Final Report for Project #238 – Water Security in Armenia, WI: Modeling for informed decision-making in a nitrate-impacted watershed

Summary

In the Central Sands region of Wisconsin, concerns have grown regarding the export of nitrogen in the form of ionic nitrate (NO_3^-) from agricultural areas to private wells, where nitrate can be a contaminant of concern particularly to infants and pregnant mothers. Reducing the risk of private well nitrate contamination requires an understanding of the source regions that contribute to water extracted by the well (i.e., the "capture zone"). The capture zone of private wells can be influenced by a variety of factors including local hydrostratigraphy (i.e., the arrangement of geologic units), aquifer parameters associated with hydrostratigraphic units (i.e., hydraulic conductivity and porosity), total depth of the well, and the portion of the well that is screened (i.e., open to the surrounding geologic formation).

This study represents an application of numerical groundwater modeling to an area of interest in Juneau and Wood counties surrounding the township of Armenia (henceforth, "the Armenia region") – part of the Central Sands region of the State. Numerical groundwater models with particle tracing provide a method for estimating the capture zones – and associated travel time for water – contributing to the water quality observed at a given location, such as a private well. We collected data relevant to the hydrology of the Armenia region to develop this numerical model, including: 1) Estimated aquifer pumping rates based on data from the DNR high capacity well database; 2) Land cover, slope, and climate data supporting estimates of annual groundwater recharge; 3) Aquifer water levels (heads) recorded at a newly-installed set of water table and multi-level wells; 4) Aquifer hydraulic property estimates obtained from a series of slug tests and a tracer test performed in the region; 5) Stream stage and flow measurements at nearby surface water bodies including Petenwell Lake and the Yellow River; and 6) depth to bedrock estimates obtained via passive seismic monitoring.

The results of this study indicate that groundwater flow directions are generally to the south and east in the vicinity of residential wells near Petenwell Lake, where the majority of wells determined to have high nitrate by EPA sampling were located. Locations “up-gradient” (i.e., to the north and west) are likely contributors to nitrate measurements at these locations. Beyond horizontal flow directions, however, our model also simulates the vertical travel of water in the region. Model results demonstrate how wells with increased depth may capture water that originates at larger distances from the receptor with associated longer travel-times.

Note: The majority of work under this project took place during the period of time when the COVID-19 pandemic affected operations at the University of Wisconsin-Madison (Spring 2020 through Spring 2022).

Task	F 2019	SP 2020	SU 2020	FA 2020	SP 2021	SU 2021	F 2021	SP 2022	SU 2022
Geophysical Surveys/Depth to Bedrock	***X								
Collection of available model inputs:	X	X							
Building Initial MODFLOW Model		X	X						
Outreach and discussion of modeling with stakeholders		X	X	X	X	X	X	X	
Stream Gauging			X	X					
Well Drilling & Installation			X	X					
Groundwater Sampling			X	X	X	X			
Model updating and refinement				X	X	X	X	X	
Production of prediction deliverables (particle tracking, geospatial data)								X	X***

Introduction

A large percentage of rural homeowners in Wisconsin are dependent on private wells for domestic use including drinking water. Groundwater pumped by these wells is often untreated before use, meaning that they are particularly susceptible to contamination that can affect human health. Outreach and testing campaigns have demonstrated that a significant proportion of private well samples are impacted by nitrate (NO_3) at levels representative of anthropogenic contamination (> 3 mg/L) (Dubrovsky et al., 2010). The Armenia region studied in this report (containing portions of Juneau and Wood counties) are indicative of these trends. In Juneau and Wood county, 14% and 6% of home water samples, respectively, have been found to have nitrate concentrations above the EPA MCL of 10 mg/L.

Several human actions can introduce nitrogen, in the ionic form of nitrate, to groundwater aquifers. Nitrogen fertilizers applied in agricultural settings can leach as nitrate, especially if recharge causes nitrogen-rich water to infiltrate below the root zones of crops. Sewage, in the form of either leaky sewer pipes or septic system discharge, can also result in nitrate contamination. When introduced into groundwater aquifers with low organic carbon concentrations – such as those in the Armenia region – nitrate often behaves as a near-conservative (i.e., non-decaying) solute below the water table. Thus, nitrate introduced into groundwater by human actions is likely to be present at similar concentrations when pumped by receptor wells, especially if nitrate is introduced to groundwater over broad spatial areas and thus not as susceptible to diffusion and dispersion effects.

The goal of this project was to provide a decision-support tool, in the form of a calibrated numerical model, that is able to simulate groundwater pathways within the Armenia region. This tool produces estimated groundwater velocities, in 3-D, throughout the Armenia region which can be used to: 1) Assess locations on the landscape that are likely contributors to water quality at individual wells; 2) Assess estimated travel times from recharged groundwater to wells; and 3) (if locations of likely contamination sources are specified), assess the depth to which water may potentially be contaminated by source regions.

Below we describe the steps that were used to produce this tool, including background information about the region, the data collection campaign carried out during the project, data processing efforts, the numerical model development, and model result post-processing The model produced (and provided with this report) is meant to provide decision support for the Armenia region, and is based on the best available data known at the time of report production. However, users of the model should be aware of potential impacts of uncertainties in the model, which may be reduced through further study or data collection.

General Field Setting

The Armenia region is located within the Central Sands region of the state of Wisconsin. Topography in the region is relatively flat, with a gentle increase in elevation to the North. The study area contains approximately 580 square miles (1,500 km^2), with the focus region located between the Wisconsin River / Petenwell Lake to the East and the Yellow River to the West. Topography in the elevation is generally flat, with land surface elevations ranging between ~1,194 feet (364 m) to 879 feet (268 m) above mean sea level (AMSL) in the NAVD88 (Orthometric) vertical datum. Elevation from the 100m State-wide Digital Elevation Model (DEM) is shown in Figure 2. Former flow channels of the Wisconsin River (some of which are flooded) are visible as sinuous topographic features to the North of Petenwell Lake.

Climatologically, Armenia experiences summer high temperatures in July that average (82°F / 27.8°C), with winter low temperatures in January (8°F / -13°C). (NOAA, Station GHCND: USW00004826). Precipitation averages range from a low of 1.2” (3.1 cm) in January to 4.3” (10.9 cm) in August, with a total of approximately 34” annually (84.8 cm). The majority of precipitation falls as snow in the region from December through March.

Local hydrogeology is influenced by the stage of local surface water bodies including Petenwell Lake, the Yellow River, and the Wisconsin River. Surface water appears in smaller features including road-side ditches, small streams / oxbow lakes, and cranberry bogs. Because of nearby surface water bodies and the gentle landscape slope, depth to the water table is generally shallow, with the majority of measured depths being less than 15 feet (4.57m). The location could be classified as rural, with landcover in the region consists primarily of a mix of agricultural and forested land, and much of agricultural activity employing high-capacity wells with center-pivot spray irrigation. Crops grown in the region include corn, potatoes, and cranberries. Due to the limited paved surfaces in the region and the high-permeability sandy soils, infiltration capacity in the region is high.

Field Data Collection

Observations specific to this project were collect during field campaigns that began in Fall 2019, with the most recent observations taking place in June 2022. Specific observations varied by date and are documented in supplementary data. Lithologic and geophysical (depth to bedrock) observations were performed during early stages of the project. During later field campaigns, observations collected included water table elevations in monitoring wells, hydraulic conductivity estimates via slug tests, water sampling, and water elevations (stages) and flowrates at selected surface water locations. Below we describe and summarize each data type collected, graphically summarized in Figure 1.

Depth to Bedrock

The depth of unconsolidated sediments beneath the study area was estimated using the horizontal-to-vertical spectral ratio technique (HVSR) using a Tromino seismometer in the Fall of 2019 by co-I DeVries. This instrument was deployed at 70 locations within the study area, and estimated depths provided by this method ranged from 9.3 feet (2.8 m) to 319 feet (97.23 m) below land surface were produced by DeVries. Similar to previously-developed data for the region, the majority of depth estimates from HVSR were <150 feet (45.7 m). An interpolated map of depth to bedrock estimated via HVSR is shown in Figure 3.

Well Installations

The map of well installations completed as part of this project is shown in Figure 1. Prior to the installation of permanent monitoring wells, temporary test borings were performed in the vicinity of planned ML-1 and ML-3 locations on October 12, 2020 via Geoprobe direct push to a total depth of 80’ (24.38 m). Permanent wells were installed between October 20, 2020 and October 30, 2020 by Soils and Engineering Services, Inc. Well installation consisted of drilling via hollow-stem auger to a diameter of 8.25” (20.95 cm). Following drilling, casing was installed consisting of flush-threaded schedule 40 PVC with 2” (5.08 cm) inner diameter (ID). Boreholes were back-filled with Red Flint sand and gravel as a filter pack surrounding the screened interval of each well. The remainder of the borehole was sealed with bentonite from the top of filter pack to within 6 feet (1.83 m) of the land surface. Red Flint sand and gravel was again used from the top of the bentonite to land surface, into which a 4” diameter (10.16 cm) protective metal pipe with cap and lock was installed to protect each well casing and prevent contamination.

Two types of installations were performed in the Armenia region. Water table (WT) well installations consist of a single well, with the well screened over a 10-foot (3.05 m) interval spanning the water table. Eight water table wells were installed, named WT1 through WT9, with WT4 omitted. Multilevel (ML) wells consist of a set of three wells in close proximity – designated shallow (S), intermediate (I) and deep (D) – each screened over successive 5-foot (1.52 m) intervals covering progressively deeper layers of the aquifer. Five multi-level nests were installed, ML1 through ML6, omitting ML5. All wells as installed are constructed with 2” (5.08 cm) inner diameter (ID) flush-threaded schedule 40 PVC.

Throughout the vast majority of drilling, the deposits encountered were consistently well-sorted (poorly-graded), fine-grained sand. Silty sand was often encountered during the first 1-2 feet of drilling. Exceptions to the relatively homogeneous well-sorted sand found during drilling include the following:

- ML2-D, which unexpectedly encountered sandstone bedrock at a depth of 25 feet (7.62 m) below land surface;
- ML3-D, which encountered a small clay lens at 120 feet to 121 feet (36.58 m to 36.88 m) below land surface;
- ML4-D, which encountered a small clay lens at 75 feet to 81.5 feet (22.86 m to 24.84 m) below land surface; and
- ML6-I and ML6-D, which encountered a clay lens from 22.5 feet – 27 feet (6.86 m to 8.23 m) below land surface.

Well Surveying and Water Levels

Well tops and depths to water were surveyed during a May 2021 field campaign. By using the shallowest multi-level well installations (ML1-S, ML2-S, etc.) as well as all water table wells, the elevation of the water table at these locations was estimated. Based on these measurements, the hydraulic gradient (direction of increasing hydraulic head) is to the north and west, indicating that horizontal components of groundwater flow are to the south and east (Figure 4). Depths to water were collected during each water chemistry sampling campaign and were remarkably consistent. For most wells, the average variability (standard deviation) in depth to water was less than 1 foot (0.3 m). In cases with higher variability (3 out of 22 wells), the cause was outlier measurements likely associated with water level equilibration immediately after drilling.

Water Chemistry Analyses

All multi-level installations were sampled on a regular basis, with water samples collected and shipped to the Water and Environmental Analysis Laboratory (WEAL) at UW-Stevens Point for analysis of nitrate (analyzed as NO3+NO2(N)) concentrations. During transport, all samples were kept in a cooler with ice packs, and were immediately transferred to refrigeration before shipment. Sample concentrations were returned by WEAL as mass of N in mg/L concentrations, with a detection limit of 0.1 mg/L as N. We had originally proposed quarterly sampling of wells, but due to funding delays and the later-than-expected drilling of wells in October, 2020, the sampling scheme was modified to conduct more intensive sampling in 2021. In total, 8 sampling rounds were completed as described in Table 1 below. The results of water sampling showed consistent trends throughout all rounds of sampling over the 2 years of the project when wells were installed. The deepest location at which nitrate concentrations >3 mg/L was detected (indicative of anthropogenic impacts) is ML6-D, which is screened from 56 feet to 61 ft below land surface (BLS). The highest average values recorded during the sampling campaign were at ML3-I and ML4-I, which are both screened from 36 feet to 41 feet BLS.

Surface Water Observations

During the May 2021 field campaign, elevations of water levels (i.e. stages) were taken at several surface water bodies including Petenwell Lake and the Yellow River. The locations of these observations are shown as yellow and white markers in Figure 1.

Well Slug Tests

Slug tests were performed at all multilevel well (ML) installations, also during the May 2021 field campaign. In these tests, a plastic cylindrical "slug" of known volume was quickly submerged (slug in) and then later removed (slug out). This process was repeated at least 3 times for each well. Water level responses were exceedingly rapid during testing, indicating high aquifer hydraulic conductivity. Early tests – recorded using a standard pressure transducer – did not obtain adequate sampling resolution before water levels had quickly recovered. Therefore a high-frequency, high-accuracy (125 Hz with millimeter-scale resolution) fiberoptic pressure transducer was used to record accurate responses after these early tests. The data from fiberoptic pressure transducers was analyzed in order to produce preliminary estimates of hydraulic conductivity.

Porosity Estimation

Near-surface cores of sediment from the region were collected using an Environmental Subsoil Profiler Plus (ESP+) tool – a hand-driven direct push sampler. By weighing of dried samples, and assuming a grain density of XX, we estimated a porosity of 17%. Following sampling, we injected a sodium bromide solution in the open hole. We then dug other test holes to collect water samples and measure the volume of aquifer that the bromide occupied. Based on the volume of water injected and the volume of aquifer occupied (assuming a hemispherical region beneath the water table), we estimated the porosity of the material. We estimate a porosity of 15%, consistent with standard literature estimates for porosity of well-sorted, fine-grained sand.

Numerical Modeling

To support decision-making related to land uses, well drilling depths, and examination of probable nitrate source areas, a numerical groundwater flow model was developed using the standard, finite-volume MODFLOW framework (MODFLOW-2005), as well as the particle tracking code MODPATH (version 2.0). This model was designed using the Groundwater Vistas (GWV) graphical user interface.

Basic Setup

MODFLOW Packages implemented in the model for the Armenia region include: 1) the Discretization (DIS) for specification of cell geometry and Basic (BAS6) package for specification of inactive cells – i.e., those outside the geographic region of interest; 2) the Layer-Property Flow (LPF) package for defining aquifer properties; 3) the Recharge (RCH), River (RIV) and Well (WEL) stress packages for simulation of hydrologic stresses; and 4) The Pre-conditioned Conjugate Gradient (PCG) package for iteration and solution of linearized matrix equations.

Due to limited temporal variability in heads observed in the field as well as limited data on time-varying stresses (pumping, river stages, etc.), the model was developed in the steady-state formulation. The full model area contains 500 cells x 300 cells, with each cell having dimension of 100 meters by 100 meters. The active model area is constrained to the East and West by the Yellow and Wisconsin River; the northern boundary of the model extends to just south of Wisconsin Rapids, and the southern boundary to just south of Petenwell Lake. For all model inputs, the coordinate system used for the model is NAD83

HARN Wisconsin Transverse Mercator. The vertical datum use is NAVD88 (Orthometric). The units used in the model are meters/day (m/d). Using the capabilities of MODFLOW to deform the vertical grid, the top of the uppermost layer (Layer 1) is defined as the land surface, and the bottom of the model is defined at the depth of bedrock. The model has 10 layers, which are divided evenly across the depth of the model.

Input data sources for model

Model top and bottom elevations (DIS Inputs)

Land-surface elevations (the top of layer 1 of the model) was assigned using a 100m resolution state-wide Digital Elevation Model (DEM) housed by the Wisconsin Department of Natural Resources (WI DNR) as shown in Figure 2. The bottom elevation of the model (bottom of layer 10 of the model) was determined by subtracting the interpolated map of depth to bedrock (Figure 3) from these DEM elevations. This depth surface was checked for consistency with the DNR issued state-wide depth to bedrock surface that is at a much larger resolution. The depth to bedrock (and there by the depth of the model) ranges from about 8 to 80 meters throughout the active model domain, with the shallowest areas existing in the northern region and deeper areas in the south near Petenwell Lake. Bottoms for layers 1 through 9 were equally spaced between the top of layer 1 and the bottom of layer 10.

Model Boundary Conditions (RIV inputs, BAS6 inputs)

The Yellow River is modeled as a river boundary condition on the western portion of the model. The Wisconsin River is modeled as a river boundary on the eastern boundary of the model, divided into two sections separated by Petenwell Lake. Petenwell Lake is modeled as a constant head boundary in the southeast area of the model, connected to the Wisconsin River. A head value for Petenwell Lake was assigned from lake elevation collected via RTK GPS in June, 2021.

Yellow River, Wisconsin River, and Petenwell Lake elevations were collected at 5 locations across the study area via Real Time Kinematic (RTK) GPS in June, 2021 and were used to inform the boundaries set in the model. Three additional river elevations (1 on the Wisconsin River and 2 on the

Yellow River) from USGS stream gages were also used to inform the river elevations. Between locations of river stage measurements, river elevations were interpolated. Riverbed hydraulic conductivity was set as 1 m/day.

Specified head boundary conditions are modelled across the north and south region of the model. Head values at the eastern and western extents of these boundaries were determined from the river boundaries, and values in between the eastern and western extents are interpolated across the boundary. Figure 5 shows the locations of each of the known surface water elevations, as well as the RIV and constant head boundary conditions of the model.

Recharge (RCH inputs)

Recharge values were estimated using the USGS Soil-Water-Balance (SWB) model. The SWB model uses inputs including precipitation, temperature, land surface slope, soil types, and land cover to partition rainfall between interception, evapotranspiration, overland flow, soil moisture storage, and recharge to groundwater. The estimated recharge to groundwater is used as input to our MODFLOW model. Data supplied to the SWB model included: 1) Daily gridded precipitation and temperature data, taken from the Daymet daily surface weather and climatological summaries, from 2000-2019; 2) Land-use information taken from the USGS Multi-Resolution Land Characteristics Consortium's 2016 National Land Cover Dataset (NLCD); 3) Soil type and available water content from the US Department of Agriculture Natural Resource Conservation Service (NRCS) soil maps; and 4) flow directions derived DEM elevations.

The output of the SWB model is daily recharge. Since our MODFLOW model operates at steady-state, we calculated average daily recharge from the SWB model during 2014, and used this result as the recharge value supplied to MODFLOW in m/day (Figure 6). The year 2014 was chosen to represent "steady-state" conditions because this year represented roughly average climactic conditions over the last 10 years.

High-Capacity Pumping Wells (WEL inputs)

High-capacity well locations and reported pumping data were supplied by the Wisconsin Department of Natural Resources (DNR). To determine a steady-state flow rate, we calculated a daily average pumping rate from the reported annual monthly pumping values. 176 pumping wells are in the model, including all those in the study area supplied by the DNR (Figure 7). Well-screen interval elevations were provided by the DNR for 98 of the 176 wells. The screened interval for the remaining 78 wells was estimated from 0-20m below land surface, or to the maximum well depth where that information as provided. This represents the average screen interval for other agricultural pumping wells in the area.

