosts petroleum production. Igneous intervals have been logged in the county below 3900' of drilled depth. The deepest well stopped in Jurassic Smackover at 10,176'.

Chlorides and Water Quality

A major goal of establishing a network of monitor wells was to develop consistency in water sampling, thereby lending reliability to the chlorides concentration data, and the changes measured. Every effort has been made to maintain consistent testing standards, but testing for chlorides in water has an inherent 10% margin of error. The DEQ lab uses the EPA-approved method and OLWR staff use consistent methods of water collection and fail-safe labeling, but the fact remains that a well measuring 520 mg/l one year and 530 mg/l the next is reflecting a fluctuation well within the margin of error, and no significance can be accorded the change. Collection of multi-year data in a consistent way allows examination of actual trends in concentrations rather than reaction to fluctuations associated with a single data point.

Formational variation

Reported high chlorides concentrations have been mapped in a large section of the county, but the data spans the several available aquifers. One task in this study was to divide the data so that chlorides within each aquifer could be mapped separately, including chlorides data for wells where the source aquifer had not been recorded. By using interpolated formational boundaries, an approximate height of the screened interval of each well within a formation and aquifer was determined.

When this was done, the lateral distribution of chlorides was still complex in the Cockfield, but did appear more strongly concentrated in the Wayside area, with peak values (above 700 mg/l) lying just east of the river-parallelling Highway 1. Figure 5 illustrates the distribution of all chlorides concentrations from analyses attributed to the Cockfield during the twentieth century. Where a well had multiple samples, the value was the historic mean for that well.

Chlorides concentrations in the other aquifers were generally lower, and were mapped from far fewer data points. In both the deep Meridian-upper Wilcox and the intermediate Cook Mountain wells, the data show a fairly smooth transition from highest chlorides over the Monroe Uplift structure to lowest in the northeast area near Leland, with isocons striking N 45°-60° W. In the Sparta, chloride values are higher in the west, around one unusually high value in the Greenville industrial area, and decline to the southeast. Tallahatta and Meridian-Upper Wilcox, as well as MRVA wells have very low (< 50 mg/l) low chlorides concentrations. However, some recent analyses of MRVA wells record anomalously high chlorides, exceeding 200 mg/l, in an area of south-central Washington County near Leroy Percy State Park.

Intraformational Variation

Within the Cockfield, the location of each intake screen in a sampled well was determined as to its vertical position, described as feet above the base of the formation. Moderate chloride levels (not exceeding 250 mg/l) predominate in the basal sand layers, in which the highest numbers of wells are screened. High chloride levels (greater than 250 mg/l) cluster most strongly in the middle shaley strata, and to a lesser extent in the upper marly strata, with no high-chloride values observed in the lower sands.

The geometry which emerges suggests a shallow, irregularly layered lens of brackish waters, encroached upon from all sides by clearer, better 'flushed' waters in more transmissive layers. Less transmissive layers appear to restrict flow of clearer waters into the lens.

One model for the location of higher chlorides concentrations has been the confinement of high-chloride waters to lenticular 'tight' sand bodies. A review of all available log signatures for screened wells did not support this concept. High chloride water was found in varying sand lithologies, from thin-bedded sand-shale sequences to thick massive sands.

A localized anomalous pattern in chlorides was seen at Wayside, where chlorides concentrations drop off steeply within a short distance westward.

The normal gradational or diffusional change present elsewhere is locally replaced by a strong gradient.

Temporal Variation

Chlorides concentrations in each monitored well fluctuate in a range of values typical for that well. The standard deviation for concentrations in a well may be as low as 3.9% of its historic mean in some of the more 'static' cases, or as high as 66% where readings have had high variance. The median standard deviation is 11.8% of the historic mean.

The median change in chlorides from fall 1995 to fall 2000 (excluding questionable data points) was +39.0 mg/l, but since the relative baseline concentration of a well can be 100 mg/l or 750 mg/l, it is more meaningful to use percentage change. The median percentage change in chlorides from fall 1995 to fall 2000 was +12.6%. In only one well was there a net decrease in chlorides over the five year period, although year to year declines are commonly recorded.

The annual variations in chlorides relative to each well's standard deviations were mapped during three recent years for which both level and sample surveys were taken in the same month.

In fall 2000, negative variations in chlorides (declines relative to historic mean) were distributed across the central part of the county, in a broad NW-SE band ranging from Greenville to east of Wayside, while positive variations in chlorides (rises relative to historic mean) concentrated in flanking belts: one along the riverside area from Greenville to Glen Allan, west of the postulated Wayside fault, and another in the eastern area, Stoneville to Arcola, east of the chloride highs.

