Water supply in the Mississippi Delta: What the model has to say

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A regional groundwater flow model has been built as a tool to better understand the system flows and to project future water levels in the Missisippi River Valley alluvial aquifer (MRVA). This a highly productive aquifer which supports vast amounts of agriculture and aquaculture in northwest Mississippi. Water levels are declining in this aquifer and will be of increasing concern in the future.

To quantify discharge, the model incorporates a method of estimating pumpage for agriculture and aquaculture, based on crop distribution patterns and rainfall-response factors.

Recharge to the aquifer is complex and unusual, since a widespread impermeable surficial unit restricts rainfall infiltration in most of the Delta plain. Good calibration was achieved only when the model fully accounted for recharge data from several sources. Positive recharge sources are: groundwater in the adjoining formations on the eastern bluff hills line, rain infiltration through the alluvial fans along the bluffline, and rain infiltration through sandy areas along the Mississippi River.

Other sources serve as both discharge and recharge areas for the aquifer, depending on season and/or location. These are: the Mississippi River, the underlying Tertiary aquifers (Cockfield and Sparta), the major rivers and the bluffline streams.

The base model period, built from known data for streams, precipitation, crops, and water levels, etc. ran 1996 through 2006. On average, the aquifer lost about 230,000 acre-ft of water per year from 1996 to 2006. During this time, pumpage per season averaged about 3 million acre-feet, with a minimum of 1.7 million acre-feet in 2002 and a maximum of 4.5 million acre-feet in 2000. Rainfall infiltration averaged about 2.4 million acre-feet per water-year, with a low of 1.9 million acre-feet in 1998 to a high of 3 million acre-feet in 2003. Over the ten year period, there were 2 years during which rainfall infiltration exceeded pumpage. In 8 of the years pumpage exceeded rainfall infiltration.

Several scenarios have been run from 2009 water levels forward, simulating conditions 20 years into the future, and the results of these are presented.

Key words: Water Quantity, Water Supply, Groundwater

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Introduction

A very prolific aquifer underlies the wide Mississippi floodplain ("the Delta") in northwestern Mississippi. The Mississippi River Valley alluvial aquifer (MRVA) averages only 107' thick, yet daily pumpage averages 6.5 billion gallons per day during the 5-month growing season (2.7 billion gpd annualized).

The Mississippi Department of Environmental Quality's (MDEQ) Office of Land & Water Resources (OLWR) oversees withdrawal of water from the MRVA, and authorizes permitting of wells under the supervision of the local agency Yazoo-Mississippi Delta Joint Water Management District (YMD). The aquifer is used principally for agriculture and aquaculture, and more than 14,000 large-capacity wells have been issued permits to pump water from it.

Declining water levels in the MRVA in a central portion of the Delta have been documented extensively (Bryant-Byrd, 2002, 2009) and are of increasing concern for long-range planning regarding water use from the MRVA. (Figure 1)

OLWR sought to update and upgrade a previous digital groundwater flow model of the MRVA, which was created in the 1990s by the United States Geological Survey (USGS) in a cooperative effort with OLWR. (Arthur, 2001)

The need to georeference the system and expand the model extent led to construction of a new model. However, some elements from the prior model were retained: type of model and discretization, most of the data points used to generate top and bottom geometry, hydraulic parameters for the MRVA such as specific yield, some channel-bottom elevations for major rivers, and approximately the same basic grid of 1-mile cells, though extended and reprojected into MSTM (Mississippi Transverse Mercator).

Objective

The objective was to produce a model to simulate the actual MRVA flow system that would be useful in three ways: understanding groundwater flow in the Delta, accurately predicting future groundwater levels, and assessing the impact of changes to any inputs in the system.

From the inception of model development, a primary goal was to represent the hydrogeology of the system with as much accuracy as possible, and to quantify parameters with as much real-world data as possible, leaving little to be estimated or 'backed into' by the model. In particular, there were new approaches to quantify the two major parts of the groundwater system: recharge and discharge.

Recharge

Surface Infiltration

Normally water enters a shallow aquifer by rainfall infiltrating down through surface soils. The recharge quantity in a model may be specified by merely applying a suitable amount of precipitation uniformly across the surface. In the case of the MRVA, this is not a realistic method.

The following statements are an excellent summary of the influence of the MRVA topstratum upon recharge.

> "Conditions for infiltration into the ground-water reservoir are excellent where the surface is permeable, and in these areas groundwater levels rise rapidly after heavy rains. Where an almost impermeable silt and clay layer, which ranges in thickness from a few feet to more then 50 feet, forms the surface, most of the recharge is from underflow from adjacent areas having more favorable recharge conditions." (Boswell et al, 1968)

While most clays transmit some water, however slowly, this topstratum layer separating soil from underlying aquifer sands and gravels is unusually impermeable, and this is documented by two lines of evidence, one experimental and one longitudinal.

Lysimeter experiments (Hoffmann et al, 2002) in typical clayey soils measured the amount of water entering, under a vacuum, into sealed tubes sunk into the subsoils at various depths. In Sharkey County specific conductance in the water of 5350 microsiemens per centimeter was measured at a depth of 12 feet. Tritium traces (from hydrogen bomb tests beginning in November of 1952) were found most abundantly (14.4. picocuries per liter) in the upper 5 feet of the topstratum thickness. Clearly meteoric water is not moving rapidly through this stratum.

