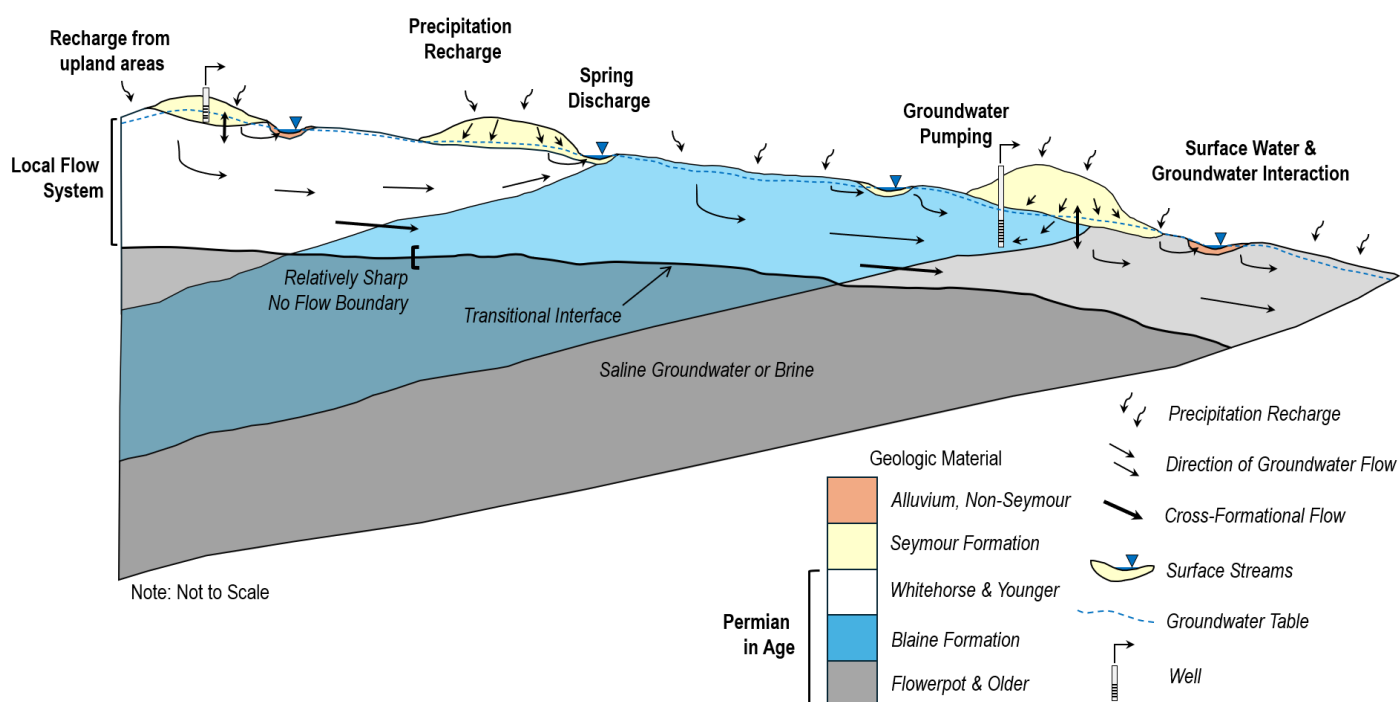


FINAL REPORT - JULY 2026

Groundwater Availability Model Update

Seymour and Blaine Aquifer System



Prepared by: Michelle Pedrazas
Allan Foster, PE
John Ewing, PE
Shuo Yang, PhD
Ryan Harmon, PhD
Jeremy White, PhD
Joseph Hughes, PhD, PG



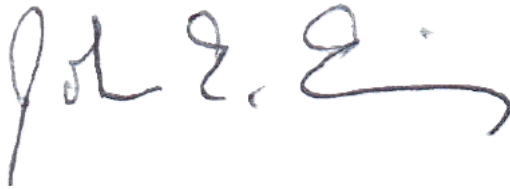
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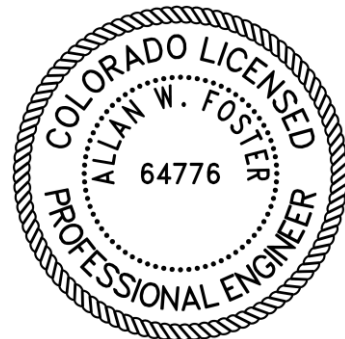
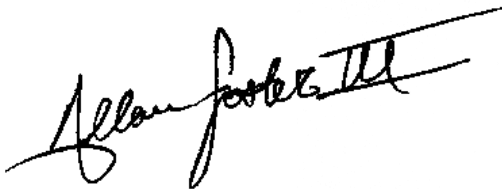
Texas Water Development Board (TWDB)
1700 North Congress Avenue
Austin, TX 78701

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

The following registered professionals are responsible for this report:



John E. Ewing, PE (Texas No. 92817)
Mr. Ewing was the Project Manager for this contract and was responsible for technical review and oversight of the project.



Allan W. Foster, PE (Colorado No. 64776)
Mr. Foster was responsible for assisting with development and calibration of the groundwater flow model.

Table of Contents

List of Figures	v
List of Tables.....	xv
1 Executive Summary	1-1
2 Introduction and purpose of the model	2-1
2.1 .. Introduction.....	2-1
2.2 .. Study area	2-6
2.3 .. Topography and climate	2-18
2.4 .. Groundwater levels.....	2-29
2.5 .. Stream flows.....	2-31
2.6 .. Spring flow and seeps	2-33
2.7 .. Geologic setting	2-37
3 Updates to the conceptual model	3-1
3.1 .. Introduction.....	3-1
3.2 .. Model area, layering, and grid properties	3-2
3.2.1 Model area delineation	3-2
3.2.2 Numerical model layers.....	3-5
3.2.3 Grid properties	3-20
3.3 .. Spring flow and seeps	3-20
3.4 .. Historical pumping	3-21
3.5 .. Recharge.....	3-22
3.6 .. Faulting.....	3-25
4 Model overview and packages	4-1
4.1 .. Introduction.....	4-1
4.2 .. Basic package	4-4
4.3 .. Unstructured discretization package	4-4
4.4 .. Ghost node correction package	4-20
4.5 .. Grid specification file.....	4-20
4.6 .. Temporal discretization package	4-20
4.7 .. Initial conditions package.....	4-26
4.8 .. Node-property flow package	4-30
4.9 .. Storage package	4-35
4.10 Well package	4-36

4.10.1	Rural and domestic estimates	4-37
4.10.2	Historical pumping estimates for non-domestic use types	4-45
4.10.3	Metered pumping estimates	4-52
4.10.4	Oklahoma pumping estimates	4-60
4.10.5	Spatial redistribution of prescribed pumping	4-60
4.10.6	Autoflow reduction settings	4-60
4.10.7	Aquifer testing data	4-61
4.11	Drain package	4-65
4.12	General-head boundary package	4-72
4.13	Recharge package	4-76
4.14	River package	4-79
4.15	Evapotranspiration package	4-81
4.16	Output control file	4-81
4.17	Solver	4-81
4.18	Observation utility	4-81
5	Model calibration and results	5-1
5.1 ..	Model parameterization and the prior	5-3
5.2 ..	History matching	5-12
5.2.1	Observation targets	5-12
5.2.2	Conceptual model constraints on calibration	5-19
5.3 ..	Calibrated results	5-21
5.3.1	Calibrated parameters	5-23
5.3.2	Hydraulic head calibration	5-85
5.3.3	Spring head calibration	5-121
5.3.4	Water budgets	5-124
6	Sensitivity analysis	6-1
6.1 ..	Sensitivity analysis procedure	6-1
6.2 ..	Sensitivity analysis results	6-3
6.2.1	Steady-state sensitivities	6-5
6.2.2	Transient sensitivities	6-7
7	Model limitations	7-1
7.1 ..	Intended use and spatial scale	7-1
7.2 ..	Hydraulic properties	7-1
7.3 ..	Recharge	7-2
7.4 ..	Historical pumping	7-2

7.5..	Surface water–groundwater interaction.....	7-3
7.6..	Observation data and calibration	7-3
7.7..	Conceptual simplifications	7-4
7.8..	Predictive simulation.....	7-5
8	Summary and conclusions	8-1
8.1..	Updates to conceptual model	8-1
8.2..	Numerical model development and calibration.....	8-2
8.3..	Sensitivity analysis.....	8-3
9	Future improvements.....	9-1
9.1..	Additional supporting data	9-1
9.2..	Future model implementation improvements	9-2
10	References.....	10-1
11	Appendix A: West-East Numerical Model Cross-Sections for Each Row, Facing North	11-1
12	Appendix B: South-North Numerical Model Cross-Sections for Each Column, Facing West	12-1
13	Appendix C: Processed Water Levels	13-1
14	Appendix D: Hydrographs	14-1
15	Appendix E: Water Budget By Counties.....	15-2
16	Appendix F: Water Budget By GCDs	16-3

List of Figures

Figure 2.1-1.	Major aquifers within Texas, including the Seymour Aquifer.	2-4
Figure 2.1-2.	Minor aquifers within Texas, including the Blaine Aquifer.	2-5
Figure 2.2-1.	Location of the study area.....	2-7
Figure 2.2-2.	Location of the study area with Seymour and Blaine Aquifer extents.	2-8
Figure 2.2-3.	County boundaries, cities, roadways in the study area.	2-10
Figure 2.2-4.	Regional water planning group areas (RWPG) in the study area.	2-11
Figure 2.2-5.	Groundwater conservation districts (GCD) and underground water conservation districts (UWCD) in the study area.	2-12
Figure 2.2-6.	Groundwater management areas in the study area.	2-13
Figure 2.2-7.	Major river basins in the study area.	2-15
Figure 2.2-8.	Rivers, streams, lakes and reservoirs in the study area.	2-16
Figure 2.2-9.	Active model area and adjacent aquifers.	2-17
Figure 2.3-1.	Physiographic provinces in the study area.....	2-20
Figure 2.3-2.	Ecological regions in the study area.	2-21
Figure 2.3-3.	Topographic map of the study area. Elevation is in feet above mean sea level.....	2-22
Figure 2.3-4.	Climate divisions in the study area.....	2-23
Figure 2.3-5.	Average annual air temperature for the study area in degrees Fahrenheit (F) 1981-2023 (source: Oregon Climate Service, Oregon State University, PRISM dataset).....	2-24
Figure 2.3-6.	Average annual net pan evaporation rate in inches per year (in/yr).	2-25
Figure 2.3-7.	Location of precipitation gages in the study area. Source: online National Climate Data Center Climate Data Online (CDO) - The National Climatic Data Center's (NCDC) Climate Data Online (CDO) provides free access to NCDC's archive of historical weather and climate data in addition to station history information. National Climatic Data Center (NCDC).....	2-26
Figure 2.3-8.	Annual precipitation time series for study area (source: Global Historical Climatology Network daily database, National Oceanic and Atmospheric Administration National Centers for Environmental Information). (in/yr = inches per year, lat = latitude, long = longitude, dd =decimal degrees.).....	2-27
Figure 2.3-9.	Average annual precipitation over the study area in inches per year 1981-2023 (source: Oregon Climate Service, Oregon State University, PRISM dataset).	2-28
Figure 2.4-1.	Wells with water level records available for the Seymour and Blaine aquifers (source: TWDB, Submitted Drillers Records, and United States Geological Survey datasets).	2-30
Figure 2.5-1.	Stream gages with flow records available (source: United States Geological Survey).	2-32
Figure 2.6-1.	Documented spring and seep locations in the study area.	2-35
Figure 2.7-1.	Map of major structural features in the study area (after Price, 1979).	2-39

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Figure 2.7-2.	Surface geology of the study area.	2-40
Figure 2.7-3.	Generalized stratigraphy across the study area.	2-41
Figure 2.7-4.	Cross-section showing the major stratigraphic units across the active model area (source: Duffin and Beynon, 1992).	2-41
Figure 2.7-5.	East-west structural cross-section across Hardeman County (source: Maderak, 1972).	2-42
Figure 2.7-6.	North-south structural cross-section across Collingsworth County (source: Smith, 1970).	2-43
Figure 2.7-7.	Geologic materials forming the Seymour Aquifer with Pod Numbers.	2-44
Figure 2.7-8.	Cross-section A-A' of regional groundwater flow hydraulics controlled by the brine interface (source: figure from Finch and others, 2016; modified from Stevens and Hardt, 1965).	2-45
Figure 3.1-1.	Conceptual model of the Seymour and Blaine Aquifer system.	3-2
Figure 3.2-1.	Model boundary delineation and supporting information.	3-4
Figure 3.2-2.	Delineation of the brine interface mapped in the Permian-age hydrostratigraphic units (source: Brackish Resources Aquifer Characterization Study [BRACS] for the Blaine Aquifer system by Finch and others [2016]).	3-9
Figure 3.2-3.	Major river elevation interpolation surface in feet above mean sea level.	3-10
Figure 3.2-4.	Isopach thickness (feet) of modeled Whitehorse and younger formations Permian-age hydrostratigraphic units in layer 2.	3-11
Figure 3.2-5.	Statistics for isopach thickness (feet) of modeled Whitehorse and younger Permian-age hydrostratigraphic units in layer 2.	3-12
Figure 3.2-6.	Isopach thickness (feet) of modeled Blaine formation Permian-age hydrostratigraphic unit in layer 3.	3-13
Figure 3.2-7.	Statistics for isopach thickness (feet) of modeled Blaine formation Permian-age hydrostratigraphic unit in layer 3.	3-14
Figure 3.2-8.	Isopach thickness (feet) of modeled Flowerpot and older Permian-age hydrostratigraphic units in layer 4.	3-15
Figure 3.2-9.	Statistics for isopach thickness (feet) of modeled Flowerpot and older Permian-age hydrostratigraphic units in layer 4.	3-16
Figure 3.2-10.	Isopach thickness (feet) of the Seymour Aquifer in model layer 1.	3-17
Figure 3.2-11.	Statistics for isopach thickness (feet) of the modeled Seymour formation.	3-18
Figure 3.2-12.	Spatial extent of all model layers in the groundwater availability model.	3-19
Figure 3.5-1.	Aquifer Footprints from the High Plains groundwater availability model (Deeds and Jigmond, 2015; Cawthon and Wade, 2025) of the Ogallala (green) and Edwards-Trinity (Plateau) Aquifers (orange) along the northern, western, and southern groundwater availability model boundaries. Upper (pink) and Lower (grey) Dockum extents are included. Seymour and Blaine groundwater availability model extent is provided (red).	3-24
Figure 4.1-1.	Conceptual model diagram with MODFLOW packages.	4-2

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Figure 4.3-1.	Active model cells (nodes) for layer 1 representing the Seymour Aquifer formation sediments.	4-7
Figure 4.3-2.	Generalized model cells (nodes) for layers 2, 3, and 4 representing the Permian-age hydrostratigraphic units, including the Blaine Aquifer. This figure excludes layer overlap.	4-8
Figure 4.3-3.	Detailed active model cells (nodes) for layers 2, 3, and 4 representing the Permian-age hydrostratigraphic units, including the Blaine Aquifer. This figure includes layer overlap.....	4-9
Figure 4.3-4.	West to east cross-section of constructed numerical model row 117, facing north.....	4-10
Figure 4.3-5.	South to north cross-section of constructed numerical model column 105, facing west.....	4-10
Figure 4.3-6.	Model layer 1 top elevation (feet) for the Seymour Aquifer formation sediments.	4-12
Figure 4.3-7.	Model layer 1 bottom elevation (feet) for the Seymour Aquifer formation sediments.	4-13
Figure 4.3-8.	Model layer 2 top elevation (feet) for the Whitehorse and younger Permian-age units.	4-14
Figure 4.3-9.	Model layer 2 bottom elevation (feet) for the Whitehorse and younger Permian-age units.	4-15
Figure 4.3-10.	Model layer 3 top elevation (feet) for the Blaine formation.	4-16
Figure 4.3-11.	Model layer 3 bottom elevation (feet) for the Blaine formation.	4-17
Figure 4.3-12.	Model layer 4 top elevation (feet) for the Flowerpot shale and older Permian-age units.	4-18
Figure 4.3-13.	Model layer 4 bottom elevation (feet) for the Flowerpot shale and older Permian-age units.	4-19
Figure 4.7-1.	Initial hydraulic heads for the Seymour formation in model layer 1.....	4-28
Figure 4.7-2.	Initial hydraulic heads for the Permian-age hydrostratigraphic units in model layers 2, 3, and 4.	4-29
Figure 4.8-1.	Model layer 1 initial horizontal hydraulic conductivity distribution (feet per day).	4-31
Figure 4.8-2.	Model layer 2 initial horizontal hydraulic conductivity distribution (feet per day).	4-32
Figure 4.8-3.	Model layer 3 initial horizontal hydraulic conductivity distribution (feet per day).	4-33
Figure 4.8-4.	Model layer 4 initial horizontal hydraulic conductivity distribution (feet per day).	4-34
Figure 4.10-1.	Initial Prescribed Texas domestic pumping rates (in acre-feet per year) for the Seymour and Blaine aquifers.....	4-39
Figure 4.10-2.	Initial Prescribed Texas domestic pumping rates (in acre-feet per year) for the Seymour Aquifer for counties with greater than 100 acre-feet per year rates. Archer, Briscoe, Childress, Clay, Donley, Hall, Kent, King, Motley, Scurry, Stonewall, Taylor, Throckmorton, and Young counties had less than 100 acre-feet per year rates across all time periods.....	4-40

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Figure 4.10-3.	Initial Prescribed Texas domestic pumping rates (in acre-feet per year) for the Blaine Aquifer for counties with greater than 100 acre-feet per year rates. Dickens, Jones, Kent, Knox, Motley, Scurry, and Wilbarger counties had less than 100 acre-feet per year rates across all time periods.....	4-41
Figure 4.10-4.	Initial Prescribed Texas domestic pumping rates (in acre-feet per year) in 1980 within the Seymour and Blaine Groundwater Availability Model.	4-42
Figure 4.10-5.	Initial Prescribed Texas domestic pumping rates (in acre-feet per year) in 2000 within the Seymour and Blaine Groundwater Availability Model.	4-43
Figure 4.10-6.	Initial Prescribed Texas domestic pumping rates (in acre-feet per year) in 2020 within the Seymour and Blaine Groundwater Availability Model.	4-44
Figure 4.10-7.	Number of non-domestic wells by county and water use type in the Seymour Aquifer.....	4-47
Figure 4.10-8.	Number of non-domestic wells by county and water use type in the Blaine Aquifer.	4-47
Figure 4.10-9.	Non-domestic use wells within the Seymour and Blaine Groundwater Availability Model.....	4-48
Figure 4.10-10.	Well depth versus yield and yield versus casing diameter for non-domestic well use in the Seymour Aquifer.	4-50
Figure 4.10-11.	Well depth versus yield and yield versus casing diameter for non-domestic well use in the Blaine Aquifer.....	4-52
Figure 4.10-12.	Spatial distributions and aquifer assignments for the metered data through the historical simulation period.....	4-54
Figure 4.10-13.	Metered pumping volumes (acre-feet) summarized by county for the historical simulation period.....	4-55
Figure 4.10-14.	Spatial distribution of metered data by aquifer.	4-56
Figure 4.10-15.	Temporal pumping volumes (acre-feet) transcribed to the model hydrostratigraphic units (hsu) for the available metered data used in development of the metered pumping package.	4-57
Figure 4.10-16.	Temporal breakdown of the modeled metered pumping data (acre-feet) for the Seymour pods from the available data.....	4-58
Figure 4.10-17.	Temporal breakdown of metered data (acre-feet) by use type.....	4-59
Figure 4.10-18.	City of Seymour aquifer testing data locations in 2024.....	4-62
Figure 4.10-19.	City of Seymour aquifer testing data analysis provided by Rolling Plains Groundwater Conservation District.	4-64
Figure 4.11-1.	Locations of major rivers and perennial and intermittent streams in the outcrop areas based on National Hydrography Dataset Plus High Resolution.	4-67
Figure 4.11-2.	Delineation of river and drain model packages based on the National Hydrography Dataset Plus High Resolution.	4-68
Figure 4.11-3.	Location of drain cells representing ephemeral and intermittent streams in the model domain. Drain package cells in blue represent springs and seeps.....	4-69

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Figure 4.11-4.	Location of drain package cells representing springs and seeps mapped in the model domain.	4-70
Figure 4.11-5.	Location of drain package cells representing Seymour pod perimeter edge drains included as additional representation of seeps.	4-71
Figure 4.12-1.	Overlap of the Ogallala and Edwards-Trinity (Plateau) Aquifer footprints in the High Plains Aquifer groundwater availability model (Deeds and Jigmond, 2015; Cawthon and Wade, 2025) with the Seymour and Blaine groundwater availability model extent in red (top panel) and cross-sections of 2020 simulated water levels in the updated High Plains Aquifer Groundwater Availability Model.	4-73
Figure 4.12-2.	Modeled extent of the general head boundaries (GHB) in the groundwater availability model update.	4-75
Figure 4.13-1.	Initial model recharge values in inches per year in the recharge model package for model layer 1 representing the Seymour formation aquifer sediments.	4-77
Figure 4.13-2.	Initial model recharge values in inches per year in the recharge model package for model layers 2, 3, and 4 representing the Permian-age hydrostratigraphic units.	4-78
Figure 4.14-1.	Location of river package cells in the model domain.	4-80
Figure 5.2-1.	Groundwater monitoring wells in the Seymour and Blaine aquifers.	5-16
Figure 5.2-2.	Spring head calibration targets.	5-18
Figure 5.3-1.	Phi reduction for every iteration of calibration. The objective Function (Φ) is the sum of squared weighted residuals.	5-23
Figure 5.3-2.	Violin plots showing the prior and posterior parameter ensembles for horizontal hydraulic conductivity for pods 1 through 8 in the Seymour Aquifer. Values are in percent (x axis) and feet per day (y axis).	5-29
Figure 5.3-3.	Violin plots showing the prior and posterior parameter ensembles for horizontal hydraulic conductivity for pods 9 through 15 in the Seymour Aquifer. Values are in percent (x axis) and feet per day (y axis).	5-30
Figure 5.3-4.	Violin plots showing the prior and posterior parameter ensembles for horizontal hydraulic conductivity for model layers 2 through 4. Values are in percent (x axis) and feet per day (y axis).	5-31
Figure 5.3-5.	Calibrated horizontal hydraulic conductivity (in feet per day) for layer 1, the Seymour Aquifer.	5-34
Figure 5.3-6.	Calibrated horizontal hydraulic conductivity (in feet per day) for layer 2, the Whitehorse and Younger Permian Units.	5-35
Figure 5.3-7.	Calibrated horizontal hydraulic conductivity (in feet per day) for layer 3, the Blaine Aquifer.	5-36
Figure 5.3-8.	Calibrated horizontal hydraulic conductivity (in feet per day) for layer 4, the Flowerpot and Older Permian Units.	5-37
Figure 5.3-9.	Violin plots showing the prior and posterior parameter ensembles for vertical anisotropy ratios (vertical hydraulic conductivity/horizontal hydraulic conductivity) for pods 1 through 8 in the Seymour Aquifer. Quantile values are in percent.	5-39

Figure 5.3-10.	Violin plots showing the prior and posterior parameter ensembles vertical anisotropy ratios (vertical hydraulic conductivity/horizontal hydraulic conductivity) for pods 9 through 15 in the Seymour Aquifer. Quantile values are in percent.	5-40
Figure 5.3-11.	Violin plots showing the prior and posterior parameter ensembles vertical anisotropy ratios (vertical hydraulic conductivity/horizontal hydraulic conductivity) for model layers 2 through 4. Quantile values are in percent.....	5-41
Figure 5.3-12.	Calibrated vertical anisotropy ratio (vertical hydraulic conductivity/horizontal hydraulic conductivity) for layer 1, the Seymour Aquifer.	5-42
Figure 5.3-13.	Calibrated vertical anisotropy ratio (vertical hydraulic conductivity/horizontal hydraulic conductivity) for layer 2, the Whitehorse and Younger Permian Units.....	5-43
Figure 5.3-14.	Calibrated vertical anisotropy ratio (vertical hydraulic conductivity/horizontal hydraulic conductivity) for layer 3, the Blaine Aquifer.	5-44
Figure 5.3-15.	Calibrated vertical anisotropy ratio (vertical hydraulic conductivity/horizontal hydraulic conductivity) for layer 4, the Flowerpot and Older Permian Units.	5-45
Figure 5.3-16.	Specific yield prior (gray) versus posterior (blue) violin plots for pods 1 through 8 in the Seymour Aquifer. Specific yield values are unitless (y axis). Values on the x-axis are percentages.	5-50
Figure 5.3-17.	Specific Yield prior (gray) versus posterior (blue) violin plots for pods 9 through 15 in the Seymour Aquifer. Specific yield values are unitless (y axis). Values on the x-axis are percentages.	5-51
Figure 5.3-18.	Specific Yield prior (gray) versus posterior (blue) violin plots for model layers 2 through 4. Specific yield values are unitless (y axis). Values on the x-axis are percentages.....	5-52
Figure 5.3-19.	Storativity prior (gray) versus posterior (blue) violin plots. Storativity values are unitless (y axis). Values on the x-axis are percentages.	5-52
Figure 5.3-20.	Calibrated specific yield for layer 1, the Seymour Aquifer.	5-53
Figure 5.3-21.	Calibrated specific yield for layer 2, the Whitehorse and Younger formation.	5-54
Figure 5.3-22.	Calibrated specific yield for layer 3, the Blaine Aquifer.....	5-55
Figure 5.3-23.	Calibrated specific yield for layer 4, the Flowerpot and Older formation.....	5-56
Figure 5.3-24.	Calibrated storativity for layer 2, the Whitehorse and Younger Permian units.....	5-58
Figure 5.3-25.	Calibrated storativity for layer 3, the Blaine Aquifer.....	5-59
Figure 5.3-26.	Calibrated storativity for layer 4, the Flowerpot and Older Permian units.	5-60
Figure 5.3-27.	Prior (gray) and posterior (blue) distributions of total annual recharge volumes during historical simulation period. Base of prior (black dashed) and posterior (blue dashed) are displayed.	5-65

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Figure 5.3-28.	Prior (gray) and posterior (blue) distributions of average recharge rates during historical simulation period. Base of prior (black dashed) and posterior (blue dashed) are displayed.....	5-65
Figure 5.3-29.	Average recharge rates (inches per year) by layer for base realization during historical simulation period.....	5-66
Figure 5.3-30.	Calibrated steady-state recharge rate map (in inches per year) in layer 1, the Seymour Aquifer.	5-67
Figure 5.3-31.	Total calibrated steady-state recharge rate (in inches per year) for all model layers, aggregated to the 1-mile model grid.	5-68
Figure 5.3-32.	Calibrated steady-state recharge rate map (in inches per year) in layer 2, the Whitehorse and Younger.	5-69
Figure 5.3-33.	Calibrated steady-state recharge rate map (in inches per year) in layer 3, the Blaine Aquifer.	5-70
Figure 5.3-34.	Calibrated steady-state recharge rate map (in inches per year) in layer 4, the Flowerpot and Older.	5-71
Figure 5.3-35.	Prior (gray) and posterior (blue) distributions of total stream drain volumes during historical simulation period. Base of prior (black dashed) and posterior (blue dashed) are displayed.	5-75
Figure 5.3-36.	Prior (gray) and posterior (blue) river inflow (top panel) and river discharge (bottom panel) volumes in acre-feet per year.	5-78
Figure 5.3-37.	Pumping use types parameterized during calibration (in acre-feet): Irrigation Pods 1 through 4.....	5-82
Figure 5.3-38.	Pumping use types parameterized during calibration (in acre-feet): Irrigation Pods 5 through 9.....	5-82
Figure 5.3-39.	Pumping use types parameterized during calibration (in acre-feet): Irrigation Pods 10 through 13.....	5-83
Figure 5.3-40.	Pumping use types parameterized during calibration (in acre-feet): Irrigation Pods 14 and 15 and the Blaine Aquifer.	5-83
Figure 5.3-41.	Pumping use types parameterized during calibration (in acre-feet): Domestic, Municipal and Metered Data.	5-84
Figure 5.3-42.	Pumping use types parameterized during calibration (in acre-feet): mining, manufacturing, livestock, and Oklahoma.	5-84
Figure 5.3-43.	Average groundwater level residuals (in feet) for each observation well location in Pod 1 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-90
Figure 5.3-44.	Average groundwater level residuals (in feet) for each observation well location in Pod 2 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-90
Figure 5.3-45.	Average groundwater level residuals (in feet) for each observation well location in Pod 3 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-91
Figure 5.3-46.	Average groundwater level residuals (in feet) for each observation well location in Pod 4 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-91

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Figure 5.3-47.	Average groundwater level residuals (in feet) for each observation well location in Pod 5 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-92
Figure 5.3-48.	Average groundwater level residuals (in feet) for each observation well location in Pod 6 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-92
Figure 5.3-49.	Average groundwater level residuals (in feet) for each observation well location in Pod 7 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-93
Figure 5.3-50.	Average groundwater level residuals (in feet) for each observation well location in Pod 8 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-93
Figure 5.3-51.	Average groundwater level residuals (in feet) for each observation well location in Pod 9 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-94
Figure 5.3-52.	Average groundwater level residuals (in feet) for each observation well location in Pod 10 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-94
Figure 5.3-53.	Average groundwater level residuals (in feet) for each observation well location in Pod 11 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-95
Figure 5.3-54.	Average groundwater level residuals (in feet) for each observation well location in Pod 12 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-95
Figure 5.3-55.	Average groundwater level residuals (in feet) for each observation well location in Pod 13 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-96
Figure 5.3-56.	Average groundwater level residuals (in feet) for each observation well location in Pod 14 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-96
Figure 5.3-57.	Average groundwater level residuals (in feet) for each observation well location in Pod 15 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).....	5-97
Figure 5.3-58.	Average groundwater level residuals (in feet) for each observation well location in Blaine Aquifer. (ft = feet, obs = observed, sim = simulated).	5-97
Figure 5.3-59.	Steady-state groundwater level residuals (observed minus simulated, in feet) in the Seymour Aquifer.	5-98
Figure 5.3-60.	Steady-state groundwater level residuals (observed minus simulated, in feet) in the Blaine Aquifer.	5-99
Figure 5.3-61.	Transient high-frequency groundwater level residuals (observed minus simulated, in feet) in the Seymour Aquifer.	5-100
Figure 5.3-62.	Transient high-frequency groundwater level residuals (observed minus simulated, in feet) in the Blaine Aquifer.	5-101
Figure 5.3-63.	Average simulated and average observed groundwater elevation contours for the Seymour Aquifer. Contour interval is 50 feet. Averages are temporal means over the calibration period.	5-102

Figure 5.3-64.	Average simulated groundwater elevation contours compared to interpolated observed groundwater elevation contours from the Brackish Resources Aquifer Characterization Study (Finch and others, 2016) for Blaine Aquifer. Contour interval is 50 feet. Simulated averages are temporal means over the calibration period.	5-103
Figure 5.3-65.	Change in simulated water level between pre-development and the start of the transient period (in feet) in the Seymour Aquifer.	5-104
Figure 5.3-66.	Change in simulated water level between pre-development and the start of the transient period (in feet) in the Blaine Aquifer.....	5-105
Figure 5.3-67.	Change in simulated water level between pre-development and the end of the transient period (in feet) in the Seymour Aquifer.	5-106
Figure 5.3-68.	Change in simulated water level between pre-development and the end of the transient period (in feet) in the Blaine Aquifer.....	5-107
Figure 5.3-69.	Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 1.	5-108
Figure 5.3-70.	Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 1 (Continued).	5-109
Figure 5.3-71.	Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 2.	5-110
Figure 5.3-72.	Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 3.	5-111
Figure 5.3-73.	Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 4.	5-112
Figure 5.3-74.	Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 5.	5-113
Figure 5.3-75.	Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 7.	5-114
Figure 5.3-76.	Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 7 (Continued).	5-115
Figure 5.3-77.	Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 9.	5-116
Figure 5.3-78.	Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 11.....	5-117
Figure 5.3-79.	Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 12.....	5-118
Figure 5.3-80.	Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 13.....	5-119
Figure 5.3-81.	Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Blaine Aquifer.....	5-120
Figure 5.3-82.	Simulated spring head elevation versus observed spring head elevation in feet above mean sea level. (% = percent, ft = feet, USGS = United States Geological Survey).	5-122
Figure 5.3-83.	Spring head residuals (in feet) for each observation (observed minus simulated).	5-123