Aquifer Properties (LPF inputs and MODPATH inputs)

As described above, the majority of all drilled depths in this region encountered uniform fine sandy deposits, suggesting a high degree of homogeneity with the exception of minor, thin clay lenses. As such, the model domain consists of a single hydraulic conductivity zone with uniform parameters. There is no evidence of lateral anisotropy (i.e., differences between hydraulic conductivity to the N/S vs. in the E/W directions), therefore no horizontal anisotropy was specified. Like all semi-layered systems, some degree of vertical anisotropy is likely, with effective hydraulic conductivity in the vertical (up/down) direction being less than hydraulic conductivity in the horizontal.

The horizontal hydraulic conductivity and vertical anisotropy ratio were allowed to vary during model calibration in order to obtain the best fit to observed head data, discussed below. Initial guesses for hydraulic conductivity were informed by the slug test results performed at our established network of wells.

Model Targets

Model targets consisted of heads measured at the 13 water table or shallow multi-level wells drilled by this project. The two parameters – horizontal hydraulic conductivity (K_h), and vertical anisotropy ratio (K_h/K_v) were estimated by minimizing the misfit between model targets and simulated model results at these locations.

Model Results

Calibration Targets & Convergence Metrics

The observed vs. modelled calibration target values are plotted in Figure 8. The modeled heads match the observed reasonably well, with most of the targets hitting within a meter of the observed values. Total inflows and outflows through the model result in a mass balance error of less than 0.01% (Figure 9).

Heads and Flow Directions

Model results indicate that groundwater in the region generally flows toward the Yellow River on the western portion of the model, and towards the Wisconsin River/Petenwell Lake on the Eastern and central portion of the model with a groundwater divide occurring at the approximate center (and slightly east in the northern portion) of the model. Heads range from 306 to 266m above sea level, exhibiting a 40m (130ft) decrease in head from the northwestern portion of the model toward the southern tip of Petenwell Lake (Figure 10). The steeper head gradient observed at the bottom of Petenwell Lake is associated with the major change in river stage caused by Petenwell Dam on the Wisconsin River.

Model Limitations

As stated above, our model is steady state, and does not attempt to simulate transient changes in conditions in the Armenia region that may occur due to seasonal effects, changes to seasonal pumping rates, or other transient forcings. Our simulation of average annual daily recharge and pumping relies on the data sources stated above and is subject to any errors or omissions in those data.

Multiple lines of evidence reinforce the conceptual model used herein, which is that the region can be treated as a homogeneous, weakly-layered system. We found consistent hydraulic conductivity values in our slug test analysis throughout the active study area. Likewise, with few exceptions the aquifer materials encountered during drilling were uniform fine sends. We thus chose to assign a uniform hydraulic conductivity throughout our model domain. However, some degree of heterogeneity likely exists within this Armenia region (as indicated partially by individual clay lenses encountered during drilling) and heterogeneity at this scale is not represented in the model.

Like many groundwater studies, we are also limited by the availability of well data that we had access to, which consisted in this study of the WT and ML wells drilled by the project. Our model is in overall agreement with the trends of heads indicated by this network, though fit to the observed head data is not perfect. While we constructed an extensive well network (13 discrete locations), we are still likely missing some variations in water table throughout the study area. Similarly, the results of the model (especially particle travel depths and travel times) will be affected by uncertainty in vertical anisotropy ratios for hydraulic conductivity and by porosity estimates.

The high-capacity pumping well database housed by the DNR is based on user-reported pumping information, and is also subject to error and omissions. Recharge values computed in SWB are highly impacted by soil type, which was represented as very uniform within the study area in the NRCS soil maps.

Land covers were assigned based on analysis products from the USGS Multi-Resolution Land Characteristics Consortium’s 2016 National Land Cover Dataset (NLCD), which may misclassify land uses, especially those that have similar seasonal and “greenness” properties. However, cursory investigation of the NLCD dataset determined that most regions marked as cropland were clearly agricultural fields.

Model Use & Pathway for Future Work

The developed MODFLOW model may be used as a decision support system to address concerns of stakeholders in the Armenia region. If specific land plots are determined to be sources of nitrate to groundwater, then forward particle tracing may be performed on a set of particles originating within this land plot to determine what locations and depths of the aquifer they will reach.

If well construction reports are available for impacted private wells – including exact location, total depth and location of screened intervals – reverse particle tracking may be used to estimate the recharge source location and the travel time between initial recharge at the water table and water arrival at the well. However, to our knowledge this data is not publicly available at present. With enough data from multiple impacted wells, this reverse particle tracking approach can suggest locations at the land surface where alternative land uses should be considered. Similarly, the particle travel time estimates provide an understanding of how much time must elapse between any land use changes and expected changes to water quality. Each of these results should be considered in light of potential uncertainty in vertical hydraulic conductivity ratios and porosity estimates. For example, users of the model may choose to perform a sensitivity analysis – altering these parameters within a range – and assessing their impact on model outcomes.

Particle Tracking Results

Here we demonstrate a use of the model to inform decision-making in the Armenia region. Given that agricultural operations may represent a source for nitrate in drinking water, we initiated particle tracking starting at the water table, coincident with the location of all 176 high-capacity wells, which are centered on individual farm fields. The outputs of the MODPATH particle tracking model were then summarized by selecting the elevation of the lowest particle path found within each model grid cell. The results of this analysis provide the depth below which groundwater would be unaffected by a hypothetical source distributed at all high-capacity wells. Cells that do not have any particles passing through them would be presumed safe at all depths, under this scenario.

Another analysis simulated the results of particle tracking with particles originating in each cell of the numerical model. Each particle was associated with a landcover, as supplied by the USGS Multi-Resolution Land Characteristics Consortium's 2016 National Land Cover Dataset (NLCD). Particles were divided into two classes: those that originated from land labeled as cropland, and those originating from other sources. MODFLOW and MODPATH were run to determine the model cells and depths through which these particle traces passed. Finally, we summarized the results of this particle tracing by calculating the following: for each model cell, and for a specified range of depths below land surface (BLS), e.g., 90ft to 100ft BLS, we calculated the proportion of particles passing through this location that originated on land designated as cropland vs. originating on non-cropland. The results of this analysis were calculated for all depths throughout the region in 10 ft increments and are returned as a percentage of particles originating from agricultural land. An example of this analysis is shown in Figure 12, for the depth range of 90ft to 100ft BLS. Areas of the map that show as white / "NaN" values are those at which either the water table has not yet been encountered (according to the model), or depths which are below bedrock. Plots for all depth intervals, ranging from 0-10 ft BLS to 300-310 ft BLS, are provided as supplemental information for this report, with screenshots included in the Appendix.

Tables

Table 1: Water chemistry sampling dates

Sampling Round	Date(s)	Samples Collected
1	3/12/21 – 3/14/21	All ML installations
2	5/12/21	All ML installations
3	6/9/21 – 6/10/21	All ML installations
4	7/13/21	All ML installations
5	8/18/21 – 8/19/21	All ML installations
6	11/7/21 – 11/8/21	All ML installations, WT5
7	3/1/22 – 3/2/22	All ML installations except ML3-D, WT3
8	6/18/22	All ML installations except ML3-D, WT3

Table 2: Summary of water sample results (*Depth is depth to center of screened interval for given well)

			NO3+NO2(N) Concentration Statistics (mg/L)			
Installation		Depth (ft) BLS*	Min	Average	Max	Count (n)
ML1	S	10	0.9	1.3	1.7	8
	I	38	0.3	0.7	0.8	8
	D	58	0.8	1.5	2.3	8
ML2	S	8.5	ND	ND	ND	8
	D	31.75	ND	ND	ND	8
ML3	S	21	1.3	5.8	13.6	8
	I	38.5	20.9	27.6	42.2	8
	D	118.5	ND	ND	ND	6
ML4	S	22	2.4	4.2	5.9	8
	I	38.5	11.0	20.6	26.6	8
	D	79	ND	ND	ND	8
ML6	S	16	0.4	0.7	1.1	8
	I	38.5	2.6	3.8	4.9	8
	D	58.5	6.1	15.4	27.2	8
WT3	WT3	10.5	1.0	1.2	1.4	2
WT5	WT5	25	0.6	0.6	0.6	1

Figures

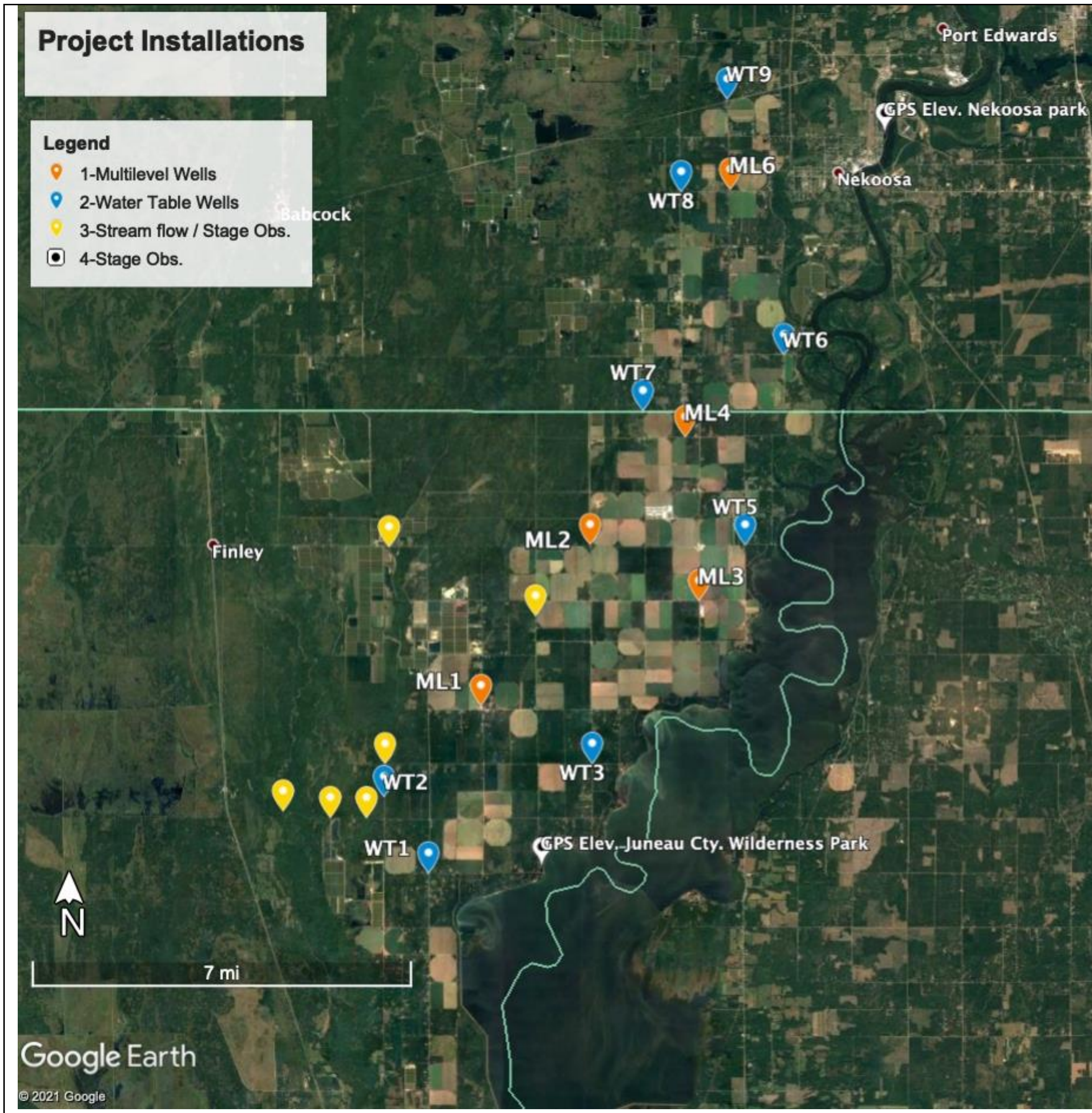


Figure 1: Locations of multilevel monitoring wells (orange) and water table wells (blue) installed within Armenia region

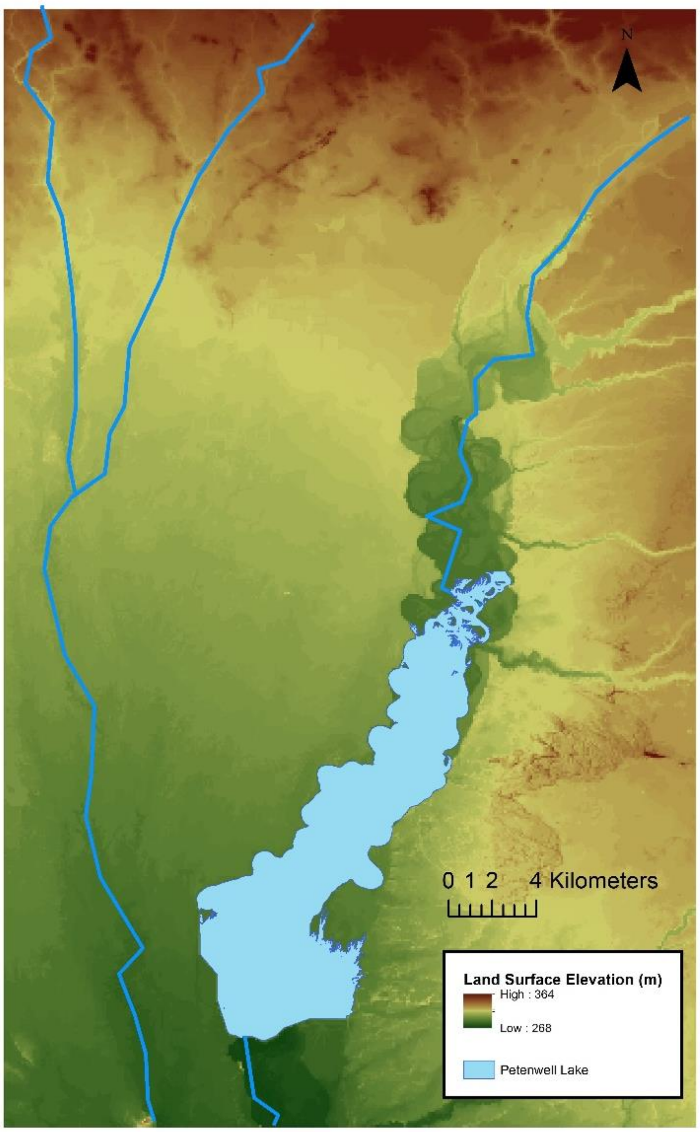


Figure 2: Land surface Elevation data from State-wide 100m-resolution DEM. Trajectory of the Wisconsin and Yellow Rivers are shown in blue to the East and West, respectively.

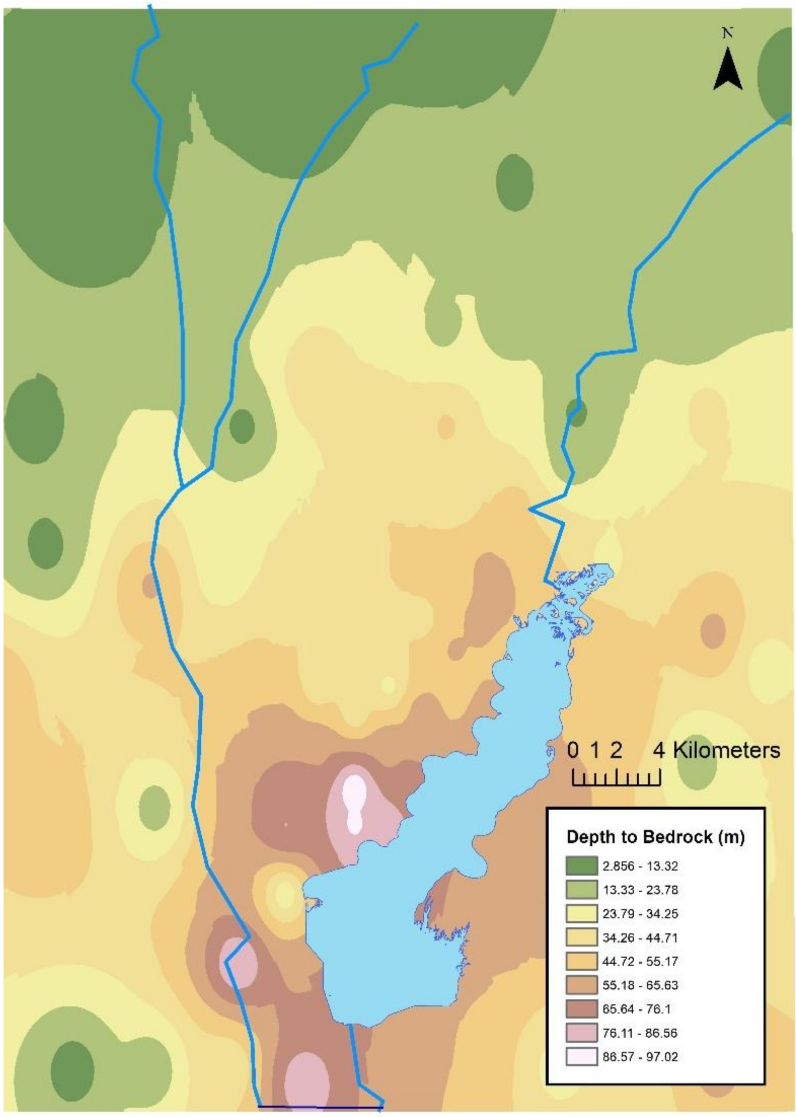


Figure 3: Depth to bedrock as interpolated from HVSR measurements

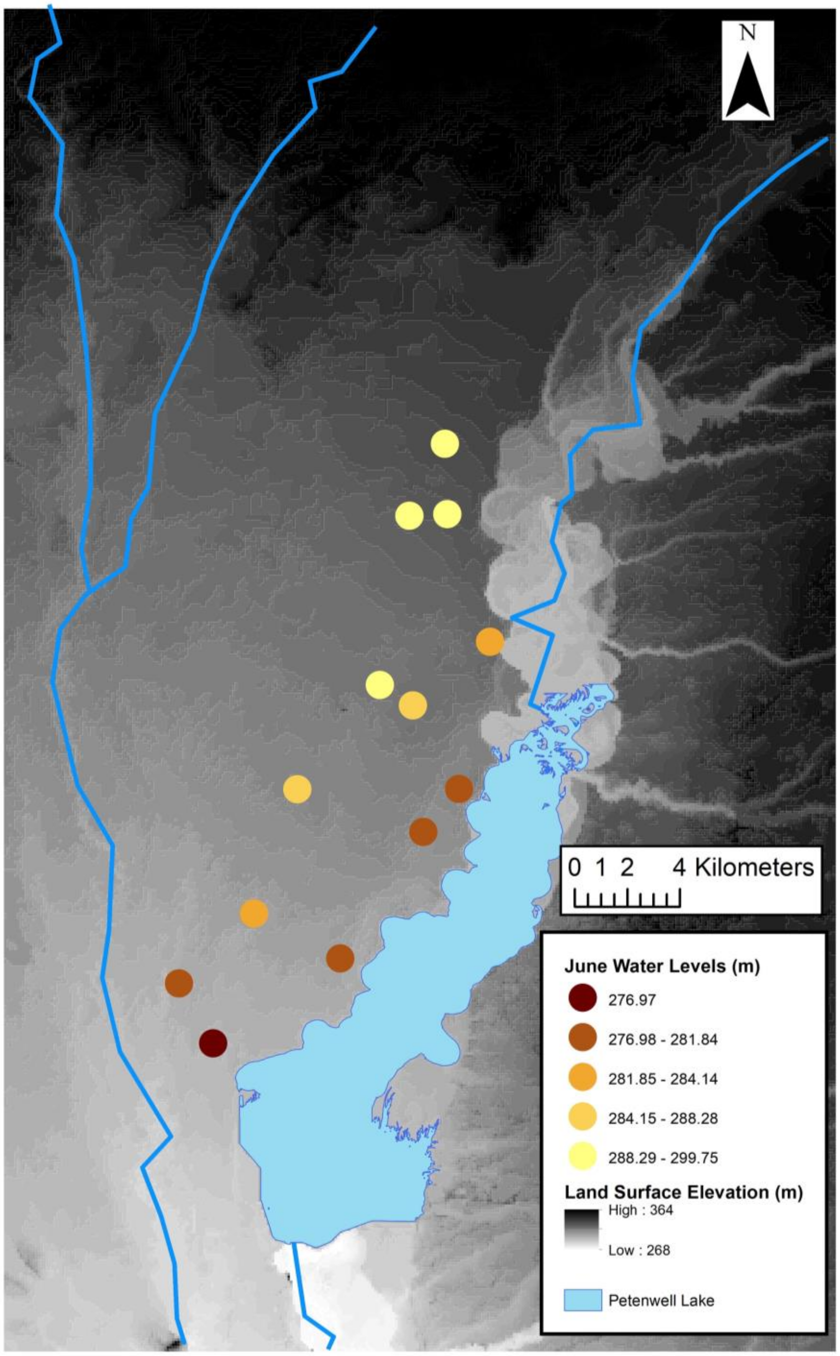


Figure 4: Water table elevations (m) estimated during June 2021.