Another line of evidence is a very low rate of 'detects' found by MDEQ-OLWR's sampling program for agricultural pesticides, carried out over a period of many years. (MDEQ-OLWR, 2009)

As for delineating more permeable zones, drilling in the MRVA by Steve Jennings and Charlotte Bryant-Byrd of OLWR uncovered several instances of sediments near the bluffline edge of the Delta which more resembled older Tertiary formations than classic MRVA sands, gravels, or clays, and where the impermeable topstratum was sometimes absent.

James Starnes of Mississippi's Office of Geology (MDEQ-OG) identified alluvial fans along the bluffline which contain reworked upland sediments, some of which appear to tongue with the MRVA deposits. (Starnes, 2008)

The entire line of fans from Memphis to Vicksburg covers more than 250 square miles of area, and would be likely to host enhanced recharge. (Figure 2)

There are also known areas to the west where sandier sediments prevail at the surface, rather than the 'tight' floodplain clays. There are irregular bands of higher permeability along the Mississippi River and Deer Creek created by natural levees, crevasses, sand boils, etc.

Because mapping and measuring permeability of all these areas was not feasible, as a proxy the 'non-hydric' parameter assigned to soils mapping within the SSURGO (Soil Survey Geographic) database compiled and distributed by the NRCS (Natural Resources Conservation Service, United States Department of Agriculture) was used. (Figure 3)

To prepare data for the model, each polygon in the SSURGO mapping was assessed for infiltration capability, and using guidelines established by the Texas Department of Transportation for estimating runoff (TDOT, 2004) each polygon was assigned an approximated runoff coefficient according to its soil series, slope, vegetation, and drainage. Slope was derived from 10-meter digital elevation model data (DEM), vegetation and drainage identified from aerial photography. Then the inverse of this coefficient was used as an infiltration factor to estimate precipitation inflow to each model cell. In the hydric soil areas, of course, infiltration was set to zero.

These are simplified assumptions which do not account for complex temporal and other aspects of rainfall events, but are only a means to estimate infiltration rates. Ideally, detailed mapping and permeability data from drilled samples or other onsite data would have been used to better approximate real infiltration values.

Boundaries

While infiltration from the surface is important, three other boundaries surround the aquifer, and these not only influence retention of water in the aquifer but also supply some water to the system.

The Mississippi River serves both as a variable head boundary at the western edge of the system, and as a gaining/losing stream seasonally contributing to and removing water from the aquifer. Gaged stream water level elevations were used to quantify this boundary.

A variable head boundary exists at the eastern bluffline, where the MRVA abuts unconsolidated Tertiary age sediments. A new network of stations was set up at this bluffline to allow measurement of water level elevation in streams as a means of quantifying the potentiometric surface which exists at the eastern boundary.

Below the aquifer is a complex boundary with the underlying Tertiary aquifers. This is the most poorly documented portion of the system. There is some water level data from the underlying aquifers acquired over many decades by both the USGS and OLWR. In some areas the potentiometric surface in these confined aquifers, the Sparta (or Kosciusko) and the Cockfield, exceeds that of the MRVA and therefore, where permeable beds of the MRVA overlie permeable beds of the Tertiary, water would flow from the underlying aquifers to the MRVA. In other areas the reverse is true, and there would be a net drain from the MRVA to the Tertiary.

The formations are very heterogeneous. While gravel commonly forms the basal beds of the

MRVA, finer grained sediments do occur in some areas. The Sparta and Cockfield are commonly described as thick formations of fine sand, but in fact contain clays, and in some locales clay sequences are substantial. The thin Cook Mountain Formation which separates the two and underlies the MRVA in a narrow band is normally considered an aquiclude or aquitard, but since it grades to sand northward towards Memphis, it also can act as an aquifer in some areas.

Thus there are two factors at work controlling passage of water to and from the MRVA at its lower boundary: the vertical hydraulic conductivity of both the MRVA and the lower formations, and the comparative potentiometric heads in both.

While the MRVA water level measurements are mostly very well distributed and well understood except for the southernmost Delta where availability of wells is limited, the water levels recorded in the Tertiary are more problematic. They tend to be clustered in cones of depression at public water systems, and they tend to be screened in the lower portions of the aquifer, not the upper beds closest to the MRVA interface. In large parts of the Delta, there are no longer actively measured water wells in the Sparta or Cockfield. A wider distribution of water wells for measurement was available in earlier decades when there were more farmstead water wells accessing the Tertiary drinking water aquifers, yet often wells were screened in the Meridian-Upper Wilcox aquifer with its artesian wells. Since there have been declines in the Tertiary heads since those older measurements, it is necessary to estimate current head levels in unmeasured areas, or allow often inappropriate interpolations between widely separated current data points.

Even less data is available regarding vertical hydraulic conductivity values across the MRVA/Tertiary interface throughout the extent of the aquifer. The circumstances were such that this parameter was the one we chose to 'back into'. This was done using a manual method, wherein the grid cells were mapped into 40 sectors corresponding to subcrop geology and facies changes, and the VCONT in each sector was manipulated up or down individually as necessary.

It became apparent during model calibration that the exchange of water with the Tertiary is not the major contributor of recharge/discharge with regard to the MRVA, but is significant. If accurate projection of future water levels in the Delta is an important objective, then a network of observation wells in the upper Tertiary should be planned.

Discharge

Pumpage

As MRVA water use is largely restricted to agriculture and aquaculture, discharge may be quantified by estimating the amount of farm and fishpond pumpage. In the past this was a very elusive goal, because unlike water pumped for industrial or public water systems, water pumped for agriculture and aquaculture is seldom metered.