Figure 5.3-84.	Natural inflow and outflow mechanisms of the entire model area. Values are in acre-feet per year. Net storage change is reported as change in stored water (negative = declining storage)	5-129
Figure 5.3-85.	Natural inflow and outflow mechanisms of the Seymour Aquifer. Values are in acre-feet per year. Net storage change is reported as change in stored water (negative = declining storage)	5-130
Figure 5.3-86.	Natural inflow and outflow mechanisms of the Blaine Aquifer. Values are in acre-feet per year. Net storage change is reported as change in stored water (negative = declining storage)	5-131
Figure 5.3-87.	Inflows over the entire model area in 2020.	5-132
Figure 5.3-88.	Outflows over the entire model area in 2020.....	5-132
Figure 5.3-89.	Domestic and non-domestic pumping within the model domain. Values are in acre-feet per year.	5-133
Figure 5.3-90.	Groundwater flow into the Seymour Aquifer and out of the Seymour Aquifer from intersecting aquifers. Values are in acre-feet per year.	5-133
Figure 5.3-91.	Groundwater flow into the Blaine Aquifer and out of the Blaine Aquifer from intersecting aquifers. Values are in acre-feet per year.	5-134
Figure 6.2-1.	Conceptual interpretation of Morris parameter sensitivity. μ^* = absolute mean sensitivity. σ = standard deviation of sensitivity.....	6-4
Figure 6.2-2.	Parameter sensitivity for the steady-state groundwater levels in the Seymour Aquifer. (K_h = horizontal hydraulic conductivity. K_v = vertical hydraulic conductivity. $Strdrncond$ = stream drain conductances. μ = mean. σ = standard deviation.)	6-6
Figure 6.2-3.	Parameter sensitivity for the steady-state groundwater levels in the Blaine Aquifer. (K_h = horizontal hydraulic conductivity. K_v = vertical hydraulic conductivity μ = mean. σ = standard deviation.).....	6-6
Figure 6.2-4.	Parameter sensitivity for the transient heads in the Seymour Aquifer. (K_h = horizontal hydraulic conductivity. μ = mean. σ = standard deviation.)	6-8
Figure 6.2-5.	Parameter sensitivity for the transient heads in the Blaine Aquifer. (S_y = specific yield. K_h = horizontal hydraulic conductivity. s = storativity. μ = mean. σ = standard deviation.)	6-8

List of Tables

Table 2-1.	Groundwater (GCD) and underground water conservation districts (UWCD) in which the Seymour and Blaine aquifers are present.	2-9
Table 2-2.	River basins in the Seymour and Blaine groundwater availability model study area (after Wermund, 1996).	2-14
Table 2-3.	Documented springs in the active model area discharge greater than 100 gallons per minute. Springs without minimum flow values listed have only one discharge rate reported. Flow is reported in liters per second (lps), gallons per minute (gpm), cubic feet per second (cfs), and acre-feet per year (AFY).	2-36
Table 3-1.	Hydrostratigraphy and model layers.	3-5
Table 3-2.	Estimated recharge rates (inches per year) for the Seymour and Blaine aquifers (after Scanlon and others, 2002; Ewing and others, 2004; and Jigmond and others, 2014). ⁽¹⁾ Estimated as 7 percent of rainfall (annual precipitation of 22 inches assumed). ⁽²⁾ Represents a mean value averaged over entire model domain and modeled time period.	3-23
Table 4-1.	Summary of simulation level files and file names.	4-2
Table 4-2.	Summary of model input files and filenames.	4-3
Table 4-3.	Summary of model output files and filenames.	4-4
Table 4-4.	Summary of stress periods and durations. Steady-state = SS, Transient = TR.	4-21
Table 4-5.	Summary of mean initial hydraulic conductivity values to be refined during model calibration.	4-30
Table 4-6.	Summary of mean initial storage properties to be refined during model calibration.	4-35
Table 4-7.	Rural domestic assumed per capita use rate.	4-37
Table 4-8.	General Summary of Available Metered Data. ⁽¹⁾ Data from Mesquite Groundwater Conservation District. ⁽²⁾ Data from Panhandle Groundwater Conservation District. ⁽³⁾ Data from Rolling Plains Groundwater Conservation District.	4-53
Table 4-9.	City of Seymour aquifer testing results for estimation of aquifer properties.	4-65
Table 5-1.	Parameter information for defining prior parameter distributions of Horizontal Hydraulic Conductivity (feet per day). Constant Multiplier = CN, Pilot Point Multiplier = PP.	5-6
Table 5-2.	Parameter information for defining prior parameter distributions of Vertical Hydraulic Conductivity (feet per day). Constant Multiplier = CN, Pilot Point Multiplier = PP.	5-7
Table 5-3.	Parameter information for defining prior parameter distributions of Specific Yield (-). Constant Multiplier = CN, Pilot Point Multiplier = PP.	5-8
Table 5-4.	Parameter information for defining prior parameter distributions of Storativity (-). Constant Multiplier = CN, Pilot Point Multiplier = PP.	5-9

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Table 5-5.	Parameter information for defining prior parameter distributions of River Conductance (feet squared per day). Constant Multiplier = CN, Pilot Point Multiplier = PP.	5-9
Table 5-6.	Parameter information for defining prior parameter distributions of Streams Drain Conductance (feet squared per day). Constant Multiplier = CN, Pilot Point Multiplier = PP.	5-9
Table 5-7.	Parameter information for defining prior parameter distributions of Recharge (feet per day). Constant Multiplier = CN, Pilot Point Multiplier = PP, Steady-State = SS, Transient = TR.	5-10
Table 5-8.	Parameter information for defining prior parameter distributions of Pumping. Constant Multiplier = CN. Pumping parameter information ranges for pod and layer combinations defined with unique temporal configurations and bounds to reflect pod-specific data considerations (as described in Section 5.3.1, Pumping). Pod / Layer: 1-15 Seymour pods / 2-4 Permian Layers, Layer 2 = Whitehorse and Younger, Layer 3 = Blaine.	5-11
Table 5-9.	Number of groundwater elevation target locations by target type.	5-15
Table 5-10.	Number of groundwater elevation observations by observation type, layer and pod. Layer 1 = Seymour pods and Layer 3 = Blaine.	5-15
Table 5-11.	Table of observation groups and their percent weighting when calculating the objective function. AUTOFLOW irrigation pumping reduction counts reflect individual irrigation cell by stress-period records used as weighted inequality constraints; groundwater elevation and spring head counts reflect individual measurements used as weighted calibration targets.	5-22
Table 5-12.	Horizontal hydraulic conductivity statistics by layer and pod for the posterior parameter ensemble. Values are in feet per day. Layer 1 = Seymour Pods, Layer 3 = Blaine.	5-32
Table 5-13.	Vertical anisotropy ratio (vertical hydraulic conductivity/horizontal hydraulic conductivity) statistics by layer and pod for the posterior parameter ensemble. Values are unitless. Layer 1 = Seymour Pods, Layer 3 = Blaine.	5-33
Table 5-14.	Calibrated base realization horizontal hydraulic conductivity (feet per day) by model layer. Layer 1 = Seymour pods, Layer 2 = Whitehorse and Younger, Layer 3 = Blaine, Layer 4 = Flowerpot and Older.	5-38
Table 5-15.	Calibrated base realization vertical hydraulic conductivity (feet per day) by model layer. Layer 1 = Seymour pods, Layer 2 = Whitehorse and Younger, Layer 3 = Blaine, Layer 4 = Flowerpot and Older.	5-38
Table 5-16.	Calibrated base realization vertical anisotropy ratio, vertical hydraulic conductivity to horizontal hydraulic conductivity (-) by layer. Layer 1 = Seymour pods, Layer 2 = Whitehorse and Younger, Layer 3 = Blaine, Layer 4 = Flowerpot and Older.	5-46
Table 5-17.	Calibrated Base Realization Specific Yield, Sy (-) by Layer. Layer 1 = Seymour pods, Layer 2 = Whitehorse and Younger, Layer 3 = Blaine, Layer 4 = Flowerpot and Older.	5-57

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Table 5-18.	Calibrated base realization storativity (unitless) by layer. Layer 2 = Whitehorse and Younger, Layer 3 = Blaine, Layer 4 = Flowerpot and Older.	5-61
Table 5-19.	Recharge rate (in inches per year) statistics for each year of the posterior ensemble. *SS = Steady-State (pre-development) conditions, which were assigned the 1960 precipitation multiplier.....	5-72
Table 5-20.	Streambed drain hydraulic conductivity (feet per day) for the calibrated base realization across all layers.	5-76
Table 5-21.	Calibrated base realization riverbed hydraulic conductivity (feet per day) across all model layers.	5-79
Table 5-22.	Calibration statistics for hydraulic heads. % = percent, MAE = mean absolute error, RMSE = root mean squared error.	5-89
Table 5-23.	Water budget of the Seymour Aquifer for the calibrated steady-state stress period. Values are in acre-feet per year.....	5-125
Table 5-24.	Water budget of the Whitehorse and Younger Permian Unit for the calibrated steady-state stress period. Values are in acre-feet per year.	5-126
Table 5-25.	Water budget of the Blaine Aquifer for the calibrated steady-state stress period. Values are in acre-feet per year.	5-126
Table 5-26.	Water budget of the Flowerpot and Older Permian Unit for the calibrated steady-state stress period. Values are in acre-feet per year.	5-126
Table 5-27.	Groundwater flow into and out of the Seymour Aquifer from other model layers for the steady-state stress period. Values are in acre-feet per year.	5-127
Table 5-28.	Groundwater flow into and out of the Blaine Aquifer from other model layers for the steady-state stress period. Values are in acre-feet per year.	5-127
Table 6-1.	Parameter groups adjusted for sensitivity analysis.	6-2

1 Executive Summary

This report describes the development and calibration of a numerical groundwater model for the Seymour and Blaine aquifers. The Seymour Aquifer is classified as a major aquifer and extends over 3,460 square miles across parts of 24 counties in north-central Texas and 2 counties in Oklahoma. The Blaine Aquifer is classified as a minor aquifer and extends over 7,535 square miles across all or parts of 18 counties in north-central Texas and 4 counties in Oklahoma. The study area is drained by three major rivers: the Red, Wichita, and Brazos.

The Seymour Aquifer is comprised of the remnant areas (pods) of the Seymour Formation and other Quaternary-age alluvium. It is underlain by Permian-age formations, which include the Blaine Aquifer, along with younger and older Permian-age formations. Younger Permian-age geologic formations (Quartermaster, Whitehorse, and Dog Creek Shale) overlie the Blaine Aquifer in the western part of the model and older geologic groups (Clear Fork and Wichita) underlie the Blaine Aquifer in the eastern part of the model. Along the western extent of the model, the Ogallala Aquifer and the Edwards-Trinity (Plateau) Aquifer influence groundwater flow and are included as general-head boundaries.

The foundation of this numerical model is the conceptual model reported in the Groundwater Availability Model for the Seymour Aquifer (Ewing and others, 2004). During development of this numerical model, INTERA made changes to the conceptual model in several critical areas to improve its representation in a numerical framework. The model domain was extended beyond that of the 2004 model to follow hydrologic boundaries better. The layering structure of the model was revised to simulate the Blaine Aquifer as an independent model layer. Historical groundwater use estimates from the conceptual model were refined better to capture the relative reliability of various pumping estimates and improve the robustness of the calibration process. Recharge estimates were also refined better to constrain the relationship between precipitation, soil infiltration, and actual groundwater recharge to the Seymour and Blaine aquifers for a more physically realistic balance of inflows and outflows.

The groundwater model was implemented using MODFLOW 6, the latest version of the widely used groundwater modeling software, which provides enhanced flexibility and modularity compared to previous versions. The calibration of the Seymour and Blaine aquifers groundwater availability model was performed using the PESTPP Iterative Ensemble Smoother routine, an advanced parameter estimation method that improves upon traditional calibration techniques by managing uncertainty efficiently while ensuring consistency with both observed data and conceptual model constraints.

The model was calibrated by adjusting aquifer properties and other parameters to align with observed conditions, primarily water levels measured in wells. A key challenge in calibrating the Seymour and Blaine aquifers model is the inherent tradeoff between fitting observed groundwater levels and maintaining fidelity to the conceptual model. To address this, the PESTPP Iterative Ensemble Smoother routine enables a hybrid calibration approach, where adjustments to key parameters—such as hydraulic

conductivity, storage properties, and streambed conductance—are constrained by conceptual model expectations while also optimizing the fit to observed groundwater levels. The ensemble-based approach allows the calibration to incorporate both measurement data and prior hydrogeologic knowledge, ensuring that the final parameter set is not only statistically optimized but also physically meaningful. Additionally, the PESTPP Iterative Ensemble Smoother framework inherently quantifies uncertainty in parameter estimates, providing a probabilistic evaluation of model reliability.

Through this process, the calibrated model effectively balances empirical accuracy with conceptual integrity, ensuring a realistic representation of groundwater conditions for both historical evaluation and future water management applications. The final calibration achieved a strong agreement with observed hydraulic heads, with most residuals falling within an acceptable range. While some localized discrepancies persist, particularly in areas with limited groundwater monitoring, these deviations are largely attributable to data sparsity rather than systemic model bias.

The sensitivity analysis provided valuable insights into how key model parameters influence simulated groundwater levels and overall model performance. By using the Method of Morris within a global sensitivity framework, INTERA was able to identify which parameters exert the strongest control on model outputs, which behave in a predictable linear manner and demonstrate nonlinear or interacting effects. The sensitivity analysis enhances our understanding of how different hydrogeologic parameters influence model behavior and provides a basis for refining future simulations. Future work should focus on improving parameter constraints through additional field data collection.

Like all models, this model has inherent limitations, particularly when applied to local-scale analyses. Its design prioritizes a regional perspective, which means it does not necessarily account for groundwater behavior in a specific well.

These constraints highlight the importance of viewing this model as a regional planning tool rather than a precise local diagnostic resource. Enhancing its utility for local applications would require more detailed data collection, particularly related to water levels and pumping. Despite these limitations, the model remains a valuable resource for assessing regional groundwater availability and informing broad-scale water management decisions.

As with all regional groundwater models, the Seymour and Blaine aquifers groundwater availability model should be treated as a living tool—one that evolves and improves as new data are collected and our understanding of the aquifer system advances. Future efforts to enhance this model would greatly benefit from targeted data collection that fills existing gaps in our understanding of key hydrologic processes. Areas for improvement include multi-well aquifer tests and spatially-refined estimates of hydraulic properties over the entire model area.

The purpose of this model is to provide a tool for making predictions of groundwater availability in the Seymour and Blaine aquifers through 2080 based on current projections of groundwater demands. This model provides a documented, publicly-available, and integrated tool for the assessment of water management strategies by state planners, regional water planning groups, groundwater conservation districts, and other interested stakeholders.

Continued use of the Seymour and Blaine aquifers groundwater availability model for scenario planning and policy evaluation—such as groundwater availability analysis, assessments of desired future conditions, and surface water interaction studies—will benefit from periodic recalibration and refinement. Future applications may also involve coupling this regional model with more refined localized sub-models or analytical tools to evaluate well spacing, permitting, or local drawdown impacts. However, it is important to recognize that the Seymour and Blaine aquifers groundwater availability model is fundamentally a regional-scale tool, and its application at finer spatial scales should always be undertaken with an understanding of its inherent limitations.

2 Introduction and purpose of the model

2.1 Introduction

Groundwater models provide a tool to estimate groundwater availability for various water use strategies and to determine the cumulative effects of increased water use and drought. A groundwater model is a numerical representation of the aquifer system capable of simulating historical conditions and predicting future aquifer conditions. Inherent to the groundwater model are a set of equations that are developed and applied to describe the physical processes considered to be controlling groundwater flow in the aquifer system. Groundwater models are essential to performing complex analyses and in making informed predictions and related decisions (Anderson and Woessner, 1992; Anderson and others, 2015). As a result, development of groundwater availability models for the major and minor Texas aquifers is integral to the state water planning process. The purpose of the Groundwater Modeling program is to provide a tool that can be used to develop reliable and timely information on groundwater availability for the citizens of Texas and to ensure adequate supplies or recognize inadequate supplies over a 50-year planning period.

Goals of the Texas Water Development Board (TWDB) Groundwater Modeling Department are defined by Texas Water Code §16.012 to include the following:

- Develop and maintain models for the major and minor aquifers of Texas (Figure 2.1-1 and Figure 2.1-2).
- Conduct groundwater availability model runs and develop reports to support groundwater conservation districts, groundwater management areas, regional water planning groups, and the legislature. These model runs are limited to water budget information for groundwater management plans, modeled available groundwater estimates based on desired future conditions, and special requests from the legislature.
- Provide technical support for petitions to appeal desired future conditions.
- Fund and oversee external contracts to develop supporting data, develop new models, and/or update existing models.

Groundwater availability models are designed to serve as dynamic and living tools to support planning and resource management at a regional level. The models are created at the regional scale, using standardized and transparent protocol with a documented stakeholder involvement process. The groundwater availability models are computer-based, three-dimensional, numerical groundwater flow models used to simulate groundwater flows at a regional scale. The models are based on hydrogeologic principles, actual aquifer measurements, and input from stakeholders. The models are run using free, open-source code, and all model materials are freely

available to the public via the TWDB webpage (<https://www.twdb.texas.gov/groundwater/models/gam/index.asp>). The models serve as a repository for available data and are regularly updated when new information becomes available. The groundwater models are essential tools used by a range of stakeholders for regional resource management, such as to calculate water budgets for groundwater conservation districts management plans, to determine modeled available groundwater for the groundwater management area joint planning processes, and to meet other legislative requests.

TWDB has identified the major and minor aquifers in Texas on the basis of regional extent and amount of water produced. The major and minor aquifers are shown in Figure 2.1-1 and Figure 2.1-2, respectively. General discussion of the major and minor aquifers is given in Ashworth and Hopkins (1995). The Seymour Aquifer is present in parts of 23 north-central and panhandle counties (Ashworth and Hopkins, 1995) and is classified as a major aquifer (see Figure 2.1-1). Groundwater use for the Seymour Aquifer in Texas was reported at 120,000 acre-feet per year in 1997, and the groundwater availability estimate under drought conditions in the year 2000 was reported at 250,000 acre-feet per year (TWDB, 2002). The majority of the water pumped from the aquifer is used for irrigation purposes (Ashworth and Hopkins, 1995) with minor pumping for livestock, domestic, municipal, and industrial use.

The Blaine Aquifer, as defined by the TWDB, is present in fifteen north-central and panhandle counties in Texas and is classified as a minor aquifer (see Figure 2.1-2). The Blaine Aquifer is also present in southwestern Oklahoma. Although the Blaine Formation extends farther south in Texas than the Blaine Aquifer does, the limited use of its water to the south has precluded its identification as a minor aquifer in that area (Ashworth and Hopkins, 1995). Groundwater use for the Blaine Aquifer in Texas was reported at 17,000 acre-feet per year in 1997, and the groundwater availability estimate under drought conditions in the year 2000 was reported at 180,000 acre-feet per year (TWDB, 2002). The majority of the water pumped from the Blaine Aquifer is used for irrigation of highly salt-tolerant crops (Ashworth and Hopkins, 1995). Due to its high sulfate content, groundwater from the Blaine Aquifer is not used for human consumption (Baker and others, 1963).

The purpose of this report is to document the development of the Seymour and Blaine numerical groundwater availability model update according to TWDB's standard groundwater availability model procedures. The purpose of this model is to evaluate groundwater availability in the Seymour and Blaine aquifers through 2080 and to support the development of water management strategies and drought planning. It provides a documented, publicly available, integrated tool for numerous stakeholders, including but not limited to regional water planning groups, groundwater conservation districts, river authorities, and state planners. The model includes year 2011 which is composed of characteristics similar to those of the 1950s drought-of-record, to help us understand how drought conditions may impact water resource availability.

The Seymour Aquifer groundwater availability model was developed using a modeling protocol standard to the groundwater modeling industry. This protocol includes: (1)

the development of a conceptual model for groundwater flow in the aquifer, (2) model design, (3) model calibration, (4) model verification, (5) sensitivity analysis, (6) model prediction, and (7) reporting.

Consistent with state water planning policy, this numerical model was developed with the support of stakeholders through stakeholder forums held approximately every four months. The purpose of the groundwater availability model is to provide a tool for regional water planning groups, groundwater conservation districts, river authorities, and state planners for the evaluation of groundwater availability and to support the development of water management strategies and drought planning. The Seymour and Blaine aquifers groundwater availability model intersects five of the 16 Texas Regional Water Planning Groups. The Seymour Aquifer supplies, characterized as maximum available groundwater based on desired future conditions, are estimated to be 157,895 to 181,289 acre-feet per year during the period from 2020 to 2080 as reported by the regional water planning groups. The Blaine Aquifer supplies, characterized as maximum available groundwater based on desired future conditions, are estimated to be 70,924 to 74,029 acre-feet per year during the period from 2020 to 2080 as reported by the regional water planning groups. The Seymour and Blaine aquifers updated groundwater availability model provides a tool for assessing water planning strategies and evaluating future water management objectives.

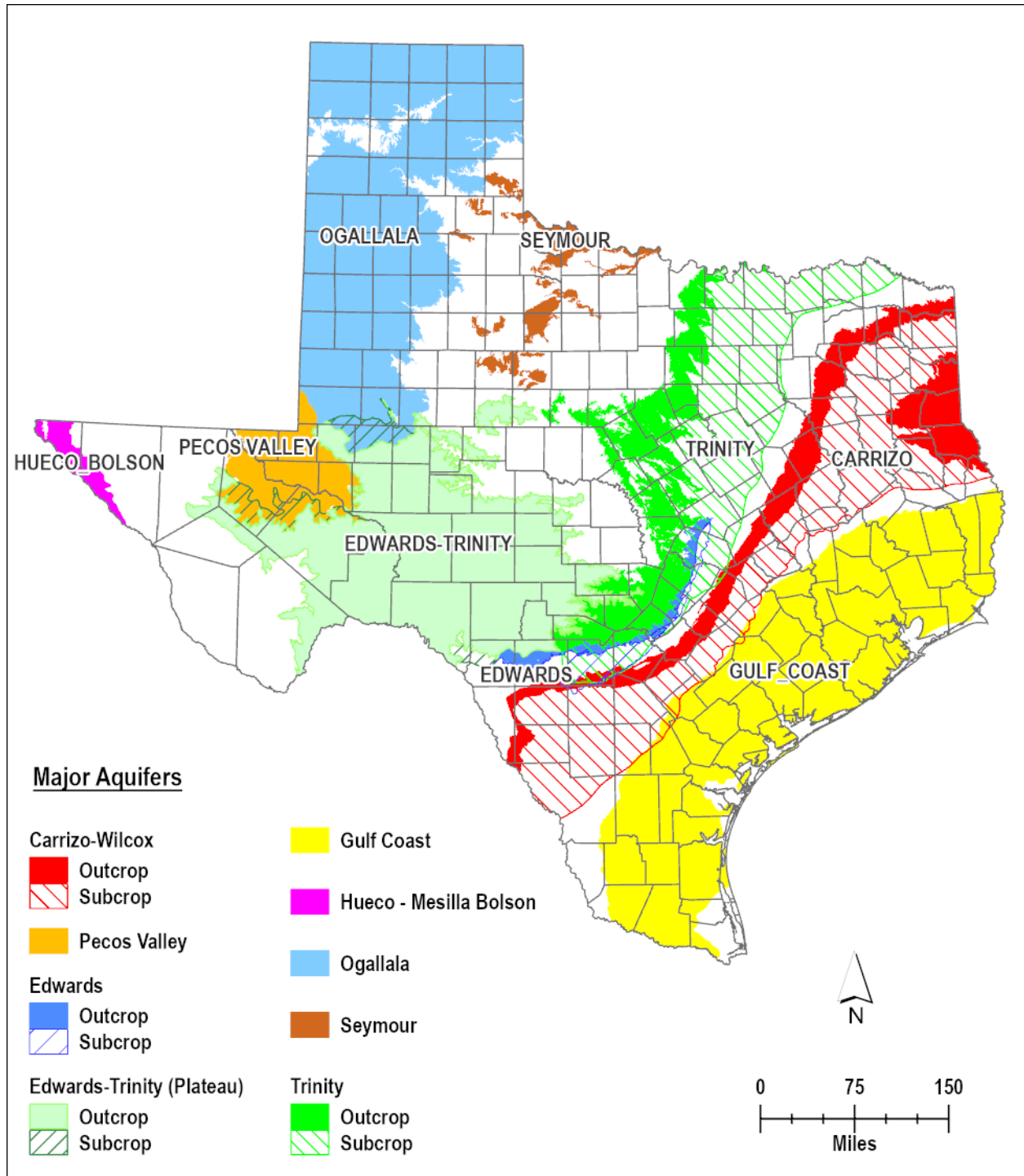


Figure 2.1-1. Major aquifers within Texas, including the Seymour Aquifer.

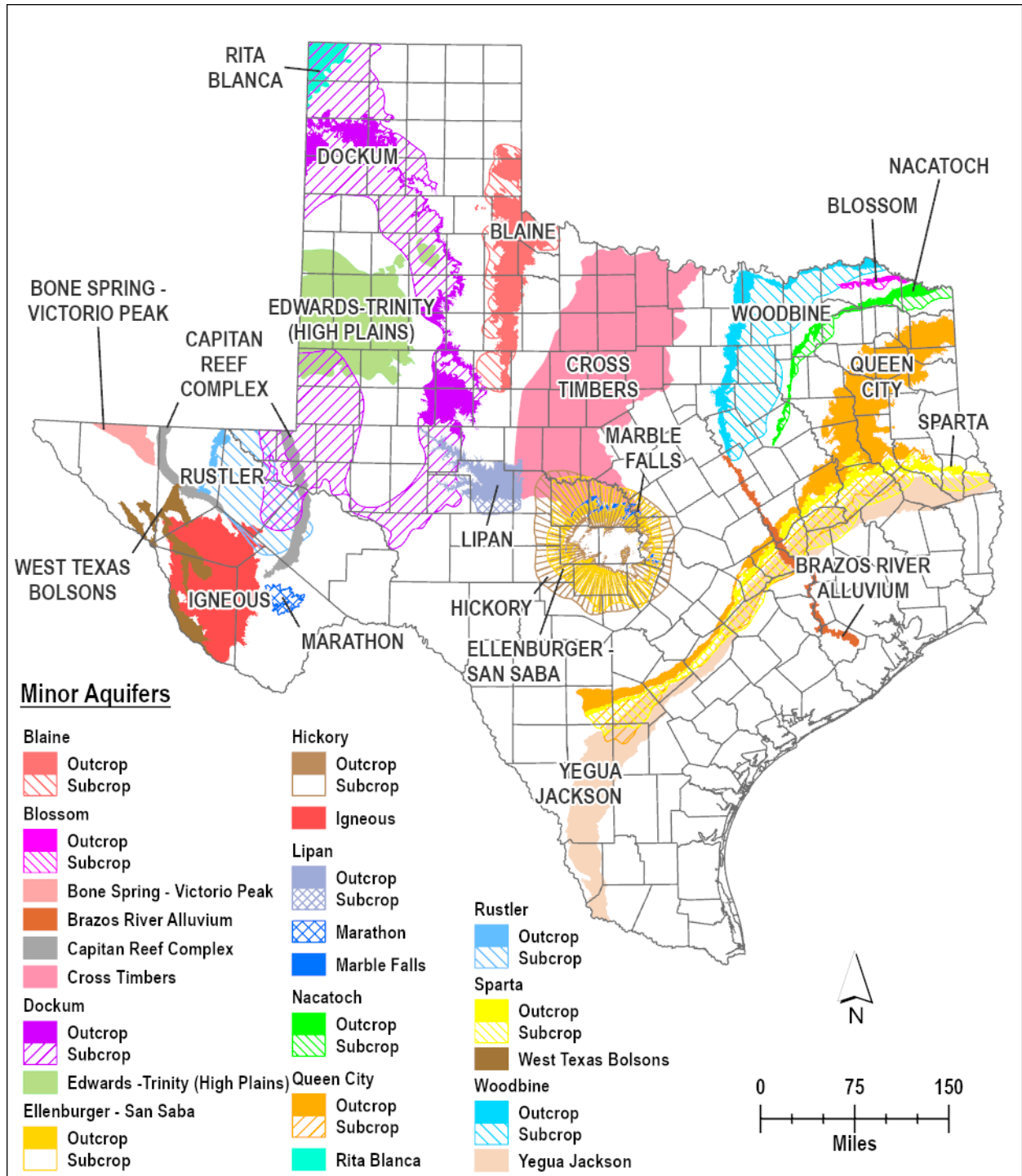


Figure 2.1-2. Minor aquifers within Texas, including the Blaine Aquifer.

2.2 Study area

The Seymour Aquifer, as defined by the TWDB, consists of isolated pods of unconsolidated alluvium deposits of Quaternary age. The aquifer, classified as a major aquifer in Texas, extends from the southern Brazos River watershed northward to the border with Oklahoma. The Seymour Aquifer overlies Permian-age deposits that generally dip to the west and strike in a north-south direction. The most important underlying formation with respect to water supply is the Blaine formation. The northern and north-central portions of this formation make up the Blaine Aquifer, which is a minor aquifer in Texas. The Blaine Aquifer consists of anhydrite, gypsum, shale, and dolomite (Baker and others, 1963). Where both aquifers are present, the Blaine Aquifer directly underlies the Seymour Aquifer with the exception of in Collingsworth, Childress, Kent, Stonewall, and northern Nolan counties, where the two are separated by the Whitehorse Group. Groundwater use for the Seymour and Blaine aquifers was 120,000 and 17,000 acre-feet per year, respectively, in 1997 (TWDB, 2002). The study area and active model boundary for the Seymour Aquifer groundwater availability model are shown in Figure 2.2-1. The individual pods of the Seymour Aquifer are shown in Figure 2.2-2. Not all of the pods are included in the groundwater availability model. Per the TWDB, only those pods shown in Figure 2.2-2 are to be included in the model. All figures in this report show only the pods included in the groundwater availability model. The extent of the Blaine Aquifer system located in the active model domain within the study area is included in Figure 2.2-2.

Groundwater model boundaries are typically defined on the basis of surface or groundwater hydrologic boundaries. The lateral boundaries of the active model area are defined to include the extent of the Seymour and Blaine aquifers. Boundaries were generally placed along topographic highs, watershed boundaries as defined by the National Hydrography Dataset Plus High Resolution, or parallel to streams or rivers, as these features should behave as lateral boundaries for the shallow flow system regime within a Tothian flow system (Tóth, 1962; 1963; 1966). This boundary, projected to plan view, is shown in report figures as a thick red or black solid line and provides the limits of the active model area. The upper model boundary is defined as ground surface across the entire model region. The lower model boundary is defined as the base of each of the Permian hydrostratigraphic units, where applicable. Further refinement to the depth of the Blaine Aquifer and the two remaining Permian-age hydrostratigraphic units lower model boundary was developed with the brine interface mapped in the Brackish Resources Aquifer Characterization Study developed for the Blaine Aquifer (Finch and others, 2016). An average depth to the brine interface mapped in Finch and others (2016) was used to augment the lower model boundary for all Permian hydrostratigraphic units where the brine interface data was not available to represent better the base of the local flow system as described within a local (shallow) Tothian flow system across the entire model domain (Tóth, 1962; 1963; 1966).