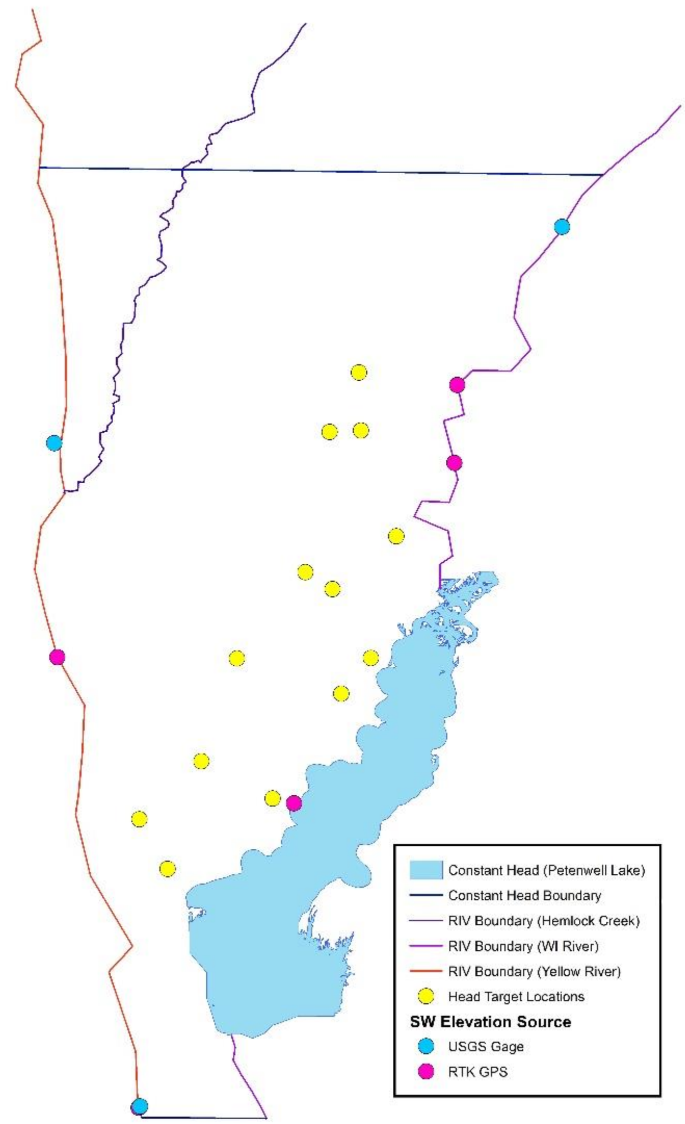


Figure 5: Locations of model boundary conditions, stage elevations measured, and head targets used in model

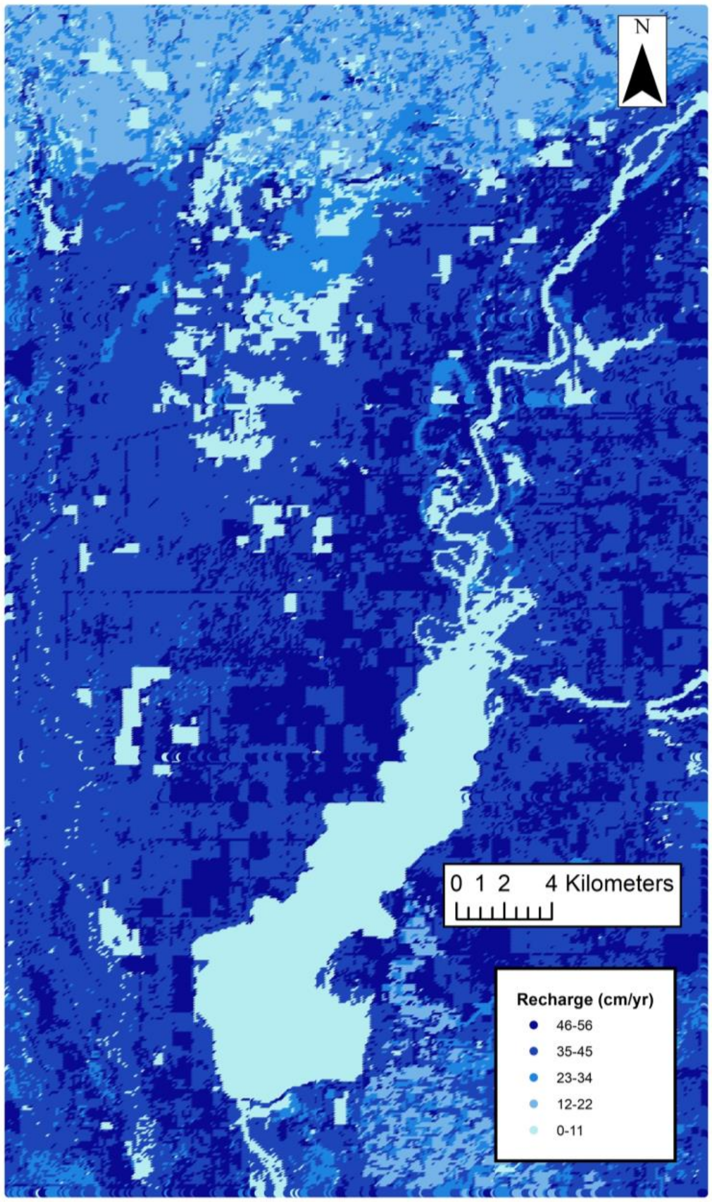


Figure 6: Annual average recharge (cm/yr) results from SWB model computed for water year 2014

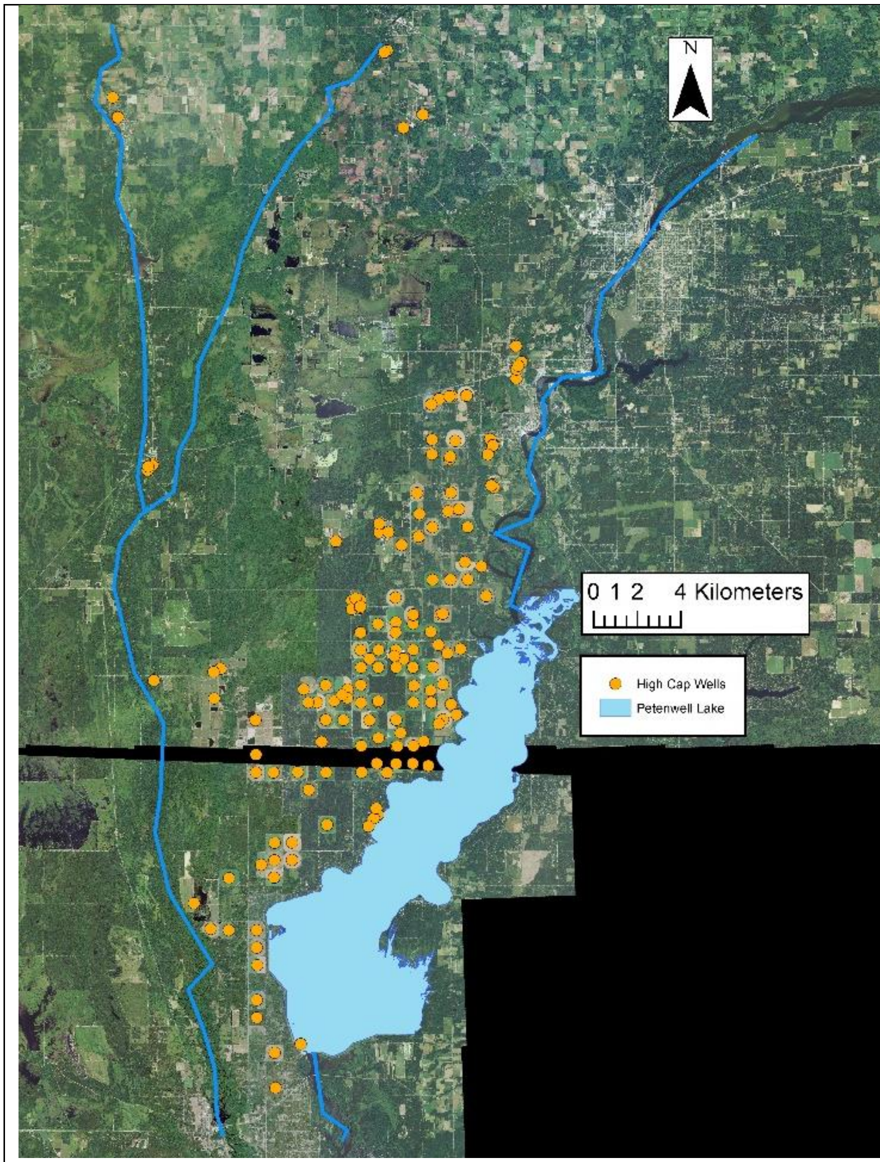


Figure 7: Locations of high-capacity pumping wells imported from DNR database

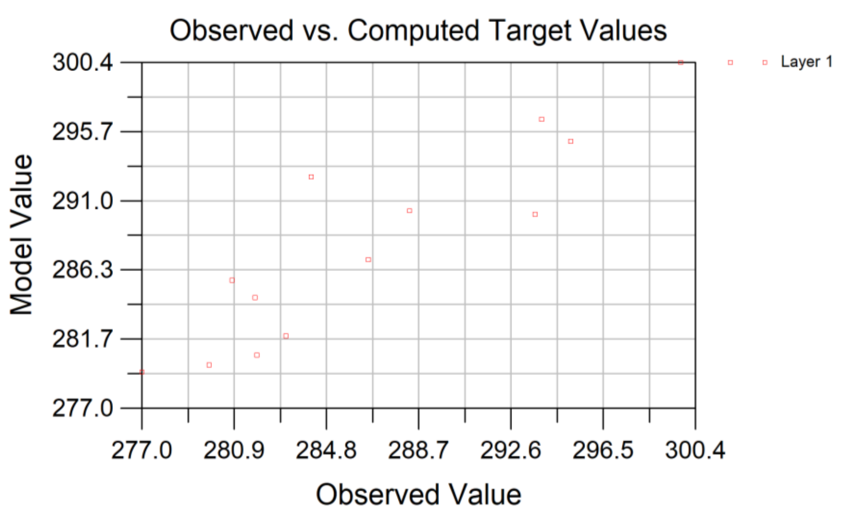


Figure 8: Observed and simulated head targets. All heads are reported in meters.

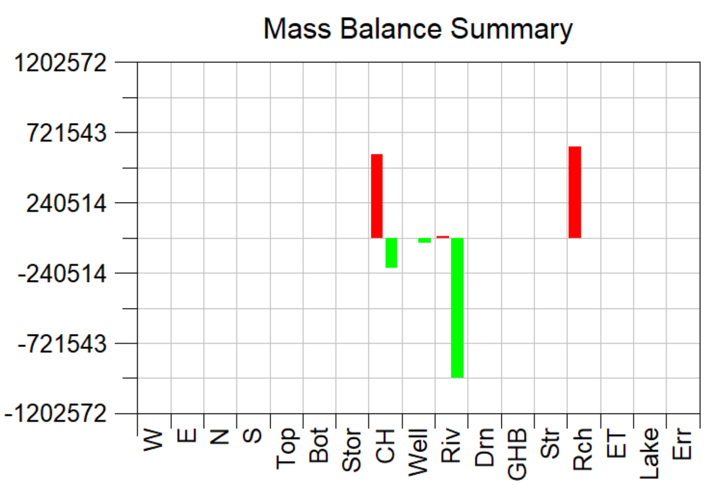


Figure 9: Mass balance summary for the numerical model. Units are cubic meters per day of water flow.

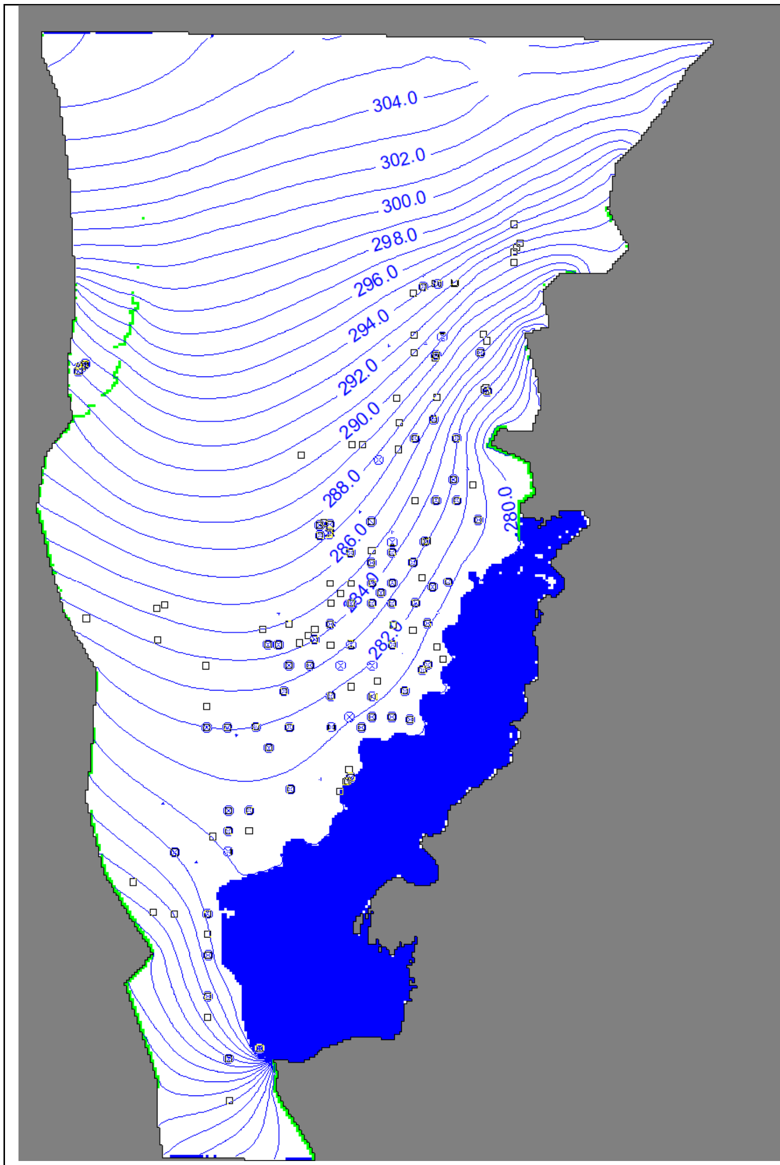


Figure 10: Model results for hydraulic head in m (Layer 1) showing river / Petenwell lake boundary conditions, high-capacity wells (black circles), water table elevation targets (blue circles). Note: Boundary conditions are only displayed in layer 1 and may appear discontinuous where boundary conditions are applied in deeper layers.

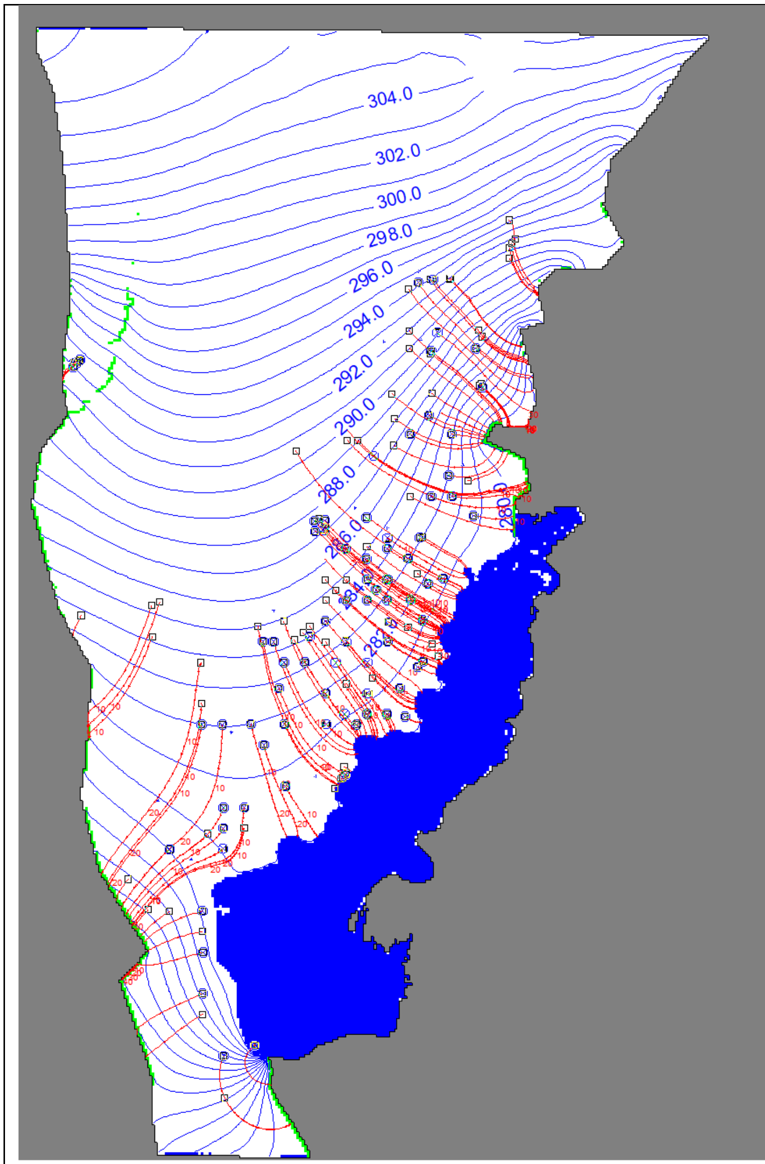


Figure 11: MODPATH results using high-capacity pumping well locations as particle origins. Map shows predicted lateral movement of hypothetical contaminants starting at high-capacity wells.