Three advances in recent years have allowed a huge leap in the ability to estimate pumpage.

1. YMD metered water use at actual farm sites in the Delta over a period of several years in order to create pumpage statistics tied to real world conditions. (YMD, 2008)
2. Dr. Jamie Dyer of the Geology and Geography Department of Mississippi State University (MSU) assembled very detailed and high quality datasets quantifying precipitation across the Delta, which were resolved to a 1-mile grid for use in this model. (Dyer, 2009)
3. The United States Department of Agriculture's National Agricultural Statistics Service (USDA-NASS) compiled crop distribution data on 56-meter pixel blocks, revised annually, for the Delta. (USDA-NASS, 1999-2009)

With these three important data sets available, it was possible to establish month-by-month relationships between the crops planted with the rainfall recorded, and therefore estimate the expected pumpage attributable in each model cell, by a rainfall-response method.

First, the data was separated into the crops of interest: rice, catfish, soybeans, cotton, and corn. For each of these, there were corresponding estimated water use data from actual farms during each of the five growing season months: May, June, July, August, September. Average estimated water use ranged from 0.5 acre-feet per acre for cotton to 3.0 acre-feet per acre for rice. (YMD, 2008)

Because the sample farms are anonymous as to specific location, it was not possible to directly relate the rainfall in each grid cell to water use in that grid cell. Instead a polygon was drawn around the area in which most of the farms cluster, and derived average rainfall within that polygon. Data from any farms lying outside the cluster were therefore excluded from the calculations.

The calculations used were similar to those used to relate rainfall and pumpage by MSU investigators. (Wax et al, 2009)

For example, for June soybeans, the average total rainfall was tabulated for each of 5 Junes, and the average water use per acre (for that crop only) during those same Junes. This allowed a graph of the five precipitation data points versus the five water use data points. A simple linear trend line was derived from these points defined as mx + b. Where the line intercepted the rainfall axis (“b”), pumpage was zero; that is, as rainfall reaches that amount, no pumpage would be necessary.

The factors derived for each of the crops and months (m and b) were then used on a grid-cell-by-grid-cell basis to calculate estimated total water use in each cell using rainfall for that cell only, for each growing season month in a ten-year period.

This rainfall-response method generated a remarkably detailed and useful 10-year set of data which projects water use in direct response to the crops planted and rainfall.

The method used simplifies a complex system into simple linear trends based on limited data points. No doubt some enhancements would be possible if data were available on more data years, winter flooding for hunting purposes, farms not using groundwater, irrigation of minor crops and hatchery operations, evaporation, etc. However, the results obtained in this current simplified rainfall-response method are superior to data previously available, and help the model to be quite predictive.

Other Discharge

The model accounts for other discharge of water from the system. In addition to the Mississippi River, the other large deep streams alternately gain and lose versus the aquifer depending on seasonal and drought or flood conditions. In the case of minor streams, only those which cross permeable areas such as alluvial fans experience baseflow gain and loss.

As discussed in the recharge section, the underlying Tertiary aquifers in many locations have potentiometric heads roughly equivalent to those in the MRVA. But there are also areas in which there is a net discharge from the MRVA to the Tertiary, with one notable example in the Greenville area, where there is a large cone of depression in the Tertiary water levels.

Calibration

The ten year base period for model calibration ran from October 1, 1996 through September 30, 2006. Data from the fall Semi-Annual Survey conducted by YMD was used both to create baseline starting heads and to compare modeled results (ending heads) to actual measurements. (Figure 4)

The conventional comparison for the accuracy of model generated heads to corresponding measured heads is root mean square error (RMSE) across all active cells. Projected heads at the end of the ten year period in 2006 had a RMSE of 3.91’. In the central delta accuracy was 3.17’.

Volumes

During the calibration period, estimated irrigation averaged 3 million acre-feet per season (134 billion cubic feet, or 999 billion gallons). Irrigation varied widely depending on weather, from a minimum of 1.7 million acre-feet in 2002, to a maximum of 4.5 million acre-feet in 2000, a drought year.

There is a pumping center in the central Delta in which water level declines are marked, and which for working purposes has been delineated as the area inside the 80’ contour in the fall of 2008 (elevation above mean sea level) for heads in the MRVA.

Within that 335 square mile zone, estimated pumpage averaged 631 acre-feet per square mile versus 421 outside the pumping center. When compared to the average delta wide, pumpage was 46% above average.

During the period 1996-2006, there was dewatering of 720,018 acre-feet of aquifer per year, and using 32% porosity in the MRVA, this means 230,406 acre-feet of water (or 75 billion gallons) was removed from the system every year on average. This ten-year cycle did include some significant dry years. Over a longer span from 1981 through 2009, the water lost annually averaged 153,343 acre-feet (about 50 billion gallons).

Forward Scenarios

Achieving a good calibration allowed development of scenarios projecting water levels in future years. This phase was begun by regenerating the rainfall-response pumpage data using 2009 crop patterns versus the base ten-year rainfall data set, while using fall 2009 data as new starting heads for the simulations.

The ‘expected’ scenario consists of crop patterns from 2009, with a ten-year period of varying rainfall including some wet and dry years; with pumpage remaining steady in the central Delta where most available land is fully irrigated, but rising 10% from existing levels to account for new permits.