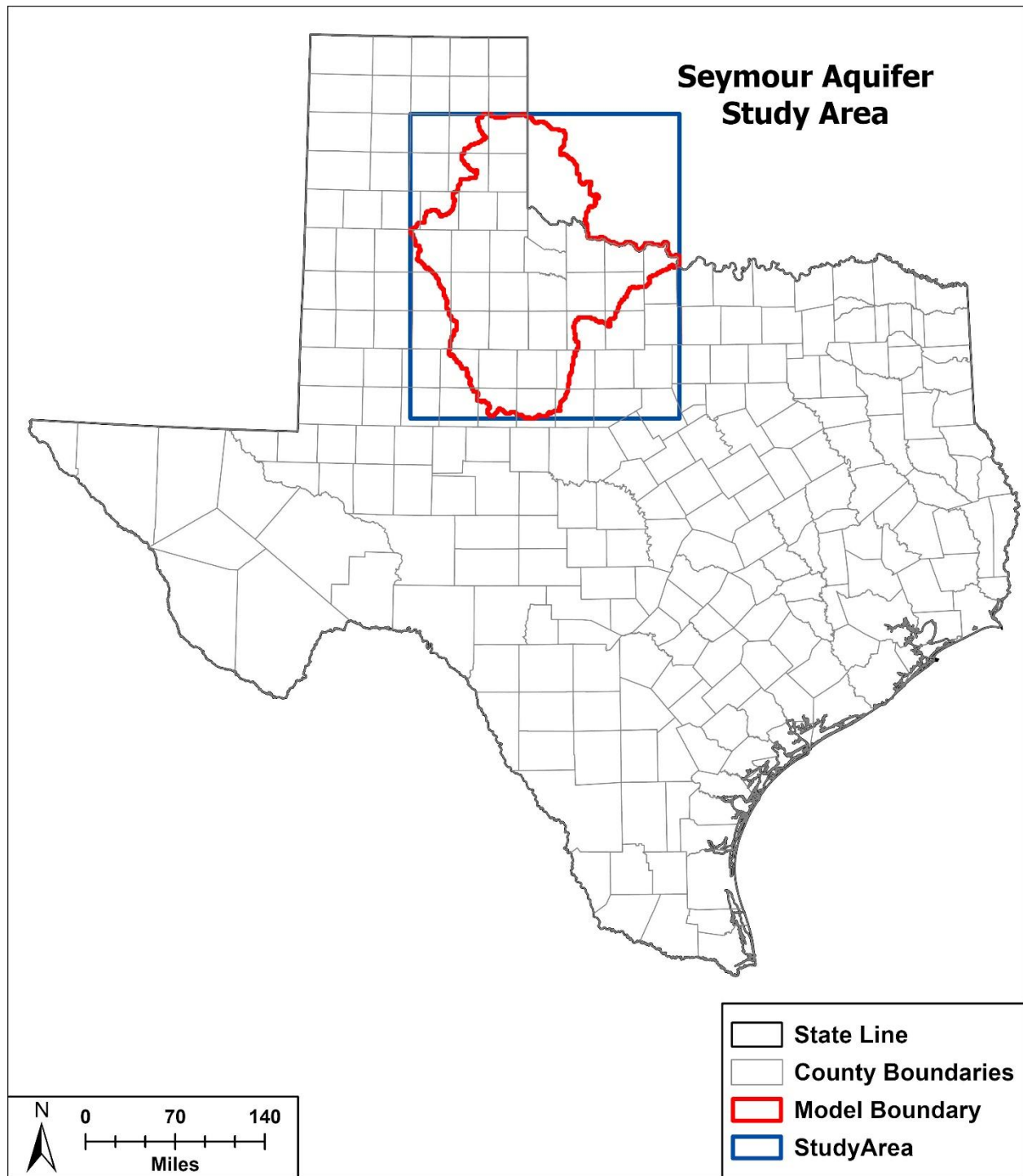


Figure 2.2-1. Location of the study area.

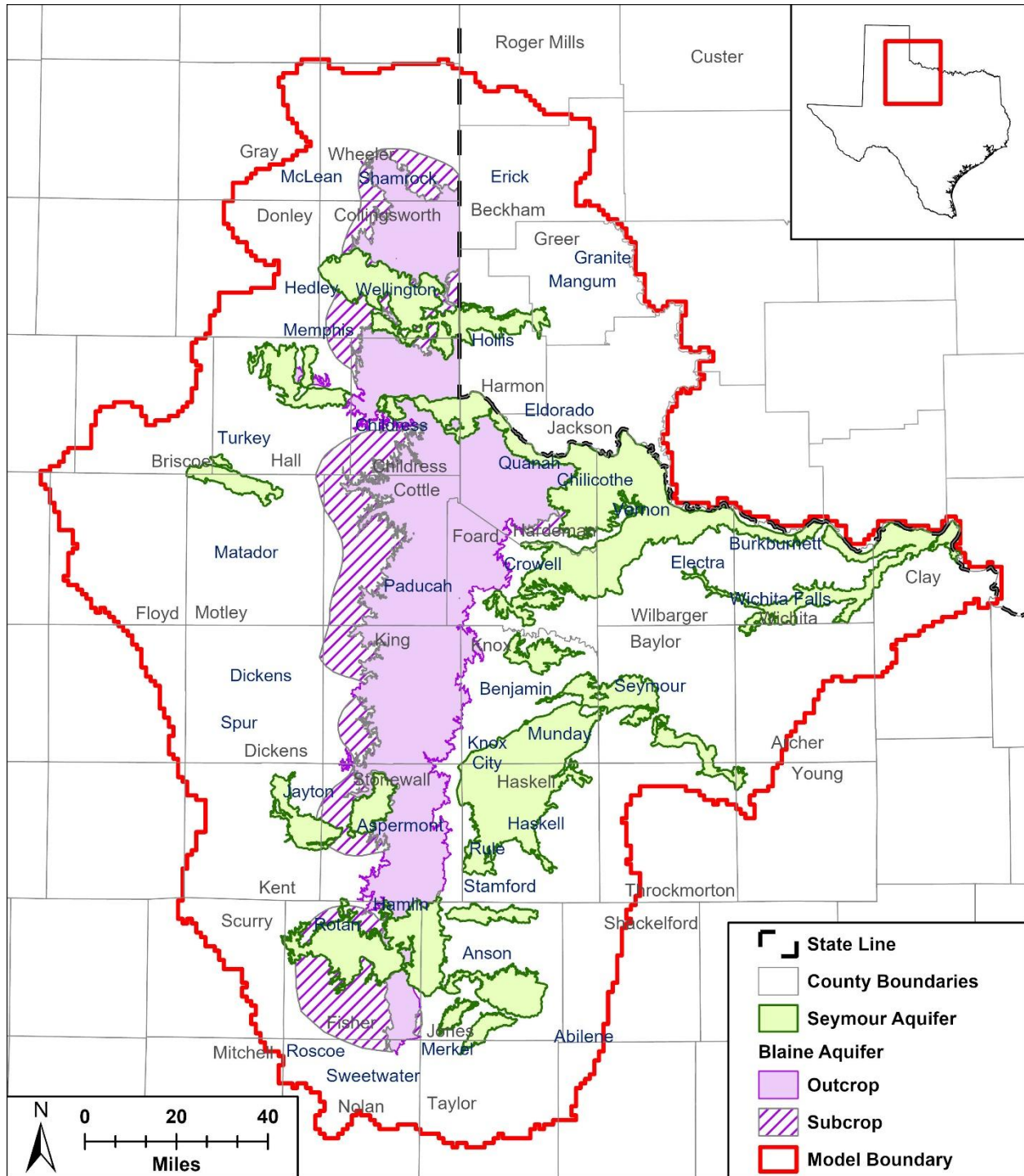


Figure 2.2-2. Location of the study area with Seymour and Blaine Aquifer extents.

Figure 2.2-3 shows the counties, roadways, cities, and towns included in the study area. All or part of 39 Texas counties and eight Oklahoma counties are included in the active model area.

The active model area encompasses all or part of five regional water planning group areas (RWPA) shown on Figure 2.2-4. From north to south, they are (1) the Panhandle RWPA (Region A), (2) the Llano Estacado RWPA (Region O), (3) Region B RWPA, (4) Region G RWPA, and (5) Region F RWPA. The active model area includes all or part of 10 groundwater conservation districts (GCD) and underground water conservation districts (UWCD) (Figure 2.2-5). Table 2-1 summarizes the groundwater conservation districts and underground water conservation districts in which the Seymour and Blaine aquifers are present.

A total of five groundwater management areas are located within the active model area and include the following: (1) Groundwater Management Area 1, (2) Groundwater Management Area 2, (3) Groundwater Management Area 6, (4) Groundwater Management Area 7, and (5) Groundwater Management Area 8 (Figure 2.2-6).

Table 2-1. Groundwater (GCD) and underground water conservation districts (UWCD) in which the Seymour and Blaine aquifers are present.

Seymour Aquifer	Blaine Aquifer
Gateway Groundwater Conservation District	Gateway Groundwater Conservation District
Rolling Plains Groundwater Conservation District	Rolling Plains Groundwater Conservation District
Mesquite Groundwater Conservation District	Mesquite Groundwater Conservation District
Clear Fork Groundwater Conservation District	Panhandle Groundwater Conservation District
	Wes-Tex Groundwater Conservation District
	Clear Fork Groundwater Conservation District

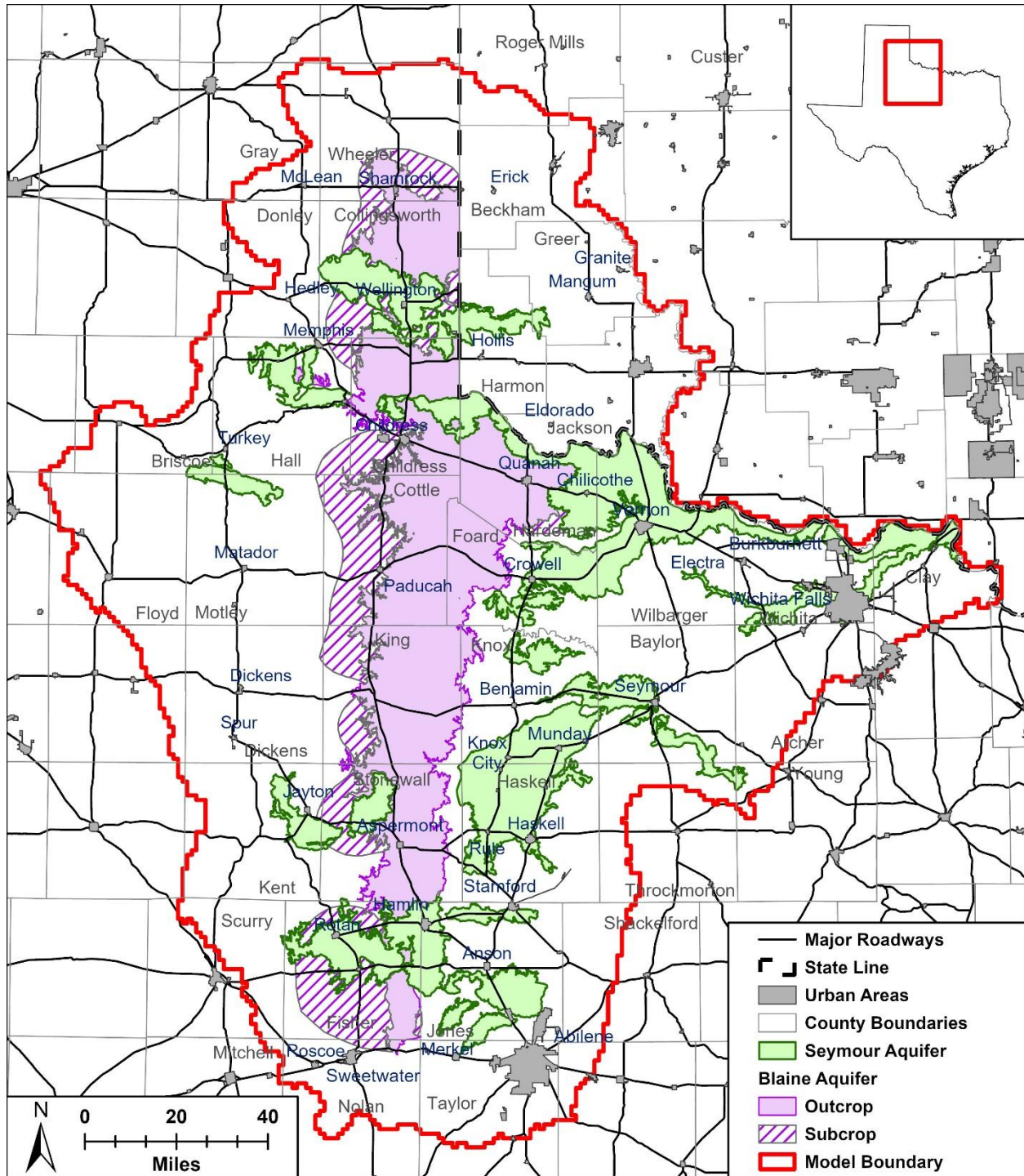


Figure 2.2-3. County boundaries, cities, roadways in the study area.

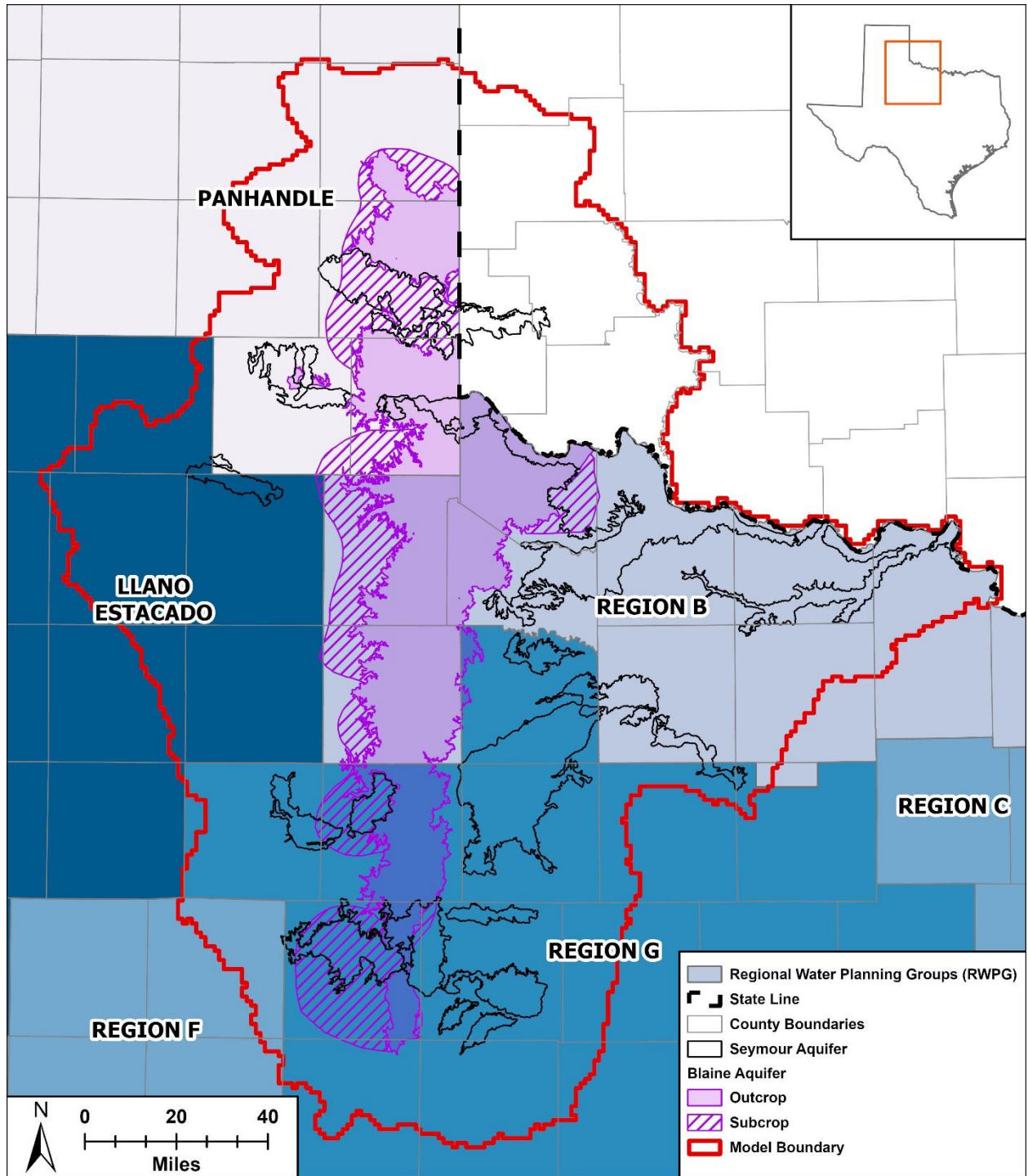


Figure 2.2-4. Regional water planning group areas (RWPG) in the study area.

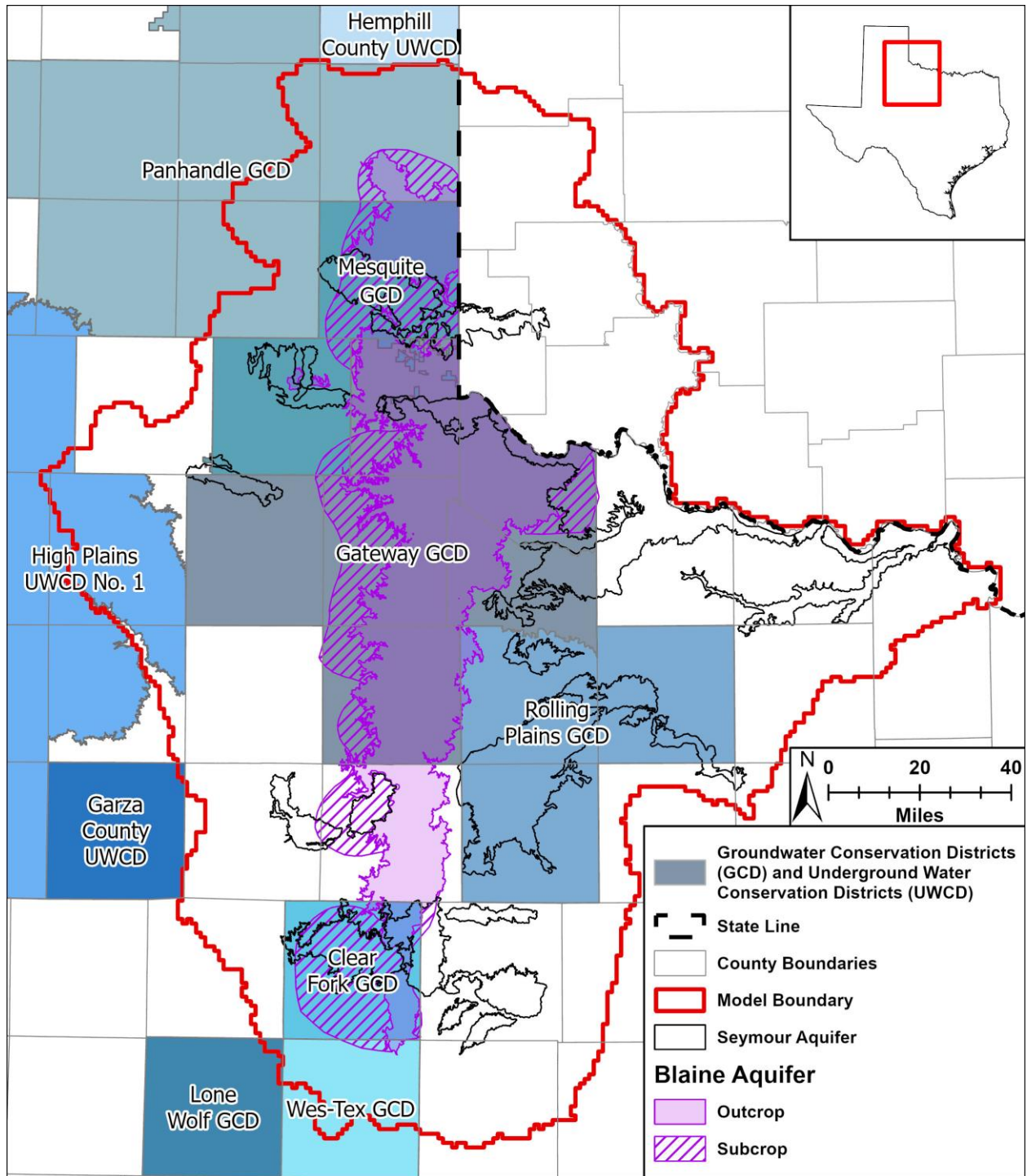


Figure 2.2-5. Groundwater conservation districts (GCD) and underground water conservation districts (UWCD) in the study area.

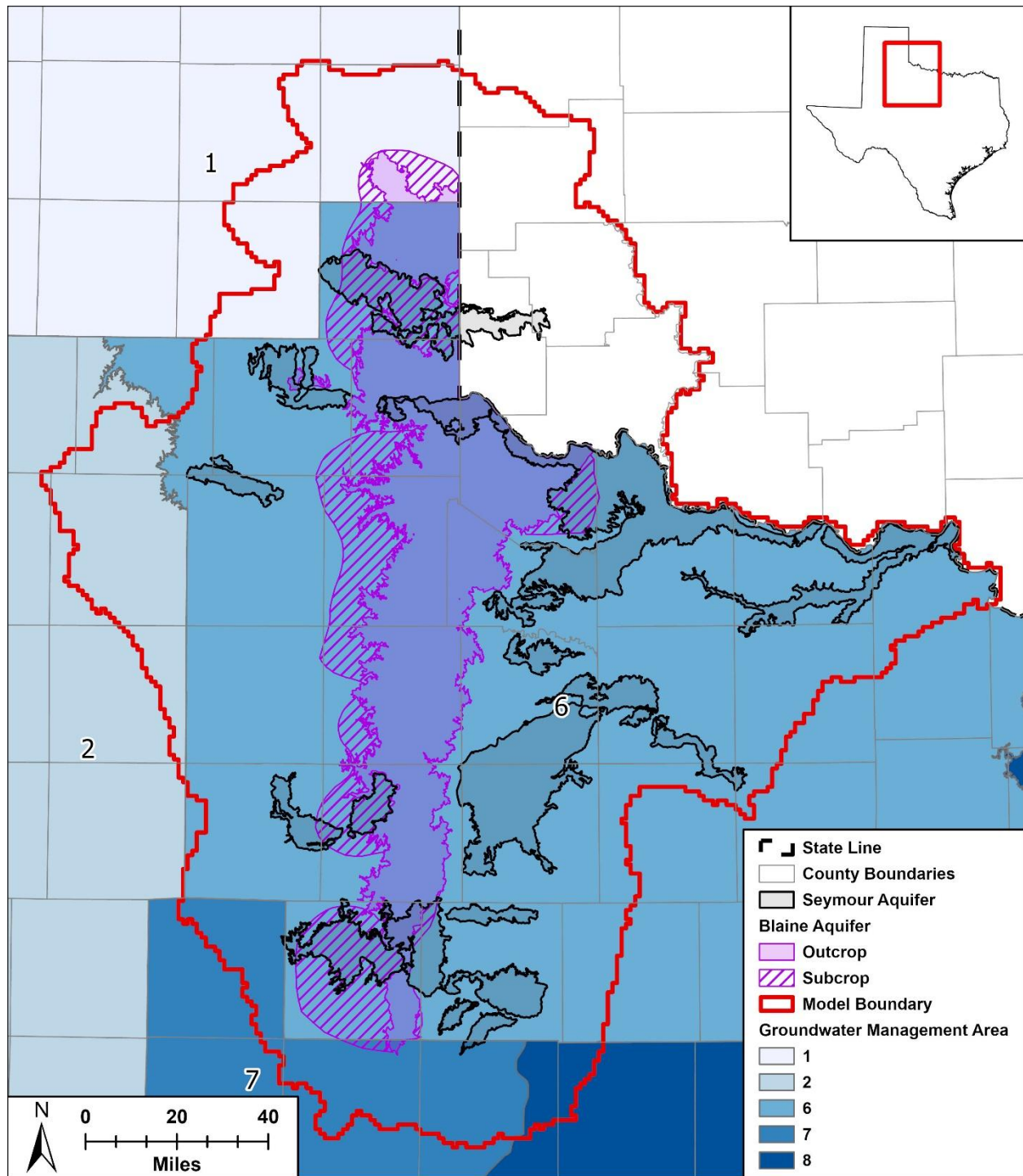


Figure 2.2-6. Groundwater management areas in the study area.

The study area intersects two river authority regions: (1) the Red River Authority of Texas and (2) the Brazos River Authority. The major river basins in the active model area are the Red and Brazos River basins (Figure 2.2-7). The locations of rivers, streams, lakes, and reservoirs in the study area are shown in Figure 2.2-8.

Climate is the major control on flow in rivers and streams. The primary climatic factors are precipitation and evapotranspiration (water not available for recharge to the aquifer due to evaporation or interception and use by the biological processes of plants). For all but the major rivers, flow in the rivers throughout the model area is generally episodic with extended periods of low-flow or no-flow conditions. In general, most rivers within the active model area tend to gain flow from the adjacent geology. Table 2-2 lists the river basins in the study area along with the river length in Texas, the river basin area in Texas, and the number of major reservoirs within the river basin in Texas.

Table 2-2. River basins in the Seymour and Blaine groundwater availability model study area (after Wermund, 1996).

River Basin	Texas River Length (miles)	Texas River Basin Drainage Area (square miles)	Number of Major Reservoirs
Brazos	840	42,800	19
Red	680	30,823	7

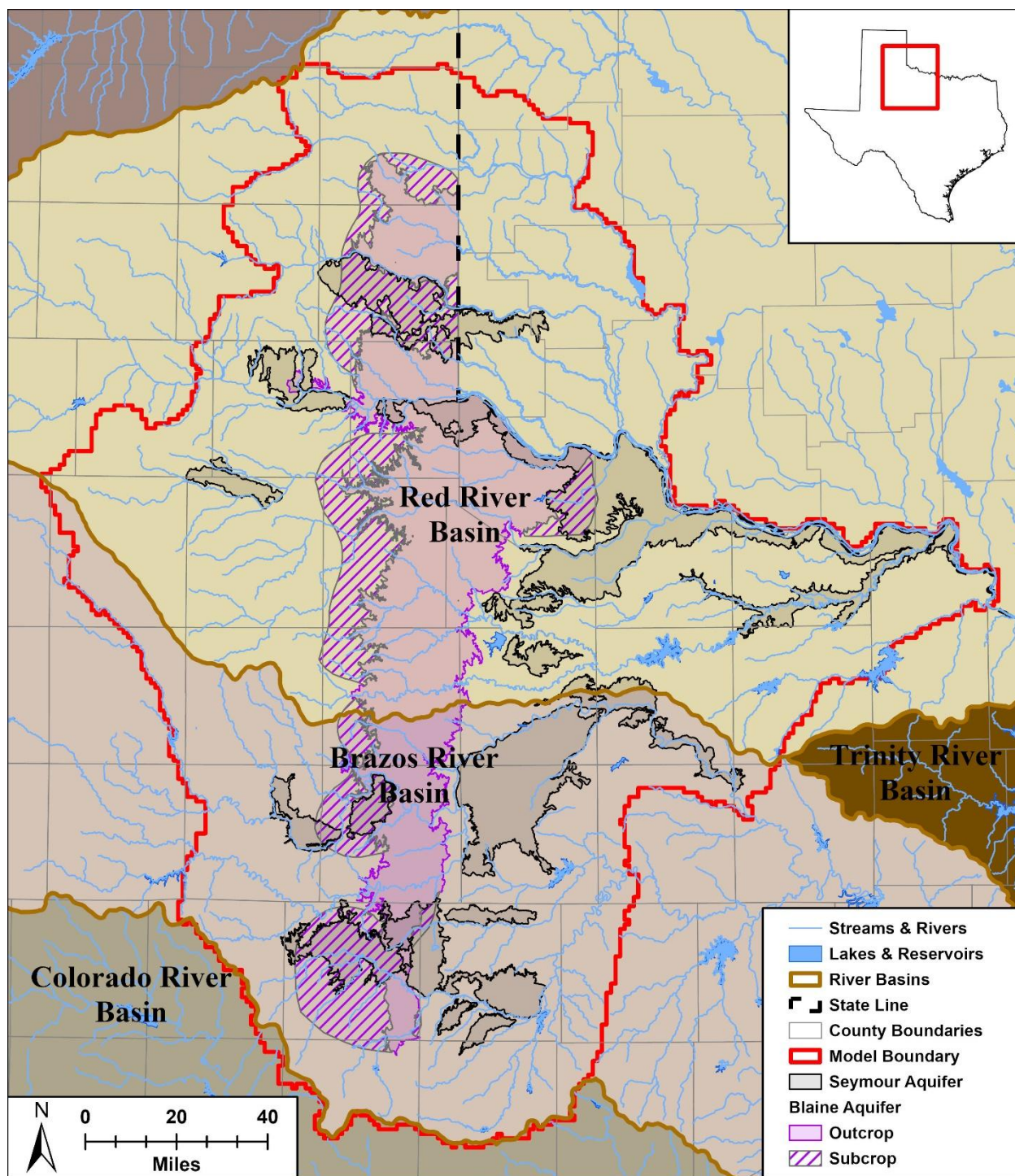


Figure 2.2-7. Major river basins in the study area.

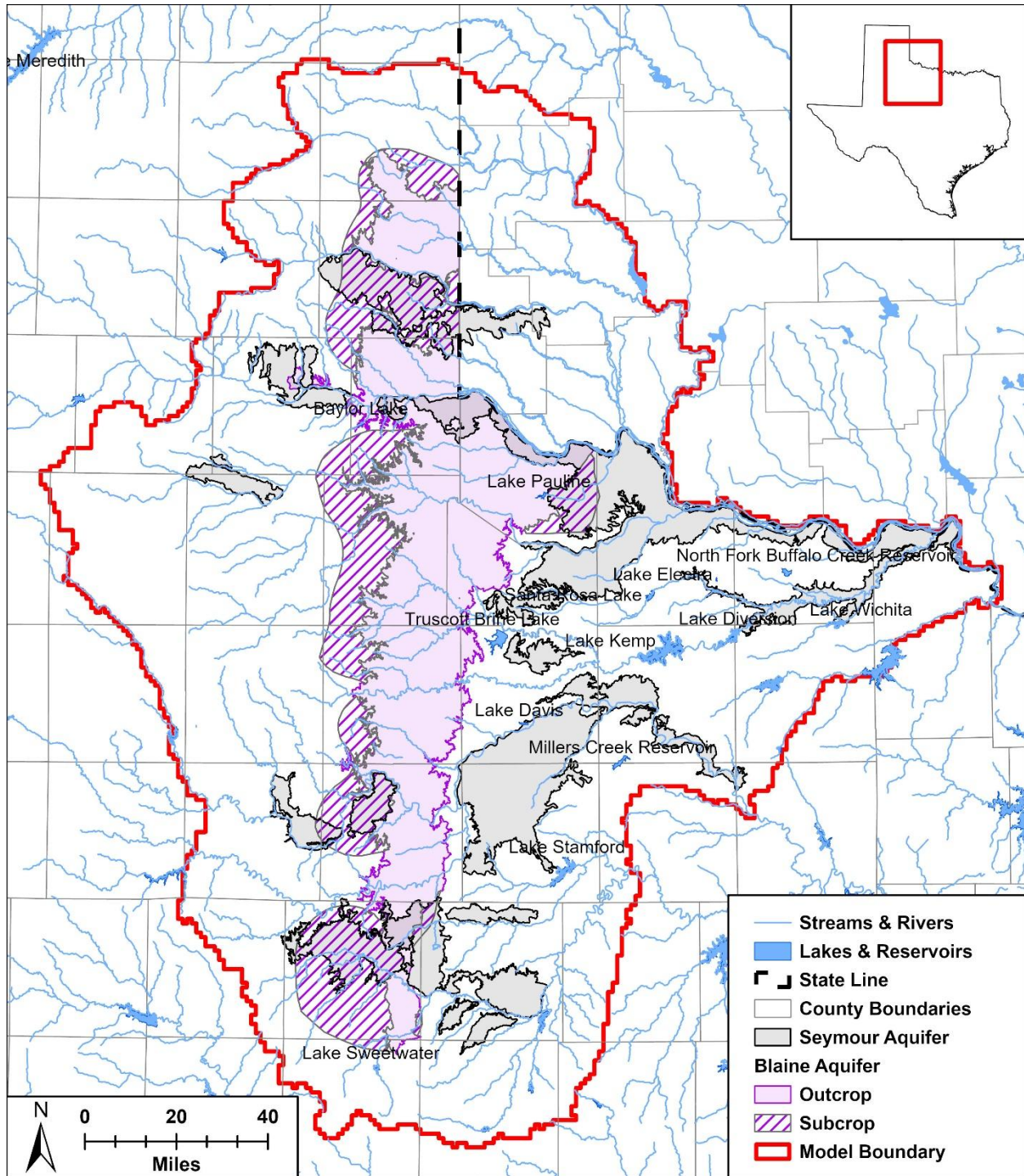


Figure 2.2-8. Rivers, streams, lakes and reservoirs in the study area.