In fall 1997, negative variations in chlorides occupied a similar central position, stretching from south Greenville through Swiftwater, then east of the Wayside discontinuity. The surrounding areas saw positive variations in chlorides concentrations.

In fall 1996, positive chloride variations occurred in a central zone beginning near Wayside and broadening eastward into the unpopulated area south of Leland. Surrounding wells in Greenville and south of Wayside showed negative variations.

In summary, fluctuations in chlorides are occurring in coherent but shifting patterns which reflect annual and seasonal variations. These patterns are believed to be related to a complex flow system capable of seasonal reversals and subject to influence from many sources, including MRVA interaction influenced by two different river basins.

Color

Amber coloring of Cockfield water, due to natural humic or tannic acids, is common and averages 59 color units in the study area. Virtually all the Cockfield waters in the study area exceed the federal secondary standard of 15 color units. In the first full survey of the sampled well network for color, in fall 2000, an extreme color maximum of 494 units was located at Wayside. This is just west of the strongest chloride maximum location. High values for color and chloride do not exactly coincide in location, yet do lie closely juxtaposed, separated by about one mile. Concentrations drop off within a short distance in this small area, an exception to the normally more diffuse gradations in concentrations seen in the study area.

Water Levels

Elevation of the potentiometric surface for the Cockfield aquifer water ranged from a high of 89 feet (above mean sea level) in northeast Washington County, to a low of 28 feet at Greenville during October, 2000. Direction of flow is southwesterly in the eastern part of the county, and strongly directed towards Greenville in the city and surrounding area. Potentiometric mapping suggests a fairly static (low gradient) area just east of Wayside, and indicates a subtle disruption along a line from Wayside to Glen Allan. (Figure 6)

Several factors were found to affect water levels in the study area.

Pumping centers

A large cone of depression is present in the Cockfield potentiometric surface at Greenville, and a much smaller one exists at Stoneville/Leland. The Greenville cone appears to be expanding asymmetrically to the south, merging with much smaller pumping centers at Swiftwater. This southerly extension area also hosted a well-defined area of lower chlorides in the fall 2000 sampling.

Margin of error

Exact water levels are subject to normal measurement variations. OLWR staff routinely wait for recovery from pumping to minimize false measurements, typically recording only when repeatable values are obtained. The effects of nearby wells pumping while measurements are taken can also affect levels.

Seasonality

Strong recoveries in water level elevations are seen after a wet season. The most extreme example seen was the change from fall 1992 to spring 1993, where the water level in the center of the cone of depression at Greenville rose by as much as 31 feet.

Annual

The amount of net drop or recovery in any given well from one fall to the next is strongly variable from year to year. Part of this is accounted for by the necessarily random conditions on the surveying day, but part of it may be attributed to overall annual variations. Comparison of annual surveys indicated some years are net recovery years, others net decline years.

River interaction

Comparison of transducer records over a two year period with daily readings from Mississippi River gauges at Greenville and Arkansas City (a few miles upriver from Greenville) revealed strong correlations. Similar comparison of transducer data with precipitation records, as well as with the Rosedale gauge further upstream, did not result in meaningful correlation.

In a central Greenville well near the center of the cone of depression, the same-day correlation coefficient was 0.72, with maximum correlation found between the 8 a.m. gauge and 11 a.m. well reading, suggesting a lag of three hours in transmission of head pressure to the well. Thereafter, correlations fell off to a minimum about six months later (-0.34 on day 160 versus Arkansas City, -.33 on day 161 at Greenville) and rose again to new peaks (0.56 on days 351, 352) almost a year later.

At well D-56, just south of Greenville, correlations were strongest but did not peak until day nine (0.87 coefficient). Minimum correlations (-0.40) were reached day 192 versus Greenville and day 194 versus Arkansas City, rebounding to peaks at 0. 49 on day 376 and 377. Subtracting the original 9 day lag, this is a nearly annual cycle.

At G-257 east of Wayside, farthest from the river, correlations were not as strong. Initial maxima occurred on days 12 and 13 (0.52). Minima were on days 272 and 273, of -0.34 versus Greenville and -0.36 versus Arkansas City. Additional peaks occurred on day 383 (.43) and 374 (0.42), and again on day 441 (0.50 and 0.51).