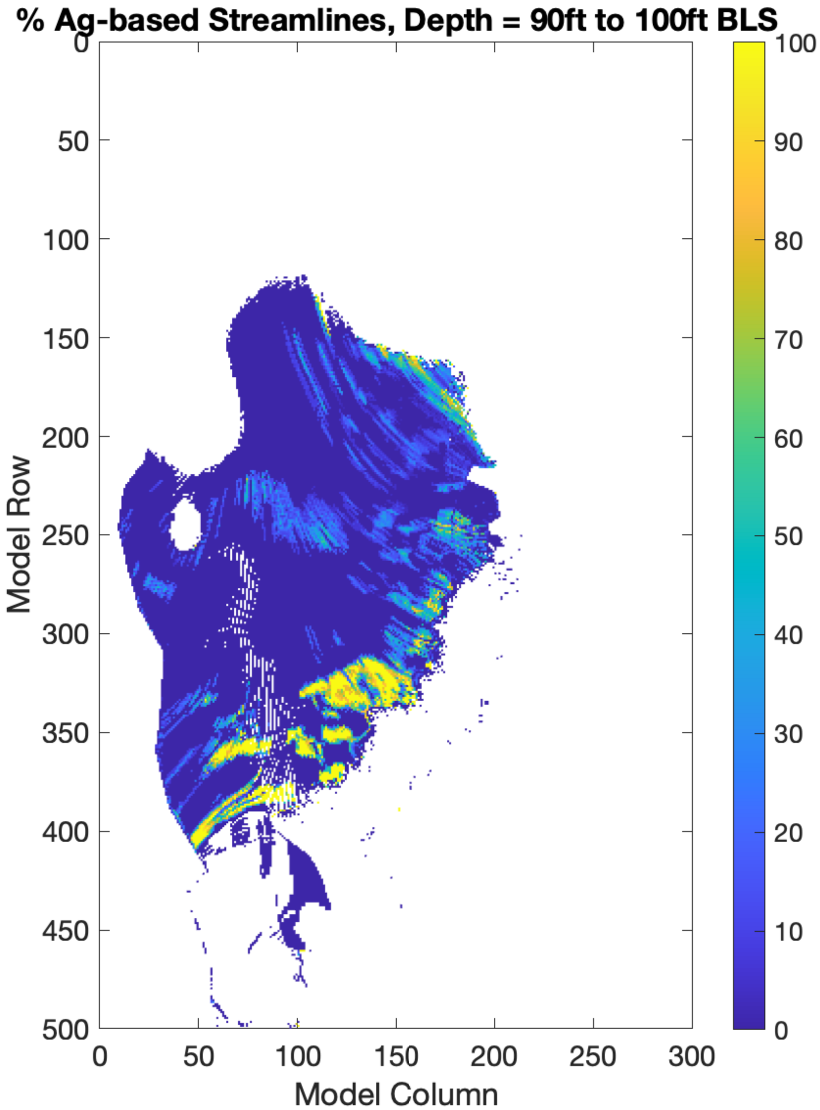
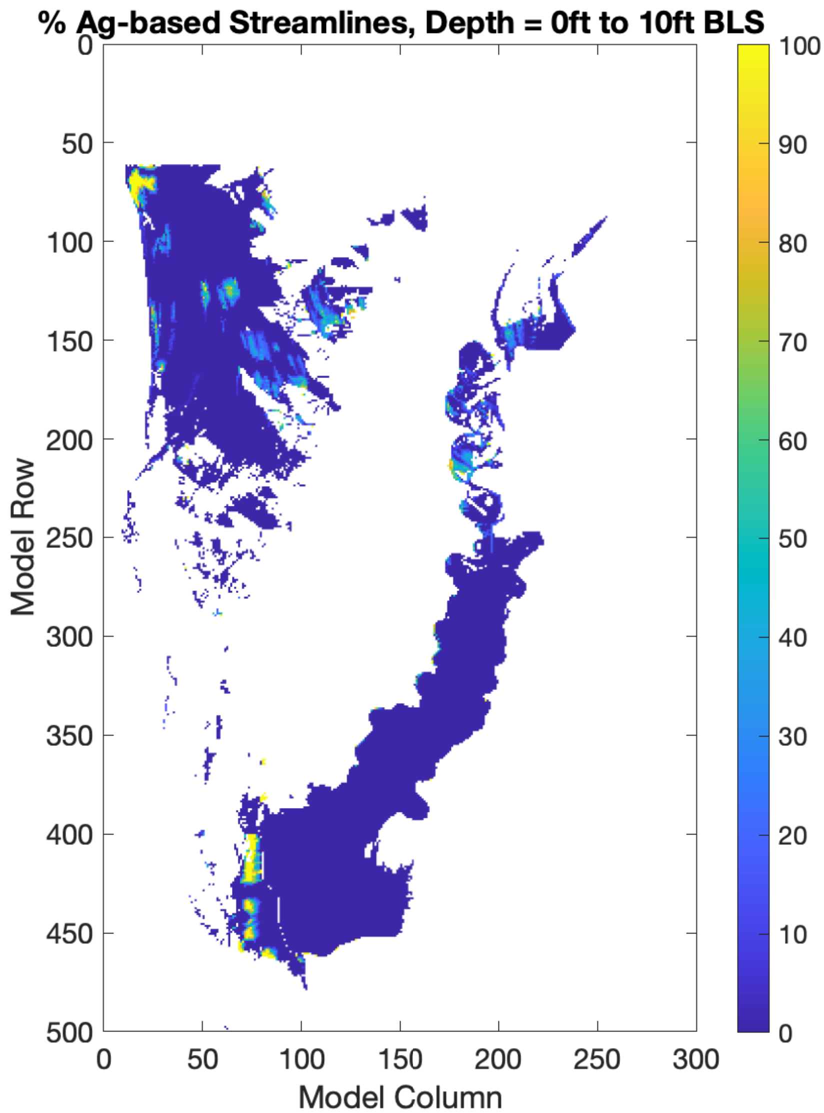
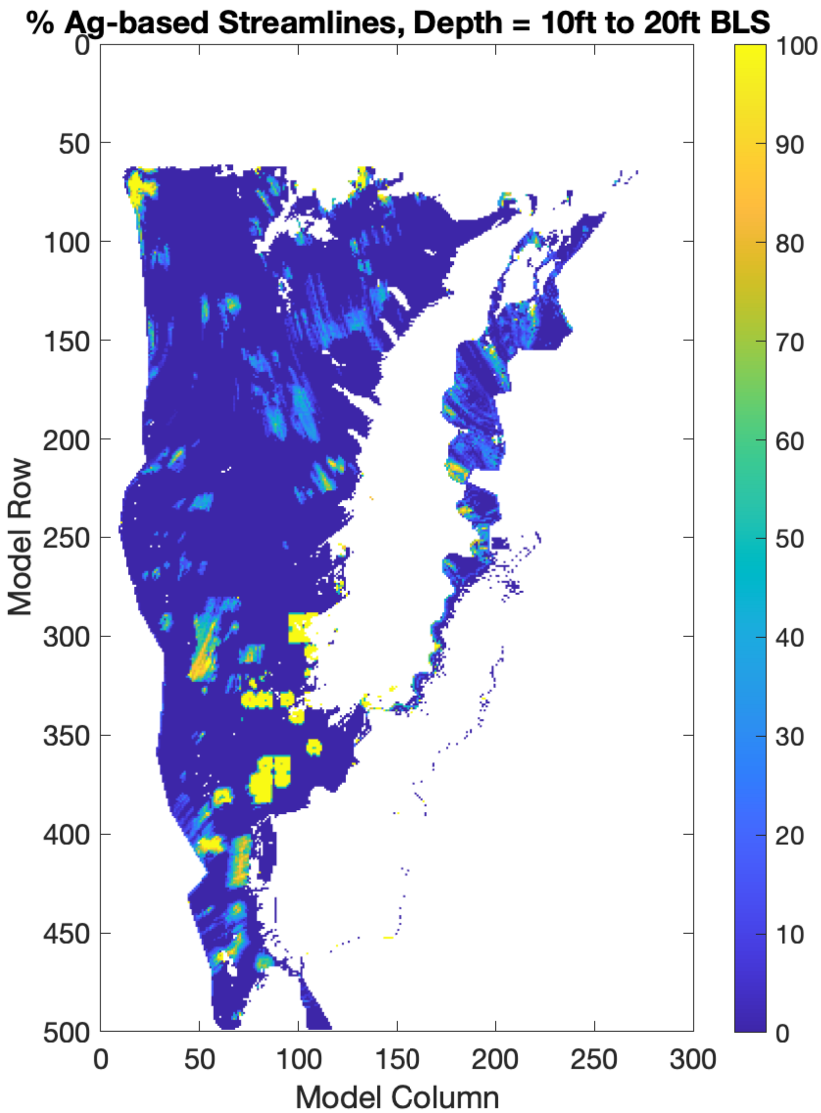


Figure 12: Results of MODFLOW / MODPATH Particle tracing post-processing, as described

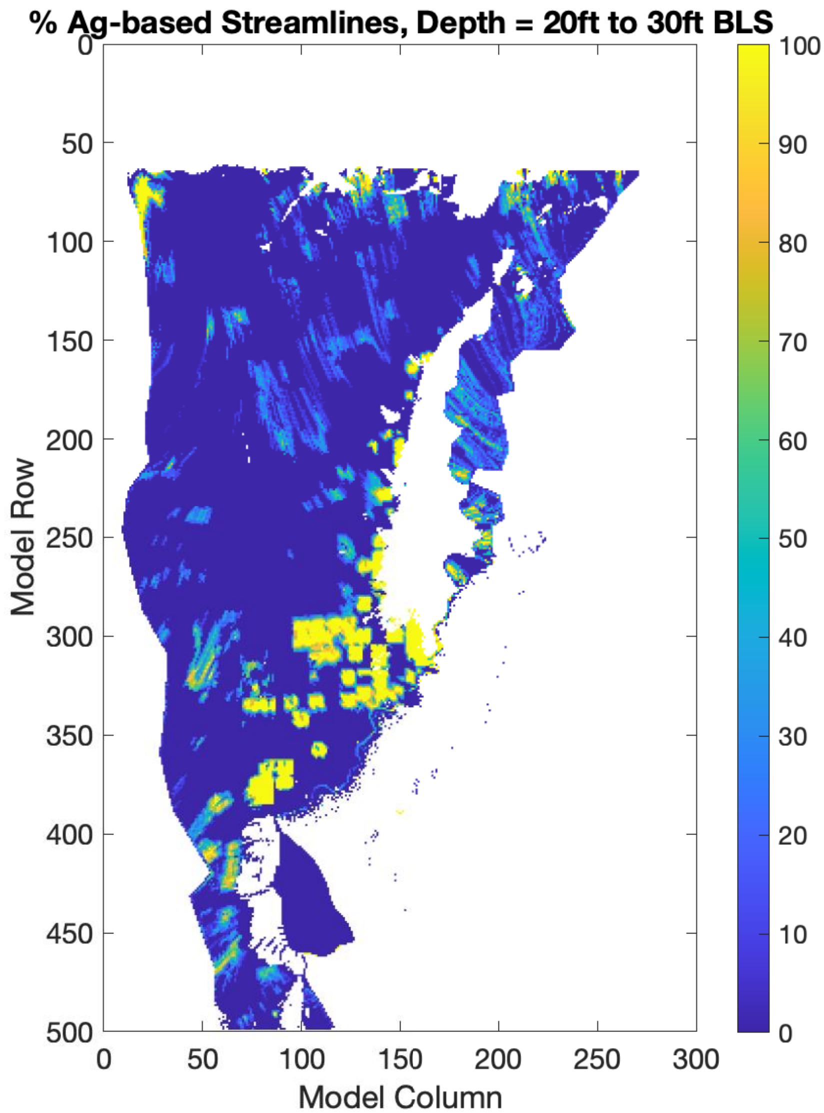
Appendix

The images contained below show graphical results of particle tracking, which have also been provided as a GIS layer, geo-referenced to latitude / longitude coordinates. In each image, the color represents the percentage of water arriving at the given model cell and depth interval that is associated with agricultural land uses, with blue representing a low percentage and yellow representing a high percentage. Regions of the plots that display as white represent either locations where the water table is not yet present, according to the model results, or where the boundary of bedrock is encountered.

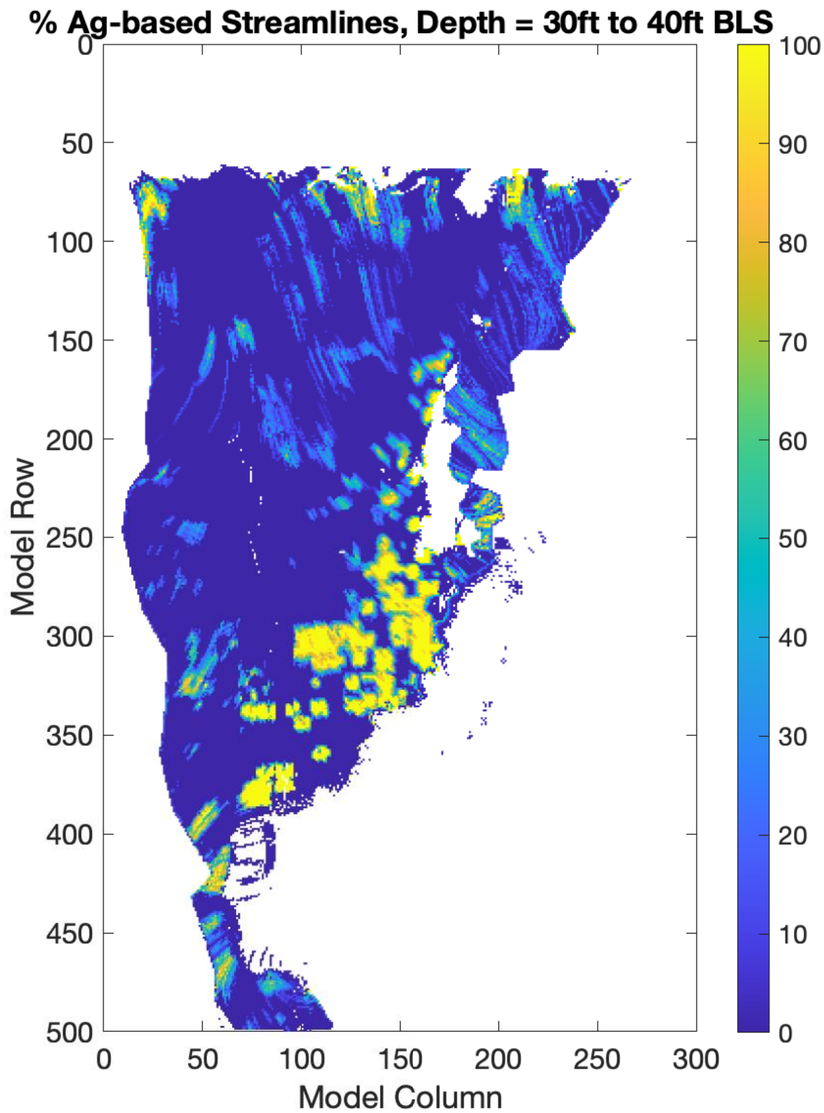

% Ag-based Streamlines, Depth = 0ft to 10ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0



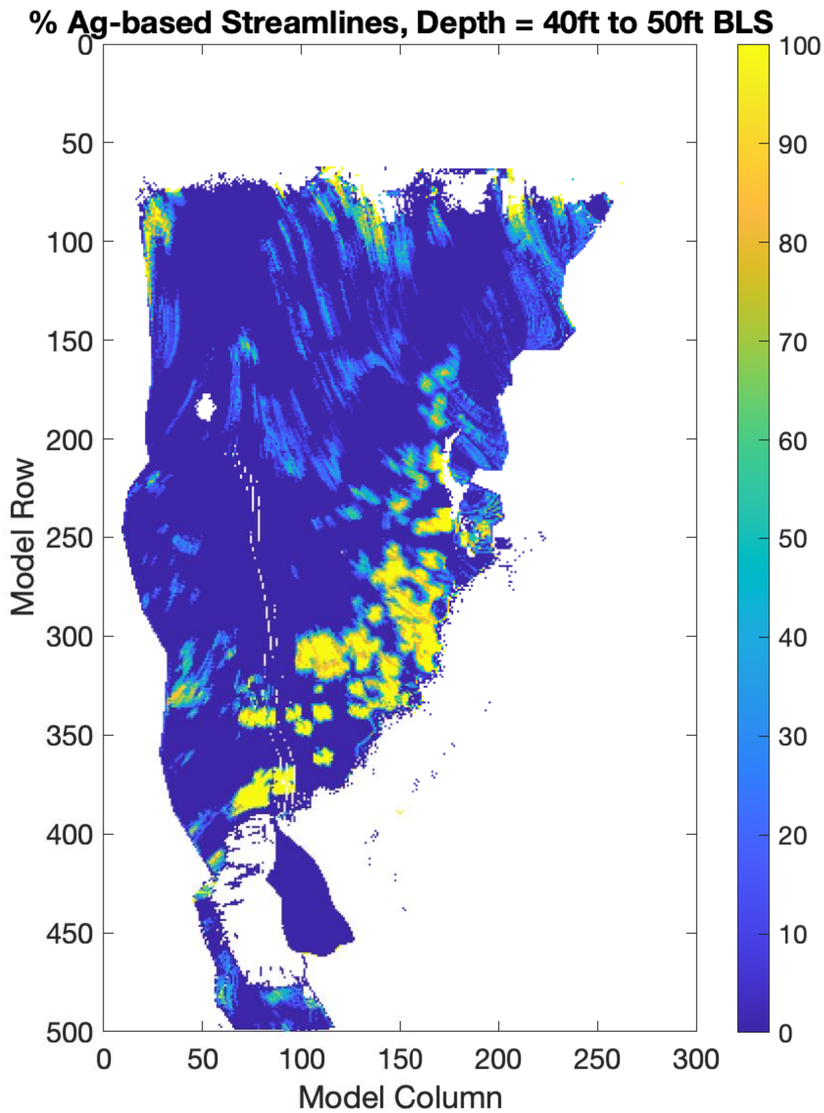
% Ag-based Streamlines, Depth = 10ft to 20ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0