Figure 2.2-9 shows the surface outcrop and downdip subcrop of the major and minor aquifers in the study area. Major aquifers located in the study area include the Seymour Aquifer and small portions of the Ogallala and Edwards-Trinity (Plateau) aquifers. Note that the Seymour Aquifer is exclusively a water-table aquifer with no subcrop. Minor aquifers located in the study area include the Blaine Aquifer and small portions of the Cross Timbers, Dockum and Edwards-Trinity (High Plains) aquifers.

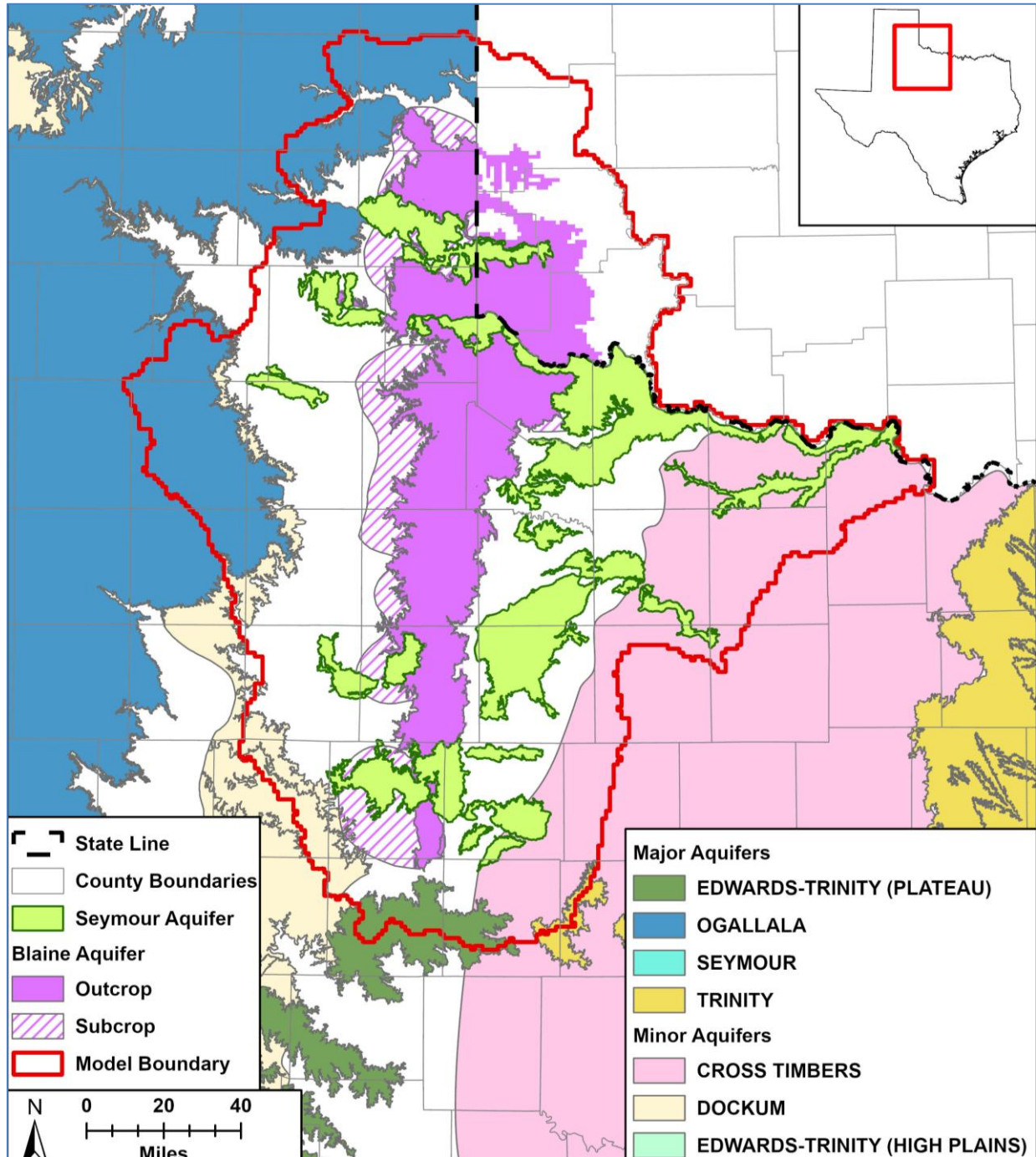


Figure 2.2-9. Active model area and adjacent aquifers.

2.3 Topography and climate

The study area is located almost completely within the North-Central Plains physiographic province (Figure 2.3-1). This province is distinguished by “An erosional surface that developed on upper Paleozoic formations...” (Wermund, E.G., 1966). The topography, which ranges in elevation from 3,800 to 700 feet above sea level from west to east, is characterized by low north-south trending ridges. The geologic structure is predominantly a westward dip with minor faults. The bedrock types for this province are limestone, sandstone, and shale.

The study area is located almost completely within the Rolling Plains ecological region, which covers an estimated 27 million acres in Texas (Texas Parks and Wildlife Department, “Rolling Plains Ecological Region”). Together with the High Plains region, the Rolling Plains represent the southern end of the Great Plains of the central United States. The Rolling Plains ecological region is bordered to the west by the High Plains ecological region, to the east by the Oak Woods and Prairies ecological region, and to the south by the Edwards Plateau ecological region (Figure 2.3-2). The northern border is less definitive and continues into the Great Plains. Changes in vegetation mark the differences between the High Plains and the Rolling Plains in Texas. The study area is characterized by mesquite and oak trees with the density of trees decreasing from the southeast to the northwest. Grasses with scattered mesquite trees dominate the prairie areas, and grasses with juniper and oak trees dominate the rough and broken ground in the study area. The active model area was considered a prairie ecosystem and was populated with bison until about 1870, when the bison were removed and most of the grassland areas with level terrain were broken out for cropland (Texas Parks and Wildlife Department, “Rolling Prairie & Plains”).

Figure 2.3-3 provides a topographic map of the study area. Generally, the surface elevations decrease from west to east across the active model area. The ground-surface elevation varies from over 3,800 feet above sea level in the west on the Caprock to 700 feet above sea level in the east along the Red and Wichita river valleys. Several canyons of moderate depth are located in the western portion of the area. West to east trending river systems have created broadly incised river valleys that are up to 100 feet lower than the surrounding ground. Erosion by these river systems has created the discrete pods of Quaternary-age alluvial deposits making up the Seymour Aquifer.

The climate in the active model area is classified as Modified Marine (Texas A&M University, “The Climate of Texas”). Onshore flow of air from the Gulf of Mexico causes the marine climate. Distinctions in the climate occur based on the moisture content of the maritime air. Air from the Gulf of Mexico decreases in moisture content from east to west as it travels across the state. Intrusion of continental air into the maritime air occurs seasonally and also affects the moisture content of the air. In Texas, the Modified Marine climate is classified as Subtropical, which is further divided into Humid, Subhumid, Steppe, and Arid. Over the study area, the subdivision Subhumid is applied. A Subtropical Subhumid climate is characterized by long, hot

summers and moderately severe winters. In general, most rainfall occurs during the growing season from April through October. Often, rainfall is heavy over short periods of time. This leads to occasional severe flooding and significant periods of drought. The most extensive drought on record in the study area was in the early 1950s. Portions of the active model area (Baylor, Haskell, and Knox counties) have experienced drought conditions since 1998. Similar drought conditions to the 1950s drought were experienced in 2011, which may provide a good analog for understanding impacts to available water supplies from drought conditions. Using 2011 as a drought of record analog is advantageous due to the increased availability of data across the model area. This can facilitate better understanding of the system under drought conditions and better constrain the model during calibration. The 2011 drought is of similar duration to the drought in the 1950s but not quite as severe. More generalized subdivisions of unique climate regions in the active area of the model domain are shown in Figure 2.3-4. From west to east, these include: (1) High Plains, (2) Low Rolling Plains, and (3) North Central. Average annual air temperature across the study area is mostly between 60 and 65 degrees Fahrenheit as illustrated in Figure 2.3-5.

The average annual net pan evaporation rate in the active model area is high, ranging from a low of 82 inches per year in northern Wichita and Clay counties to a high of 102 inches per year in Scurry County (Figure 2.3-6). Precipitation data are available at over 90 stations within the active model area (Figure 2.3-7). Measurement of precipitation at most gages began in the 1930s or 1940s, with some gages beginning measurements in the 1890s and early 1900s. In general, measurements are not continuous on a month by month or year by year basis for the gages. Historical average annual precipitation varies from a low of 19.8 inches in Hall County to a high of 28.9 inches in Wichita County. The absolute minimum and maximum annual precipitation within the active model area over the period of record varies from 6.0 inches in 1956 in Motley County to 53.6 inches in 1941 in Hardeman County, respectively. Annual precipitation recorded at six stations within the active model area is shown in Figure 2.3-8.

The PRISM (Parameter-elevation Regressions on Independent Slopes Model) precipitation dataset developed and presented online by the PRISM Climate Group at Oregon State University provides a good distribution of average annual precipitation across the model area based on the period from 1981 to 2023. Figure 2.3-9 provides a summary of the PRISM average annual precipitation across the model study area. Generally, the average annual precipitation decreases from the east to the west. The pan evaporation rate significantly exceeds the annual average rainfall, with the greatest rainfall deficit (approximately 78 inches per year) occurring in the central and western portion of the active model area.

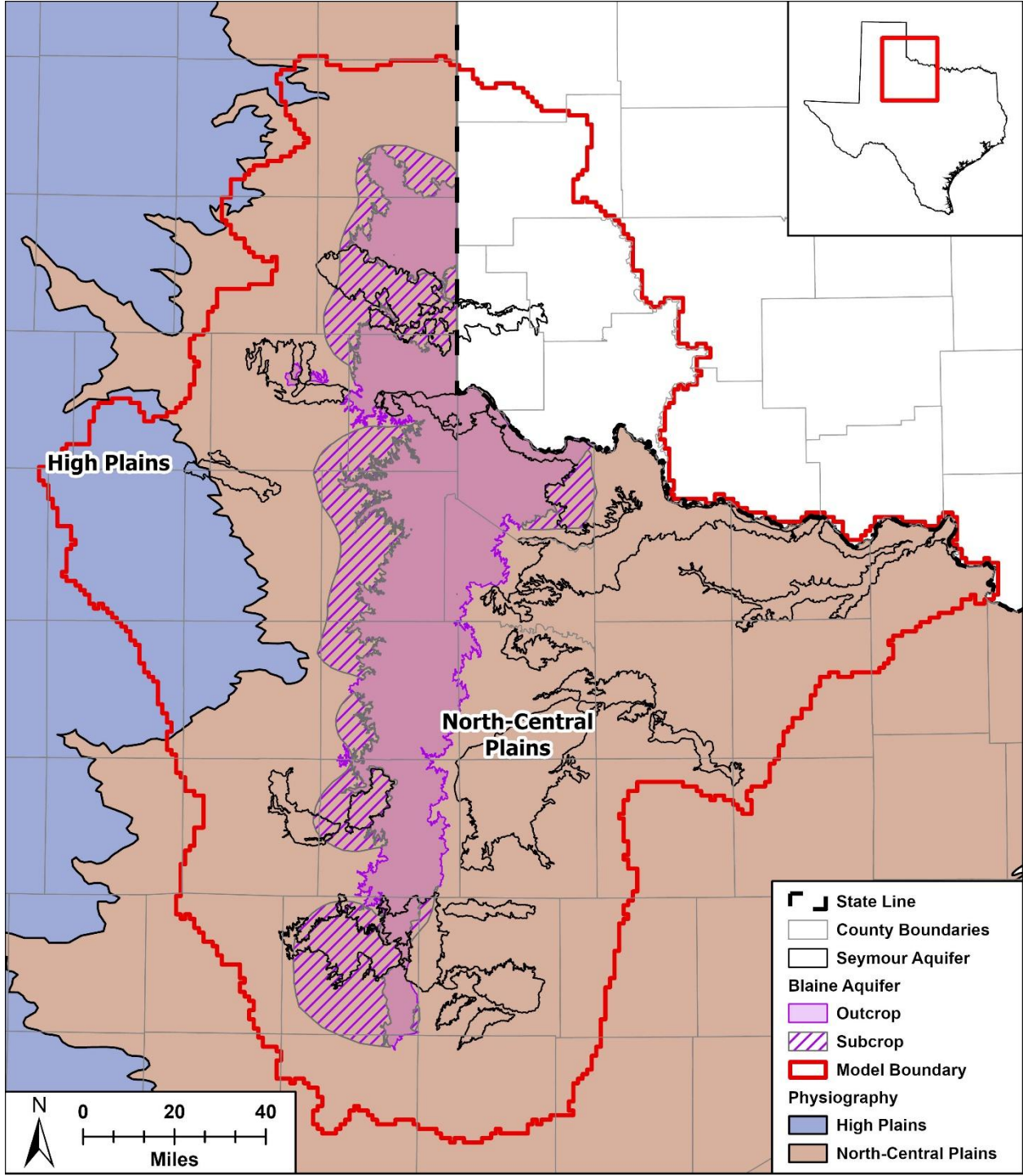


Figure 2.3-1. Physiographic provinces in the study area.

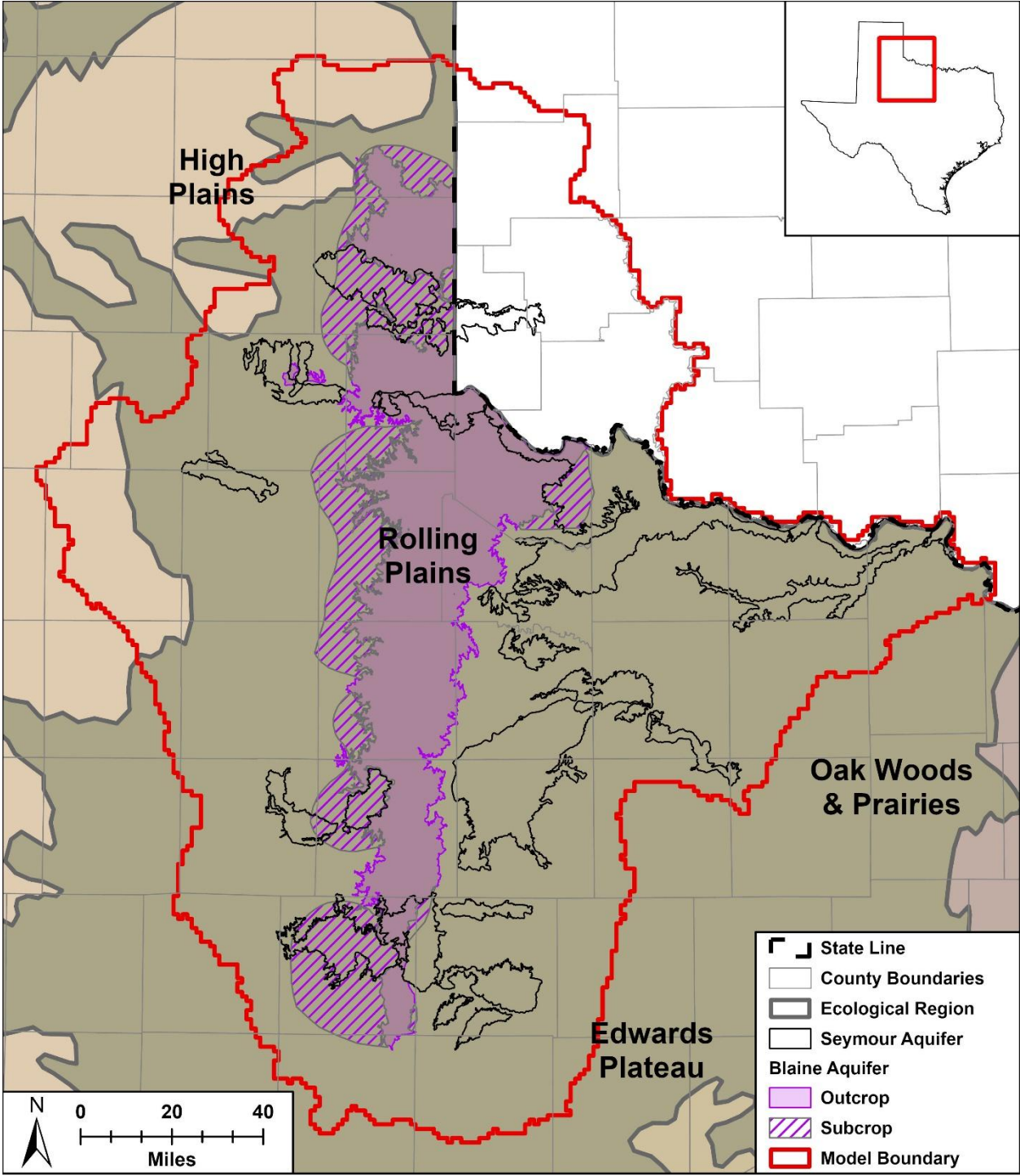


Figure 2.3-2. Ecological regions in the study area.

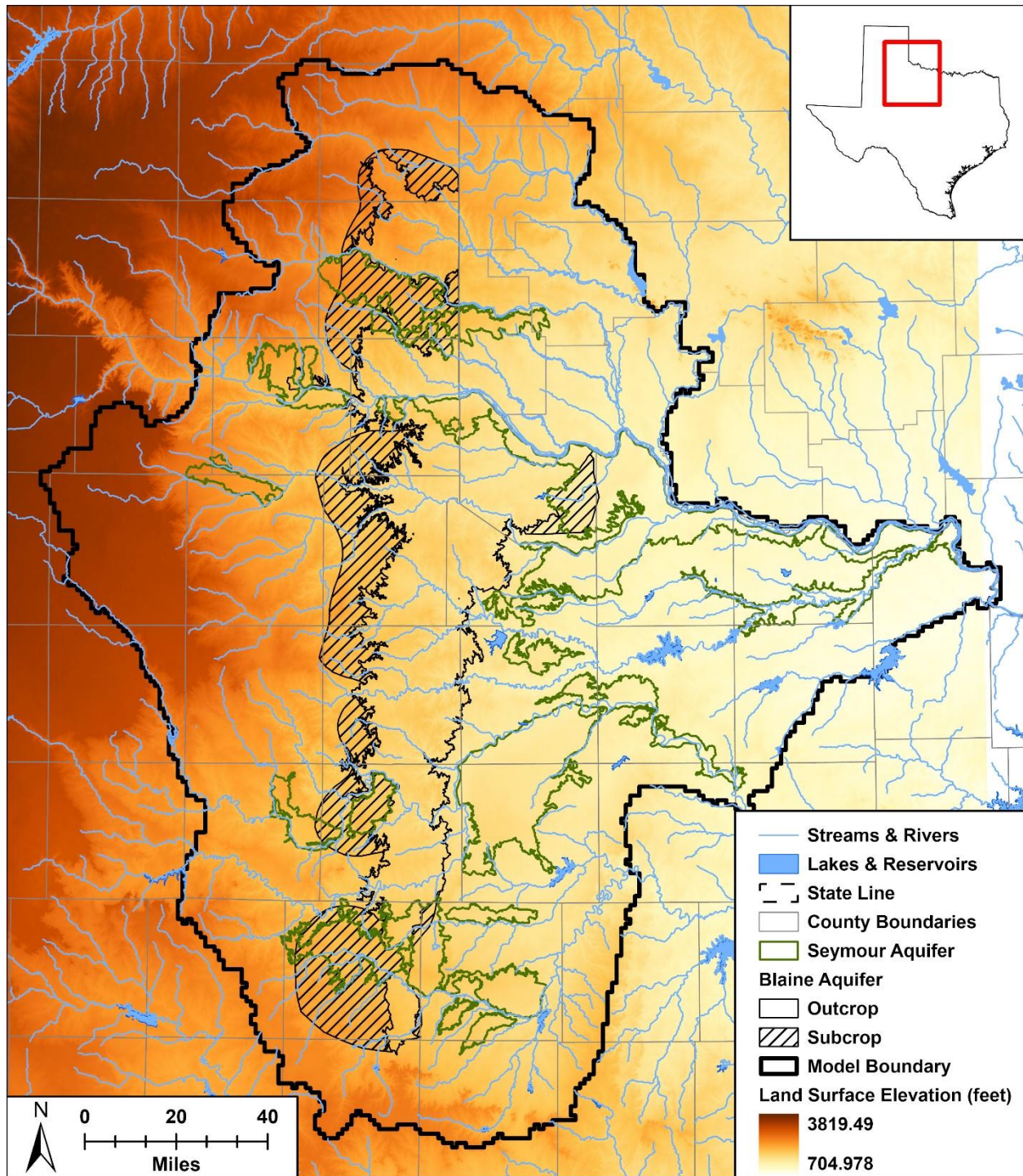


Figure 2.3-3. Topographic map of the study area. Elevation is in feet above mean sea level.

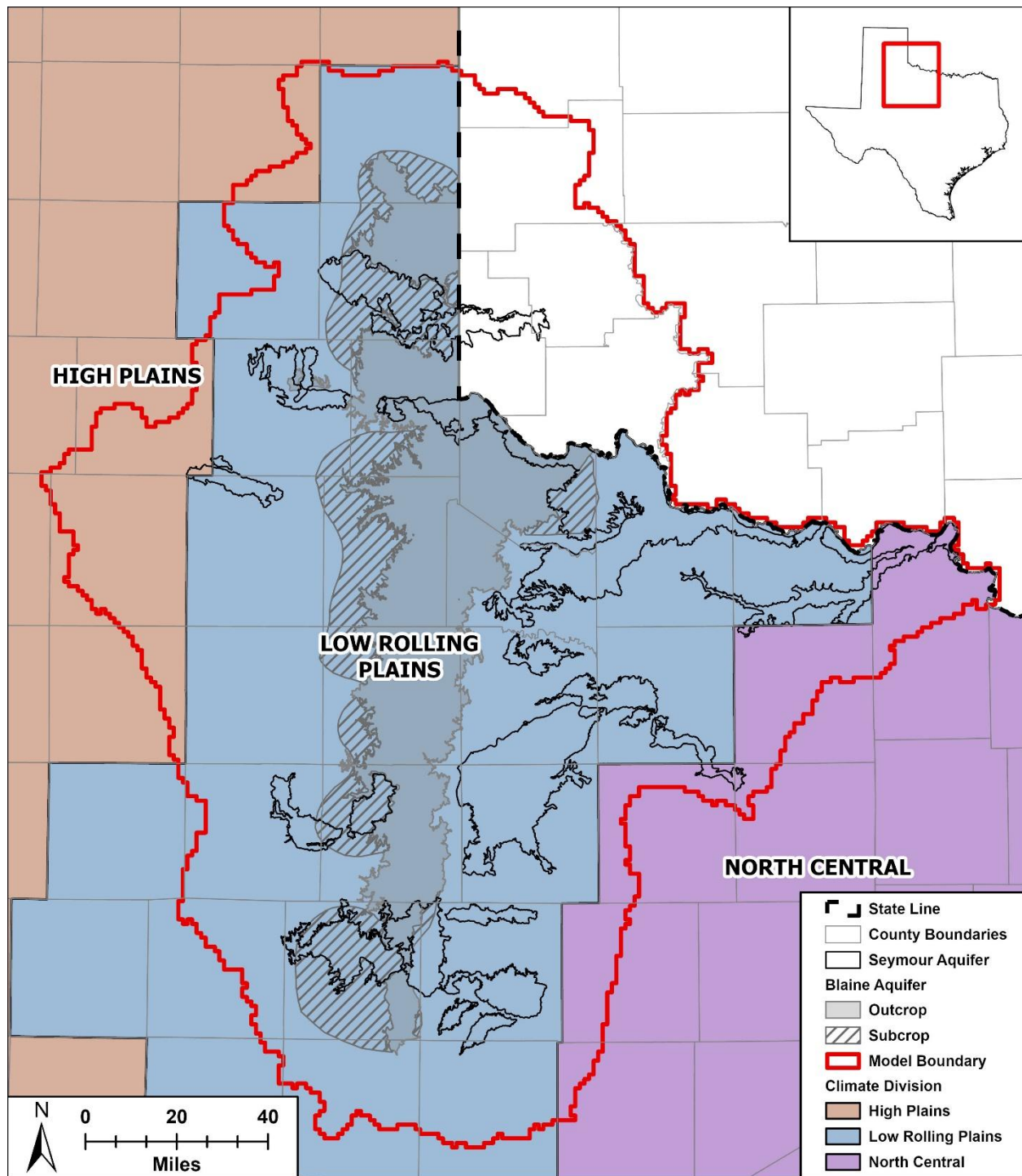


Figure 2.3-4. Climate divisions in the study area.

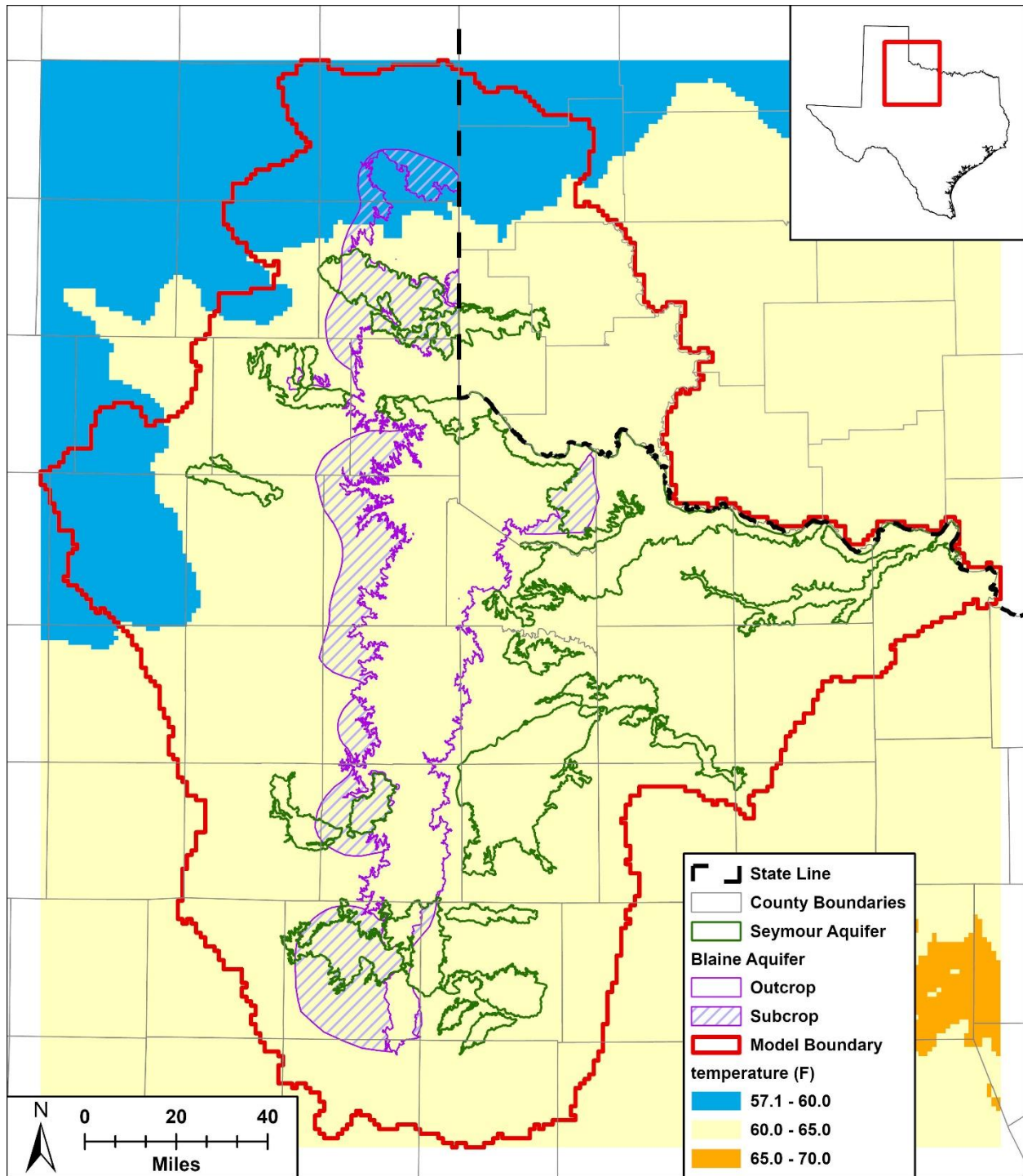


Figure 2.3-5. Average annual air temperature for the study area in degrees Fahrenheit (F) 1981-2023 (source: Oregon Climate Service, Oregon State University, PRISM dataset).

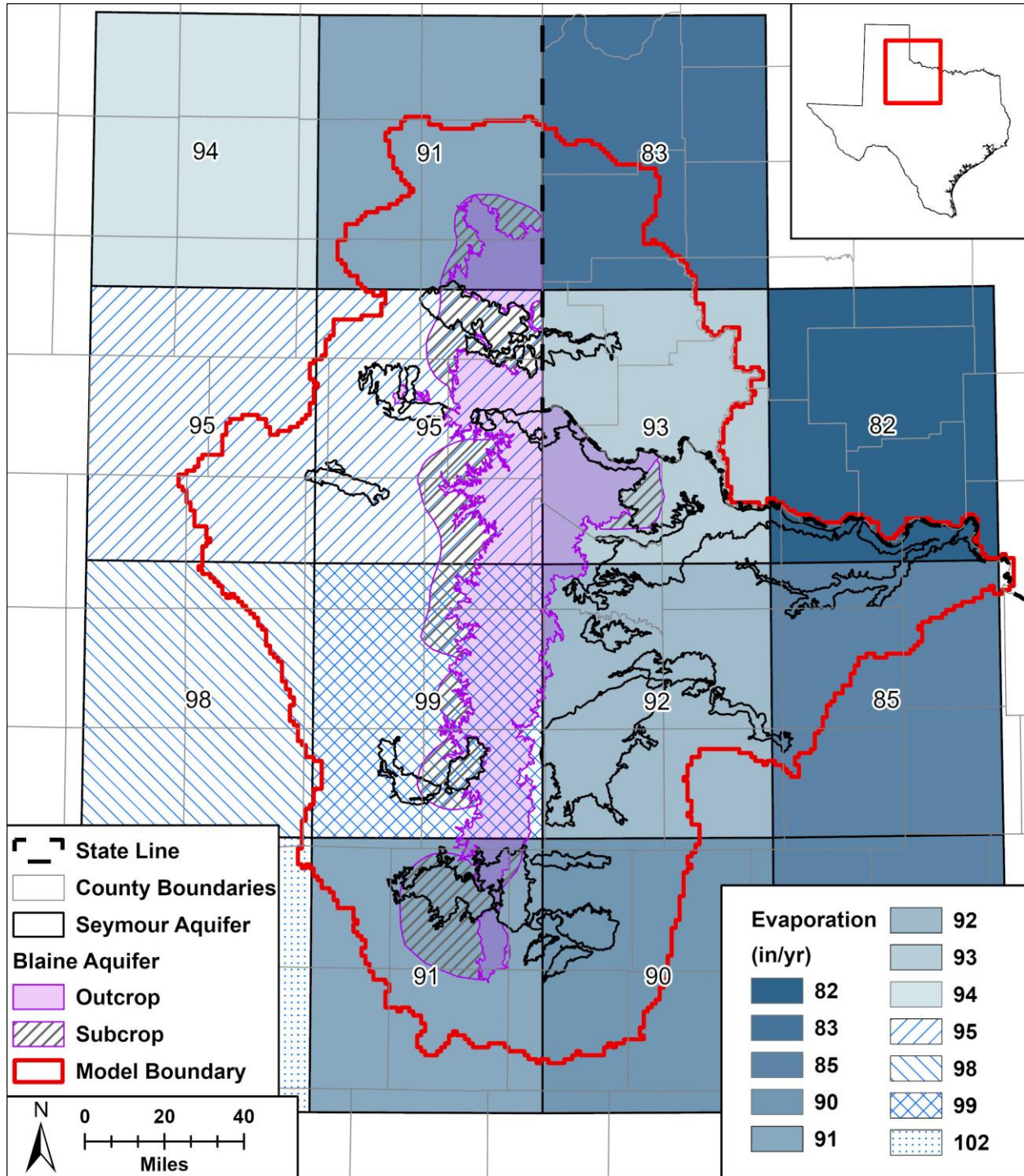


Figure 2.3-6. Average annual net pan evaporation rate in inches per year (in/yr).