MRVA interaction

The data suggests much greater interaction between surface water and Cockfield ground water than had been expected. By inference, interaction with the alluvial aquifer which separates the Cockfield from surface waters will also exist.

To describe the possibility of any interaction between the two aquifers, the head differential between the MRVA and Cockfield potentiometric surfaces was mapped from the October 2000 measurements. Both positive (MRVA exceeding Cockfield) and negative (Cockfield exceeding MRVA) areas of head differential exist within the study area. In the Greenville cone, the MRVA potentiometric surface was as much as 78 feet higher than that of the Cockfield. This positive differential declined strongly towards the southeast. In areas of the southern part of the county, the gradient reversed. There were slightly negative (0' to 6') head differentials in a broad area near Leroy Percy State Park, and another slightly negative area was centered at the Humphreys County border at the Sunflower River.

Chlorides and Water Levels

Direct comparison of the relationship between chloride concentrations and water levels is difficult. Because of the varied ranges of chloride concentrations, the strong relief on an ever-shifting potentiometric surface, and because few water level observation wells are also sampled for chlorides, an indirect approach had to be taken to search for any relationships between salinity and directions and rates of flow.

Annual variations as a fraction of standard deviations have already been described in the chlorides section. For the fall 2000 surveys, variation of each water level as a fraction of the standard deviation from mean (of fall levels 1995-2000) was computed. When these variation patterns were mapped and compared, there appeared a loose overlap of lower chlorides concentrations with lower water levels, though not a direct correspondence. The distributions gave evidence of compartmentalization. One distinct center of chlorides decline was seen centered northeast of the Greenville cone, but not fully surrounding it. Another center of relative lower chlorides was located east of Wayside at the chlorides maximum.

Sites where chlorides variations were positive versus means were concentrated around the periphery of the county, at Wayside, Swiftwater, Stoneville, loosely correlating with areas where water levels for 2000 were positive (higher) versus means. These also exhibited a compartmentalized pattern.

These patterns are complex and suggest that, although the aquifer has a unified flow system, the relationship of salinity to water level is highly localized. If the postulated faults are present, and if there has been some mineralization or selective cementation of faulted zones, then some retarding of free ground water flow between fault 'blocks' could be responsible for the compartmentalization effect seen in several parameters, such as color, chlorides, and pH.

Chlorides concentrations are lower where either natural or induced recharge is proceeding unhampered; where: 1) transmissive sands, such as in the basal or Cockfield, efficiently route fresher Cockfield waters into the system, or 2) downward leakage from the MRVA has a dilutive effect.

Chlorides concentrations are higher where recharge has been rerouted or obstructed. Partially sealed fault zones may act as obstructions. Recent rerouting of water by human activity towards the pumping centers has also decreased the rate of flow of water available to some other areas, particularly the Wayside chloride maximum, where the flow gradient is practically flat. (Figure 6)

Potential Sources

There are theoretically many sources of the high chlorides in this area. Several can be considered unfeasible in light of the data accumulated in this and other studies.

Unfeasible sources include:

- The clay seal at the surface of the alluvial sequence, and lack of nitrates or other human pollutants in the MRVA rules out surficial/human sources.
- Alluvial salt enrichment is known in other heavily irrigated areas, but the fresh waters in the MRVA rule out sourcing from the alluvial aquifer.
- The known presence of high chlorides in the Cockfield even prior to petroleum exploration drilling in the 1940s, and the apparent lack of direct correlation of chloride highs to drill sites indicate oilfield contamination is an unlikely primary source, although localized brine leakage via old wells should not be ruled out.
- Direct contact of salt or evaporite formations with the Cockfield aquifer is not known to occur in the study area.

Feasible sources include:

In-place source:

- Original trapping of brackish waters during deposition of the Cockfield.

Outside sources:

- Lateral migration of chlorides from saline waters elsewhere in the Cockfield.
- Upward migration of chlorides from lower formations.

Original waters

The 'original waters' model has been favored by previous workers, and has the advantage of being the simplest explanation, requiring no mode of transport into the aquifers. The current data do not disprove this theory, but do not support it strongly. The highest concentrations of chlorides do not center in the deepest part of the structural basin, nor in the area of greatest marine deposition, nor in the least permeable areas, though it would be logical to expect the remnants of original waters to center in one of these locations. Instead the highest chlorides concentrations are located near the structural hinge or dip reversal onto the Monroe Uplift, suggesting that even if the waters are original, some movement and structural control has been involved.