After 20 years, the heads generated in this projection result in a greatly enlarged area of marked drawdown. The 70’ contour expands in all directions but particularly to the north and west, where cultivated acreage, particularly for rice, is increasing. (Figure 5)

Projected saturated aquifer thickness was mapped, highlighting areas in which saturated thickness was 60’ or less. Since typical Delta irrigation wells are constructed with screens 40’ in length, and during pumping water levels are drawn down in a cone towards the screen, pumping water could be problematic in those areas in which only 60’ of saturated thickness remains.

In 2009, there were a total of 7 one-square-mile grid cells in the central delta which averaged less than 60’ of saturated thickness remaining. (Figure 6) Ten years later in 2019, under the ‘expected’ scenario, 41 square miles will meet the criteria. And twenty years later, the model projects 77 square miles which will have less than 60’ of saturated thickness remaining. (Figure 7)

Conclusions

Incorporation of detailed data and new methodologies provided improved calibration and predictive ability to this groundwater modeling system.

Significant land areas in the Delta could be affected by water level declines sufficient to inhibit groundwater irrigation within the next 10 to 20 years.

A new network of monitoring wells is needed in the upper sands of the Tertiary formations which subcrop beneath the MRVA.

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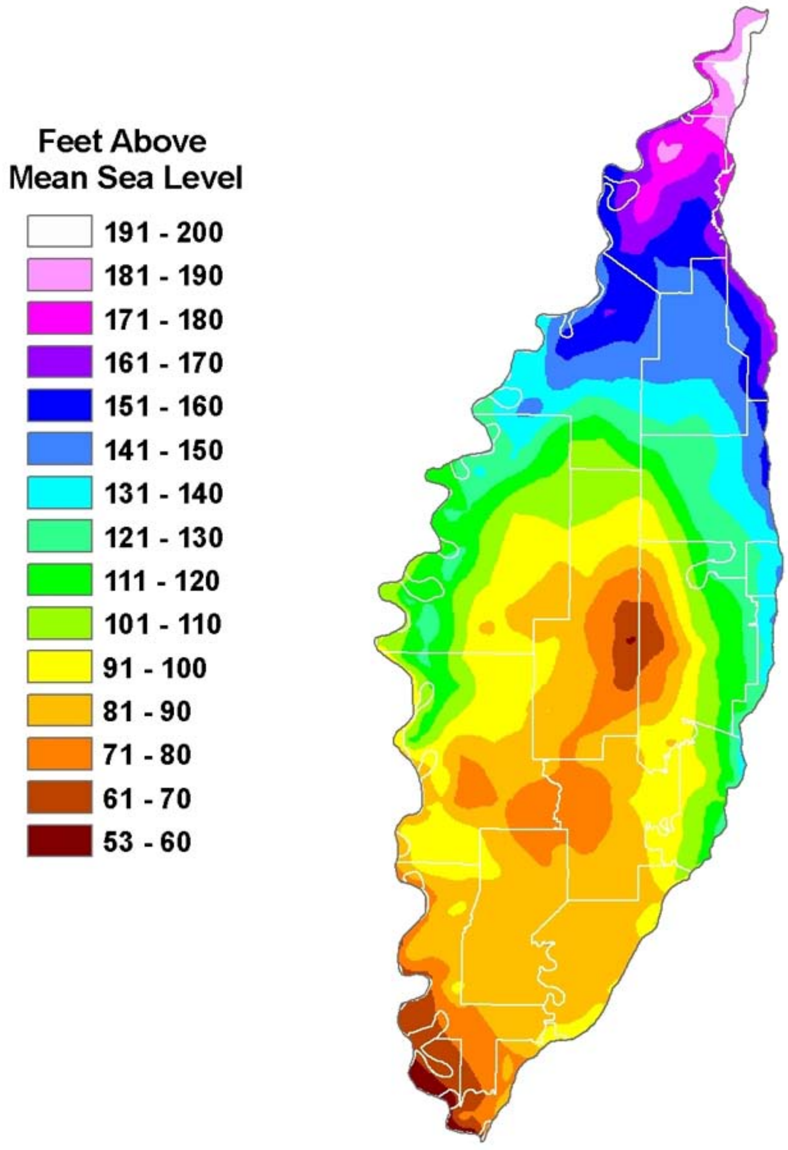

Figure 1. MRVA water levels, Fall 2009.