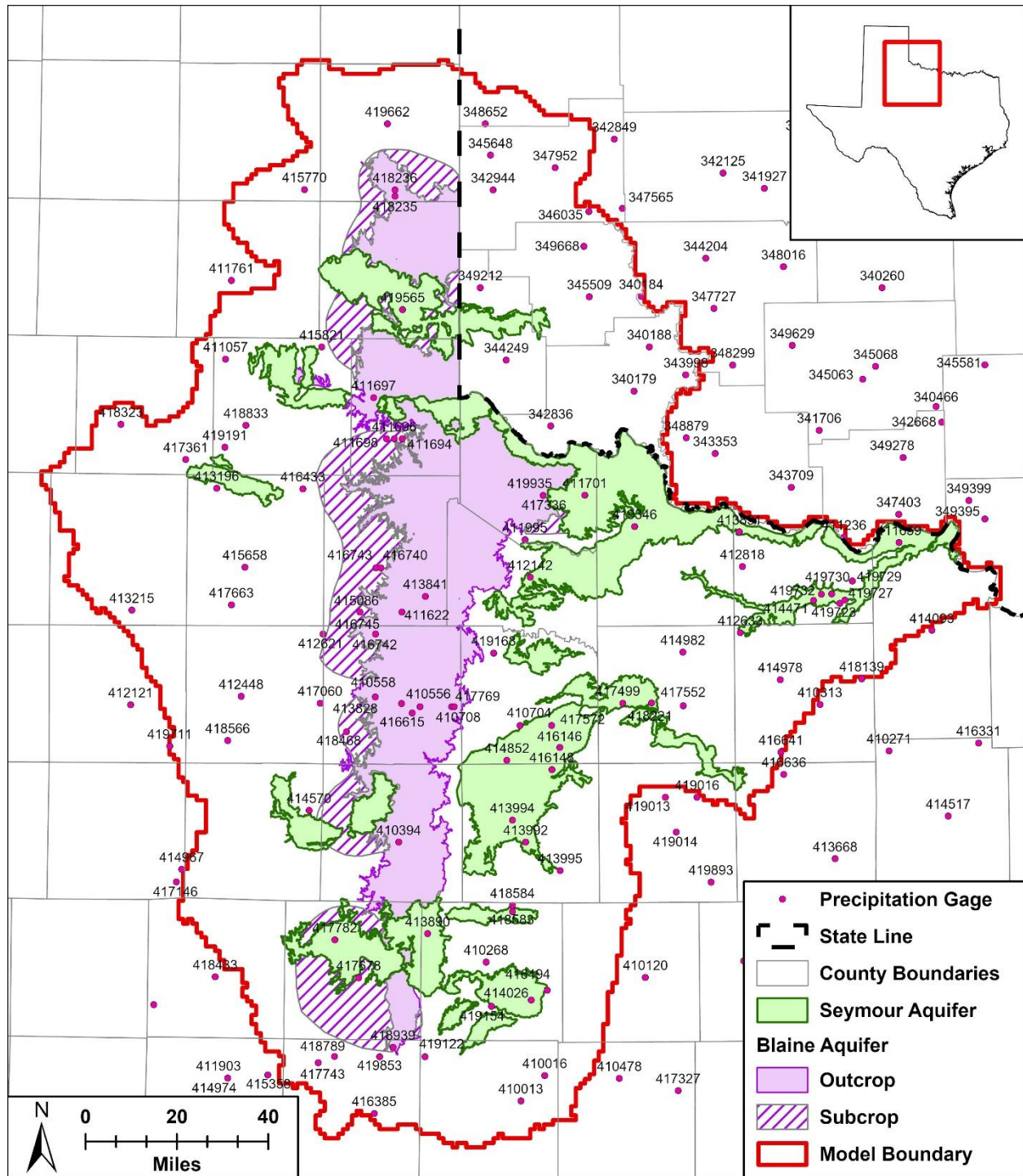


Figure 2.3-7. Location of precipitation gages in the study area. Source: online National Climate Data Center Climate Data Online (CDO) - The National Climatic Data Center's (NCDC) Climate Data Online (CDO) provides free access to NCDC's archive of historical weather and climate data in addition to station history information. | National Climatic Data Center (NCDC).

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

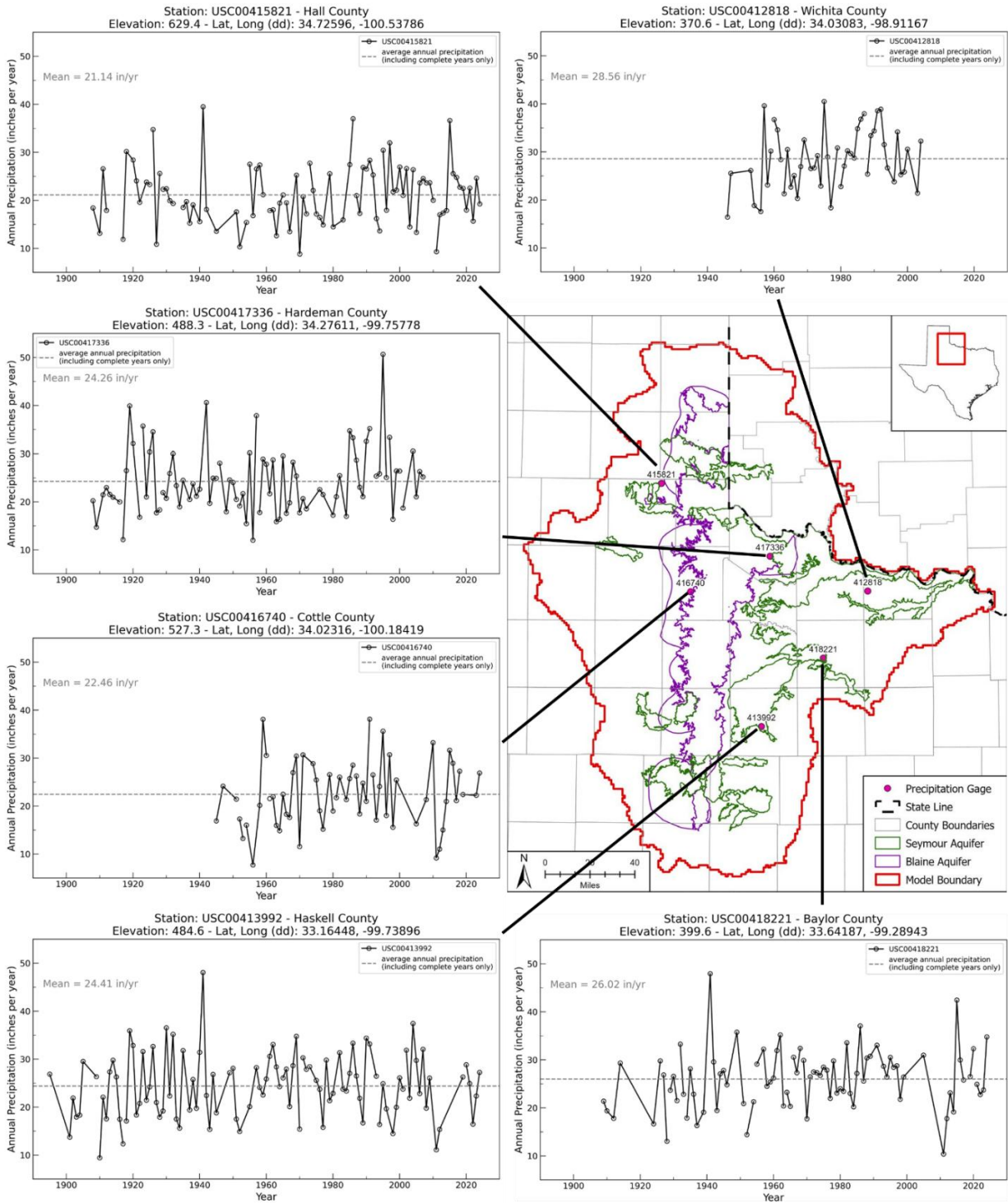


Figure 2.3-8. Annual precipitation time series for study area (source: Global Historical Climatology Network daily database, National Oceanic and Atmospheric Administration National Centers for Environmental Information). (in/yr = inches per year, lat = latitude, long = longitude, dd = decimal degrees.).

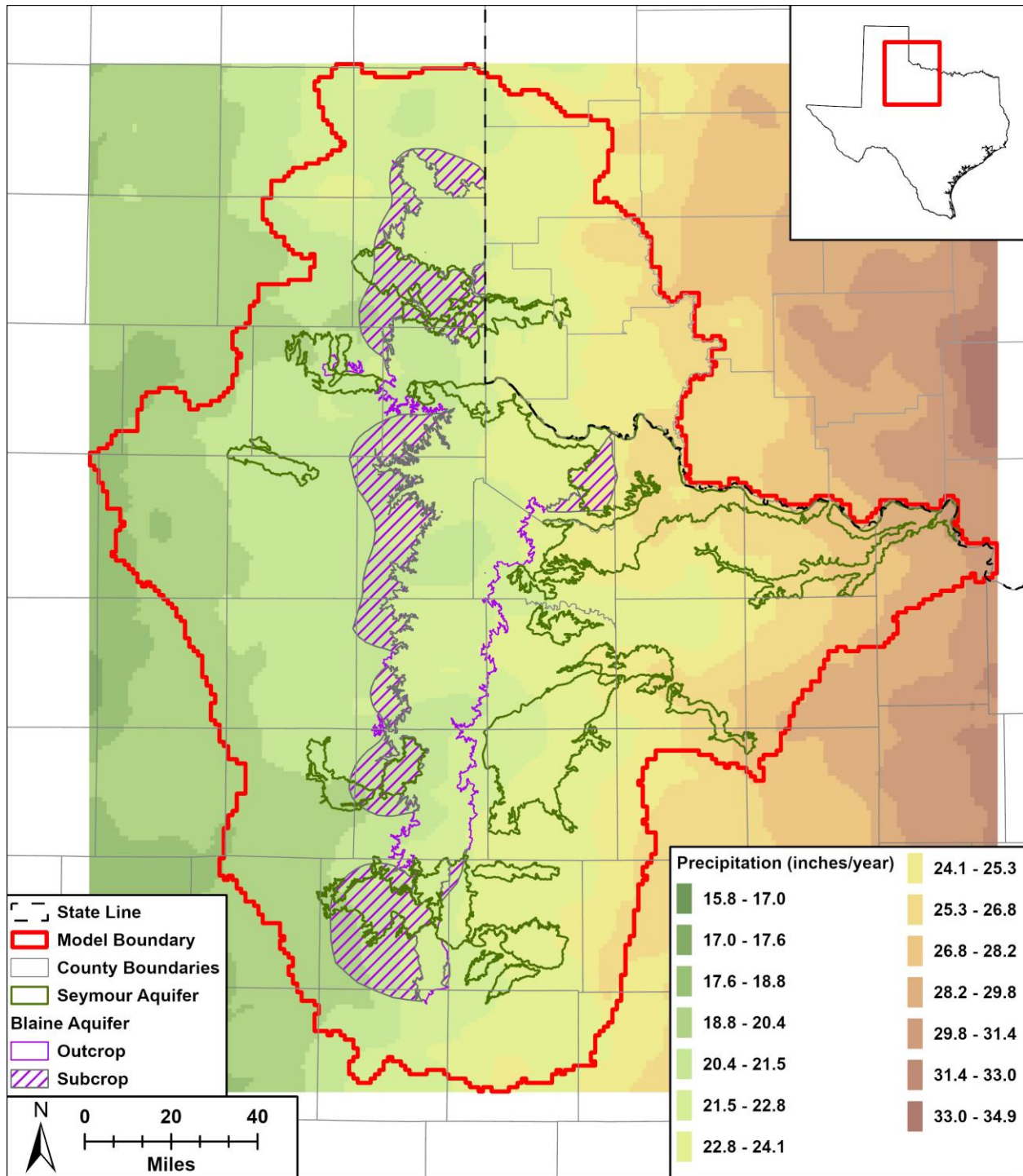


Figure 2.3-9. Average annual precipitation over the study area in inches per year 1981-2023 (source: Oregon Climate Service, Oregon State University, PRISM dataset).

2.4 Groundwater levels

Groundwater levels are important data to inform calibration of the numerical model. Data were compiled from the TWDB Groundwater Database, Submitted Driller Reports database, and the United States Geological Survey (TWDB, 2025a; TWDB, 2025b). There are 3,531 unique well locations that have at least one water level measurement in the Seymour Aquifer, though some pods are data-poor and have sparse coverage. There are 924 unique well locations that have at least one water level measurement in the Blaine Aquifer. The spatial distribution of water level measurements for both aquifers is provided in Figure 2.4-1.

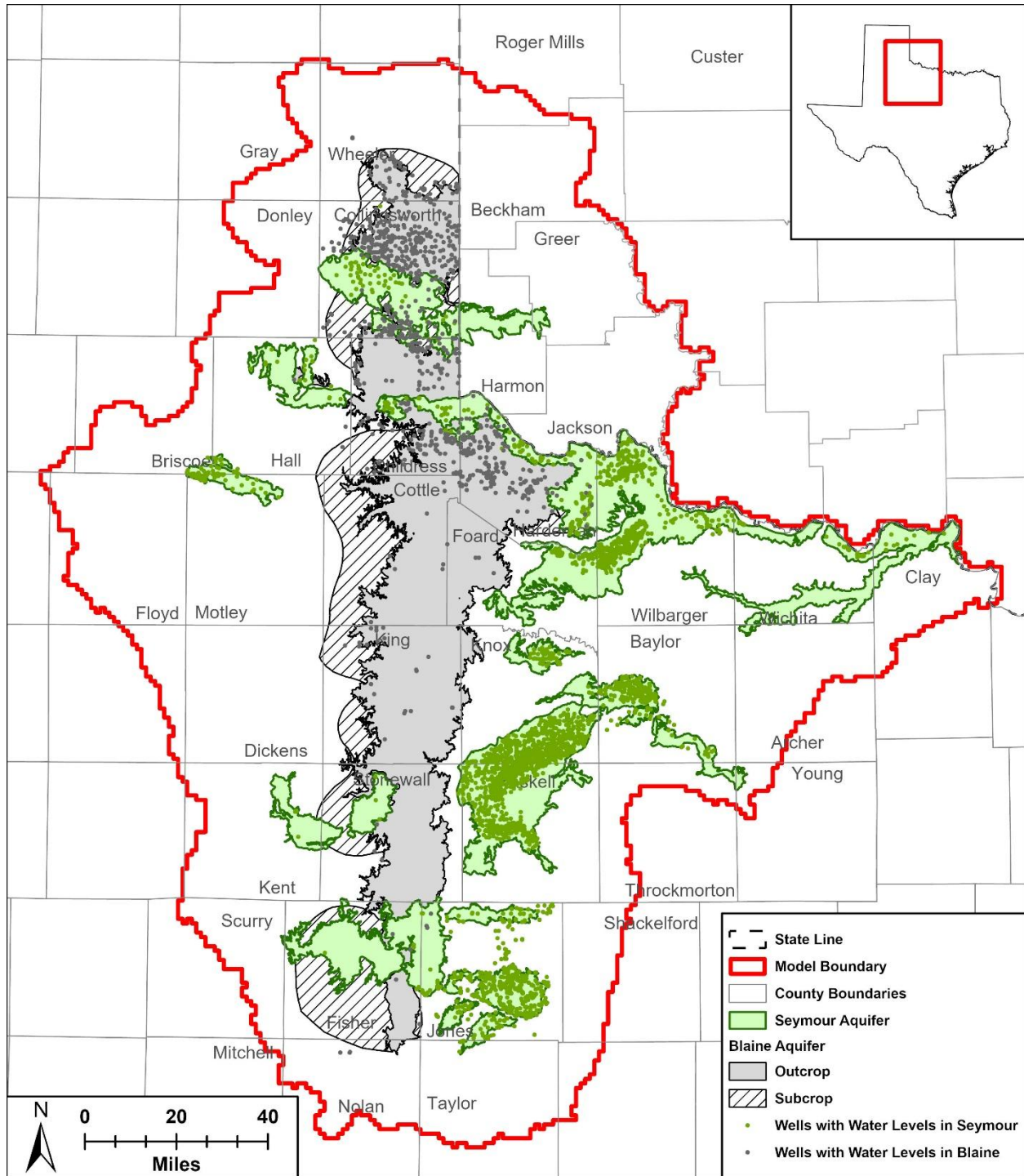


Figure 2.4-1. Wells with water level records available for the Seymour and Blaine aquifers (source: TWDB, Submitted Drillers Records, and United States Geological Survey datasets).

2.5 Stream flows

Flow in rivers and streams are important data to inform calibration of the numerical model. Data were compiled from records kept by the United States Geological Survey. There are approximately 30 United States Geological Survey stream gages in the active area of the model domain with records that generally span from the 1960s through the 1990s. There are some gages that have flow data starting as early as the 1950s and run through the 2020s to present. Mean stream flow generally appears to be intermittent at most gages where data are available. Temporal data gaps in measurements appear evident across most gages. Some gages appear to be influenced by anthropogenically-controlled processes such as stream diversions and reservoir releases. The spatial distribution of the stream gages within the active model area is shown in Figure 2.5-1.

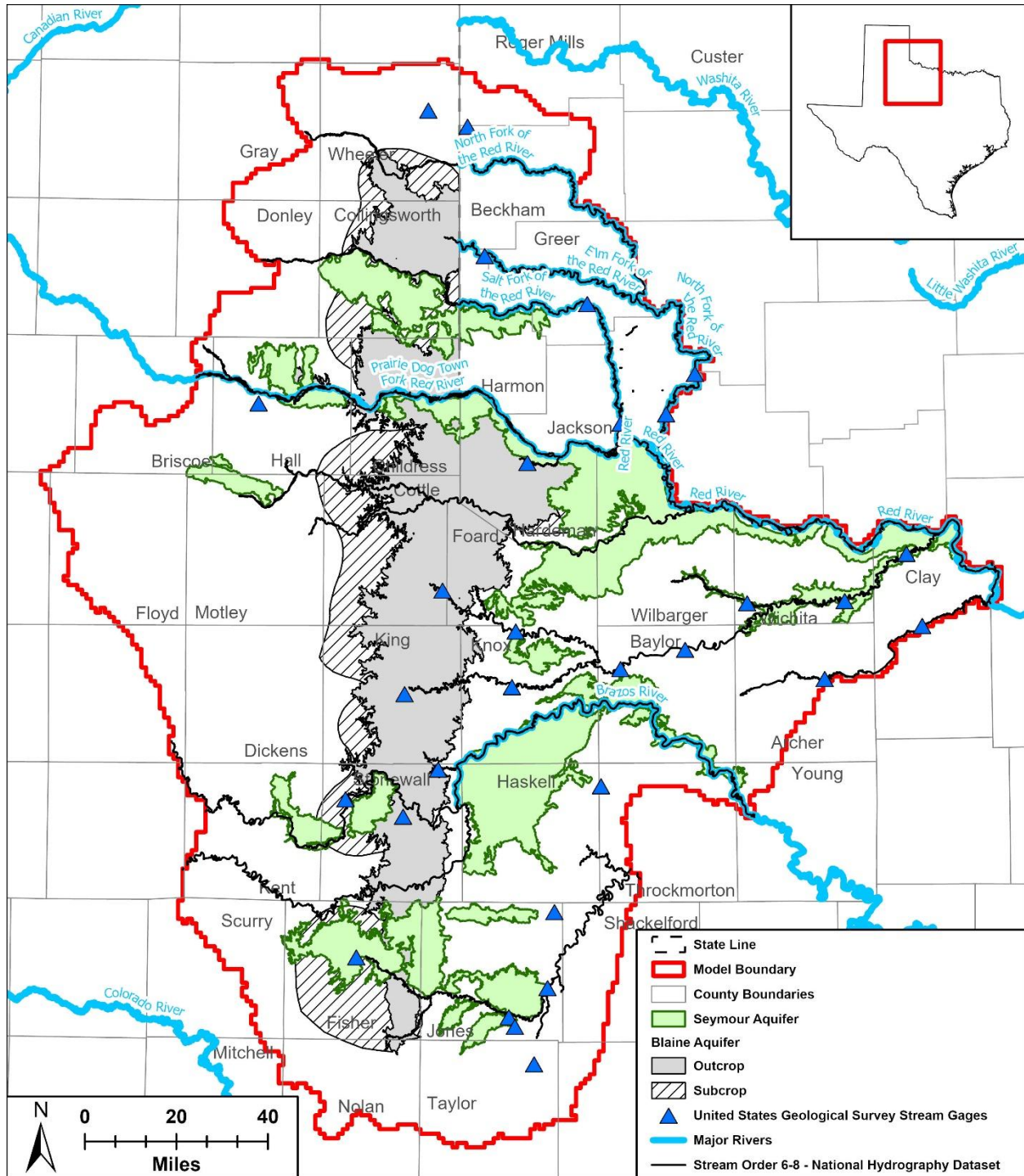


Figure 2.5-1. Stream gages with flow records available (source: United States Geological Survey).

2.6 Spring flow and seeps

Discharge occurs in areas where the water table intersects the surface at springs or seeps. These springs usually occur in topographically low areas in river valleys or in areas where hydrogeologic conditions preferentially reject recharge. Figure 2.6-1 shows the results of a literature survey for springs located within the active model area. Source data were collected from the TWDB website, Brune (1975), Brune (1981), and United States Geological Survey data from Heitmuller and Reece (2003). It should be noted that one source for spring locations (Brune, 1981) includes spring surveys for all counties in the study area except Fisher and Jones. Spring data for Oklahoma were not available. It should also be noted that there are likely thousands of undocumented smaller springs and seeps.

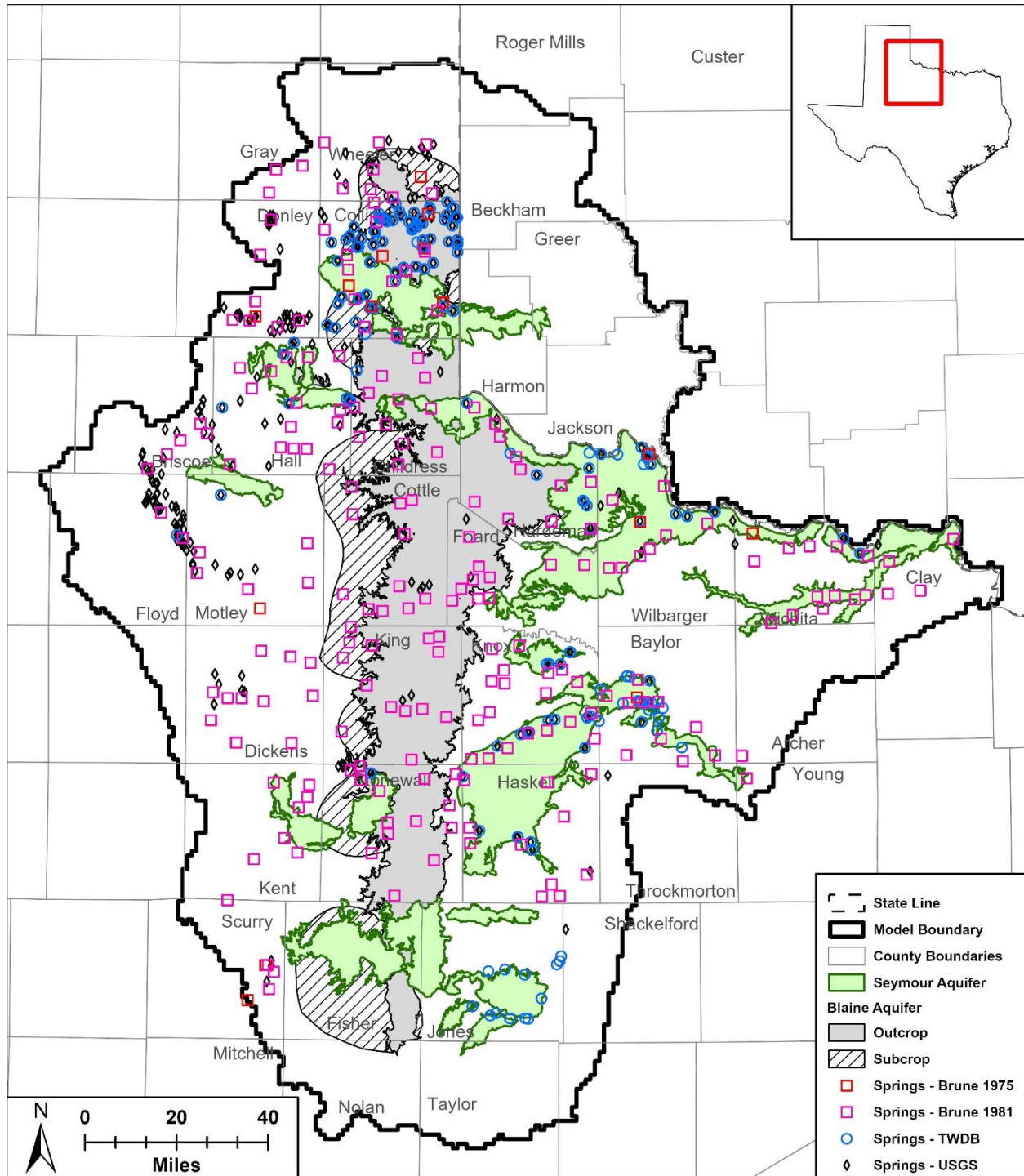
Of the more than 600 springs or groups of springs located in the active model area, 26 flowed at rates of 100 gallons per minute (0.22 cubic feet per second) or higher based on measured flow rates (Table 2-3). However, because flow rates were not provided for many of the documented springs, this number may be higher. The available measured spring flow rates range from less than 0.01 cubic feet per second (7 acre-feet per year) to a high of 3.5 cubic feet per second (2,533 acre-feet per year) measured at Salt Springs in Childress County and originating from the Permian System (Brune, 1981). Springs with multiple measurements over time show that fluctuations in precipitation can strongly influence spring flow. Table 2-3 shows some of the variation in spring flow for the springs that have discharge over 100 gallons per minute. For example, Jonah Spring in Childress County, which discharges from the Blaine formation, has measured discharge variations between 491 and 1,315 gallons per minute measured in 1974 and 1978, respectively.

Almost all of the major springs in the model area (those discharging greater than 100 gallons per minute) are found within the Pease River Group, which includes the Dog Creek Shale, Blaine formation, and Flowerpot Shale. These formations are karstic due to the dissolution of halite, gypsum, and anhydrite beds commonly present in the Pease River Group. There also appears to be a concentration of large discharging springs in close proximity to the existing river systems, especially to the Red River system. Many large springs are evident in Childress and Collingsworth counties in conjunction with the Salt Fork Red River and the Prairie Dog Town Fork Red River.

Throughout much of the Permian system within the active model area, spring flows have not shown any significant decline over time. Brune (1981) notes that, throughout Texas, declining groundwater levels due to pumping and flowing wells have resulted in the drying out of thousands of smaller springs and reduced flow in many of the larger springs. However, this trend does not appear to be representative of the Permian system within the active model area. Numerous springs and seeps with either low or unreported flows discharge from the edges of the Seymour formation where it sits above river valleys. While the individual spring flows are comparatively low from the Seymour Aquifer, aggregate flows of a few hundred gallons per minute

have been noted for groups of springs in close proximity (R.W. Harden and Associates, 1978).

Some loss of groundwater from the Seymour Aquifer occurs through flow to underlying Permian formations. The amount of this flow is unknown and, in the literature (R.W. Harden and Associates, 1978; Preston, 1978), is assumed to be small due to the low permeability of the underlying Clear Fork and Wichita groups of the Permian system in the eastern portion of the active model area. Some measurable discharge from the Seymour to the Bullwagon Dolomite Member of the Vale formation within the Clear Fork Group may occur in Jones County (Price, 1978). In the north-central region of the model domain, where the Seymour Aquifer overlies the Blaine Aquifer, appreciable, localized cross-formational flow to the Blaine formation may occur, depending largely on the thickness of the Dog Creek Shale and the location of solution channels within the Blaine formation.



Note: USGS = United States Geological Survey

Figure 2.6-1. Documented spring and seep locations in the study area.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Table 2-3. Documented springs in the active model area discharge greater than 100 gallons per minute. Springs without minimum flow values listed have only one discharge rate reported. Flow is reported in liters per second (lps), gallons per minute (gpm), cubic feet per second (cfs), and acre-feet per year (AFY).

County	Spring	Formation	Max flow (lps)	Max flow (gpm)	Max flow (cfs)	Max flow (AFY)	Date of Max	Min flow (lps)	Min flow (gpm)	Min flow (cfs)	Min flow (AFY)	Date of Min	Source
Childress	Salt	Permian	99	1,569	3.5	2,533	1978	45	713	1.59	1,151	1974	Brune (1981)
Childress	Jonah	Blaine	83	1,315	2.9	2,123	1978	31	491	1.09	793	1974	Brune (1981)
Collingsworth	Baxter	Permian	88	1,395	3.11	2,252	1962 & 1963	26	412	0.92	665	1971	Brune (1981)
Collingsworth	Spring	Alluvium	48	761	1.7	1,228	1968						TWDB
Collingsworth	Wischkaemper	Permian	48	761	1.7	1,228	1967	7.1	113	0.25	182	1971	Brune (1981)
Collingsworth	Buck	Permian	48	761	1.7	1,228	1968	1.6	25	0.06	40	1977	Brune (1981)
Collingsworth	Sand	Permian	40	634	1.41	1,023	1967	2.3	36	0.08	58	1971	Brune (1981)
Collingsworth	O'Hair	Permian	37	586	1.31	946	1967	3.4	54	0.12	87	1971	Brune (1981)
Collingsworth	Cottonwood	Permian	25	396	0.88	639	1967	14	222	0.49	358	1977	Brune (1981)
Collingsworth	Spring	Alluvium	14.4	229	0.51	370	1967						TWDB
Collingsworth	Corral	Blaine	24	380	0.85	613	1967	14	222	0.49	358	1977	Brune (1981)
Collingsworth	Wills	Permian	11	174	0.39	281	1967	0.15	2	0.010	3	1977	Brune (1981)
Collingsworth	Gyp	Permian	11	174	0.39	281	1967	11	174	0.39	281	1977	Brune (1981)
Collingsworth	Hale	Permian	10	159	0.35	257	1967	1.9	30	0.07	48	1977	Brune (1981)
Collingsworth	Spring	Alluvium	9.1	144	0.32	232	1967						TWDB
Collingsworth	Cottonwood	Permian	8.5	135	0.3	218	1979						Brune (1981)
Collingsworth	Big Sandy	Permian	8.1	128	0.29	207	1967	3.1	49	0.11	79	1977	Brune (1981)
Collingsworth	Baggett	Permian	7.4	117	0.26	189	1967	2.8	44	0.1	71	1977	Brune (1981)
Collingsworth	Coleman	Permian	28	444	0.99	717	1951	0.71	11	0.03	18	1956 & 1957	Brune (1981)
Cottle	Otta	Blaine	71	1,125	2.51	1,816	1979						Brune (1981)
Foard	Y	Blaine	17	269	0.6	434	1979						Brune (1981)
Foard	Boiling	Blaine	15	238	0.53	384	1979	32	507	1.13	818	1936	Brune (1981)
Knox	Spring	Seymour	6.3	100	0.22	161	1957						TWDB
Stonewall	Salt Flat Brine	Blaine	34	539	1.2	870	1969	16	254	0.57	410	1964	Brune (1981)
Stonewall	Mc Broom	Seymour	6.5	103	0.23	166	1979						Brune (1981)
Wichita	China	Alluvium	6.8	108	0.24	174	1969	6.5	103	0.23	166	1970	Brune (1981)

2.7 Geologic setting

The structural setting for the active model area is shown in Figure 2.7-1. In the subsurface, the area is characterized by the Hardeman Basin (also referred to as the Hollis Basin in the literature), the Wichita Mountains, the Red River Arch, the Baylor Syncline, and the Concho Shelf. The following discussion of these features is from Price (1979) unless otherwise indicated. The oldest feature is the Red River Arch, which has existed since Cambrian time and has been buried since Pennsylvanian time. Development of the Hardeman Basin and Wichita Mountains was coincident. Further deepening of the basin occurred during the Arbuckle orogeny in Pennsylvanian time. The Baylor Syncline along with the Bend Flexure were also formed during Pennsylvanian time. The Concho Shelf “is the result of subsidence and tilting, beneath the Midland basin, of the Concho arch which was once the most dominant feature of north-central and northwest Texas.” (Price, 1978). This shelf, which is actually a portion of the former Concho Arch, is of upper-Pennsylvanian, early-Permian age (Price, 1978). None of these structural deformations have affected the Seymour or Blaine aquifers.