Outside sources

There are ample other sources for saline waters at depth in the vicinity, so that sourcing from waters other than original is reasonable. In addition to the generally increasing brackishness of ground water in deeper confined aquifers towards the gulf, some additional salinity sources of greater concentration are known to exist in and near the study area.

During petroleum exploration drilling in the 1940s and 1950s in the study area, saltwater was produced during drill stem tests at depths ranging 3700 to 4400 feet. In at least one test the water was described as a 'surging flow'. The beds containing this water were lower Cretaceous 'ashy sands', likely reworked volcanics.

While salt beds or domes have not been drilled in the immediate area, in the Kings Dome area, 40 miles to the south, some wells reported bottoming in domed salt in the range of 3800 to 4100 feet of depth. This fairly shallow salt occurrence is separated from the study area by the Monroe uplift structure, also by the margin of the salt basin province. However, conditions during the time between the Eocene and the present may have once been amenable to transport of brines from this area, likely via the 'ashy sands', and then perhaps aided by faulting into vertical invasion of overlying formations.

Migration intra-Cockfield

No shallow high-chloride Cockfield waters occur in comparable positions along strike to the east, but some high chloride Cockfield waters have been documented in Arkansas and Louisiana. The Cockfield has been more deeply eroded in Arkansas and Louisiana, where the MRVA often lies directly upon Sparta sands. In those areas, brackishness in both the Sparta and MRVA have been problematic.

During a time in later Tertiary or early Quaternary history, when regional flow was presumably towards an ancestral Mississippi River running in a course further east, waters from a westerly saline zone could have been transported along a normal gradient to the east into this area. In short, current structural strike may have at one time been the direction of down-dip ground water flow. At the southeast end of the Desha structure, trapping would have occurred. Subsequently, with time and a shifting river course, the flushing effect from proximity to the modern Mississippi River could have helped cause a fresher zone of waters to divide the two areas of brackishness, and erosion of some of the intervening Cockfield may have further confused the issue.

Another hypothetical direction of intra-Cockfield movement would be from down-dip, although a zone of fresher Cockfield water over the Monroe structure is immediately adjacent. While brackish waters do occur in the Cockfield to the south, the persistence of the Monroe Uplift as a positive feature through so much of geologic time, and therefore as a barrier to flow, tends to undermine this as a credible source.

Upward flow

Williamson, Grubbs and Weiss (1990) describe a regional flow model within the coastal plain system which calls for ground water to flow normally downdip from recharge zones, until it reaches either the base of the flow system (Midway confining unit) or the boundary of the overpressured zone. When such boundaries are reached, flows are deflected upward to discharge into higher formations.

In this scenario, water in deeper saline aquifers might have traveled such a flow path, coming up into the Cockfield at some past time when flowpaths deflected upward in the area, perhaps if the overpressured zone were closer to the study area than it lies today (at the present time, the boundary of the overpressured zone in the Gulf coastal plain passes roughly east-west through southern Louisiana).

An episode of renewed uplifting of the Monroe structure is one mechanism which could have then 'cut off' the Desha Basin Cockfield from its deep supply, stranding a brackish lens.

Problems with the upward flow model are that we do not see Sparta chlorides concentrations as high or higher than those present in the Cockfield, and such values would be expected in order to support this theory of generalized upward flow. However, there is little deep-aquifer data available in the southwestern corner of the study area, and additional information might identify such a zone.

A variation of the upward-flow model would pass deeper waters upward through a more restricted conduit, such as a fault zone. Pressured fluids rising along a fault zone would preferentially invade the most transmissive strata encountered (Cockfield and Sparta sands) and would achieve less invasion in less permeable materials such as the Tallahatta siltstones. Problems with this model remain: the comparatively low chloride values in the Sparta, and the location of high Sparta chloride values towards the west rather than over the postulated Monroe margin fault zone.