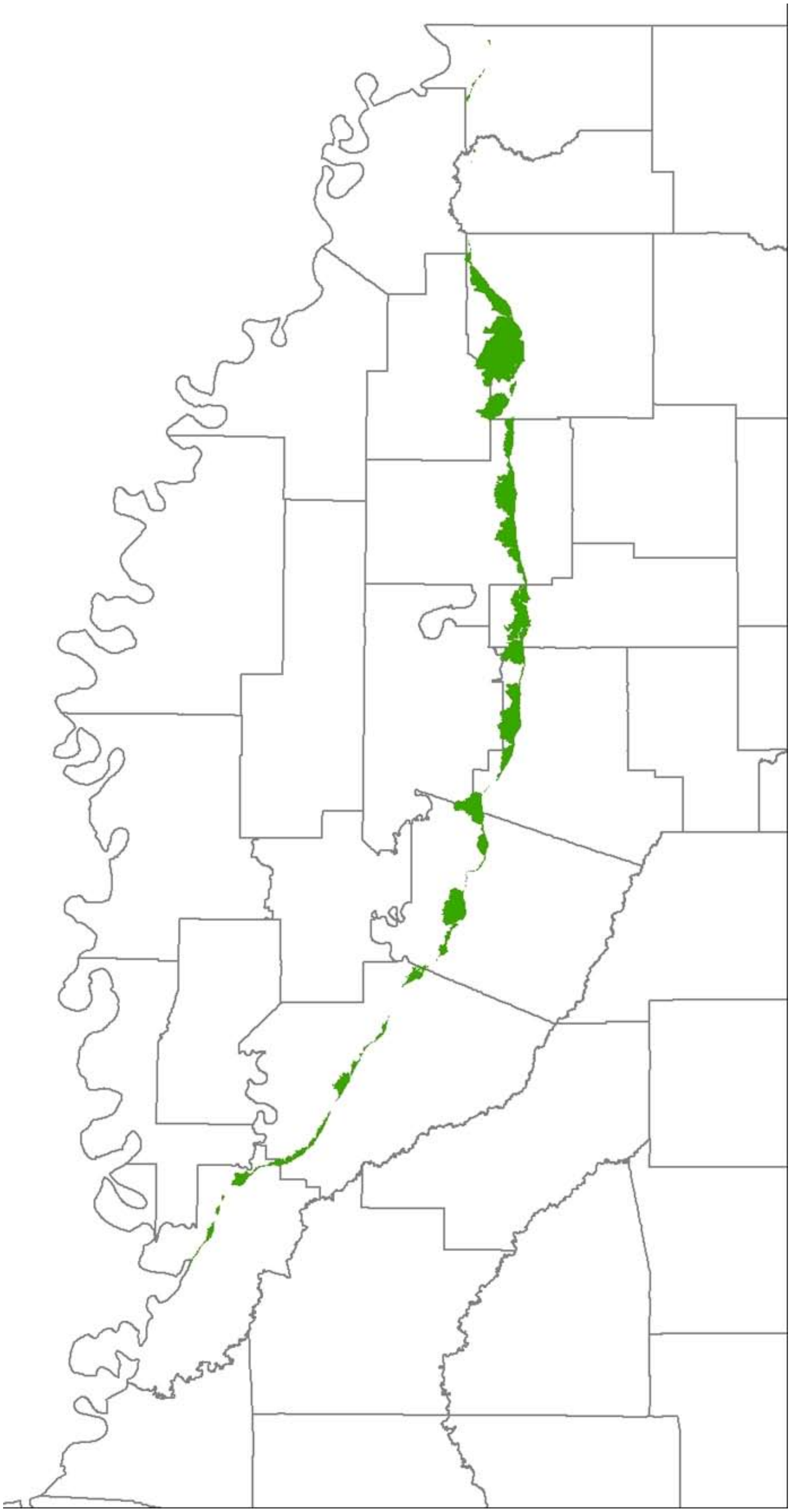

Figure 2. Bluffline Alluvial Fans.

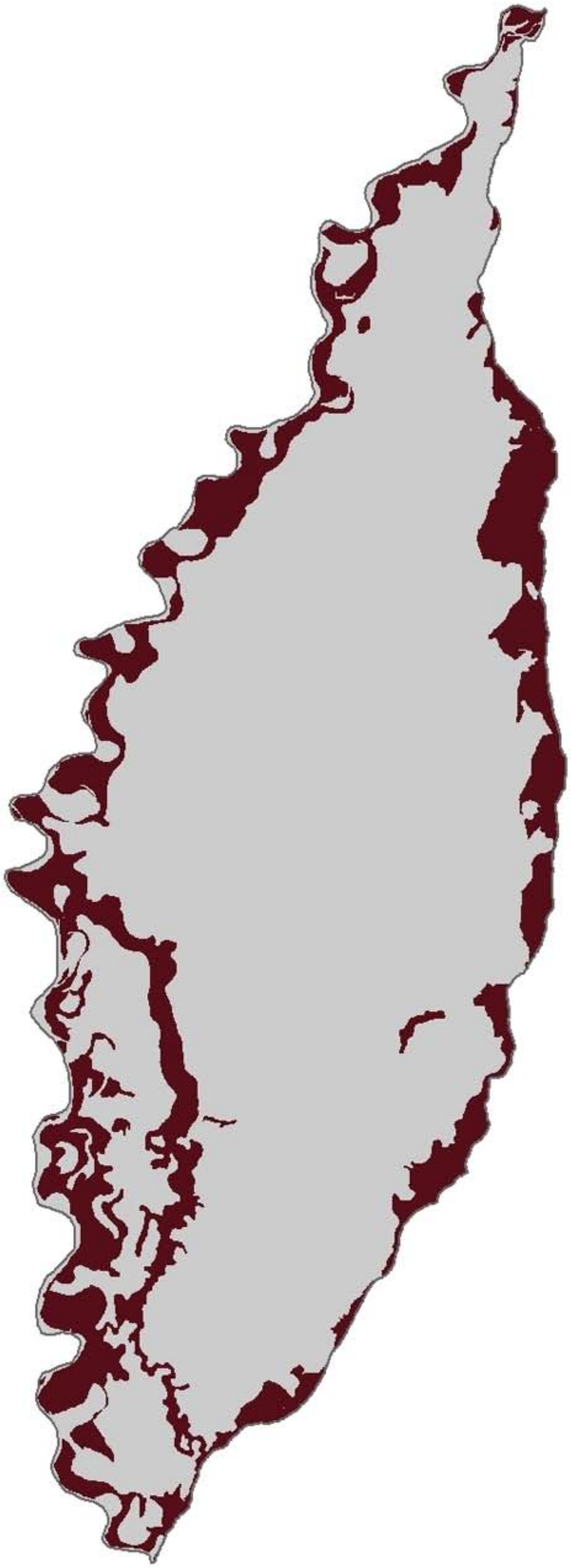

Figure 3. Non-hydric soils.