The surface geology in the study area (Figure 2.7-2) consists of Permian- through Quaternary-aged deposits. The Quaternary-age deposits making up the Seymour Aquifer almost exclusively overlie Permian deposits. From oldest to youngest and east to west, these Permian deposits form the Wichita Group, the Clear Fork Group, the Pease River Group (of which the Blaine Formation is a member), the Whitehorse Group, and the Quartermaster Formation. The strike of the Permian units is from north-northeast to south-southwest. A schematic of the stratigraphy in the active model area is provided in Figure 2.7-3. The westerly dip of the Permian strata shown on this figure is the result of westerly tilting caused by development of the Concho Arch. Stratigraphic cross sections in Figure 2.7-5 and Figure 2.7-6 show the eastwardly dip of the ground surface and the westerly dip of the Permian formations. The cross section in Figure 2.7-4 shows the relationship between the alluvium deposits (Seymour Aquifer), the Whitehorse Group, the Dog Creek Shale, and the Blaine formation in Collingsworth County.

The Seymour Aquifer, as defined by the TWDB, is composed of remnants of the Seymour formation, the Lingos formation, and younger alluvial deposits of Quaternary age (Figure 2.7-7). All materials forming the Seymour Aquifer are unconsolidated alluvial sediments of non-marine origin deposited on the erosional surface of Permian beds. In general, sediments of the Seymour Aquifer are predominantly material eroded from the High Plains and deposited by eastward-moving streams (R.W. Harden and Associates, 1978; Nordstrom, 1991; Duffin and Beynon, 1992). It is likely that the sediments originally blanketed the entire region but were subsequently eroded by recent streams, leaving only remnants of the once continuous deposits (Ogilbee and Osborne, 1962; Preston, 1978; Price, 1978). Alluvial deposits of the Seymour Aquifer also include recent fluvial sedimentation from rivers and streams, terrace deposits, and eolian (windblown) sands.

Sediments of the Seymour Aquifer are composed of clay, silt, sand, conglomerate, gravel, and some caliche. In general, the sediments are finer near the top and coarsen with depth. The upper portion contains beds of fine-grained sand with silt or clay and some caliche. A basal section of coarse sand and gravel beds is present in many portions of the aquifer. Individual beds within the Seymour Aquifer are discontinuous and grade laterally into beds of coarser or finer grained material. The thickness of the Seymour Aquifer varies from 0 to 360 feet but is usually less than 100 feet (Duffin and Beynon, 1992). This variation is due to the uneven erosional surface of the underlying Permian beds. Where the aquifer overlies a buried channel, it has a greater thickness and an increased amount of coarse material at its base. Where the aquifer is thin, it consists predominantly of finer-grained material.

The Blaine formation of the Pease River Group was created during the Permian-age deposition of redbeds and evaporites when the southwestern United States was covered by a broad, shallow sea. The formation consists of beds of gypsum, anhydrite, halite, dolomite, sandstone, and shale. The evaporite beds originated from marine deposits from the shallow sea, and the sandstone and shale deposits originated from the deposition of stream and river sediments into the sea (Johnson, 1990). Not all bed materials are found throughout the formation. In general, the individual beds of gypsum and dolomite are laterally continuous. The different beds within the Blaine formation were deposited in a cyclic manner (Johnson, 1990). More than seven distinct cycles have been identified within the formation. The Blaine formation is described as having five predominant members in both Hardeman and Wheeler counties and eastern Gray County. In Hardeman County, the major members consist of three gypsum beds and two dolomite beds (Maderak, 1972). Four gypsum beds and one dolomite bed make up the five major members in Wheeler and eastern Gray counties (Maderak, 1973). Sediments of the Blaine formation were deposited in the Hardeman Basin between the Wichita Mountains and the Red River Arch. The Blaine formation is overlain by the Dog Creek Shale. In some areas, distinguishing between these two units is difficult, and the two are combined. The Flowerpot Shale confines the Blaine formation from below. Findings from a recent Brackish Resources Aquifer Characterization Study refined previous conceptual understandings of the groundwater flow hydraulics along the brine interface identified within the Blaine Aquifer and other Permian-age hydrostratigraphic units (Finch and others, 2016). The brine interface serves as an important control on groundwater flow due to differences in density of the brine relative to less saline and more fresh groundwater resources and was used as a constraint in the development of the numerical model basal structure for the Permian hydrostratigraphic units (Figure 2.7-8).

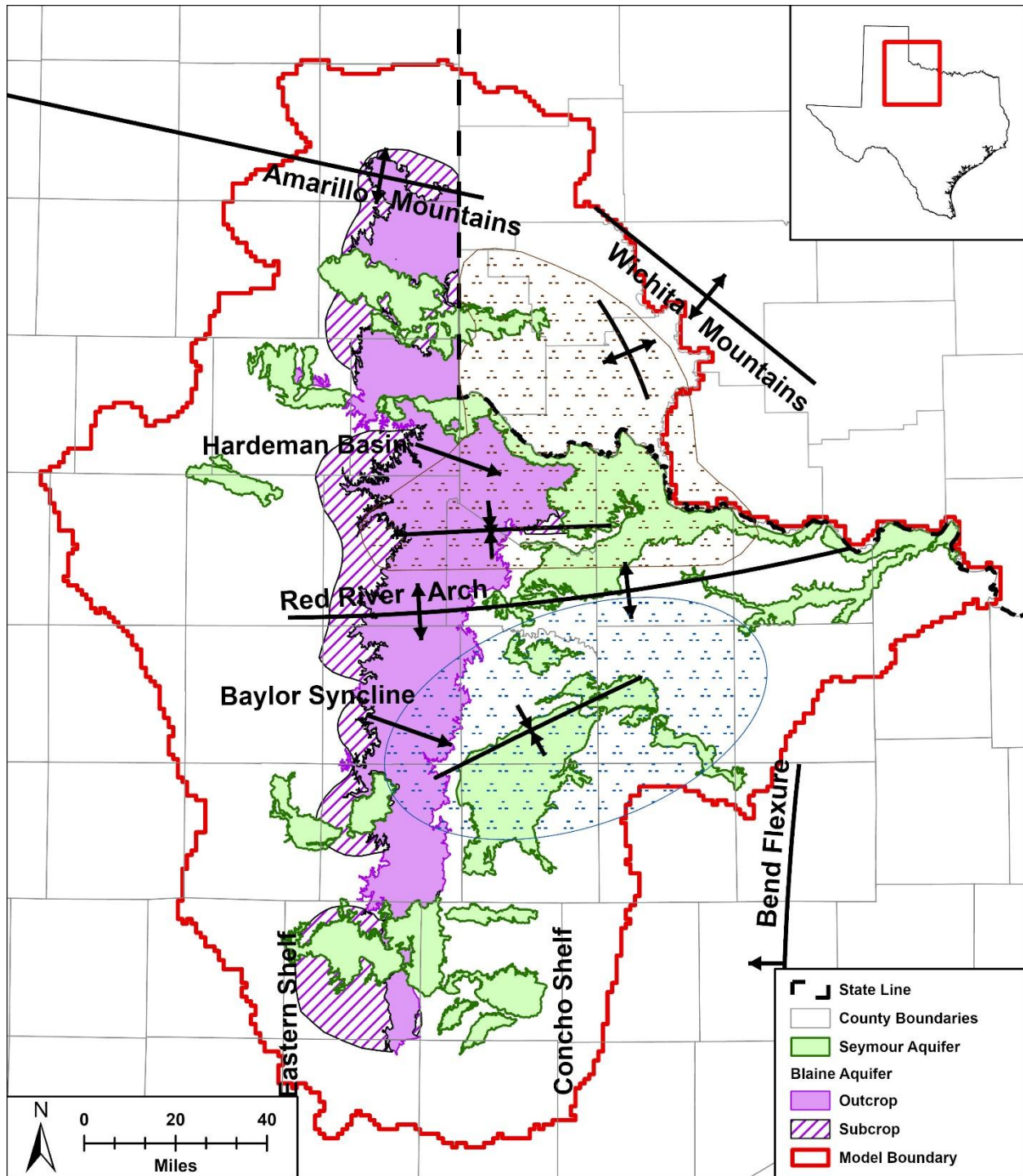


Figure 2.7-1. Map of major structural features in the study area (after Price, 1979).

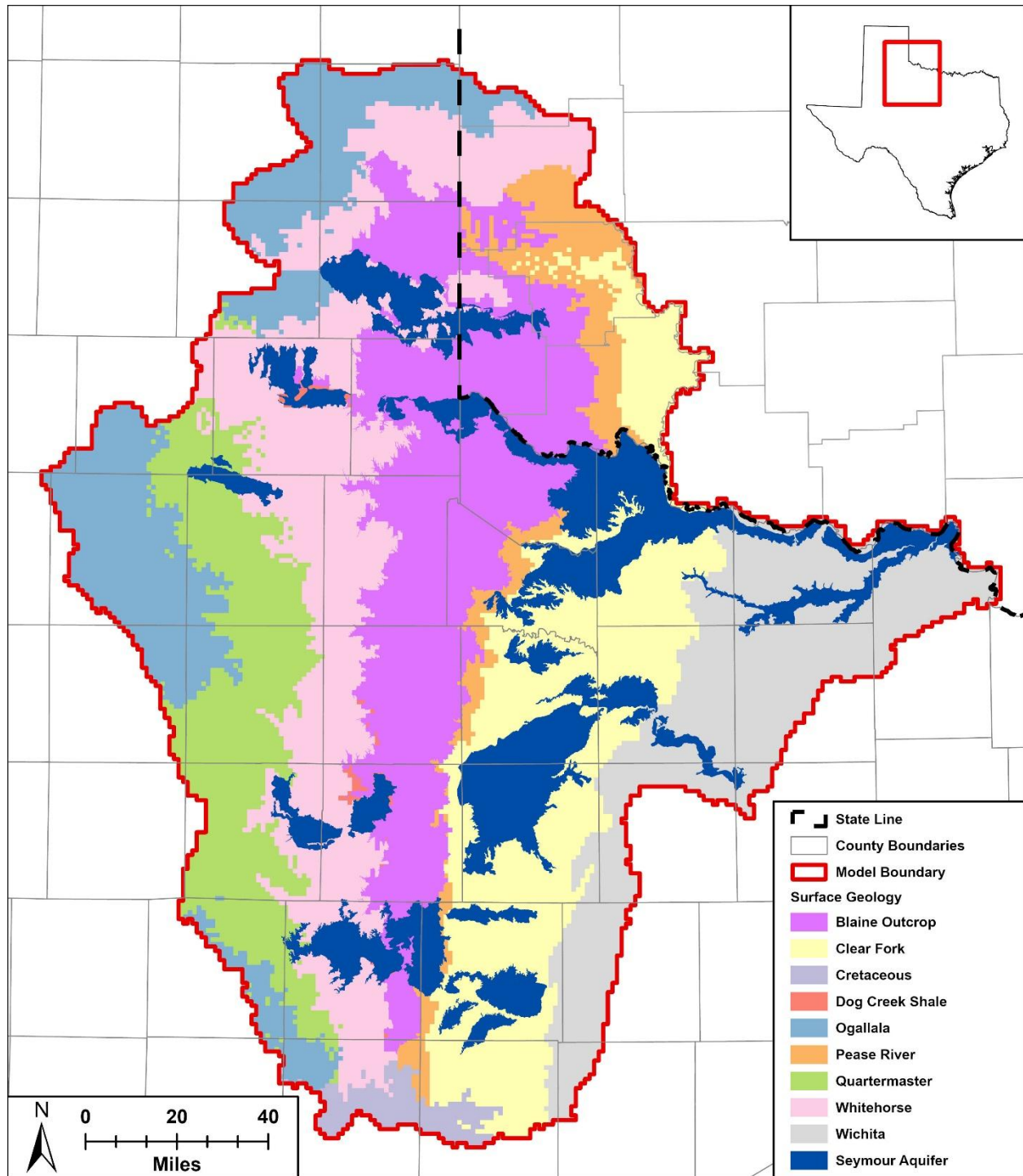


Figure 2.7-2. Surface geology of the study area.

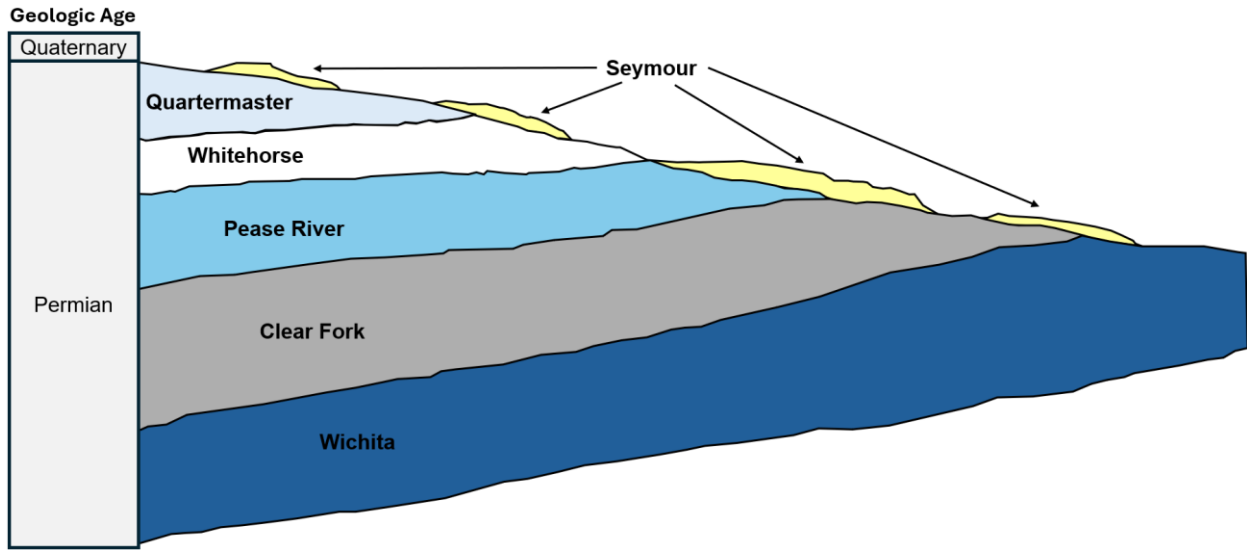


Figure 2.7-3. Generalized stratigraphy across the study area.

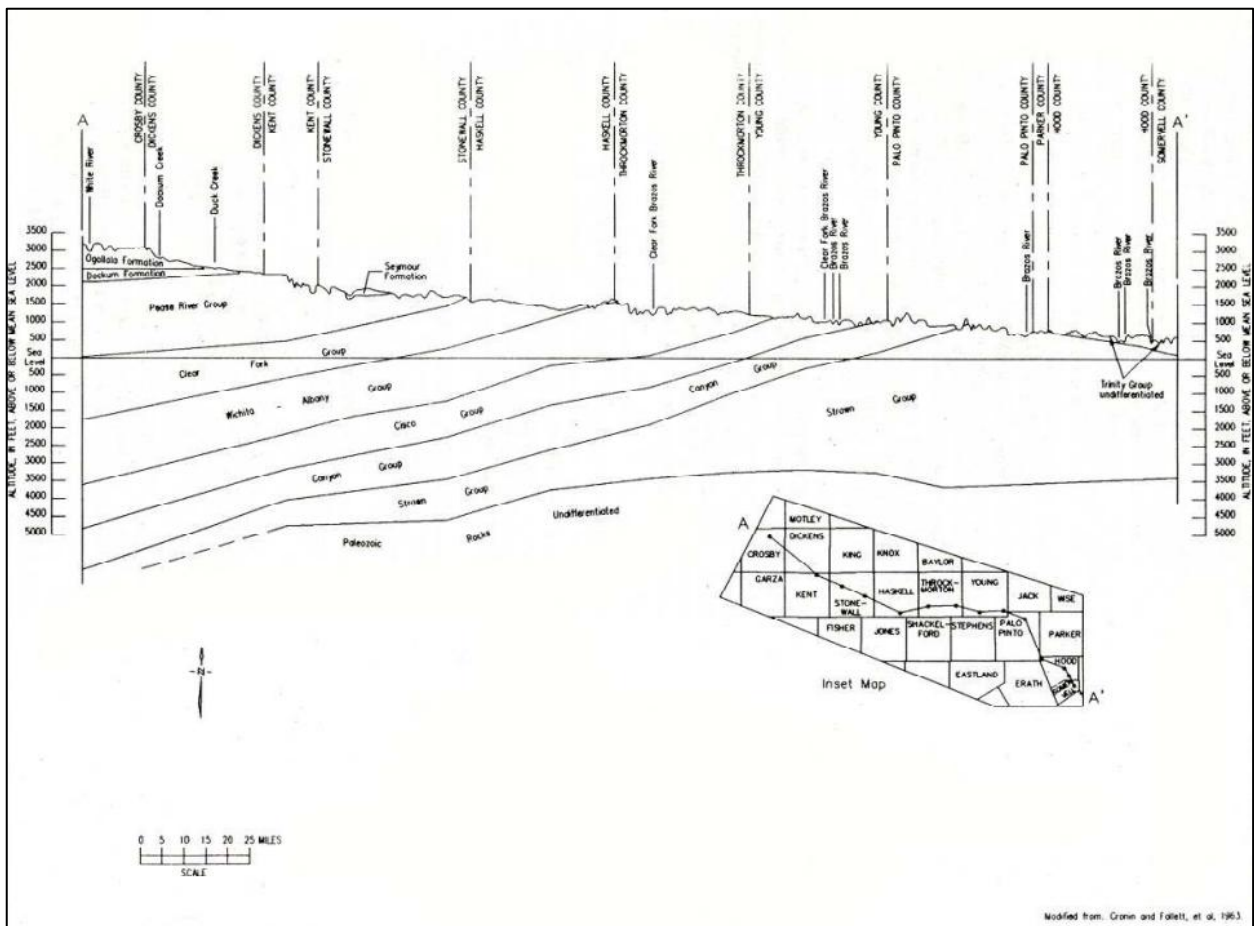


Figure 2.7-4. Cross-section showing the major stratigraphic units across the active model area (source: Duffin and Beynon, 1992).

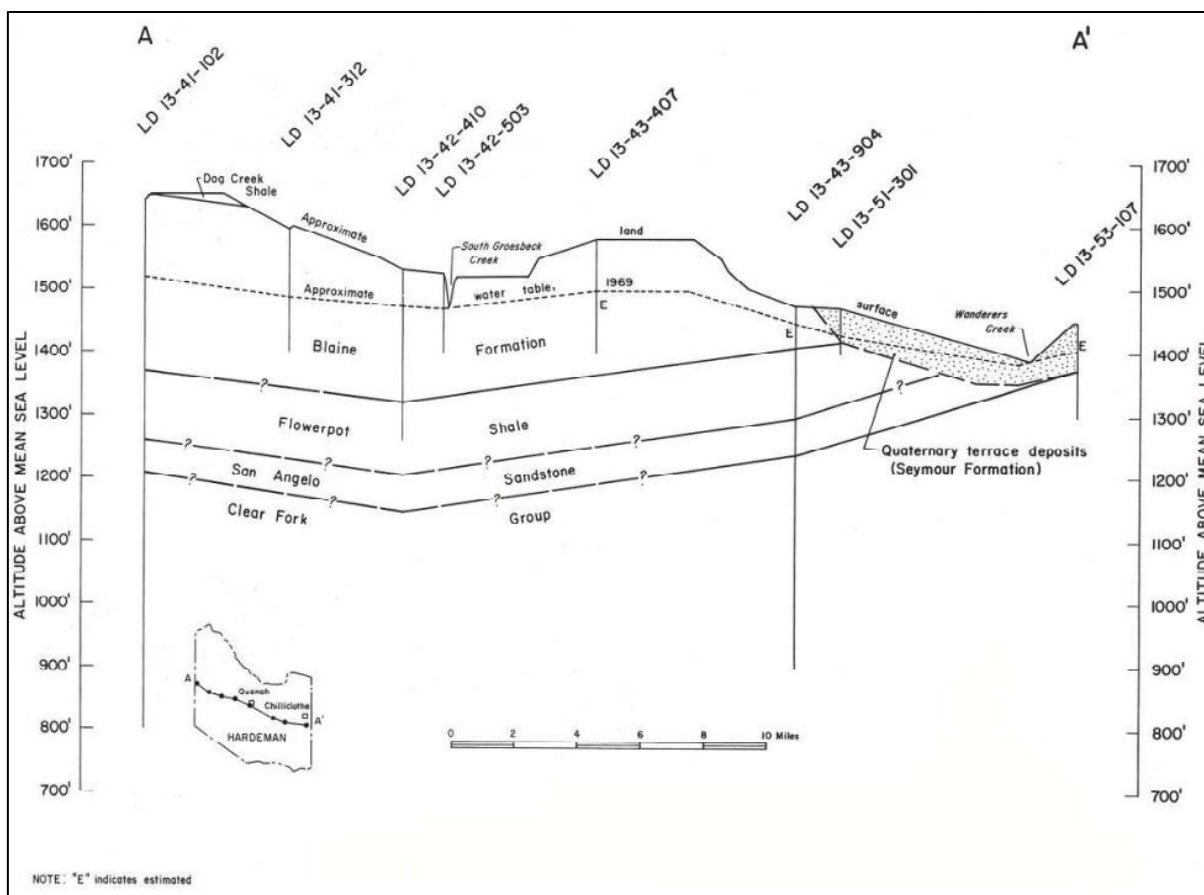


Figure 2.7-5. East-west structural cross-section across Hardeman County (source: Maderak, 1972).

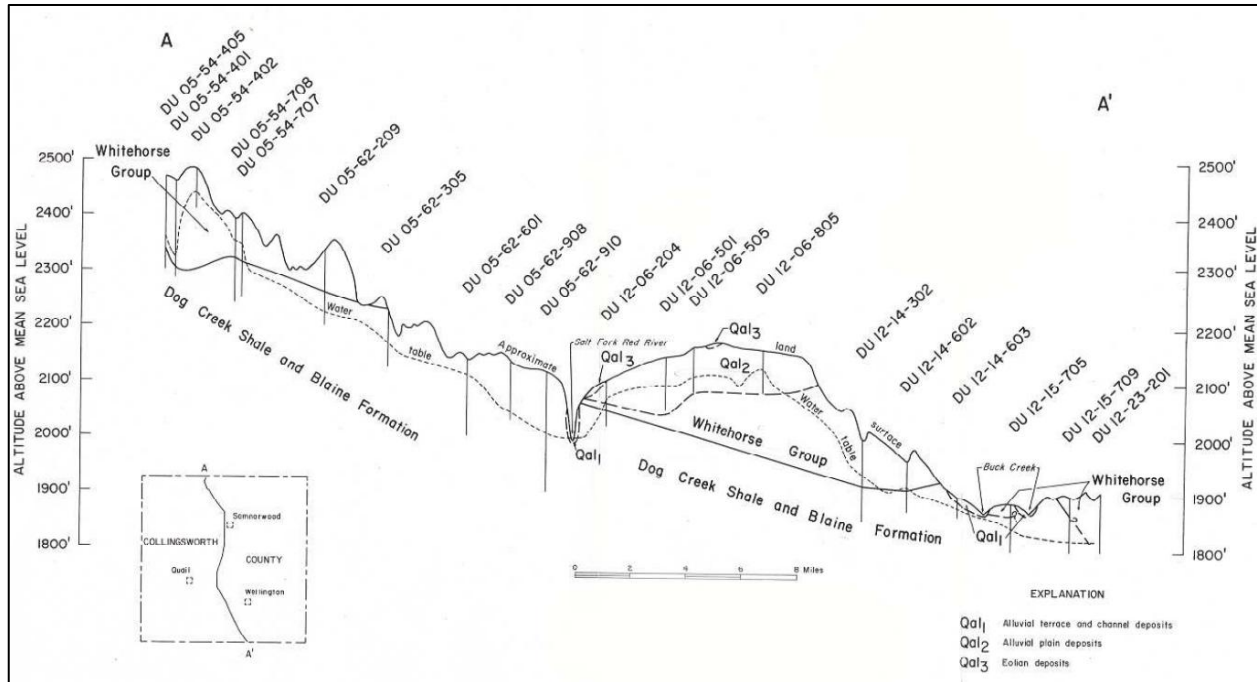


Figure 2.7-6. North-south structural cross-section across Collingsworth County (source: Smith, 1970).

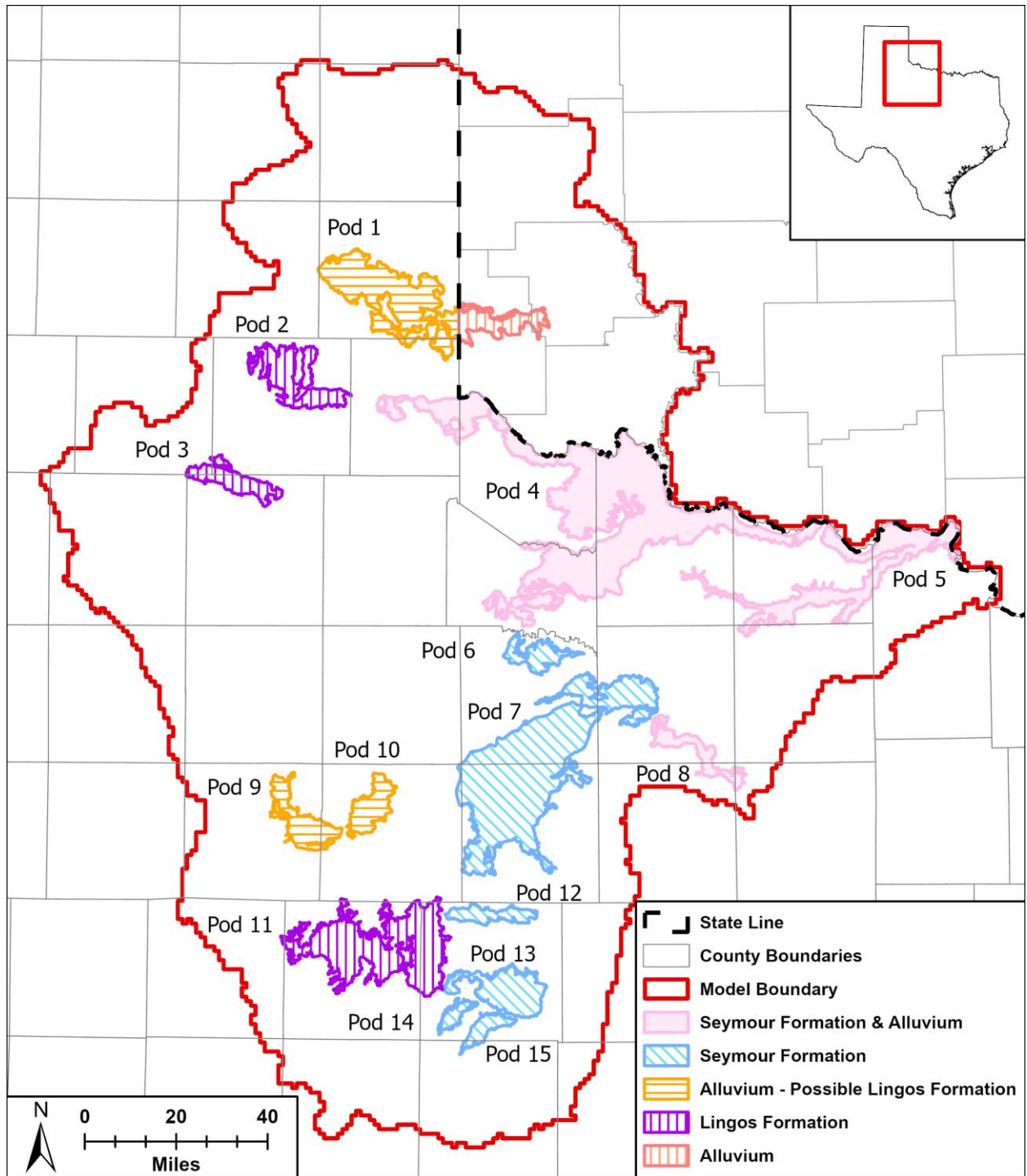


Figure 2.7-7. Geologic materials forming the Seymour Aquifer with Pod Numbers.

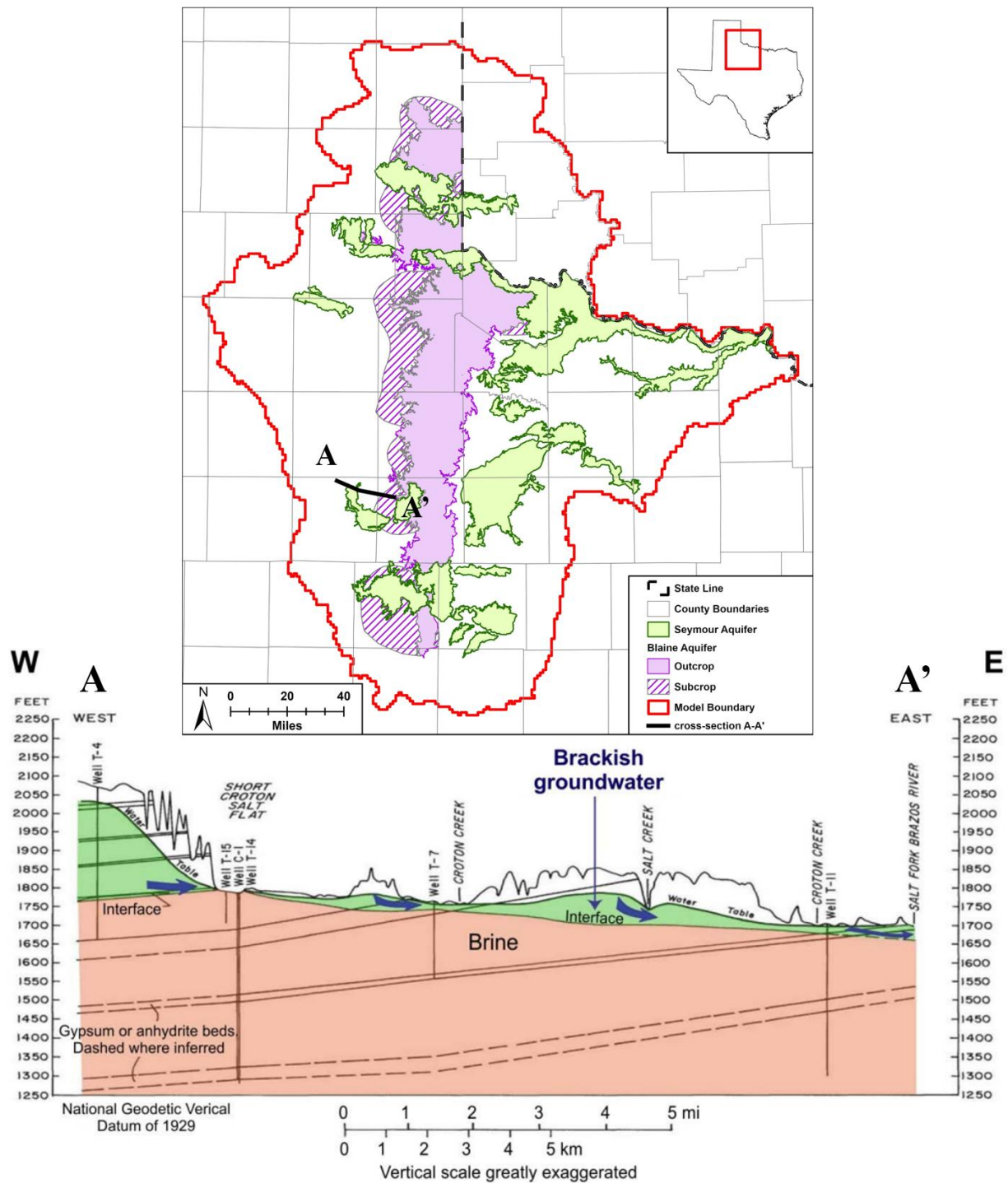


Figure 2.7-8. Cross-section A-A' of regional groundwater flow hydraulics controlled by the brine interface (source: figure from Finch and others, 2016; modified from Stevens and Hardt, 1965).