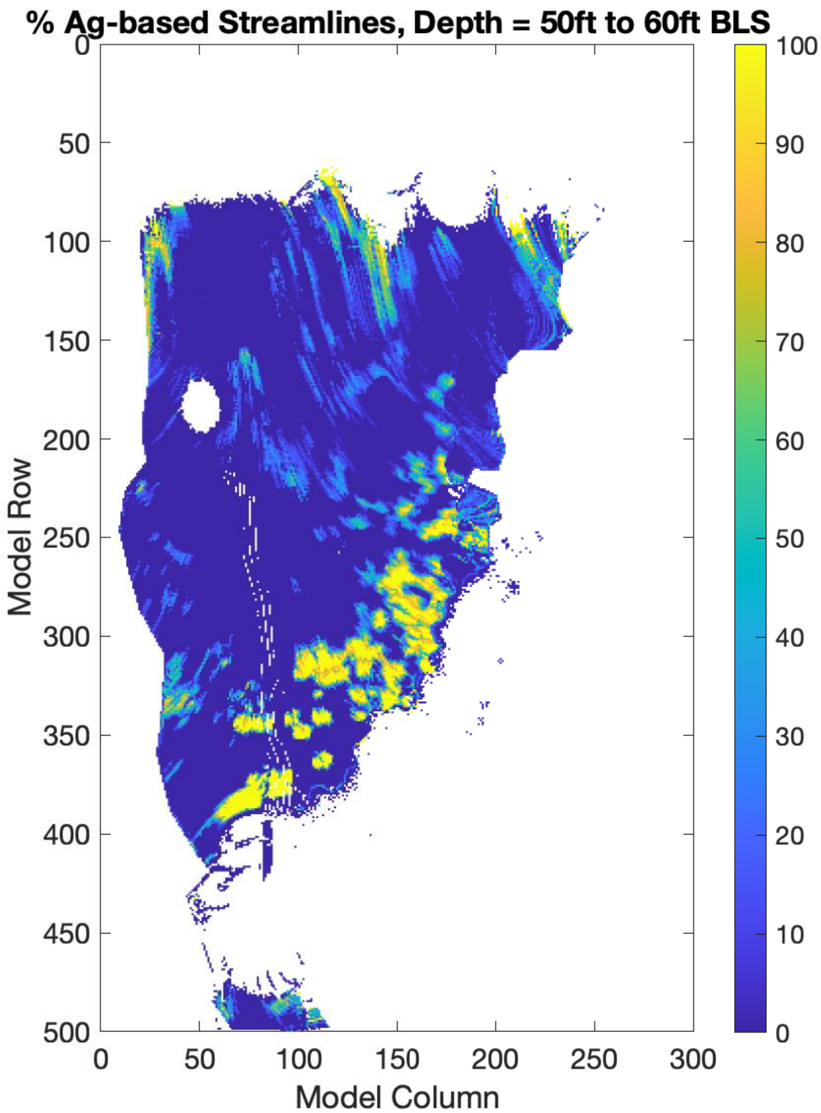
% Ag-based Streamlines, Depth = 20ft to 30ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
0
10
20
30
40
50
60
70
80
90
100



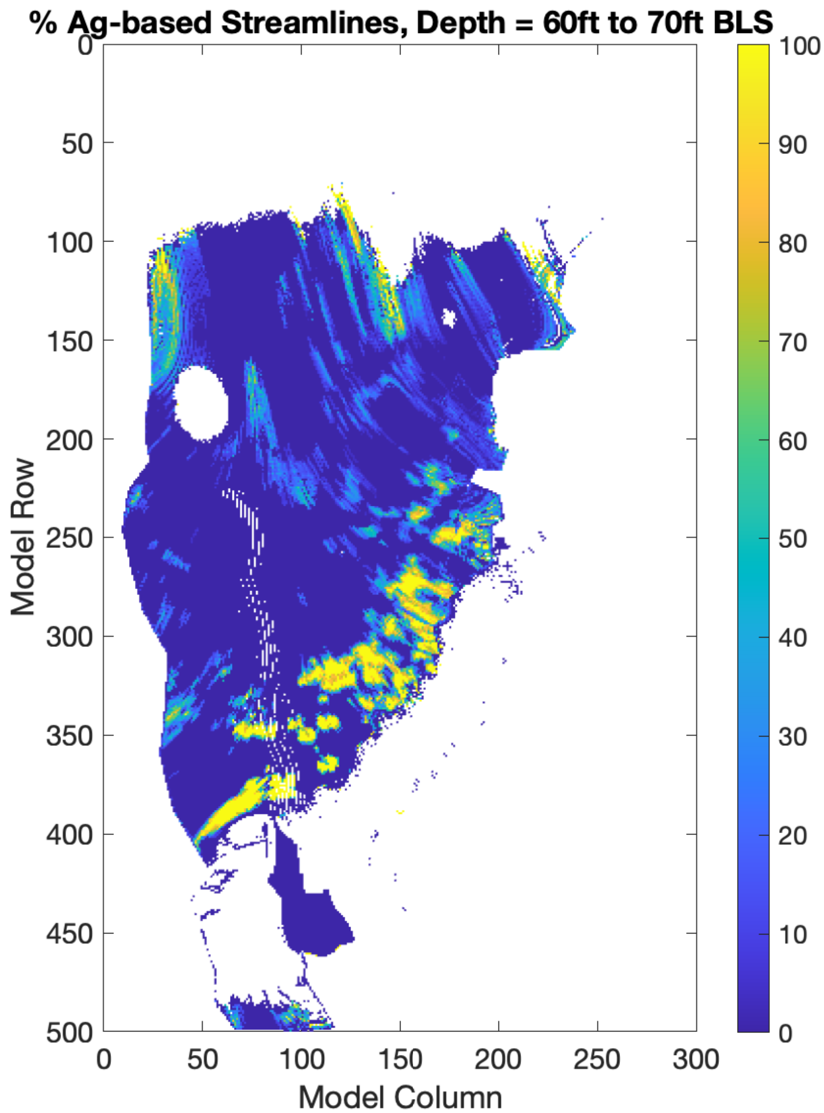
% Ag-based Streamlines, Depth = 30ft to 40ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0



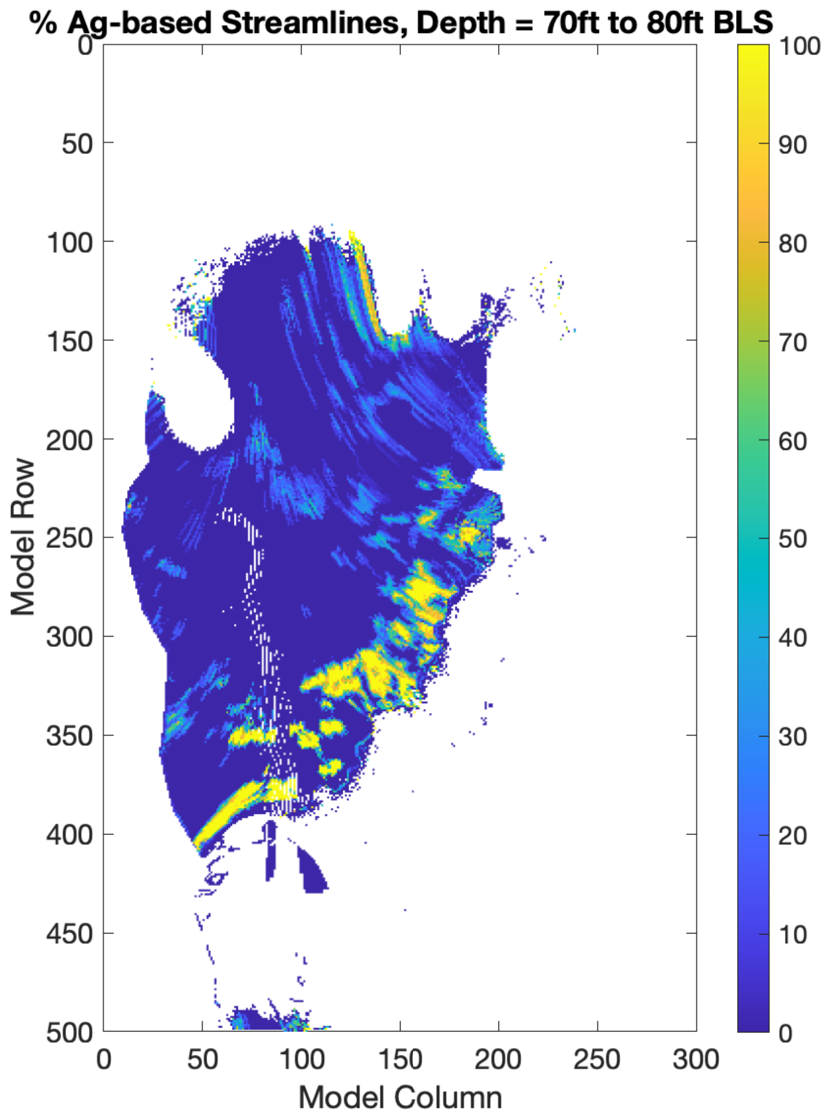
% Ag-based Streamlines, Depth = 40ft to 50ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
0
10
20
30
40
50
60
70
80
90
100

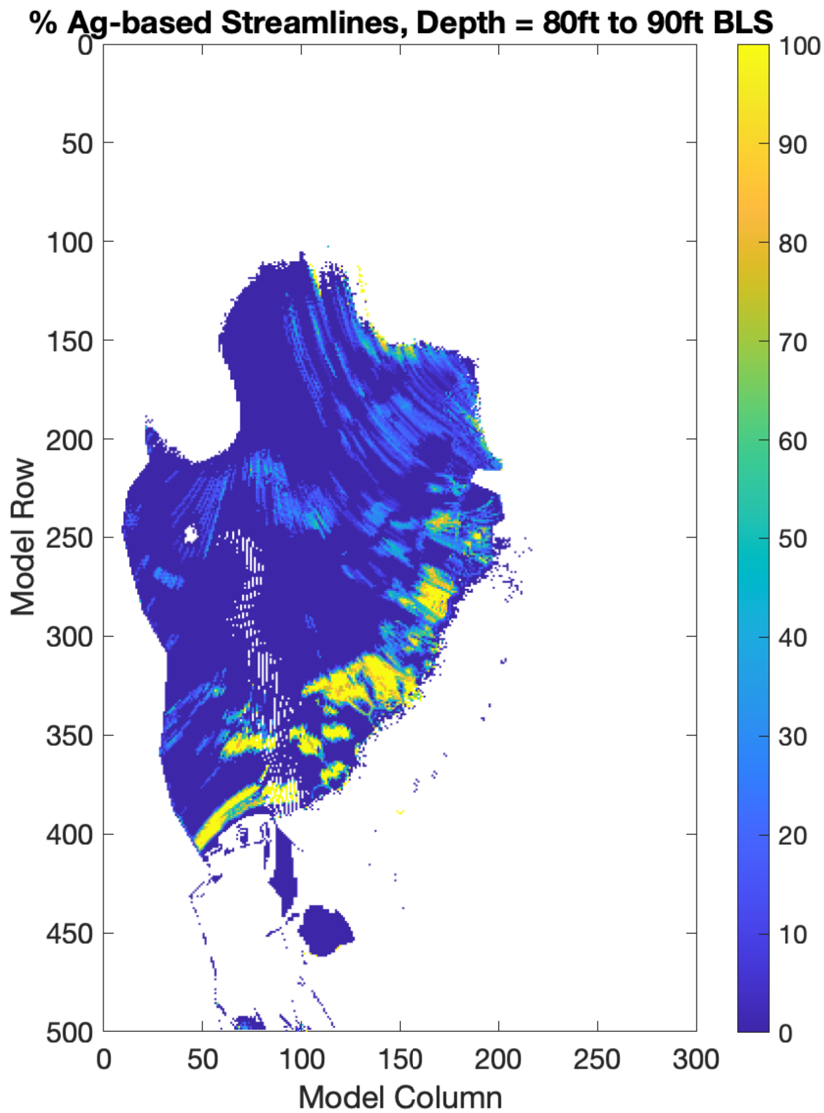


% Ag-based Streamlines, Depth = 50ft to 60ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0

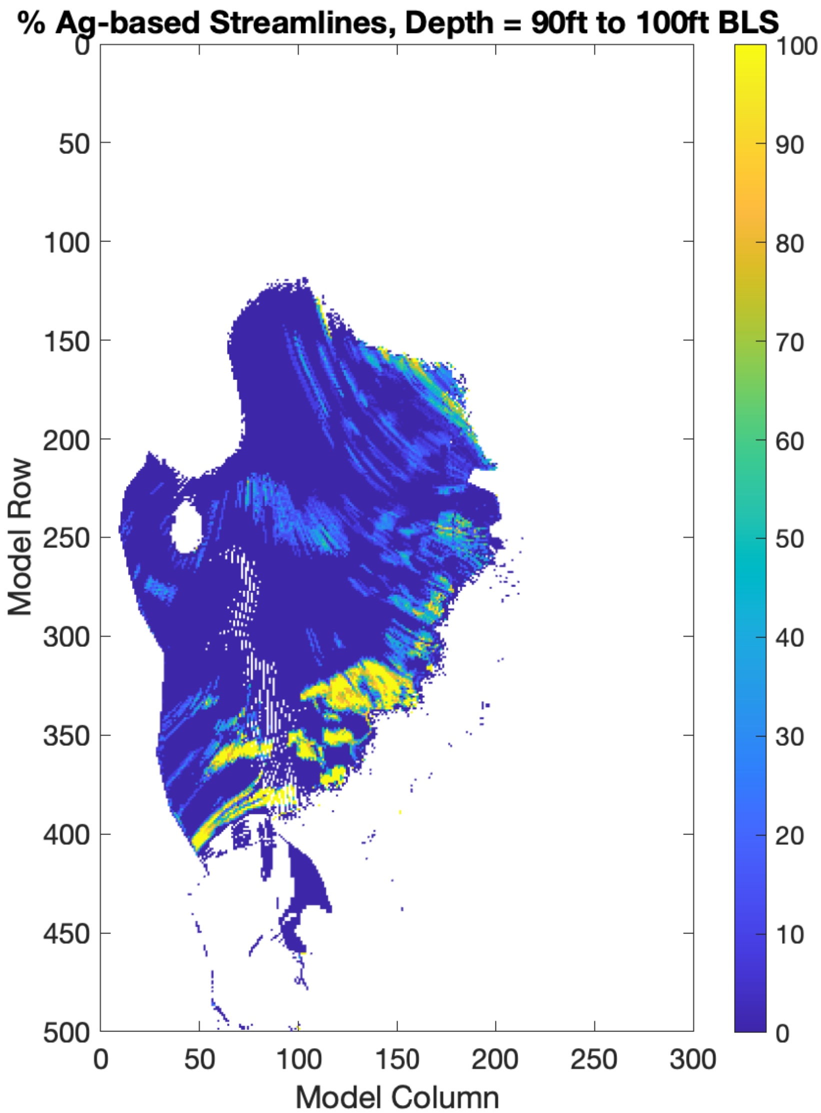


% Ag-based Streamlines, Depth = 60ft to 70ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0

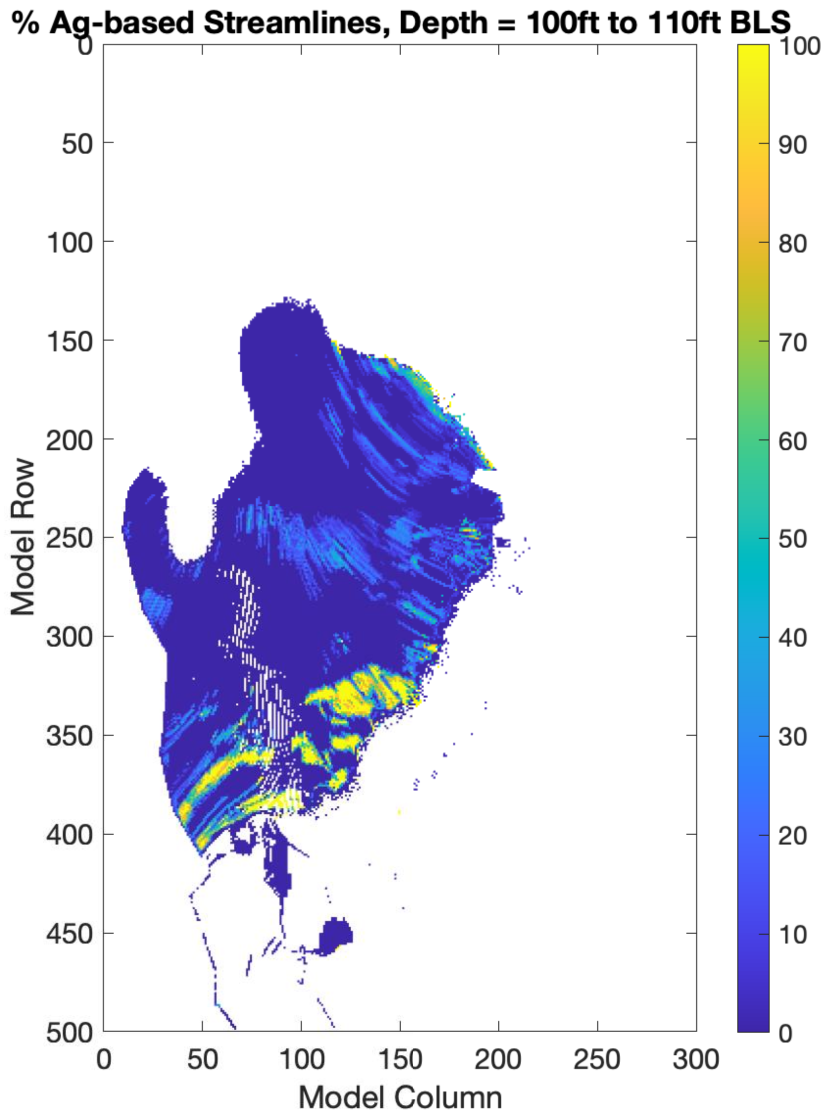

% Ag-based Streamlines, Depth = 70ft to 80ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0

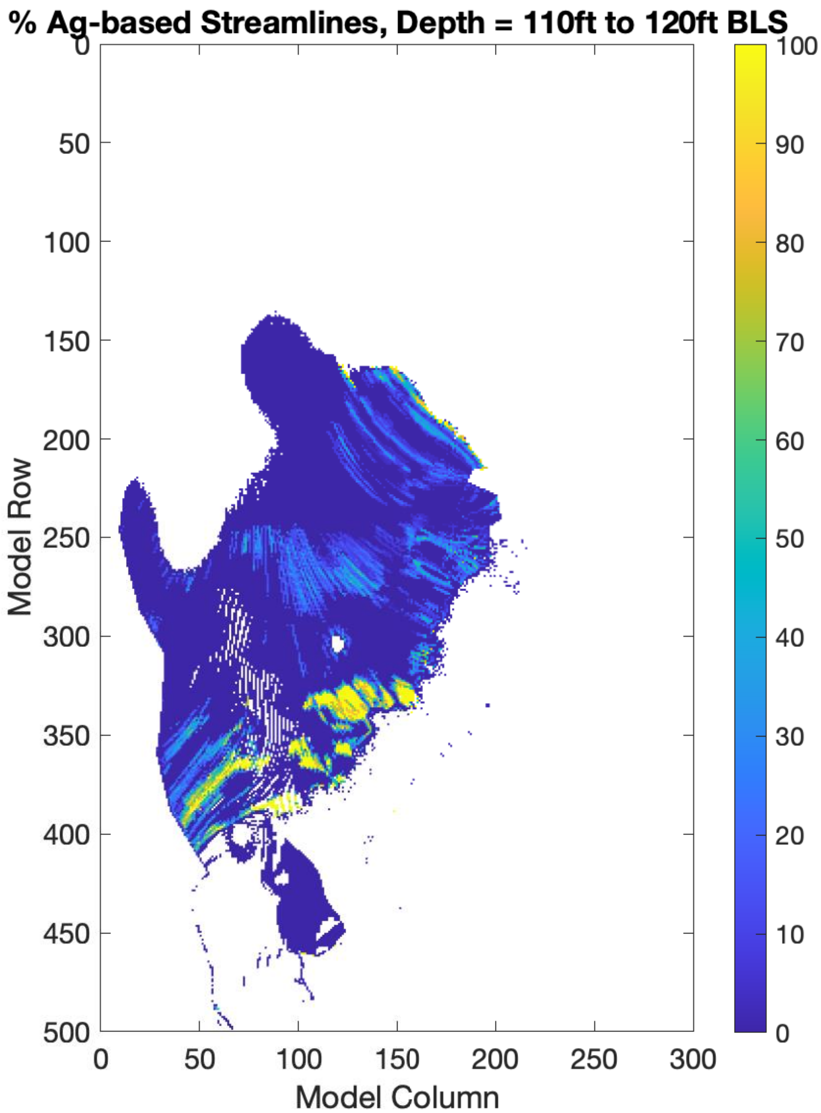


% Ag-based Streamlines, Depth = 80ft to 90ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0