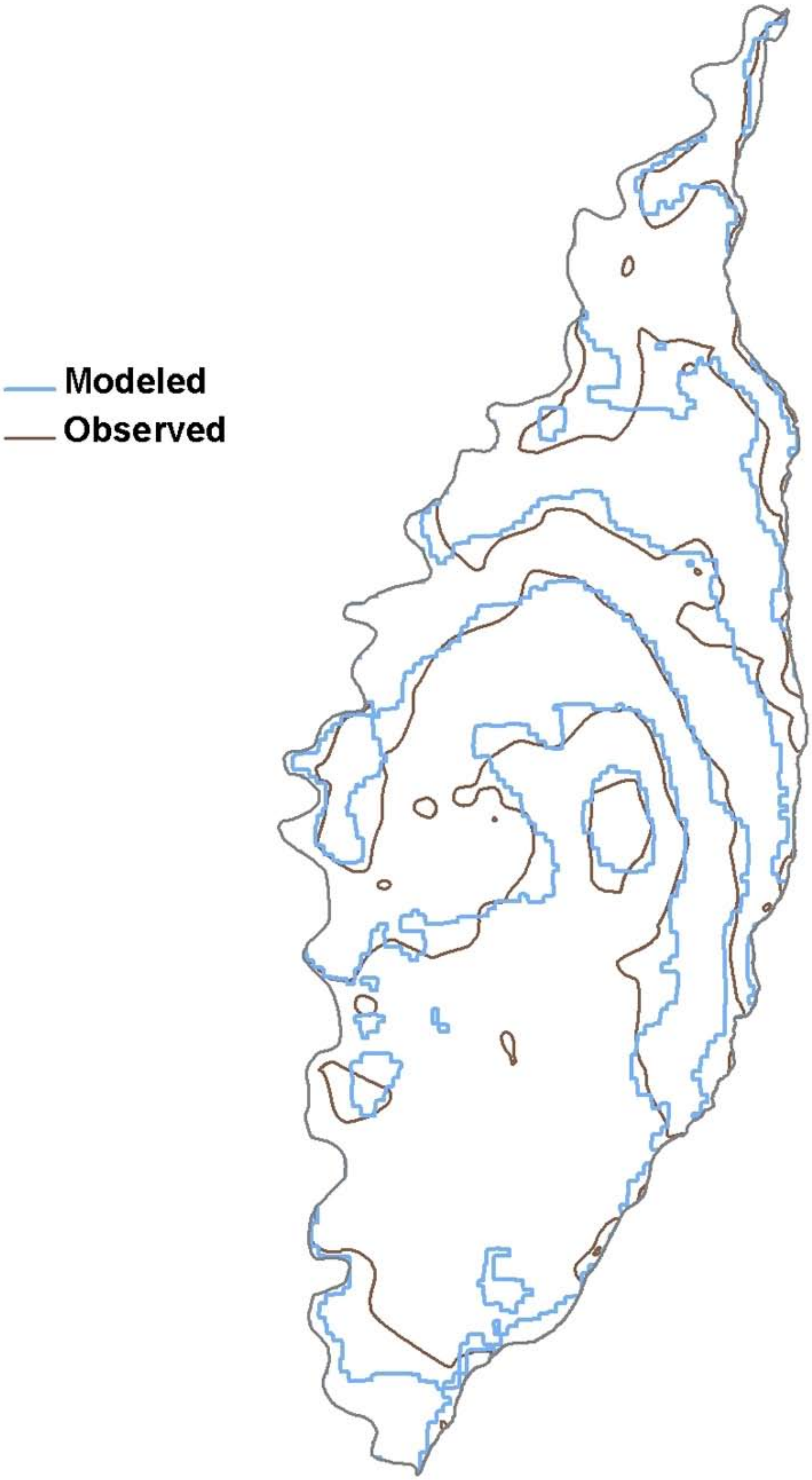

Figure 4. MRVA water levels, Fall 2006.