CONCLUSIONS

General Conclusions

- Chlorides concentrations within the Cockfield aquifer vary within limited ranges annually and seasonally, but in general have risen gradually over the last five years. Most changes are likely expressions of shifting ground water flow patterns and variations in dilution, although sampling and testing error account for some variations.
- Chlorides concentrations in the Cockfield aquifer are partially stratigraphically controlled, dependent on location within a system of horizontal strata. Maximum concentrations occur in the middle and parts of the upper layers of the Cockfield. Recharge is actively flushing the lowermost horizons and portions of the upper strata.
- Compartmentalization by permeability barriers appears to further control chloride concentrations laterally.
- The Wayside area hosts a zone of anomalously high gradients in water level, color, chlorides, and pH, which suggests the presence of faulting.
- Chlorides concentrations in the other aquifers are lower, and maximum concentrations in them tend to cluster west of the Mississippi.
- Moderate levels of salinity may be developing in recent years in the Mississippi River Valley Alluvial aquifer.
- Ground water flow is complex and strongly affected by human activity. Potentiometric levels, gradually falling in both the Cockfield and MRVA, are shifting. The possibility of increased vertical flow between the two aquifers, in both directions, in response to hydraulic gradients, will likely become greater.
- There is a strongly fluctuating supply of water coming into the Cockfield from the overlying MRVA. This is a response to varying head influenced by Mississippi River stages, in a zone created by a large cone of depression in the Cockfield potentiometric surface at Greenville. The result is seasonal periods of induced recharge of fresher water.

Interpretive Conclusions

The source of chlorides in the Cockfield aquifer and the prediction of movement of the chlorides-rich water is a matter for subjective interpretation until more data becomes available, such as might be acquired from seismic work and/or dense well control. However, from the evidence gathered to date, the possibilities have been narrowed somewhat.

The current trend of gradually increasing chlorides concentrations with time appears to be due to salinity being shifted by changing flow patterns, including seasonal flow reversals, and the bypassing of some areas by recharge by fresher waters. The possibility that there is or has been some upward flow through fault conduits has not yet been documented in the area.

The structural framework of the region suggests that higher salinity waters migrated into the Cockfield, and to a lesser extent the adjacent lower formations. In the study area there has not been identified a direct pathway along which these waters could have traveled, yet left surrounding aquifers much less affected.

In Arkansas, such a zone has been documented, where Sparta waters are most brackish at depth and grade systematically upward into lower concentrations. During historic times there is documentation indicating intense localized pumping pulled brackish waters up into the alluvium at fairly alarming rates. The coincidence of this zone with a major magnetic anomaly indicating a zone of crustal weakness suggests there has been upward transport of saline fluids via faulting. From existing data, this is the most reasonable source of saline fluids in the upper aquifers.

Similar but unrecognized conditions may be present in the study area, but deep stratigraphic and chloride data from the lower aquifers is generally unavailable in southwestern Washington County. The postulated fault zones would be apt areas for further investigation into that possibility.

There is a large hiatus in the record of conditions that existed between the Jackson Group Eocene and the present Holocene. During that time, the Embayment and coastal plain continued to receive deposition, then the seas began to recede Gulfward. We do not know how much additional Tertiary deposition occurred and then underwent erosion, truncated by the alluvial plain basal surface. We also do not know the exact history of the Mississippi River and its alluvial plain, but we do know that for some time in the Holocene the course of the river followed a valley considerably east of its present position, roughly where the Sunflower River currently bisects the Mississippi Delta alluvial plain. It is possible, then, that at some time in the past, ground water flow in the Cockfield aquifer likely began at recharge areas in Arkansas, and traveled east-southeast, through the Chicot saline invasion zone, towards discharge into the ancient river basin. The linear trend of the Desha Basin may have at first been a preferential pathway for such flow in the Cockfield, but where the syncline closed to the southeast, the structural rise would have trapped these western-origin waters.

The lack of contamination in the MRVA may relate to the timing of arrival of saline water possibly pre-dating MRVA deposition. Salinity moved furthest in the Cockfield because its hydraulic gradient was more favorable, and/or it was more transmissive than the lower formations.

At some point, minor faulting during the growth of the Embayment may have further affected the area, in particular at the postulated Wayside fault, and perhaps in other local faults, further complicating the chlorides distribution. The main chloride high may be trapped between permeability barriers: one could be the postulated fault at Wayside, particularly if it has become partially mineralized or otherwise sealed.

Future status and movement of saline water will depend upon the interweaving of increasing pumping activities with the inexorable process of recharge, within the framework of the buried structures and flow paths.