The remainder of this report includes thorough documentation of the Seymour and Blaine numerical model as required by the TWDB groundwater availability model standards. Documentation includes a description of updates to the conceptual model (Chapter 3), model overview and packages (Chapter 4), model calibration and results for the steady-state and transient conditions (Chapter 5), sensitivity analysis (Chapter 6), discussion of model limitations (Chapter 7), summary and conclusions (Chapter 8), and future improvements (Chapter 9).

3 Updates to the conceptual model

3.1 Introduction

Numerical groundwater flow models are important tools for understanding complex natural systems. Numerical models are simplified representations of complex environmental systems that are built upon the conceptual understanding of the system. Conceptual model development is paramount to develop a numerical groundwater model that can be used as an effective tool. The numerical groundwater availability model developed in this update builds upon and expands on the frameworks previously developed in the groundwater availability model for the Seymour and Blaine aquifer system developed by Ewing and others (2004) and a conceptual model refinement developed in Jones and others (2012) for the Seymour Aquifer in Haskell, Knox and Baylor counties.

The conceptual model and respective components for the Seymour and Blaine aquifer system are presented in Figure 3.1-1. The Seymour and Blaine aquifer system consists of a shallow groundwater flow system bounded below by a saline/brine water interface that occurs at a relatively shallow depth (ranging from surface to several hundred feet) as mapped partially across the study area in Finch and others (2016). At a conceptual level, this can be approximated as a Tothian local (shallow) flow system across the model domain (Tóth, 1962; 1963; 1966). The inflow components to be considered are: (1) groundwater recharge from precipitation and (2) leakage from losing reaches of streams and rivers. The outflow components considered are: (1) discharge from groundwater pumping, (2) discharge to springs and seeps, and (3) discharge to gaining reaches of rivers and streams. Changes in groundwater storage are considered during transient model periods. The steady-state period that will set the starting point for the transient period will assume changes in groundwater storage are zero, subsequently requiring a balance between inflow and outflow components. Flow between formations, or cross-formational flow, as documented in the previous groundwater availability model (Ewing and others, 2004), is also considered.

To represent the local (shallow) flow system overlying the brine and saline groundwater, the numerical model includes a total of four hydrostratigraphic units: (1) layer 1 comprises the Seymour Aquifer formation sediments, (2) layer 2 is composed of the Whitehorse and younger Permian-age formations, (3) layer 3 is composed of the Blaine formation, and (4) layer 4 is composed of the Flowerpot shale and older Permian-age formations (Figure 3.1-1). All layers represent flow in the local (shallow) flow system; however, layer 1 (Seymour Aquifer) and layer 3 (Blaine Aquifer) represent the portion of the groundwater system containing the majority of freshwater resources that are focused on for characterization in this study.

Groundwater availability models are designed to simulate the behavior of the fresh portions of aquifers and exclude considerations such as density-dependent flow, which, while important in controlling groundwater movement, falls outside the scope of these models. Due to the inherent variability of transitions between fresh, brackish, and saline water zones, simplifying assumptions are often necessary in developing

model structure as shown in the conceptual model (Figure 3.1-1). It is important to emphasize that layer 1 representing the Seymour Aquifer and layer 3 representing the Blaine Aquifer represent the focus of this groundwater availability model update. From a management perspective, it is not advised to use model layers 2 and 4 for defining quantities such as modeled available groundwater and total estimated recoverable storage, as is traditionally done with Texas groundwater availability models.

Lastly, the following are addressed: (1) model area delineation, layering, and grid properties, (2) springs and seeps, (3) historical pumping, (4) recharge, and (5) faulting.

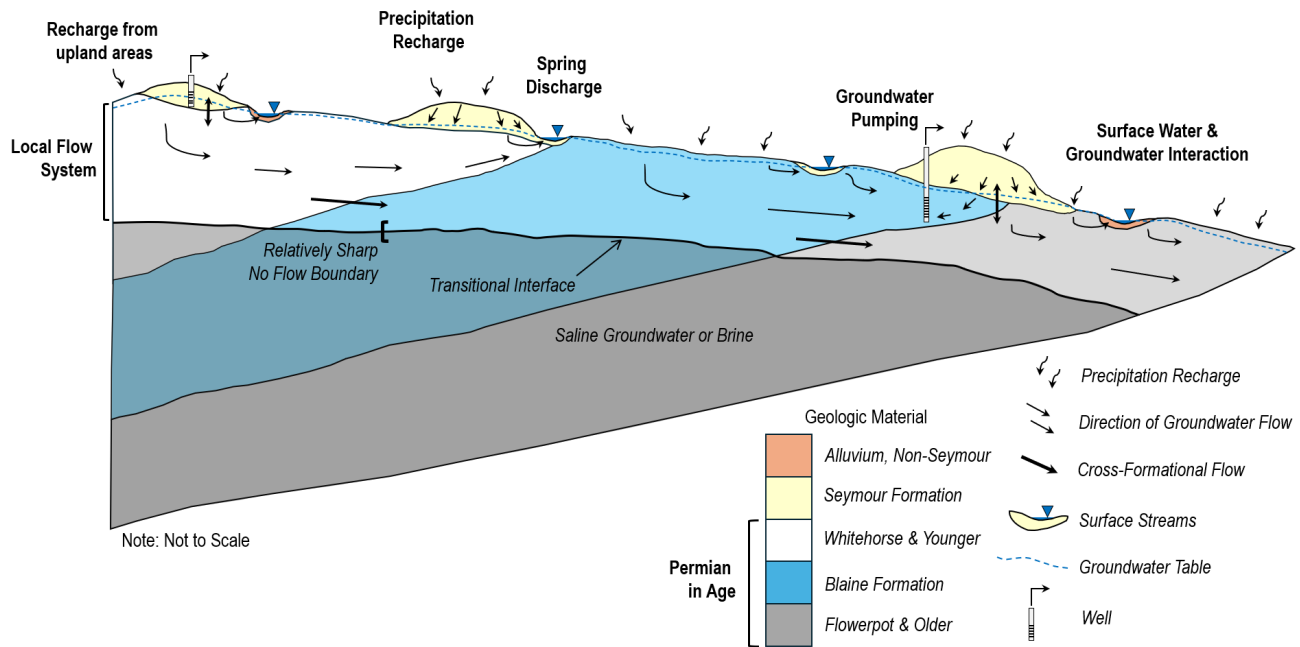


Figure 3.1-1. Conceptual model of the Seymour and Blaine Aquifer system.

3.2 Model area, layering, and grid properties

The following subsections detail the updates made to key aspects of the model compared to the previous groundwater availability model developed by Ewing and others (2004).

3.2.1 Model area delineation

The model area boundary for the updated groundwater availability model was consistent with the previous groundwater availability model developed by Ewing and others (2004) in most regions. The northern, western and southern boundaries of the updated model were extended modestly based on new, more recent hydrologic data and studies. The extent of the groundwater availability model developed by Ewing and others (2004) is provided in Figure 3.2-1 in the yellow boundary. The model boundary for the updated groundwater availability model is shown in the black boundary. The updated boundary was delineated based on: (1) more recent

hydrologic watershed boundary definitions from the National Hydrography Dataset Plus High Resolution, (2) the spatial extents of aquifers as defined by the Texas Water Development Board, (3) locations of pumping centers, (4) stream gage data availability from the United States Geologic Survey, (5) minimization of boundary effects, and (6) the general availability of data to inform the development of the conceptual model, numerical model, and model calibration. Where available, drainage basin divides and major perennial streams and rivers were used to delineate the updated model boundary (Figure 3.2-1). When not available, watershed boundary delineations from the National Hydrography Dataset Plus High Resolution were used. Additionally, flow accumulation analysis using high resolution (10-meter) surface elevation data from the United States Geological Survey and analysis of relatively higher-order streams from the National Hydrography Dataset Plus High Resolution were used to check the extended area of the numerical model boundary independently for the updated groundwater availability model. Generally, the model area boundary for the updated groundwater availability model is consistent with the previous groundwater availability model developed by Ewing and others (2004).

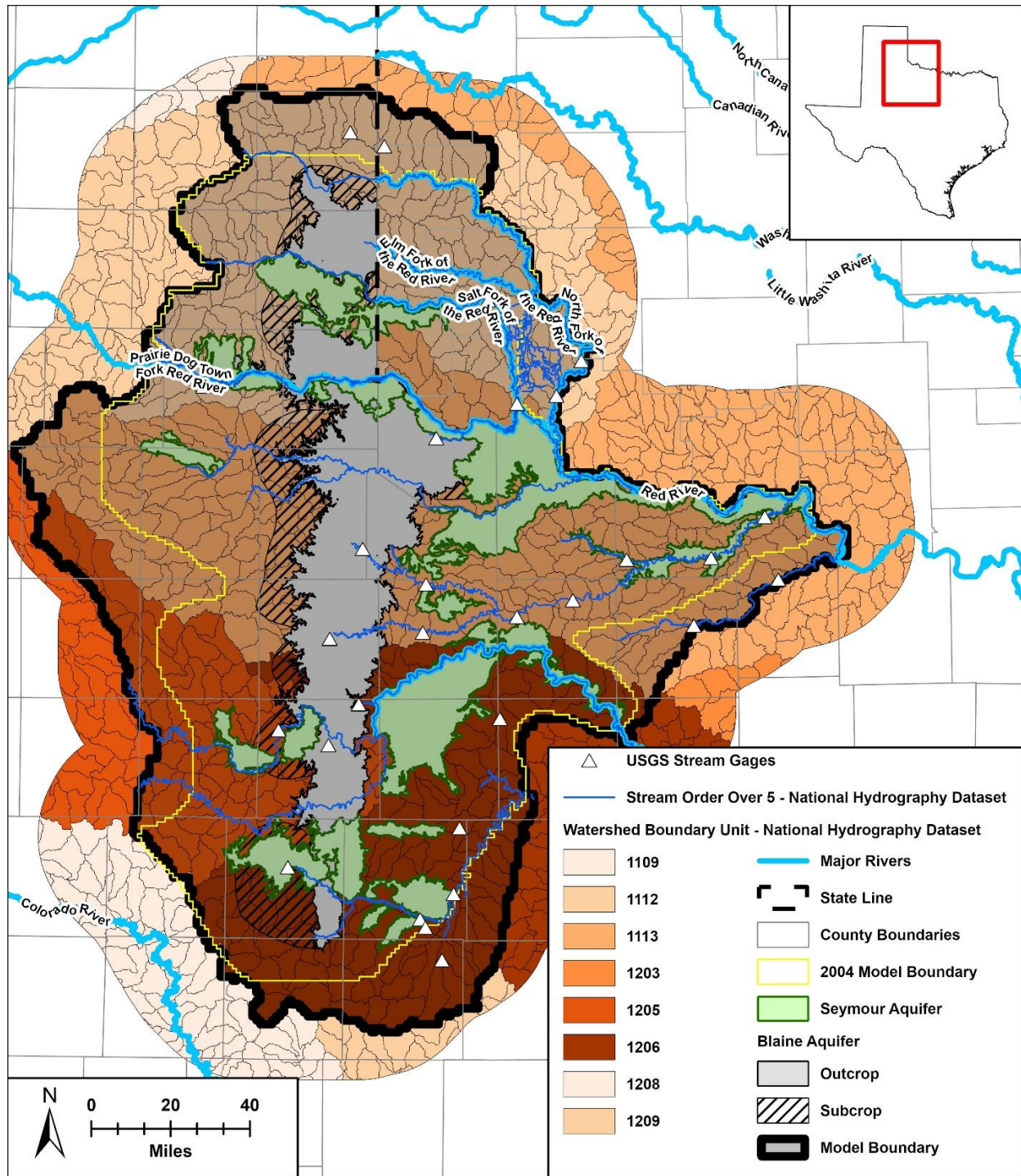


Figure 3.2-1. Model boundary delineation and supporting information.

3.2.2 Numerical model layers

Model layering in the updated groundwater availability model was generally consistent with the previous groundwater availability model developed by Ewing and others (2004) from the perspective that the Seymour Aquifer formation sediments comprised the top-most layer in the model (layer 1), and the underlying, generally Permian-age units, including the Blaine Aquifer, were included in the numerical model beneath the Seymour. Model layering derived from the conceptual model explicitly incorporates hydraulic connection to accommodate the potential for cross-formational flow between respective layers. The primary distinction in the updated model layering from the previous groundwater availability model is that the Permian-age units were separated into three unique layers representing hydrostratigraphic units. The model layering in the updated groundwater availability model shown in Table 3-1 includes a total of four hydrostratigraphic units: (1) layer 1 comprises the Seymour Aquifer formation sediments, (2) layer 2 is composed of the Whitehorse and younger Permian-age formations, (3) layer 3 is composed of the Blaine formation, and (4) layer 4 is composed of the Flowerpot shale and older Permian-age formations. The added detail in the model layering for the Permian-age units allowed for improved representation of the Blaine formation through consideration of it as a unique model layer. The refinement was supported by incorporating data and findings from a recent Brackish Resources Aquifer Characterization Study performed for the Blaine Aquifer system by Finch and others (2016). It is important to note that the spatial extent of the Blaine Aquifer as defined by TWDB extends farther to the south than what was modeled in the previous groundwater availability model developed by Ewing and others (2004) as a result of more recent available data and interpretation.

Table 3-1. Hydrostratigraphy and model layers.

System	Series	Group	Formation	Model Layer
Quaternary	Recent to Pleistocene	-	Alluvium	1
		-	Seymour	
Tertiary				
Cretaceous				
Jurassic				
Triassic				
	Ochoa	-	Quartermaster	
		Whitehorse	-	2
	Guadalupe	Pease River	Dog Creek Shale	3
			Blaine Gypsum	
			Flowerpot Shale	
Permian			San Angelo	
			Choza	
		Clear Fork	Vale	4
			Arroyo	
		Leonard	Lueders	
			Wichita (upper portion)	Clyde

As previously mentioned, assumptions regarding the definition of the basal boundary of the local flow system for the updated model are grounded in characterization of the interface of saline groundwater/brine with the local flow system's relatively fresher groundwater being modeled. In the previous model by Ewing and others (2004), the basal boundary and thickness of the Permian-age hydrostratigraphic units in layer 2 was grounded in a constant thickness assumption of 500 feet below ground surface where data supporting the delineation of Blaine formation base were not present. More recent data, particularly from the Brackish Resources Aquifer Characterization Study focused on the Blaine Aquifer system performed by Finch and others (2016), has allowed for the refinement of the previous assumption better to represent: (1) the approximate base of the local flow system, represented as the interface between the saline groundwater/brine interface with relatively fresher groundwater supplies, (2) the structure of the Blaine Aquifer system, and (3) complex cross-formational flows controlled by the structure of all hydrostratigraphic units within the model domain.

To refine this constant thickness assumption, data, and interpretations from the Finch and others (2016) study, specifically, the mapped spatial extent and depth of the: (1) brine interface, (2) base of the Whitehorse formation, and (3) base of the Blaine formation (top of the Flowerpot shale) across the updated model domain were used as shown on Figure 3.2-2. In this figure, the mapped brine interface elevation in Finch and others (2016) was superimposed on the surface expression of the hydrostratigraphic units defined for the updated groundwater availability model. Structural data directly from the study for the following units: (1) base of the Whitehorse formation, (2) base of the Blaine formation (top of the Flowerpot shale), and (3) the brine interface elevation were all used as a starting point for the layer tops and bottoms for the Permian-age hydrostratigraphic units for layers 2, 3, and 4. At model grid cell level, where the brine interface elevation was above the base of the Permian-age hydrostratigraphic units, the brine interface elevation was defined as the structural base of that hydrostratigraphic layer at that specific spatial location. For modeled regions outside of the Finch and others (2016) study footprint, planar surfaces were fit to respective geologic formation contacts, extrapolated where needed, and sampled from to define Permian-age surfaces consistent with respective, regional dip and dip-direction.

A few additional steps were performed to constrain better the local flow system as controlled by the basal saline groundwater/brine interface with the overlying relatively fresher groundwater across the entirety of the updated model area. First, an interpolated surface was fit across all the entirety of the model domain using the major rivers surface elevations (Figure 3.2-3), and the average depth to the brine interface for each Permian-age hydrostratigraphic unit based on the mapped interface in Finch and others (2016) was used to define the average depths to the brine interface where: (1) structural data was not available from source data or interpolated surfaces, or (2) the brine interface was above the base of the hydrostratigraphic unit. The resultant isopach thicknesses and accompanying summary statistics for model layers 2, 3, and 4 are presented in Figure 3.2-4 through Figure 3.2-9. It is shown that the mean and median of the isopach thickness for the Whitehorse and younger Permian-age unit are approximately 385 and 316 feet, respectively, across model

layer 2. It is shown that the mean and median of the isopach thickness for the Blaine formation are approximately 207 and 208 feet, respectively, across model layer 3. It is shown that the mean and median of the isopach thickness for the Flowerpot and Older Permian-age unit are approximately 165 and 157 feet, respectively, across model layer 4. As shown with the shallowing thicknesses near the major streams and rivers, the resultant basal surface for the updated model's Permian-age hydrostratigraphic units for layers 2, 3, and 4 is relatively consistent with a local (shallow) flow system as defined by Tóth 1962; 1963; 1966. The range in the mean and median for the updated model isopach thickness for the Permian-age hydrostratigraphic units is generally lower than what was used in the previous groundwater availability model developed by Ewing and others (2004) and also incorporates more realistic spatial variability that better represents the local (shallow) flow system.

On top of the Permian-age units defined in layers 2, 3, and 4 lies the Seymour formation pods composing layer 1 of the updated model. The Seymour Aquifer base elevations were developed independently for each of the fifteen Seymour pods, with structural development performed across twenty pod-segment outlines because several pods are spatially divided into discrete segments. For each pod-segment, base-of-Seymour control points were assembled from multiple sources. The primary source was wells with bottom-of-screen or total-depth information from the TWDB Groundwater Database. These were supplemented by several of the data sources used in the previous groundwater availability model developed by Ewing (2004), including drillers' log reports available on the TWDB website, county report tables, TWDB reports (Turner, 1936a, 1936b), and Texas Commission on Environmental Quality well log records. The Texas Commission on Environmental Quality records were added for pods 3, 4, 8, 10, and 11 where they improved local control. For Pod 7, driller log records compiled in 2012 by the Rolling Plains Groundwater Conservation District in the Haskell-Knox-Baylor area were also incorporated. Land surface elevations along each pod boundary and river cell elevations from the surface drainage network were also included as control points.

Basal elevations from driller's logs and well databases were calculated by subtracting the reported depth to base from the corresponding land surface elevation extracted from the United States Geological Survey 10-meter (32.8-foot) digital elevation model (USGS, 2019), providing a higher-quality and internally consistent land surface reference across all source databases. Wells from the TWDB Groundwater Database were retained only where the well construction record contained either a screened-interval bottom depth or a total depth, with bottom-of-screen used preferentially and total depth used as a fallback or as a substitute on a case-by-case basis where the screened-interval pick was inconsistent with surrounding control. Because land surface elevation along each pod boundary approximates the Seymour Aquifer base where the aquifer pinches out laterally, points along each pod outline were assigned land surface elevations from the digital elevation model, and where these boundary points coincided with cells in the River package they were updated with the corresponding river cell elevations. The compiled control points for each pod were then subjected to outlier analysis using the interquartile range method, with river cell

elevations and pod boundary points retained as fixed values; six additional well-based picks across Pods 1, 12, and 13 were removed manually where they conflicted with the boundary point elevation control.

The Seymour base surface was generated by interpolating the control points within each pod-segment boundary using the Topo to Raster tool in ArcGIS Pro at a 330-foot (one-sixteenth of a mile) cell size, corresponding to one-half of the Layer 1 model grid cell dimension. Topo to Raster was selected over kriging because it better honored hydrologic continuity along pod boundaries adjacent to drainage features and produced surfaces with fewer artifacts in pods with clustered control point distributions.

The isopach thickness for layer 1 in feet for the Seymour formation is provided in Figure 3.2-10, with accompanying summary statistics in Figure 3.2-11. The mean and median of the isopach thickness are approximately 35 and 27 feet, respectively, across the entire model domain (Figure 3.2-10). Generally, the Seymour formation is much thinner than the Permian-age units in the model. Most regions indicate that the base of the Seymour pods are generally 100 feet thick or less, with rare instances in pods broadening to thicknesses of 150 to 200 feet. The largest thickness of the Seymour formation mapped to the model grid is approximately 255 feet.

In summary, the spatial extent of each hydrostratigraphic unit in the model is provided in Figure 3.2-12. The figure highlights the complexity in both the local and regional structure of the model layer connectivity. The model domain includes the following model layering instances as controlled by the geologic structure:

- model layer 1 overlying model layers 2, 3, and 4 in subsequent order by geologic age,
- model layer 1 overlies only model layer 2, model layers 3 and 4 are not present,
- model layer 1 overlies only model layer 3, model layers 2 and 4 are not present,
- model layer 1 overlies only model layer 4, model layers 2 and 3 are not present,
- model layer 1 overlies model layer 2, which is underlain only by model layer 4,
- model layer 1 overlies model layer 3, which is underlain by model layer 4,
- model layer 2 with no overlying or underlying layers,
- model layer 3 with no overlying or underlying layers, and
- model layer 4 with no overlying or underlying model layers.

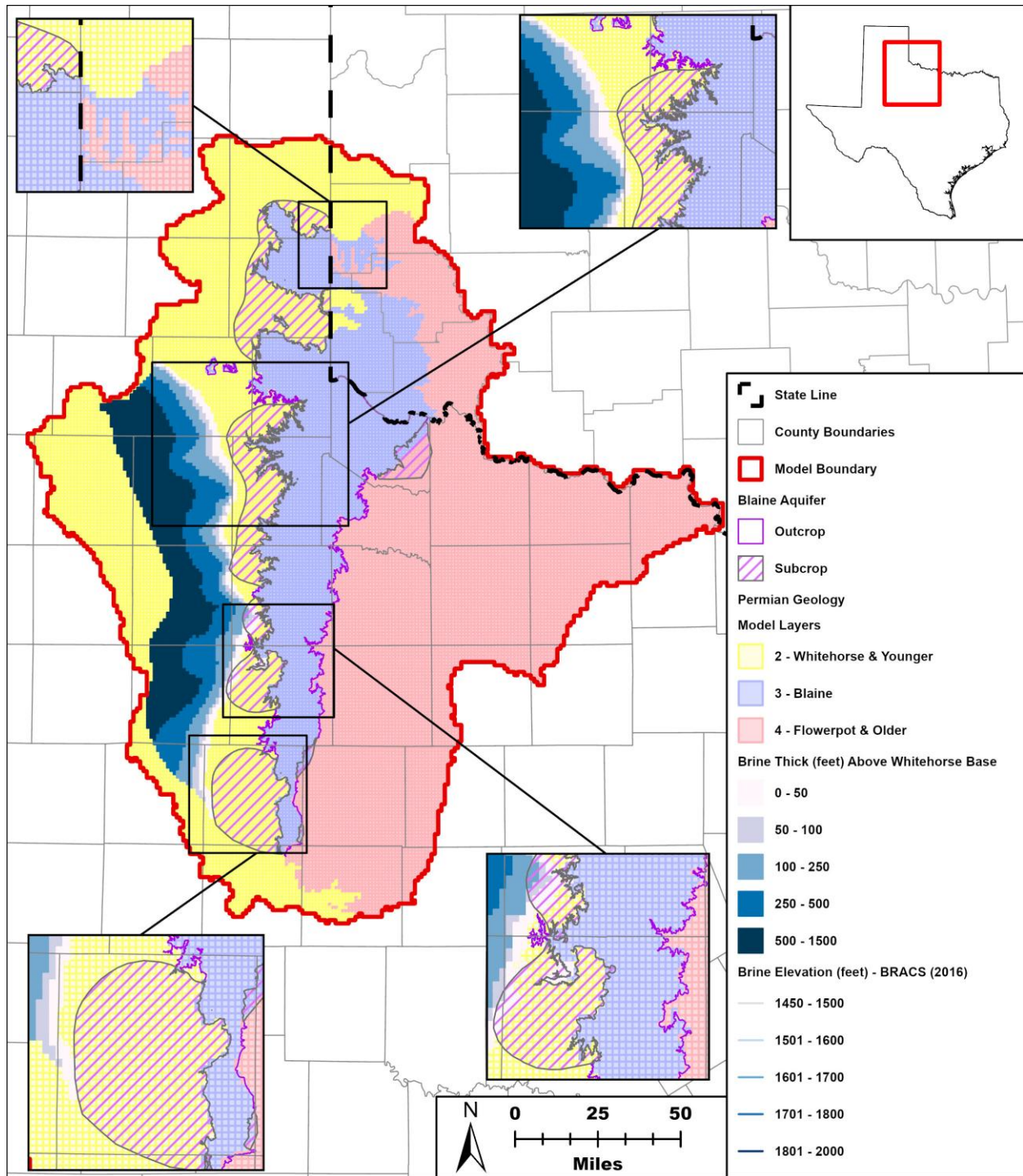


Figure 3.2-2. Delineation of the brine interface mapped in the Permian-age hydrostratigraphic units (source: Brackish Resources Aquifer Characterization Study [BRACS] for the Blaine Aquifer system by Finch and others [2016]).

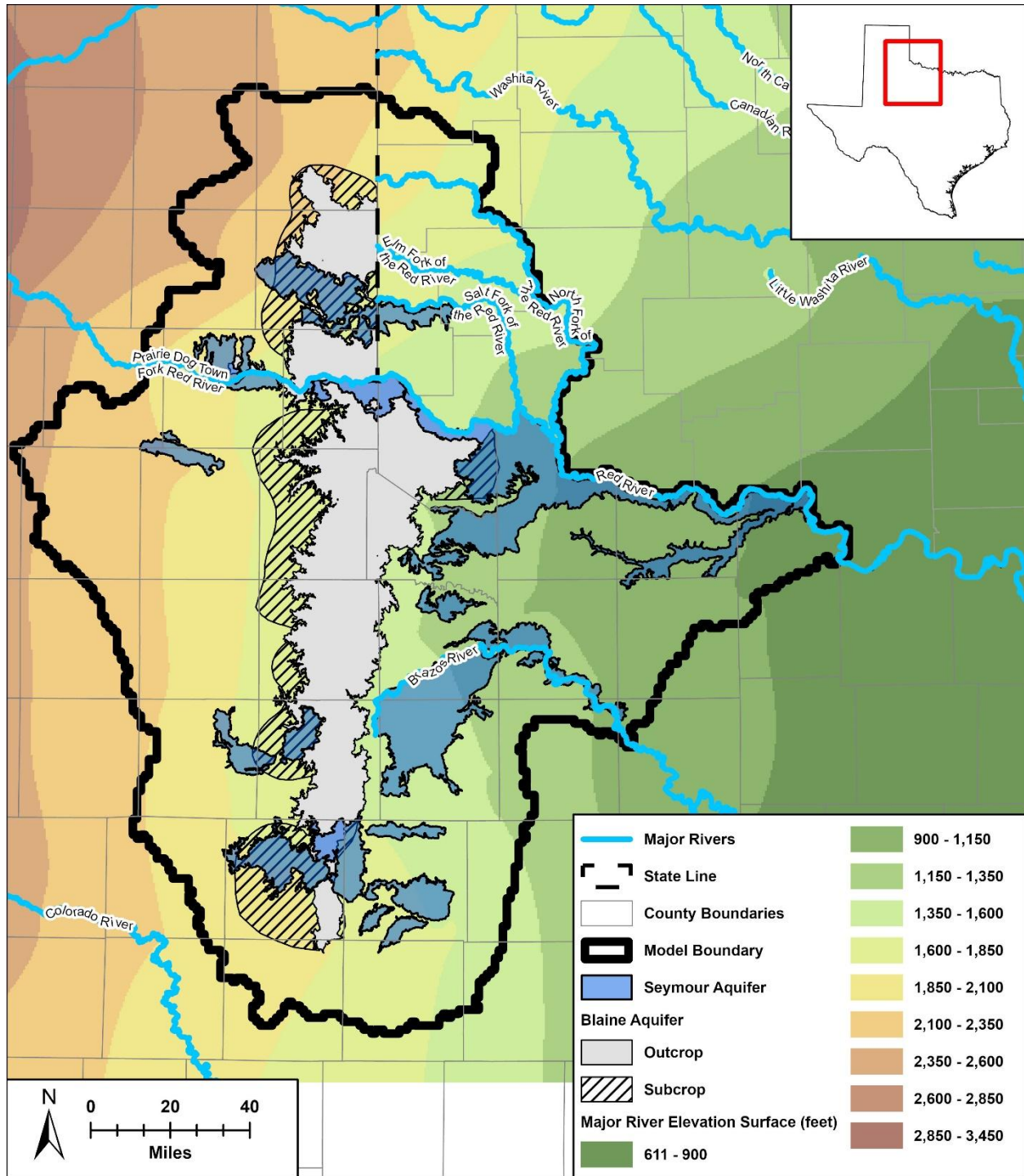


Figure 3.2-3. Major river elevation interpolation surface in feet above mean sea level.

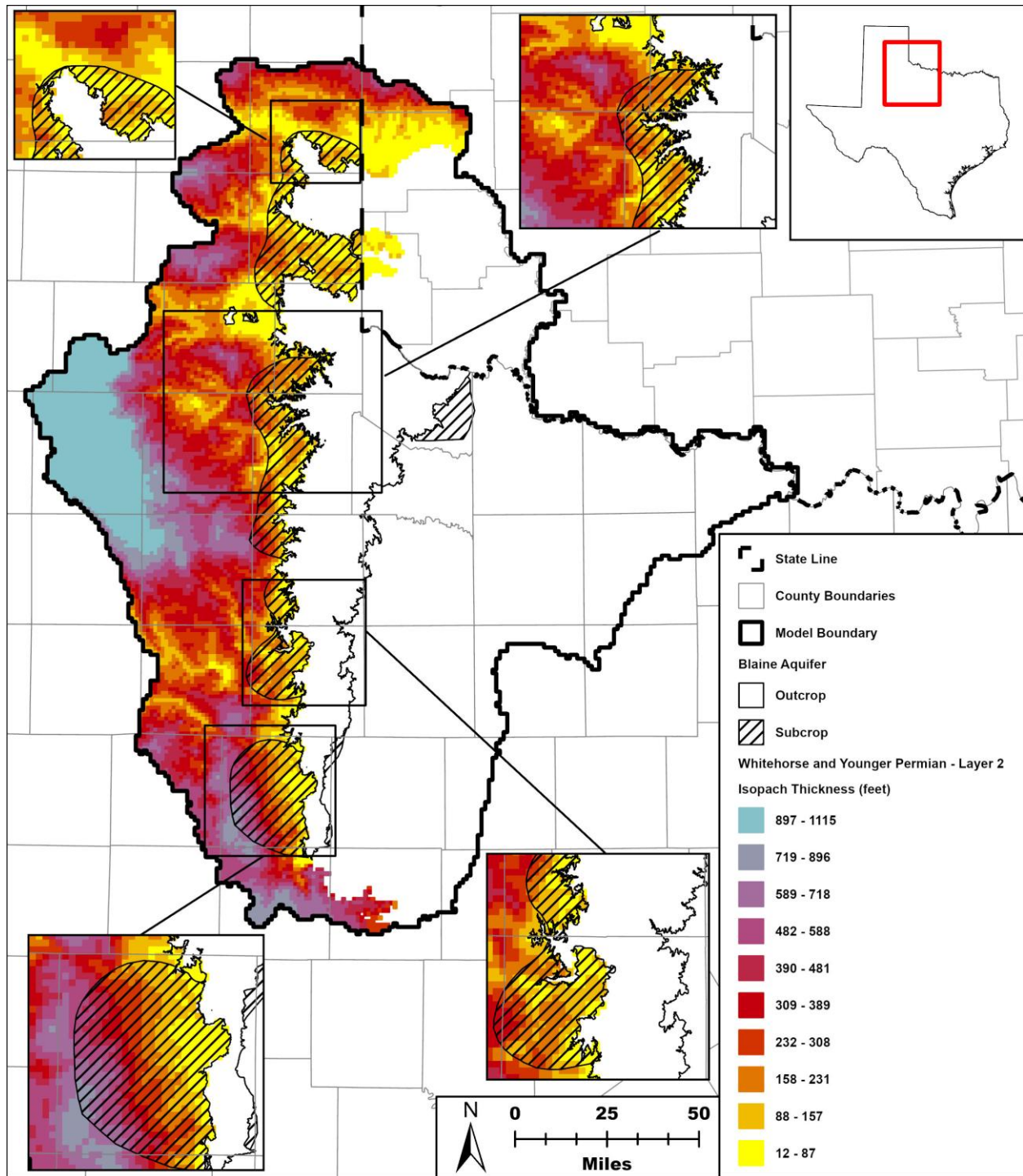


Figure 3.2-4. Isopach thickness (feet) of modeled Whitehorse and younger formations Permian-age hydrostratigraphic units in layer 2.