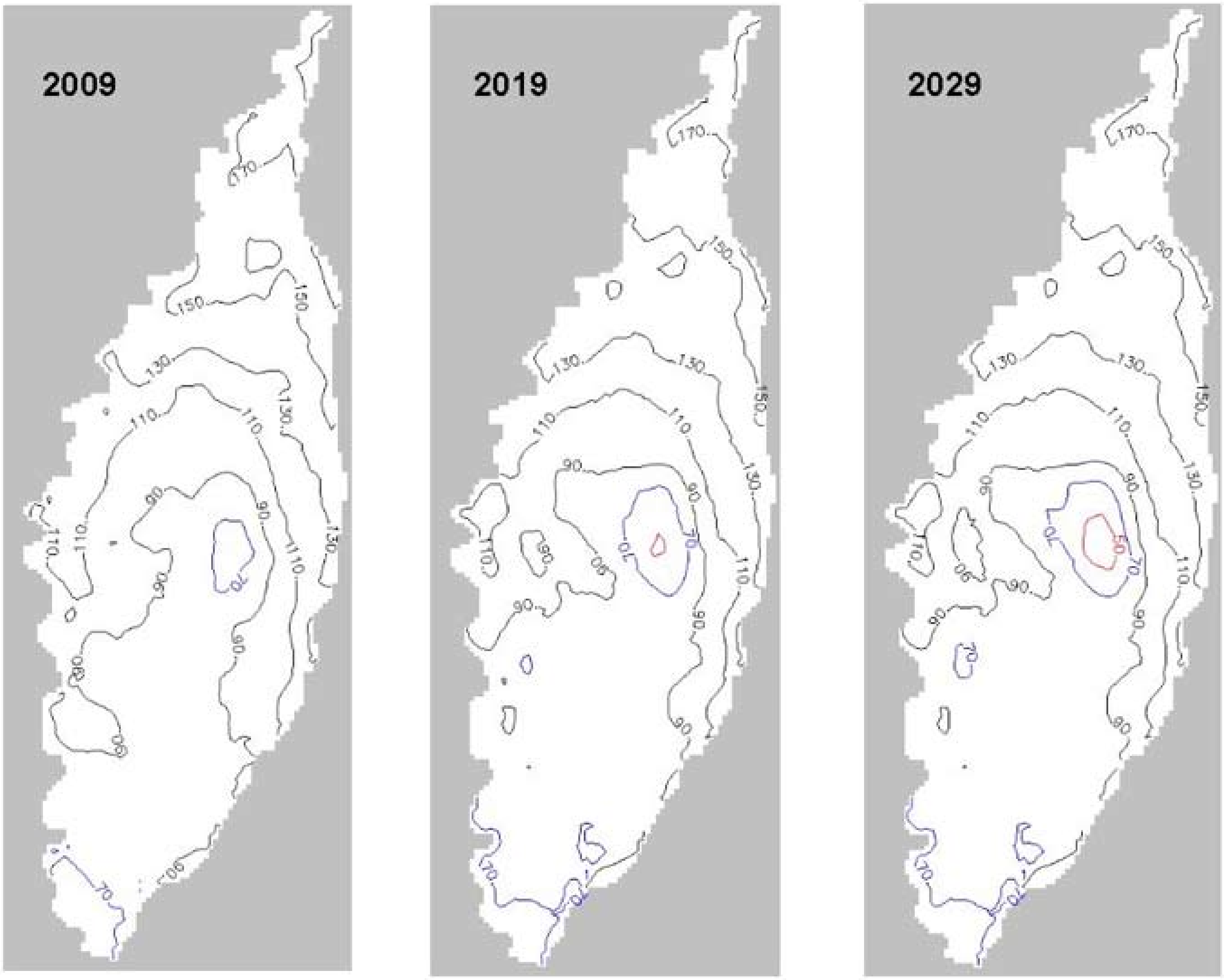

Figure 5. MRVA heads with pumpage increased 10% outside ‘hole’ area.