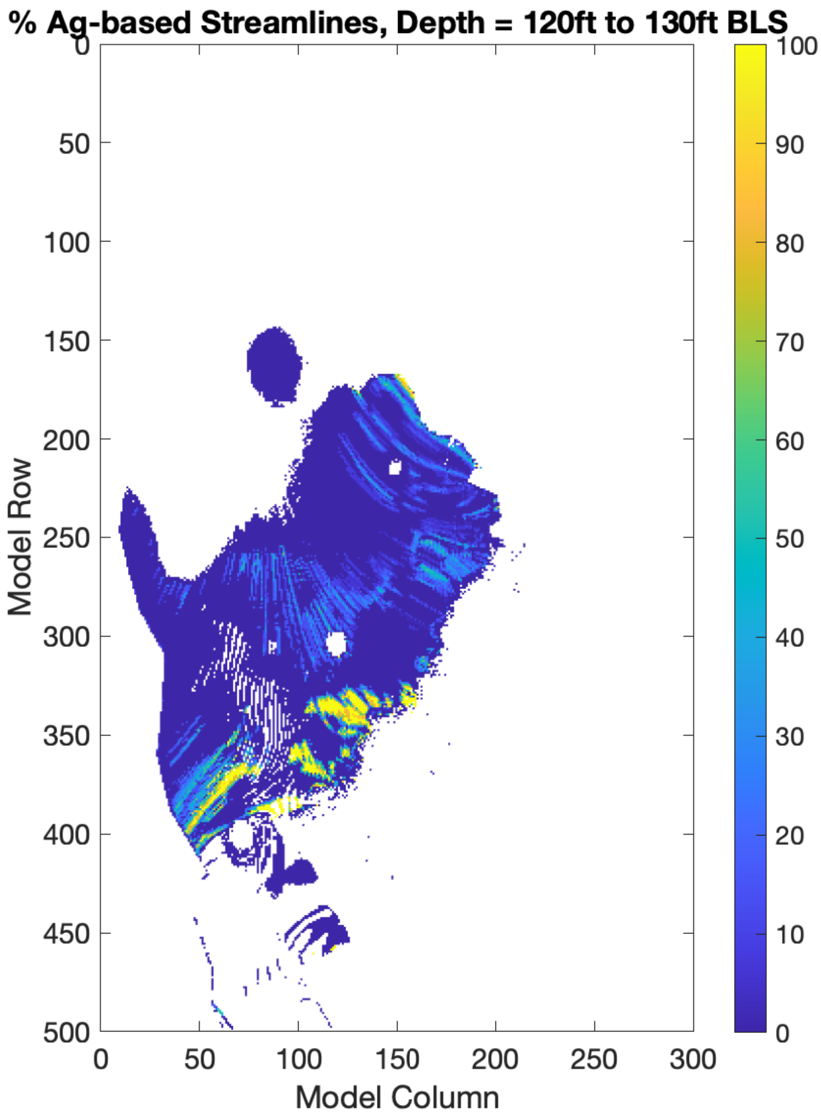


% Ag-based Streamlines, Depth = 90ft to 100ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0

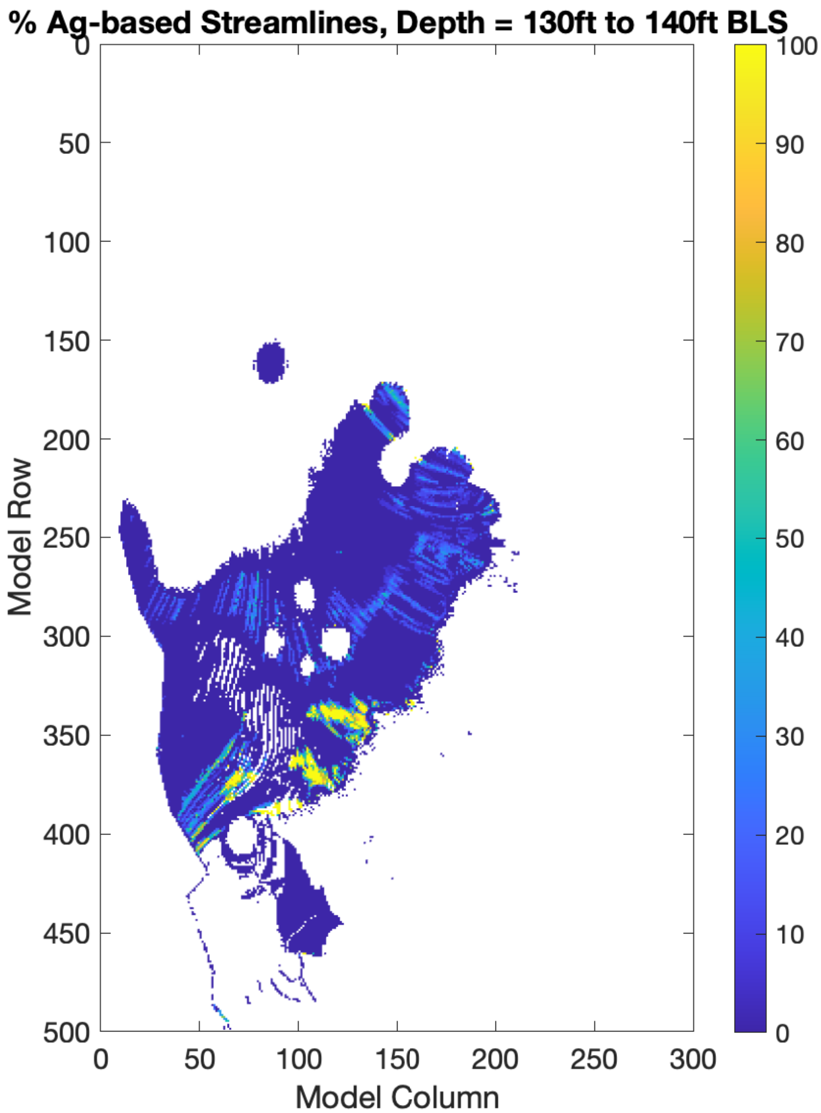

% Ag-based Streamlines, Depth = 100ft to 110ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
0
10
20
30
40
50
60
70
80
90
100

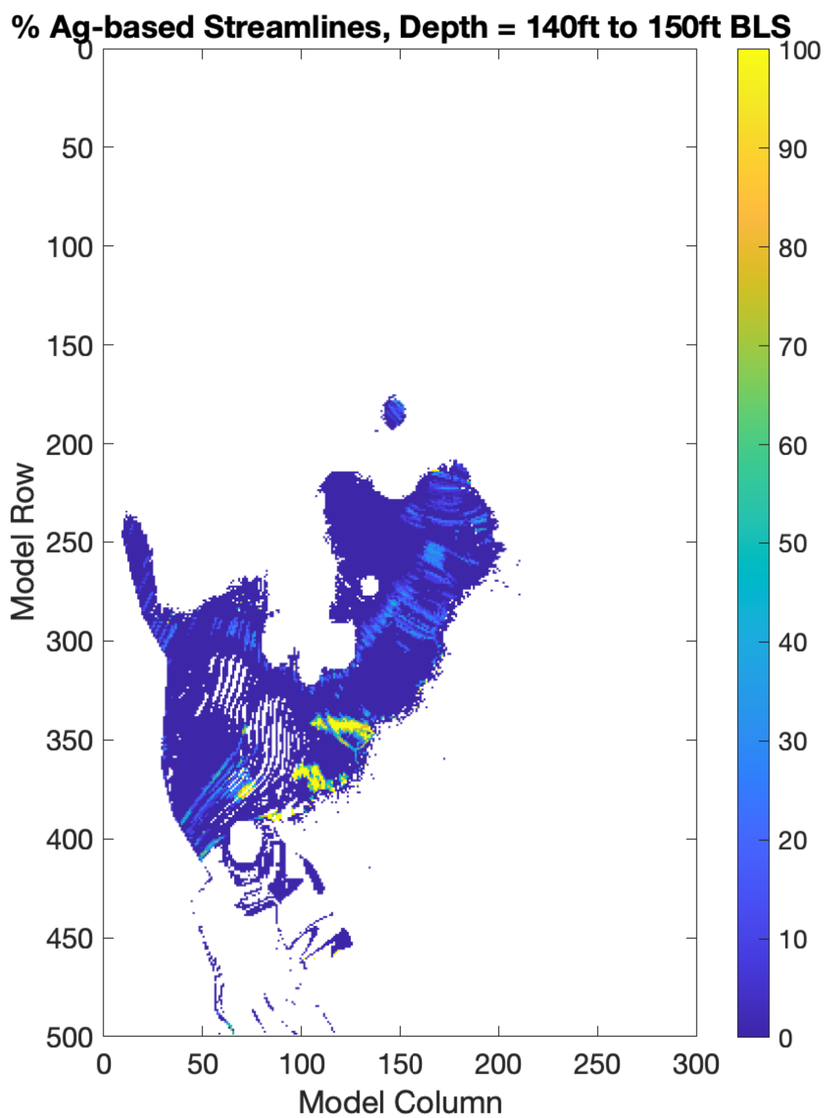


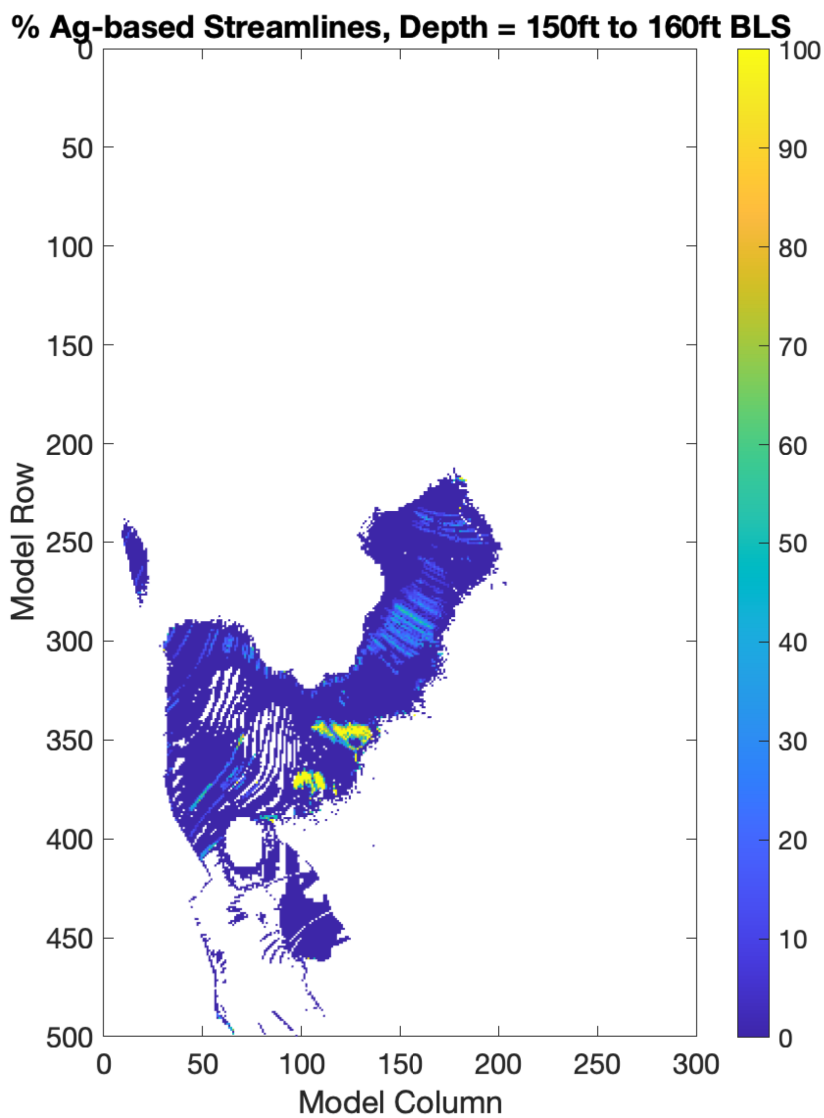
% Ag-based Streamlines, Depth = 110ft to 120ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0



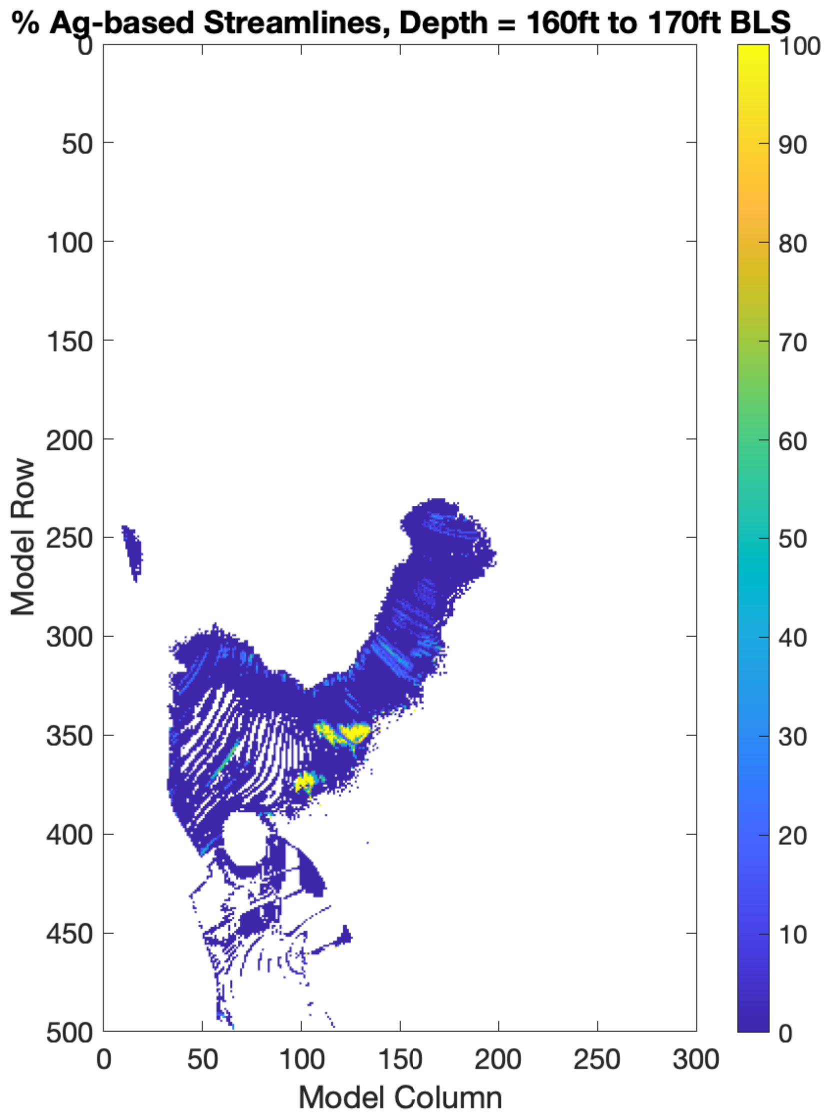
% Ag-based Streamlines, Depth = 120ft to 130ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0


% Ag-based Streamlines, Depth = 130ft to 140ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0

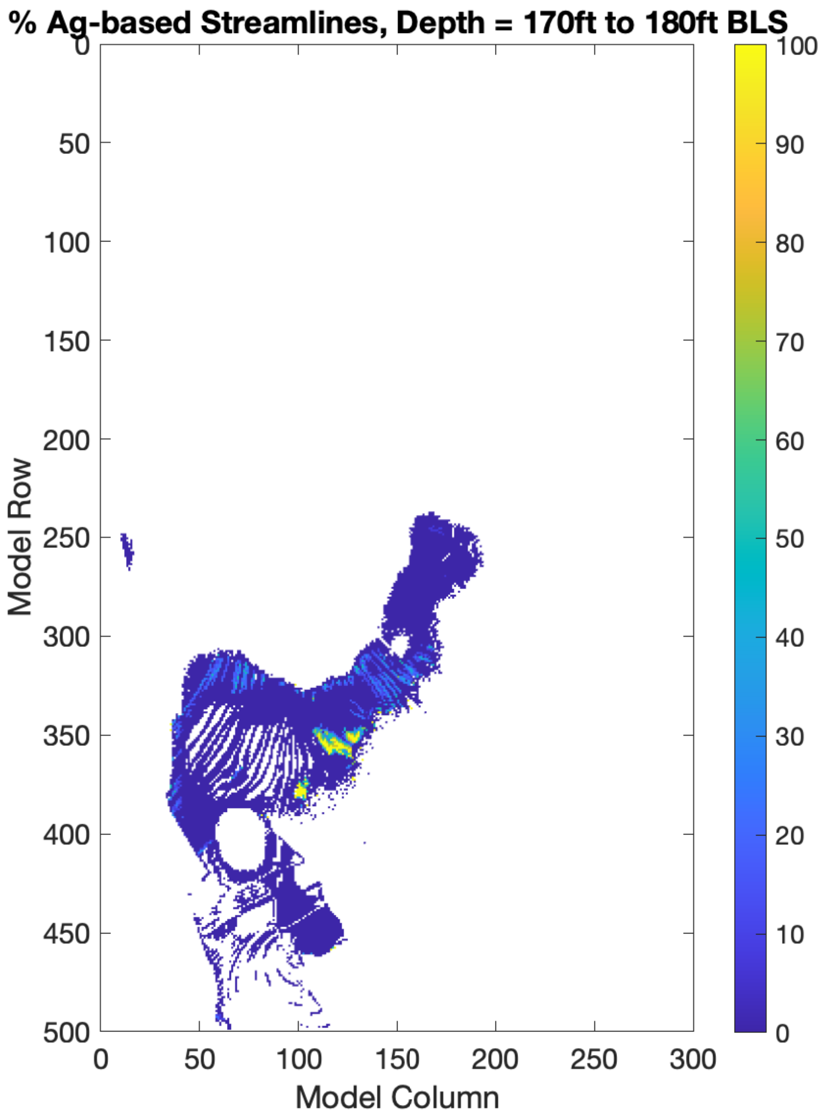

% Ag-based Streamlines, Depth = 140ft to 150ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0