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Figure 1
Study area and selected regional features

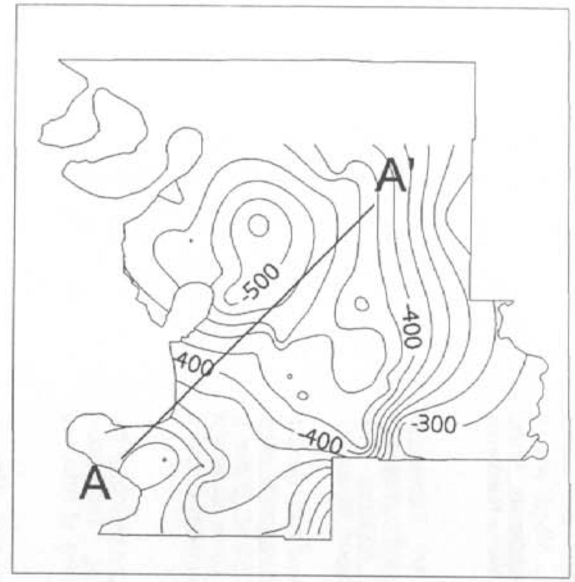

Figure 2
Base of Cockfield Formation; location of cross-section A-A'

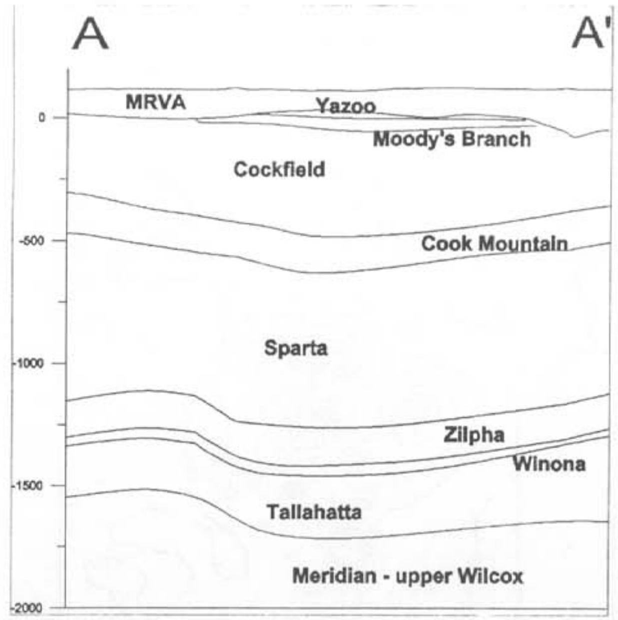

Figure 3
Cross Section A - A', datum mean sea level

Figure 4
Magnetic field, in residual milligammas

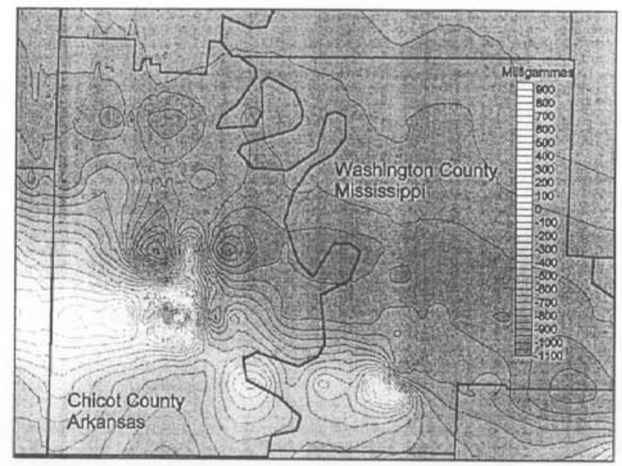

Figure 5
Chlorides in Cockfield ground water, mg/l

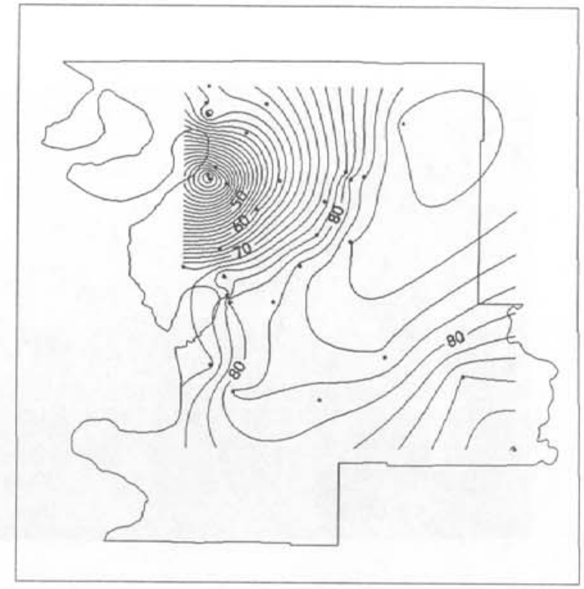

Figure 6
Cockfield water levels, elevation above MSL, October 2000