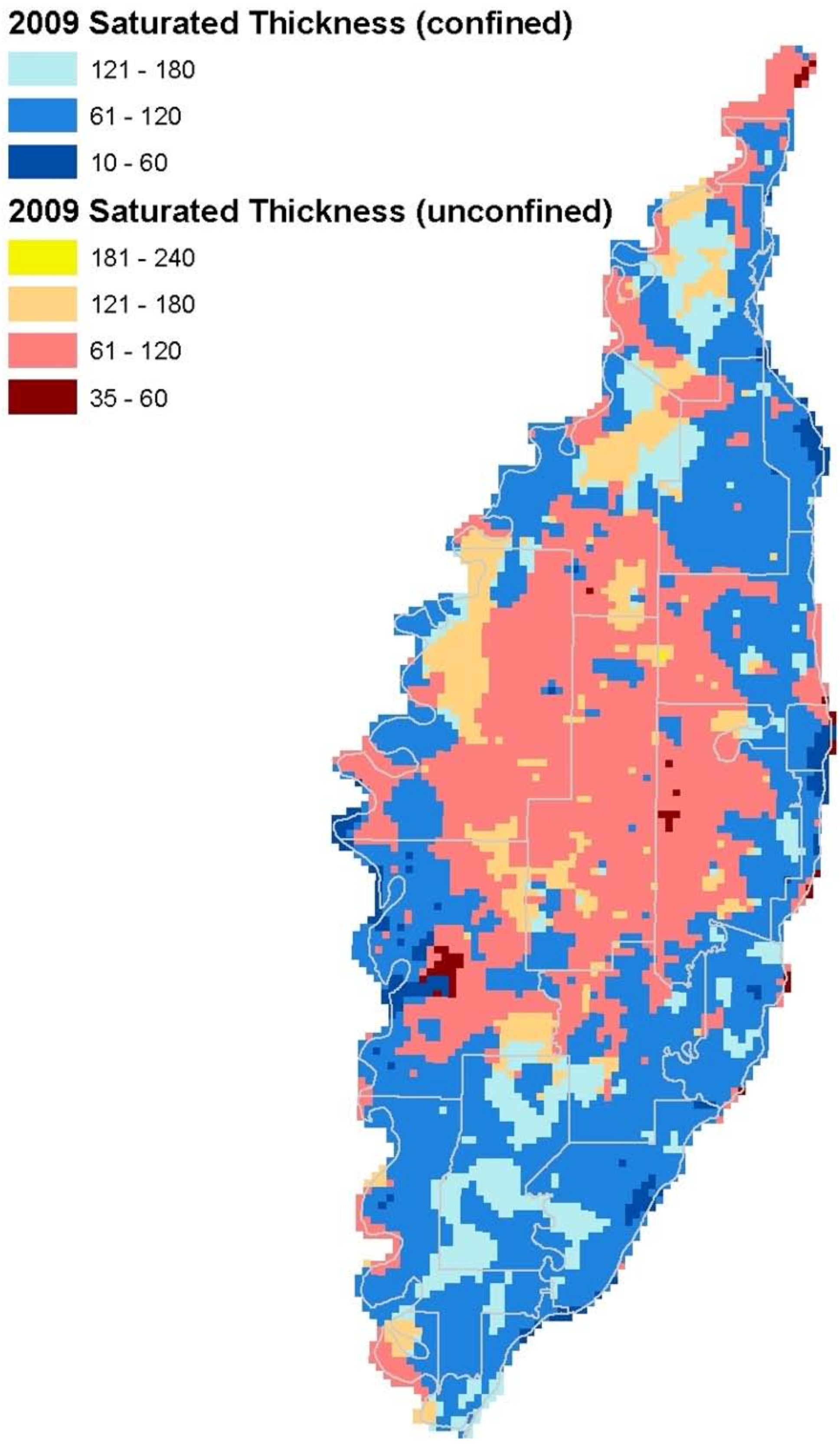

Figure 6. MRVA saturated thickness, Fall 2009.

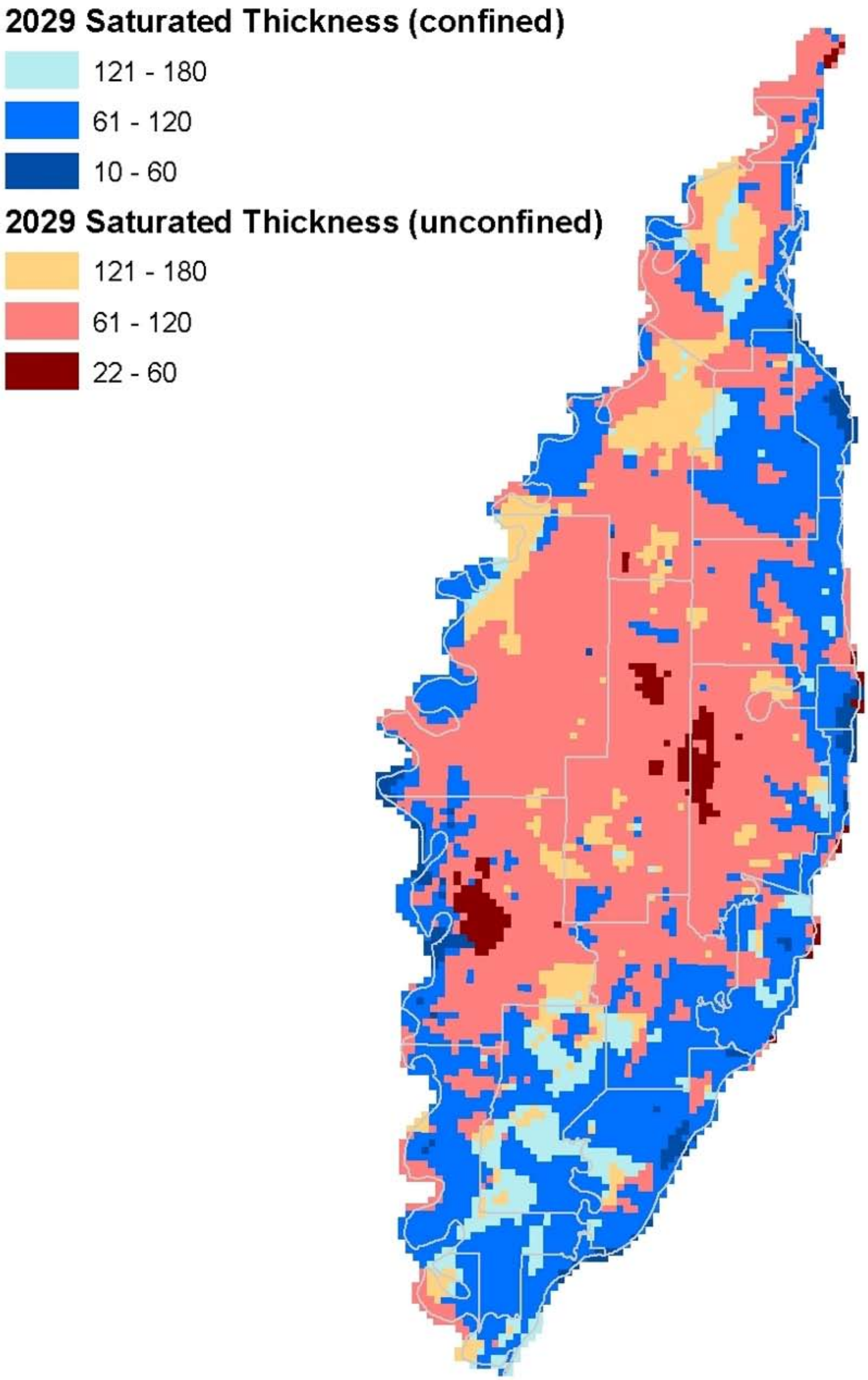

Figure 7. MRVA saturated thickness, Fall 2009.