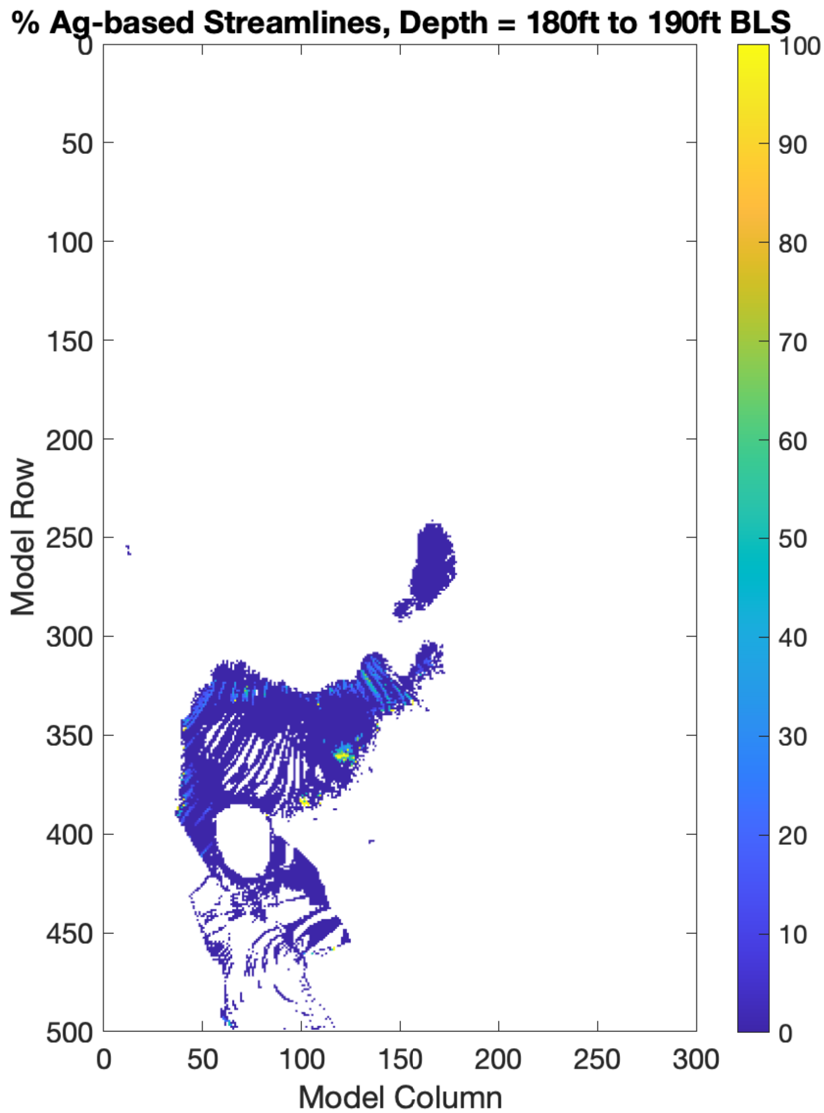
% Ag-based Streamlines, Depth = 150ft to 160ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0



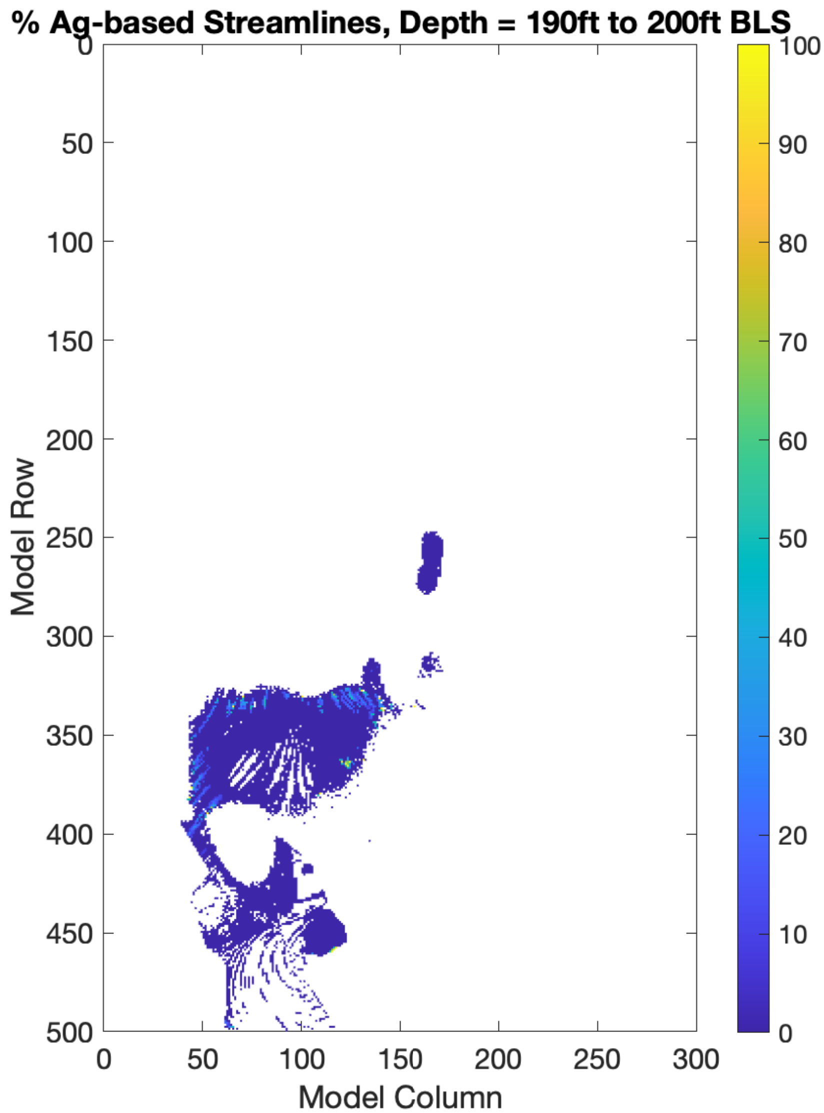
% Ag-based Streamlines, Depth = 160ft to 170ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
0
10
20
30
40
50
60
70
80
90
100



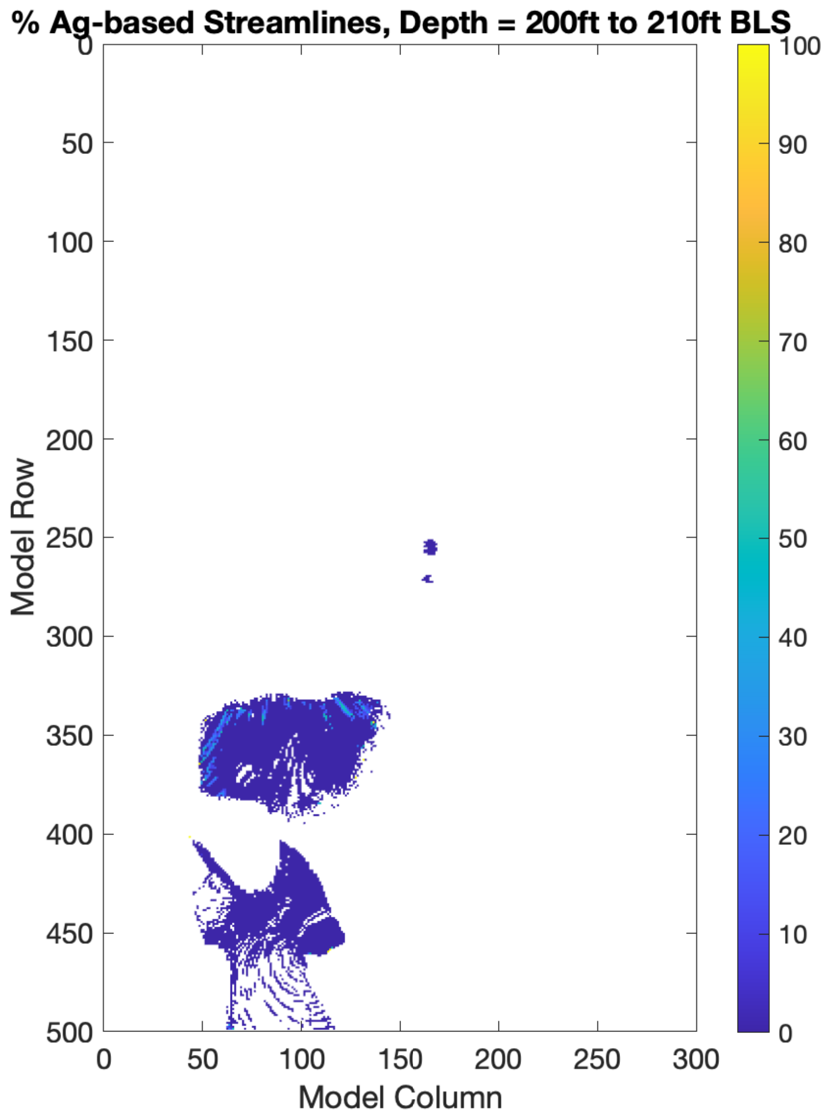
% Ag-based Streamlines, Depth = 170ft to 180ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0



% Ag-based Streamlines, Depth = 180ft to 190ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0



% Ag-based Streamlines, Depth = 190ft to 200ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0


% Ag-based Streamlines, Depth = 200ft to 210ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
0
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30
40
50
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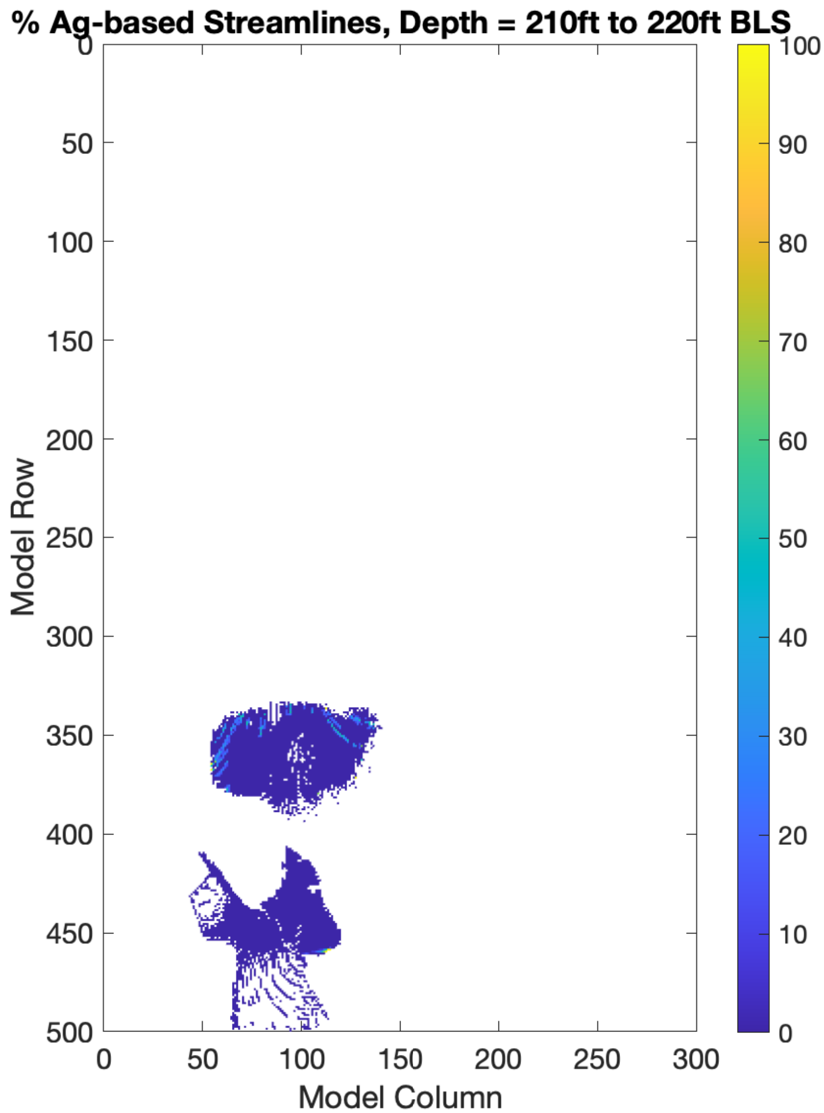
70
80
90
100



% Ag-based Streamlines, Depth = 210ft to 220ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
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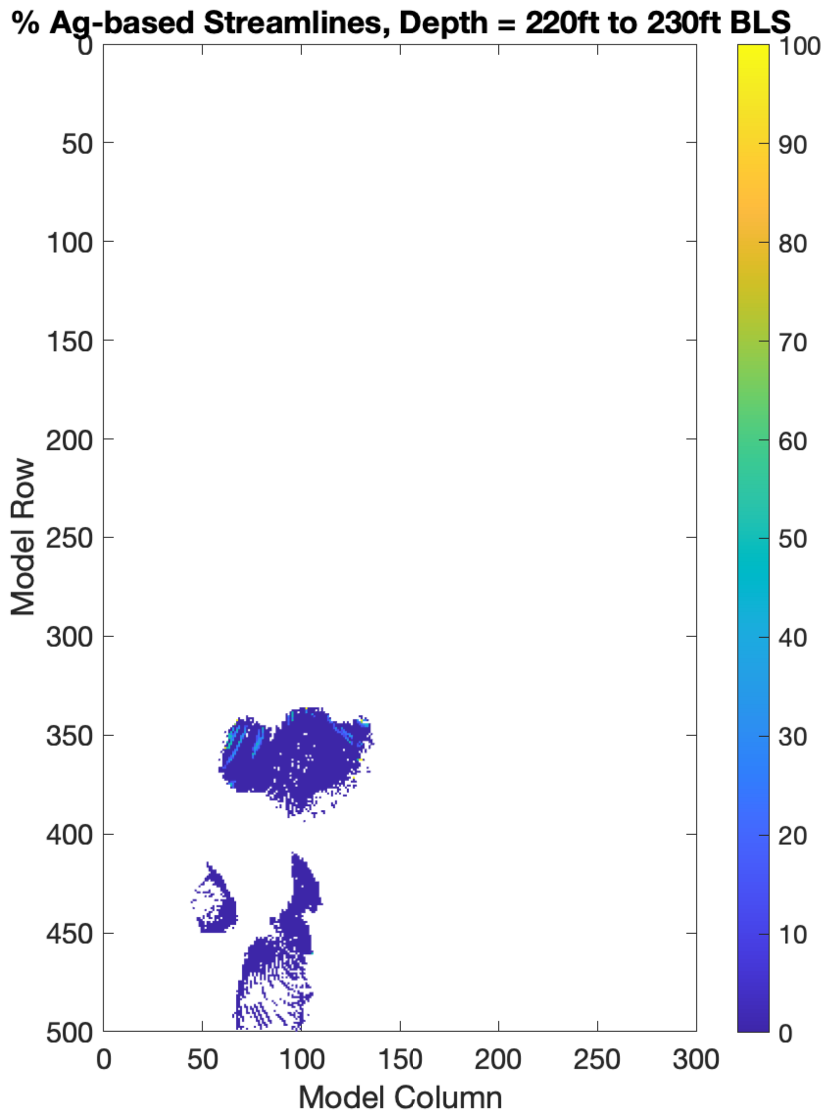
70
60
50
40
30
20
10
0


% Ag-based Streamlines, Depth = 220ft to 230ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
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100
150
200
250
300
100
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70
60
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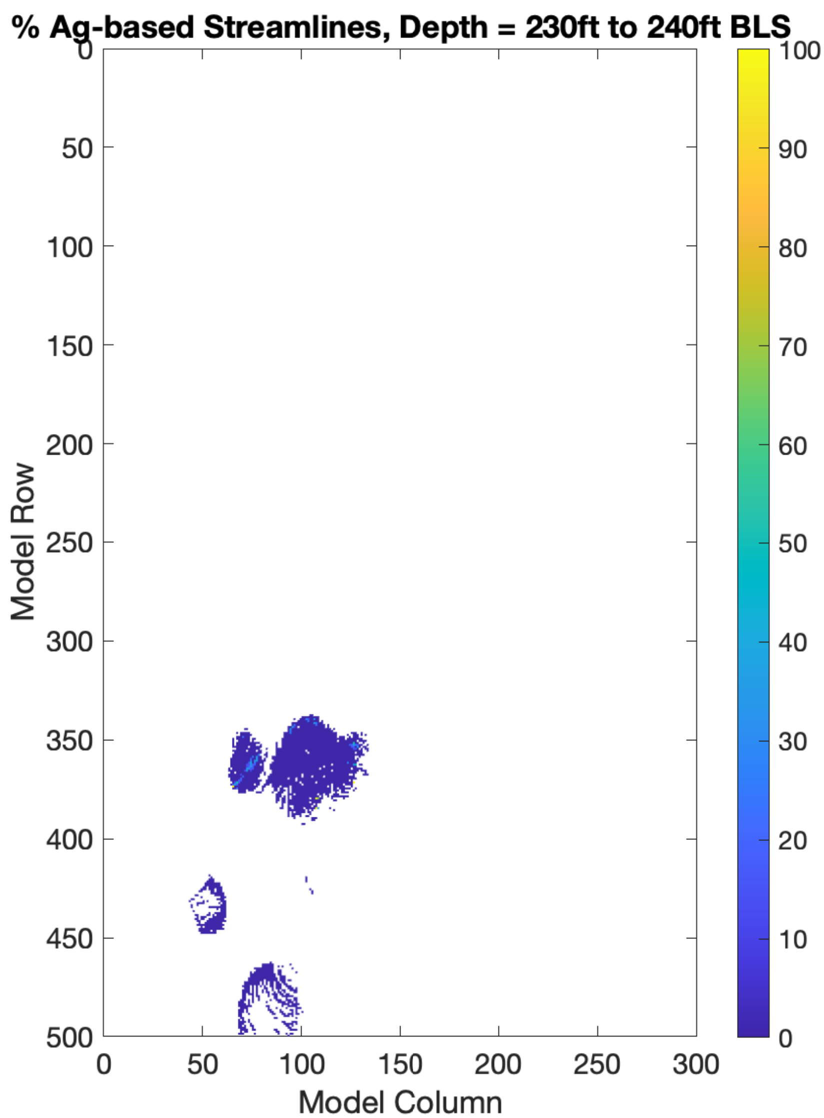
30
20
10
0



% Ag-based Streamlines, Depth = 230ft to 240ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
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100
150
200
250
300
100
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70
60
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30
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10
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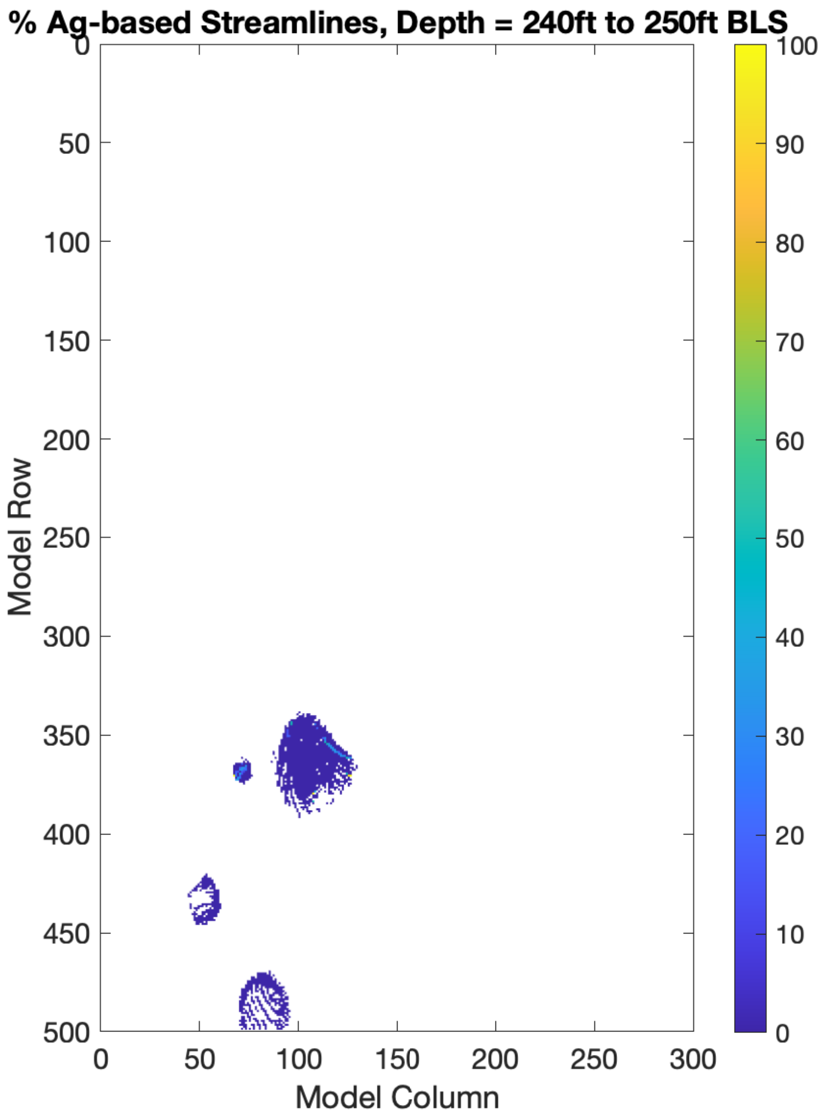
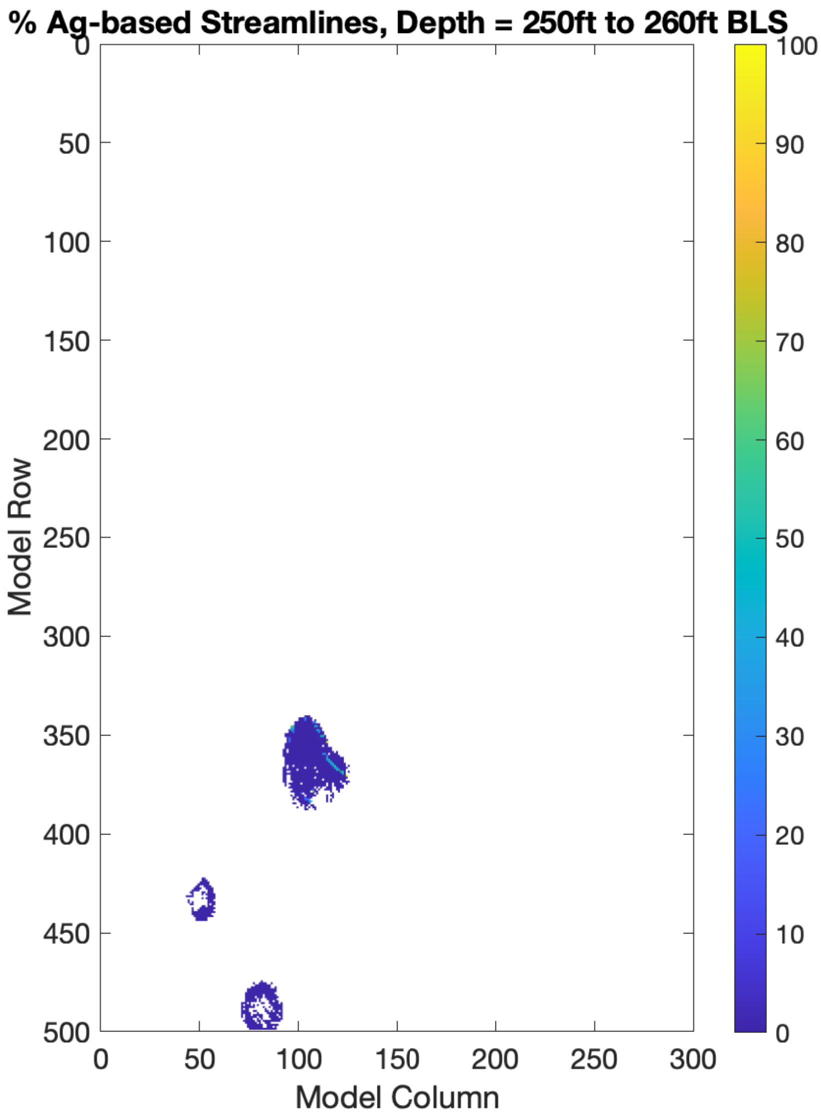
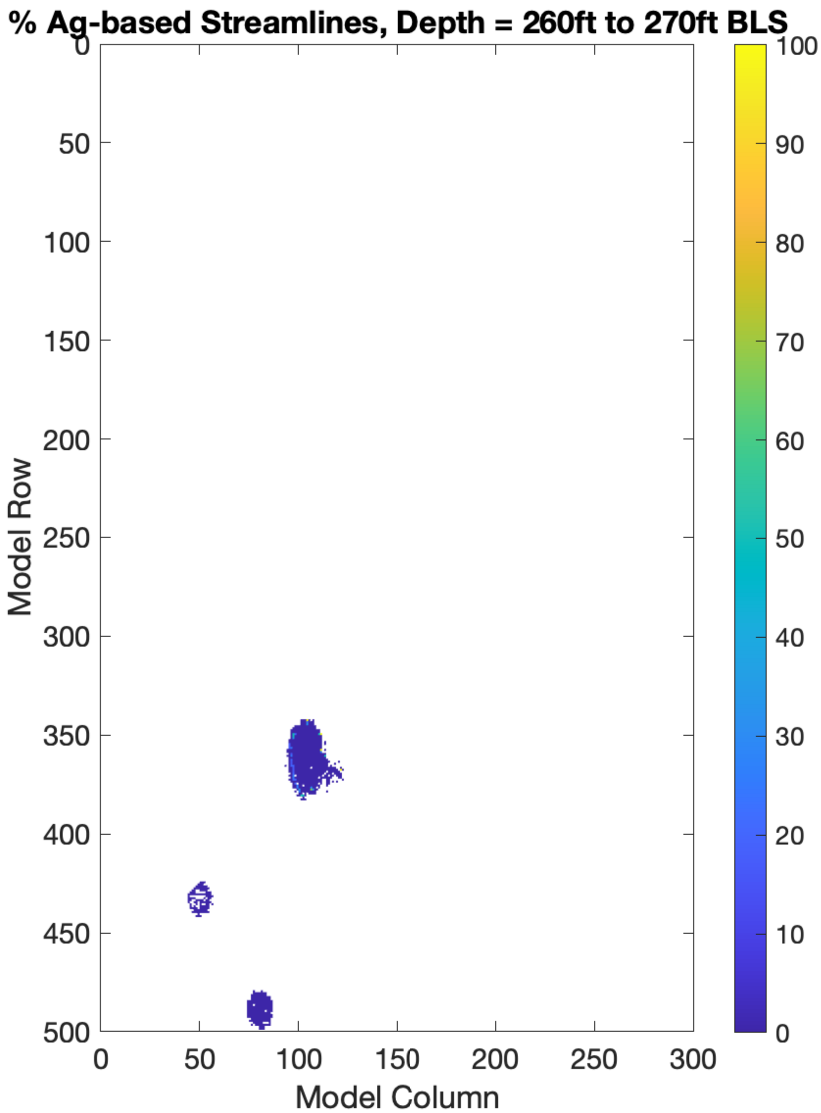
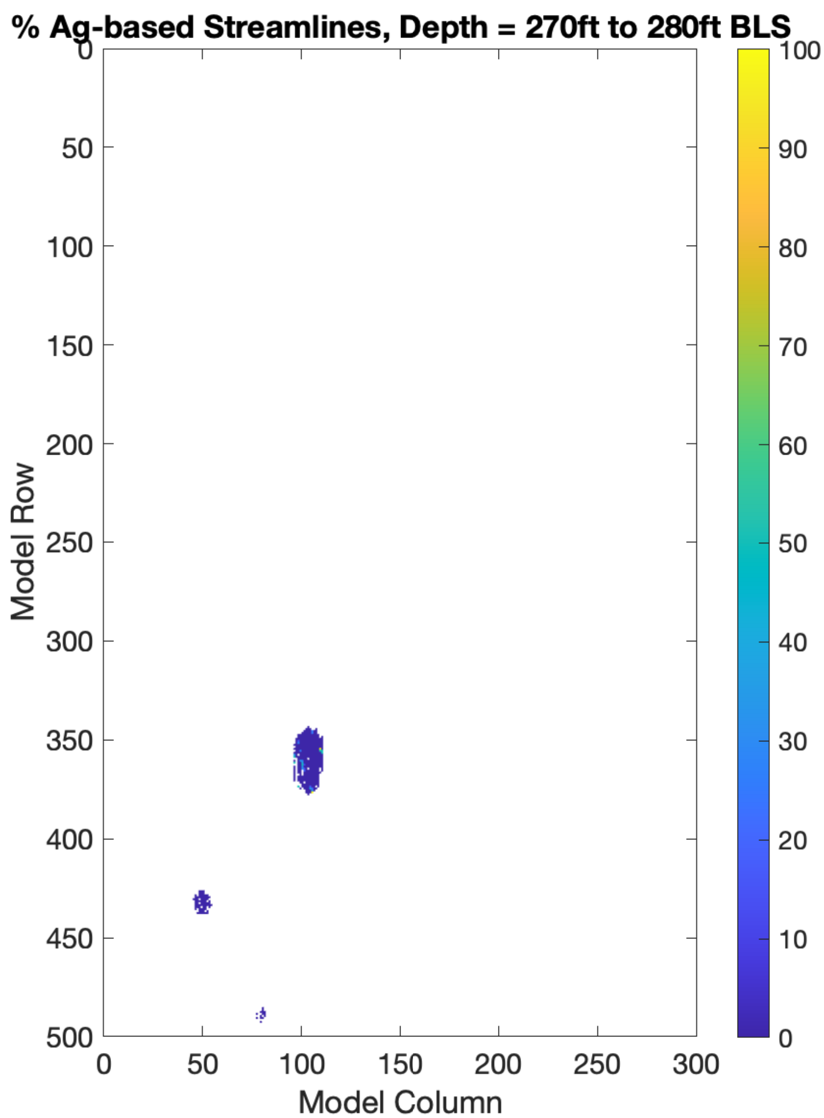

% Ag-based Streamlines, Depth = 240ft to 250ft BLS
Model Row
0
50
100
150
200
250
300
350
400
450
500
Model Column
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0

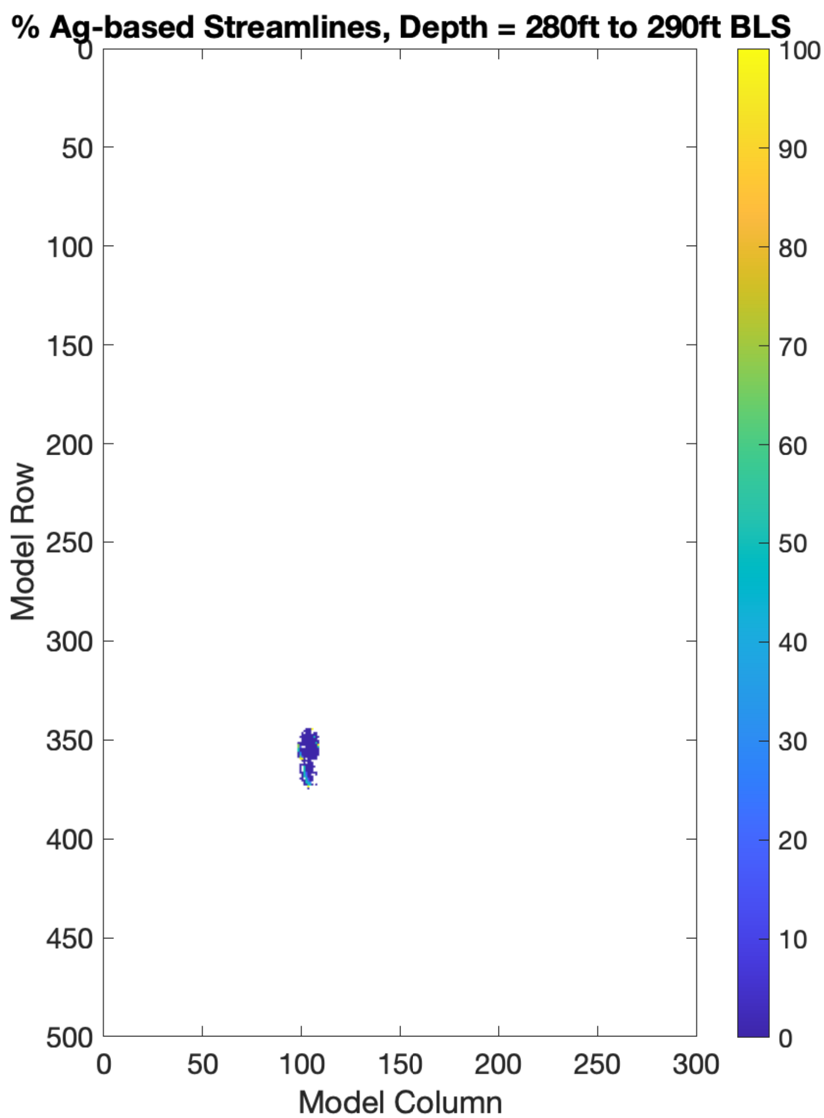

% Ag-based Streamlines, Depth = 250ft to 260ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0



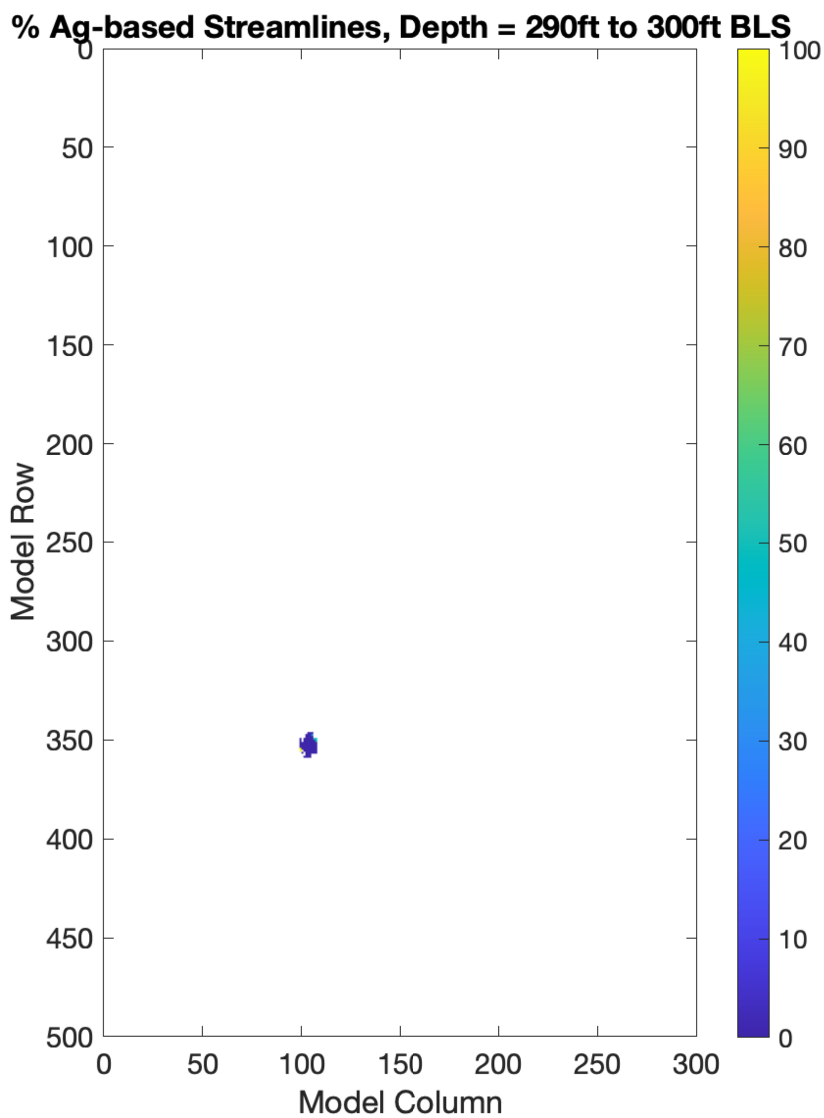
% Ag-based Streamlines, Depth = 260ft to 270ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0



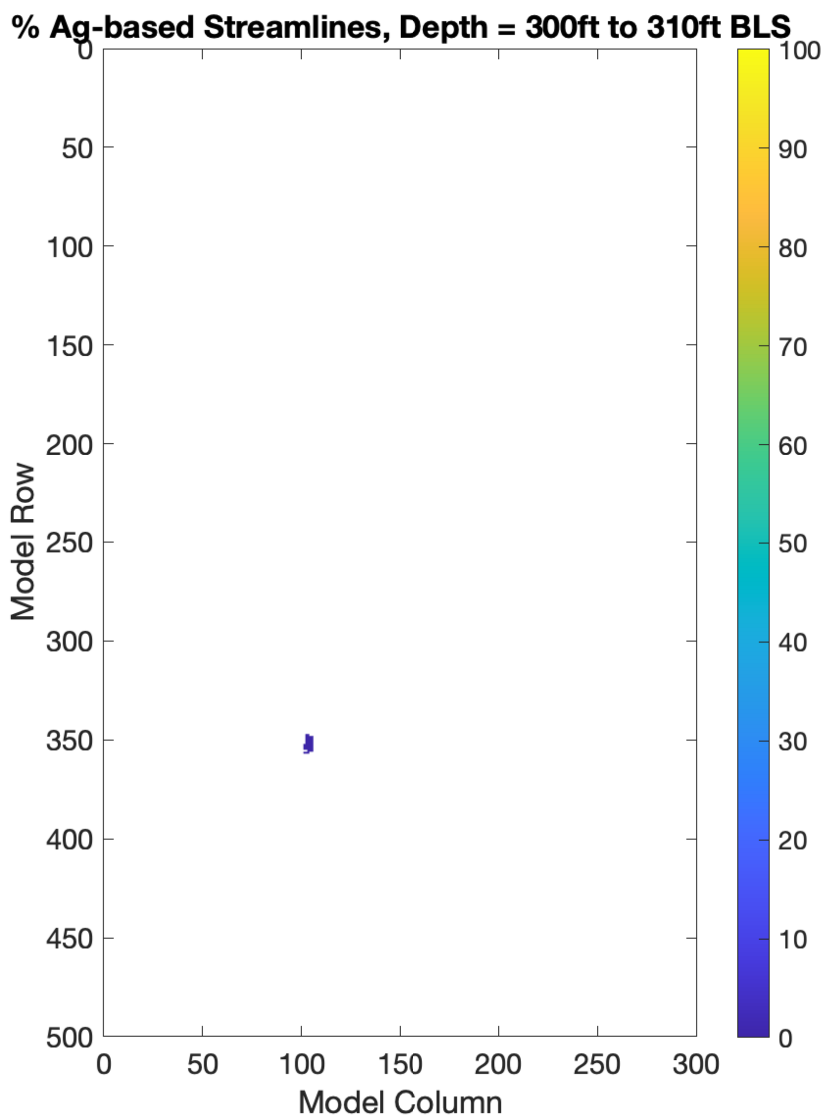
% Ag-based Streamlines, Depth = 270ft to 280ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0



% Ag-based Streamlines, Depth = 280ft to 290ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0



% Ag-based Streamlines, Depth = 290ft to 300ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
100
90
80
70
60
50
40
30
20
10
0


% Ag-based Streamlines, Depth = 300ft to 310ft BLS
Model Row
Model Column
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
0
10
20
30
40
50
60
70
80
90
100