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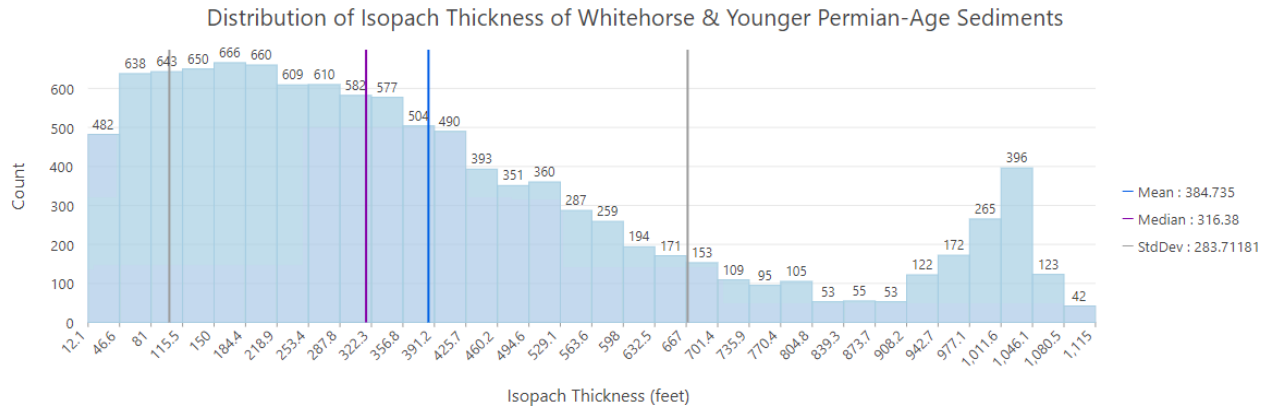


Figure 3.2-5. Statistics for isopach thickness (feet) of modeled Whitehorse and younger Permian-age hydrostratigraphic units in layer 2.

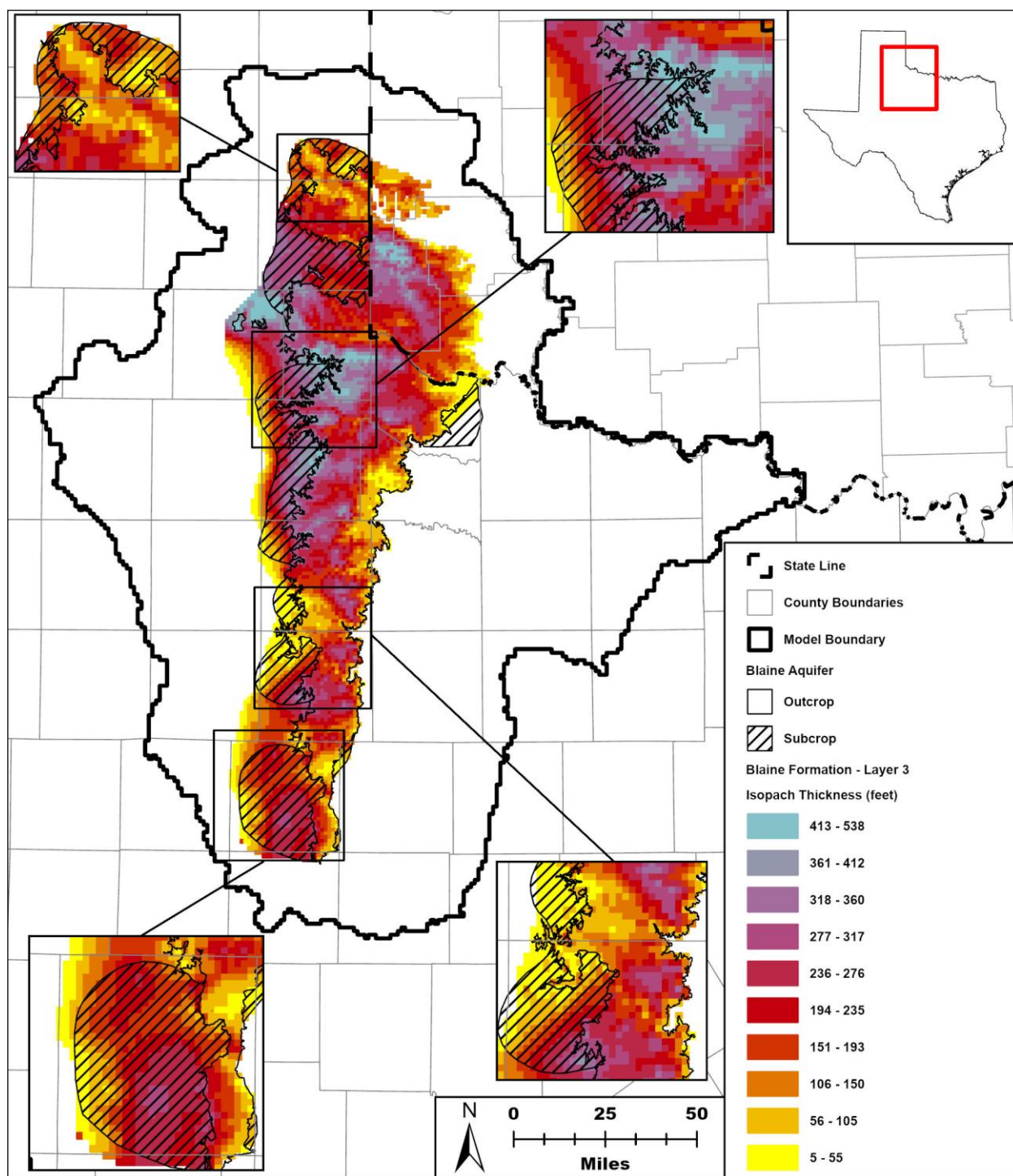


Figure 3.2-6. Isopach thickness (feet) of modeled Blaine formation Permian-age hydrostratigraphic unit in layer 3.

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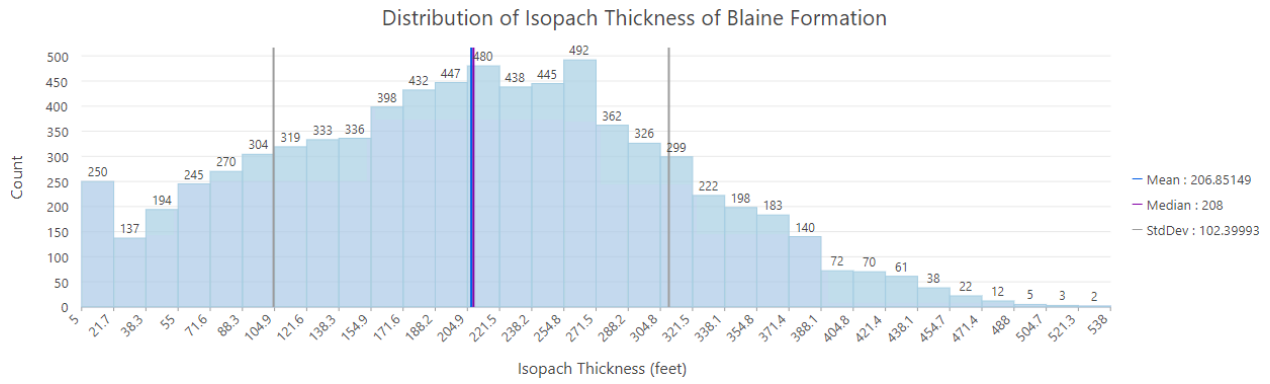


Figure 3.2-7. Statistics for isopach thickness (feet) of modeled Blaine formation Permian-age hydrostratigraphic unit in layer 3.

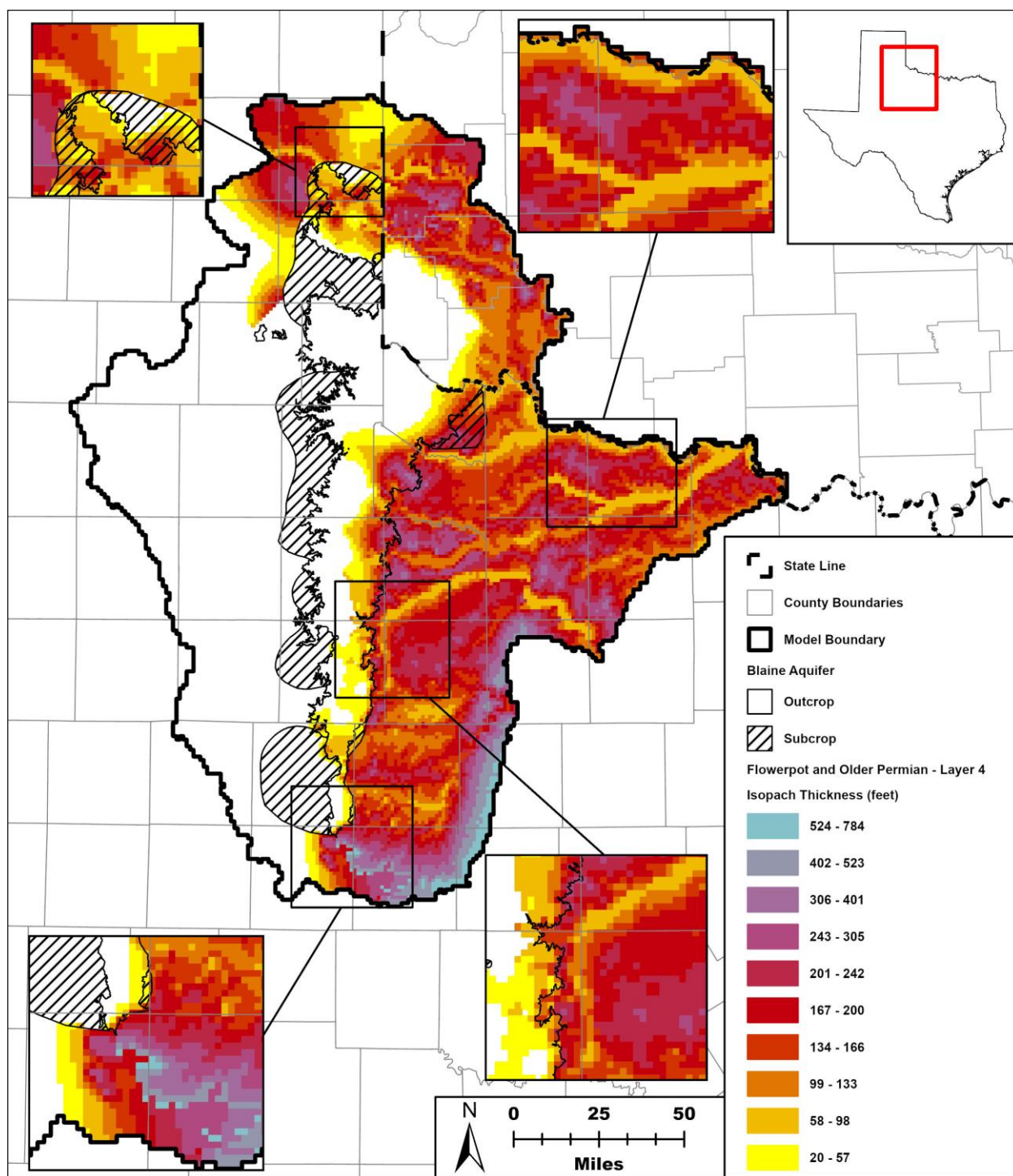


Figure 3.2-8. Isopach thickness (feet) of modeled Flowerpot and older Permian-age hydrostratigraphic units in layer 4.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

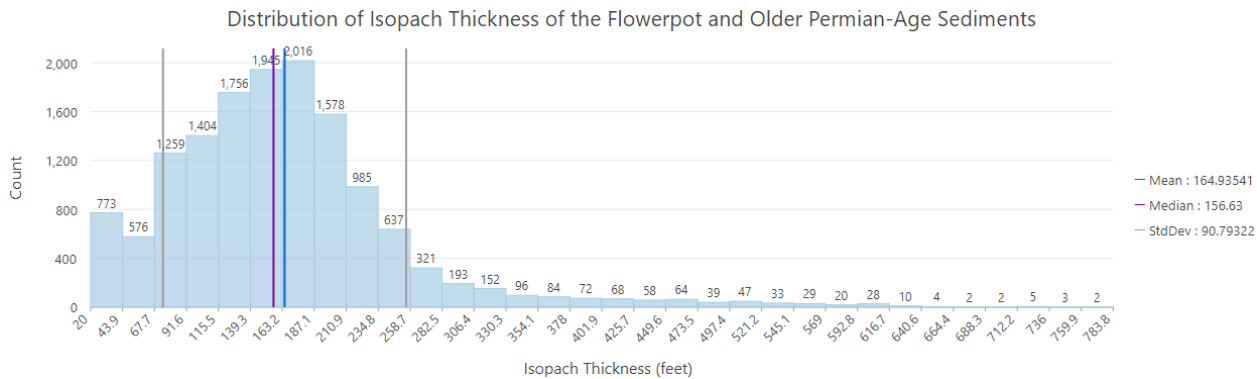


Figure 3.2-9. Statistics for isopach thickness (feet) of modeled Flowerpot and older Permian-age hydrostratigraphic units in layer 4.

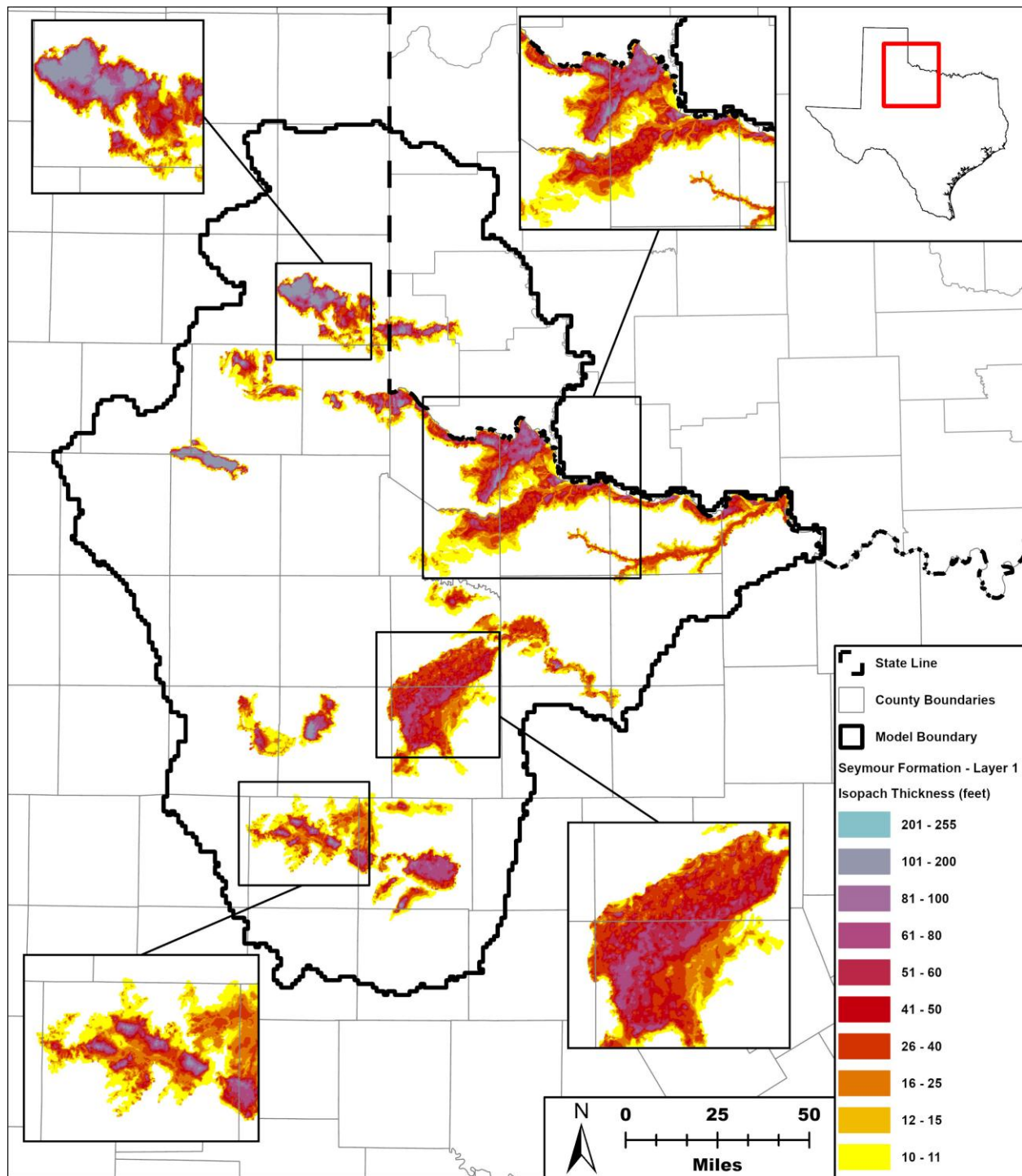


Figure 3.2-10. Isopach thickness (feet) of the Seymour Aquifer in model layer 1.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

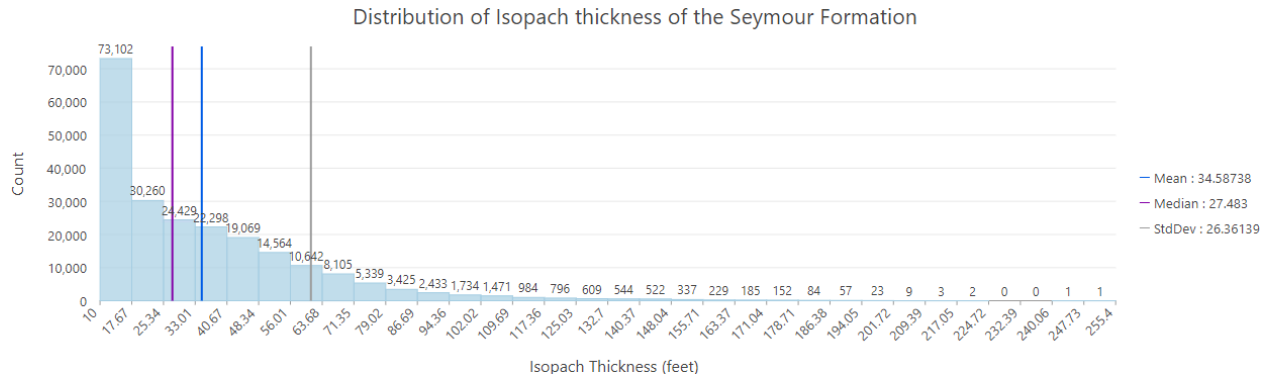


Figure 3.2-11. Statistics for isopach thickness (feet) of the modeled Seymour formation.

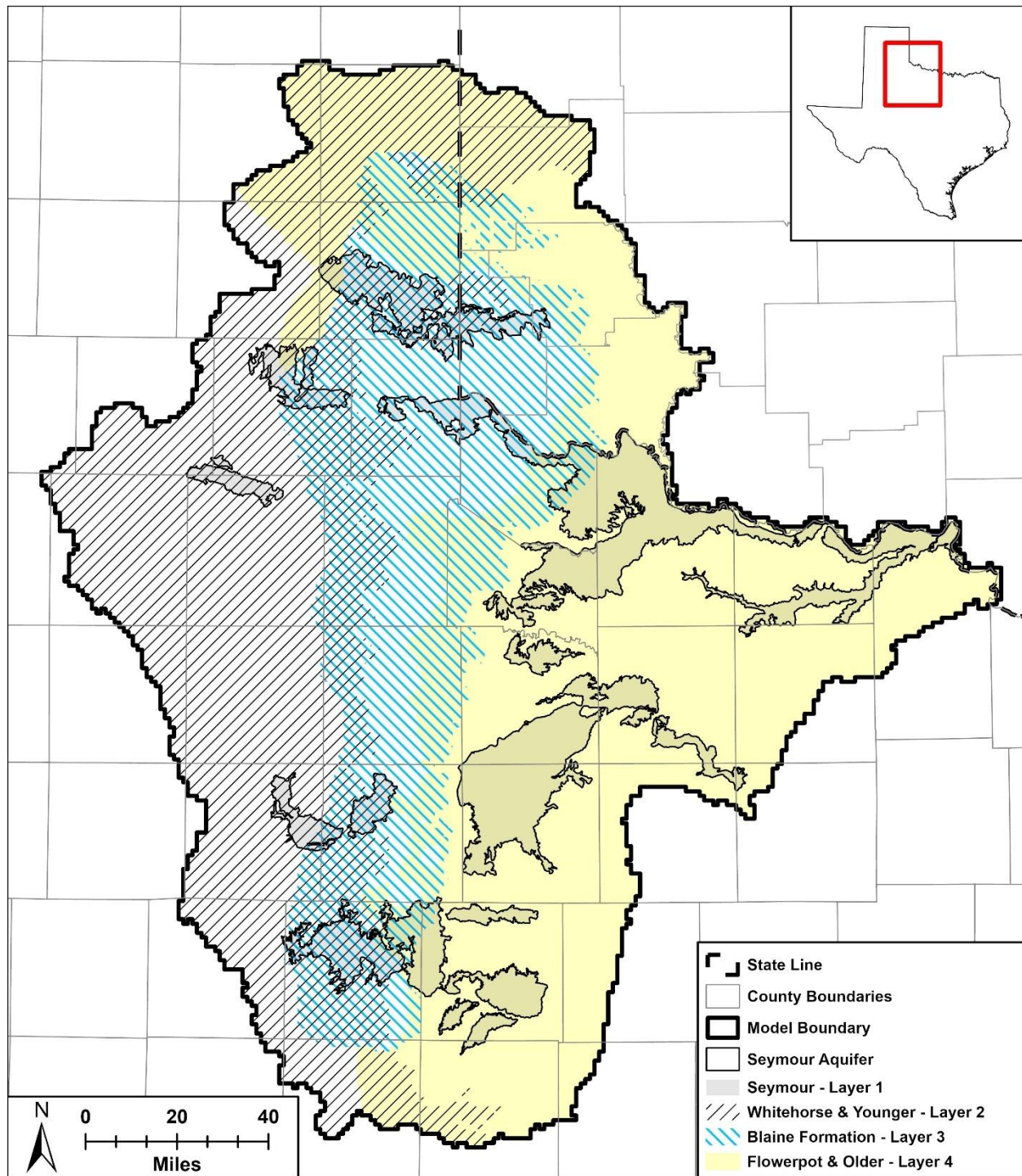


Figure 3.2-12. Spatial extent of all model layers in the groundwater availability model.

3.2.3 Grid properties

The active area model grid spans 238 miles in the north-south direction and 210 miles in the east-west direction. The updated model grid area boundary is shown in Figure 3.2-1. As shown in Figure 3.2-12, model layers are not laterally continuous across the entirety of the model domain. Due to the complexities in local and regional geologic structure detailed in Section 3.2.2, a fully unstructured grid for the numerical model was determined to be the best approach to accommodate the complexities and to represent best the local groundwater flow system, while maintaining flexibility and reasonable model run times. This unstructured approach deviates from the structured grid approach implemented in the previous groundwater availability models developed by Ewing and others (2004) and Jigmond and others (2014). The grid is aligned north-south with no rotation, because no general flow direction is apparent across the entire model domain across all hydrostratigraphic units. Rotation was determined not necessary after planar assessment of topographic gradient directions, regional strike of the geologic units, general groundwater flow direction, and general trends of major stream and rivers within the model domain were reviewed. This is consistent with the previous groundwater availability model. Layer 1, representing the Seymour Aquifer formation sediments, incorporated guidance from recent groundwater modeling for the Seymour Aquifer in Jigmond and others (2014) where the model cell sizes for the Seymour were refined to 1/8th-mile by 1/8th-mile from the previous groundwater availability model developed by Ewing and others (2004), which had a model cell size for the Seymour of 1 mile by 1 mile. Consistent with the previous groundwater availability model developed by Ewing and others (2004), the model layers representing the Permian-age hydrostratigraphic units are spatially discretized with cell sizes of 1 mile by 1 mile for layers 2, 3, and 4 across the model domain where the units are present. It is important to note that, for a single Permian-age grid cell, up to 64 overlying layer 1 grid cells may be present to represent the cross-formational flow between the Seymour Aquifer and the Permian-age sediments. To provide efficiency in building on the previous work in Ewing and others (2004), the same southwest anchor point coordinates were used for the updated model. Model-related geographic information system files that will be viewed in ArcGIS Pro software will include model row and model column, consistent with each east-west and north-south mile the active model area encompasses as would typically be included in a structured model grid, where possible.

3.3 Spring flow and seeps

Spring flows and seeps are an important discharge mechanism for the Seymour and Blaine aquifer system as shown in Figure 3.1-1, despite being a small portion of the overall outflow from the system as characterized in the previous groundwater availability model (Ewing and others, 2004). Spring flows from the literature and publicly available data, documented in report Section 2.6 and displayed in Figure 2.6-1, were included in the conceptual model for discharge of groundwater from the model. These mapped spring locations were implemented with a separate drain package into the numerical model as a mechanism to represent spring flows as groundwater discharge from the numerical model. To accommodate spring flows and

seepage out of each Seymour Aquifer pod further, perimeter drains around each pod were also included to represent better the lateral seepage out of the Seymour Aquifer pods. No changes were made to the conceptual model regarding the representation of spring flow as a discharge mechanism in the updated groundwater availability model.

3.4 Historical pumping

Historical pumping estimates are a critical discharge mechanism for the conceptual model and generally a large portion of the water budget. Historical estimates for the groundwater availability model update were developed primarily using data from the Texas Water Development Board's water use surveys. Insights from previous groundwater availability models developed by Ewing and others (2004) and Jigmond and others (2014), as well as conceptual model reports by Jones and others (2012) for the Seymour and Blaine aquifer system, were incorporated. The water use survey estimates provided by the Texas Water Development Board were augmented with metered data and rural, livestock, and domestic pumping based on population data. Water use survey data were collected for years 1974, and 1980 through 2020. Assumptions were required for estimates for each use type based on the available data to cover the temporal gaps in the model between 1960 to 1974 and 1974 to 1980.

Several updates were made to the previous conceptual model. First, the historical pumping period was extended beyond the prior groundwater availability model timeframe (1975–1999) to cover 1959 through 2020. The initial stress period was defined as a steady-state spin-up period representing pre-1960 conditions, during which no pumping was simulated. This approach provides a stable starting point for the transient model and helps minimize artificial drift in boundary conditions observed in the 2004 groundwater availability model. Second, where available, metered pumping data provided by groundwater conservation districts were explicitly incorporated into the model. Third, pumping estimates were compiled separately for Texas and Oklahoma, with Texas estimates further subdivided into specific categories described in the following subsections.

These updates were driven by data availability and were designed to improve the clarity and interpretability of modeled pumping estimates. The following pumping use types were included for both the Seymour and Blaine aquifers:

- Irrigation,
- Municipal,
- Livestock,
- Mining,
- Manufacturing,
- Rural, Domestic, and

- Metered

The metered data were typically composed of irrigation pumping from Seymour pods one-(1), two-(2), three-(3), and seven-(7), with the remainder composed of municipal pumping. There was metered pumping included in some portions of the Blaine Aquifer. Where metered data were provided with no aquifer designation, pumping was assigned to the underlying outcropping unit. The Oklahoma pumping estimates from the previous groundwater availability model were used as the foundation to which the estimates were extended both backward and forward in time.

Based on previous studies and the estimates from the TWDB water use survey, irrigation pumping typically makes up 90% or greater of the total pumping estimated for the years that data are available. This is an important conceptual consideration when considering the importance of other types of pumping and their overall impact, or lack thereof, on groundwater levels in the Seymour and Blaine aquifers simulated by the groundwater availability model.

3.5 Recharge

Recharge to the groundwater system is the primary mechanism of inflow to the Seymour and Blaine aquifer system as shown in the conceptual model (Figure 3.1-1). Within the active model extent of the study area, estimated values for recharge were compiled from various literature sources as documented in the previous groundwater availability model report (Ewing and others, 2004). As documented in Ewing and others (2004), precipitation-derived recharge estimates to the groundwater system provided in the literature and previously developed numerical models are generally 10 percent (%) or less of annual precipitation for the Seymour and Blaine aquifer system. Generally, the recharge rate to the Seymour Aquifer system approaches 10%, of annual average precipitation, which is generally higher than the approximate recharge to the underlying Permian-age hydrostratigraphic units. These estimates are summarized in Table 3-2. No material updates to the conceptual model for incorporating precipitation events as a recharge mechanism are included in the groundwater availability model.

Table 3-2. Estimated recharge rates (inches per year) for the Seymour and Blaine aquifers (after Scanlon and others, 2002; Ewing and others, 2004; and Jigmond and others, 2014). ⁽¹⁾ Estimated as 7 percent of rainfall (annual precipitation of 22 inches assumed). ⁽²⁾ Represents a mean value averaged over entire model domain and modeled time period.

County/Area	Aquifer	Recharge (inches/year)	Reference	Technique
Haskell and Knox counties	Seymour	2.2	R.W. Harden & Associates (1978)	water budget
Hardeman County	Seymour	1.0	Maderak (1972)	Darcy's Law
Baylor County	Seymour	2.6	Preston (1978)	baseflow discharge
Jones County	Seymour	1.8	Price (1978)	baseflow discharge
Wilbarger County	Seymour	2.5	Willis and Knowles (1953)	baseflow discharge
Haskell County	Seymour	0.20 to 1.18	Scanlon and others (2003)	field study
Fisher/Jones counties	Seymour	0.28	Scanlon and others (2003)	unsaturated flow modeling
Greer and Jackson counties, Oklahoma	Blaine	1.5 ⁽¹⁾	Maderak (1972)	water budget
Greer, Harmon, Jackson counties, Oklahoma and Childress, Collingsworth, Hardeman counties, Texas	Blaine	1.5	Runkle and McLean (1995)	numerical model calibration parameter
Refer to Ewing and others, 2004	Seymour	1.9 ⁽²⁾	Ewing and others (2004)	numerical model calibration parameters
Refer to Ewing and others, 2004	Blaine	0.38 ⁽²⁾	Ewing and others (2004)	numerical model calibration parameters
Haskell, Knox, and Baylor counties	Seymour	0.0 to 4.9	Jigmond and others (2014)	numerical model calibration parameter

Recharge derived from precipitation was included for all modeled hydrostratigraphic units: Seymour, Blaine, Whitehorse and younger Permian, and the Flowerpot and older Permian units. Additionally, the extension of the active model area relative to the previous groundwater availability model to the north, west, and south (as described in Section 3.2.1 and shown in Figure 3.2-1) introduced the need to consider recharge inputs from leakage from overlying hydrostratigraphic units not explicitly included in the model. The High Plains groundwater availability model (Deeds and Jigmond, 2015) and the High Plains groundwater availability model update (Cawthon and Wade, 2025) show that the Ogallala Aquifer overlies the northern and western extension of the active model area, and the Edwards-Trinity (Plateau) overlies the southern extension of the active model area. Recharge from these overlying units were considered and are shown in Figure 3.5-1.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

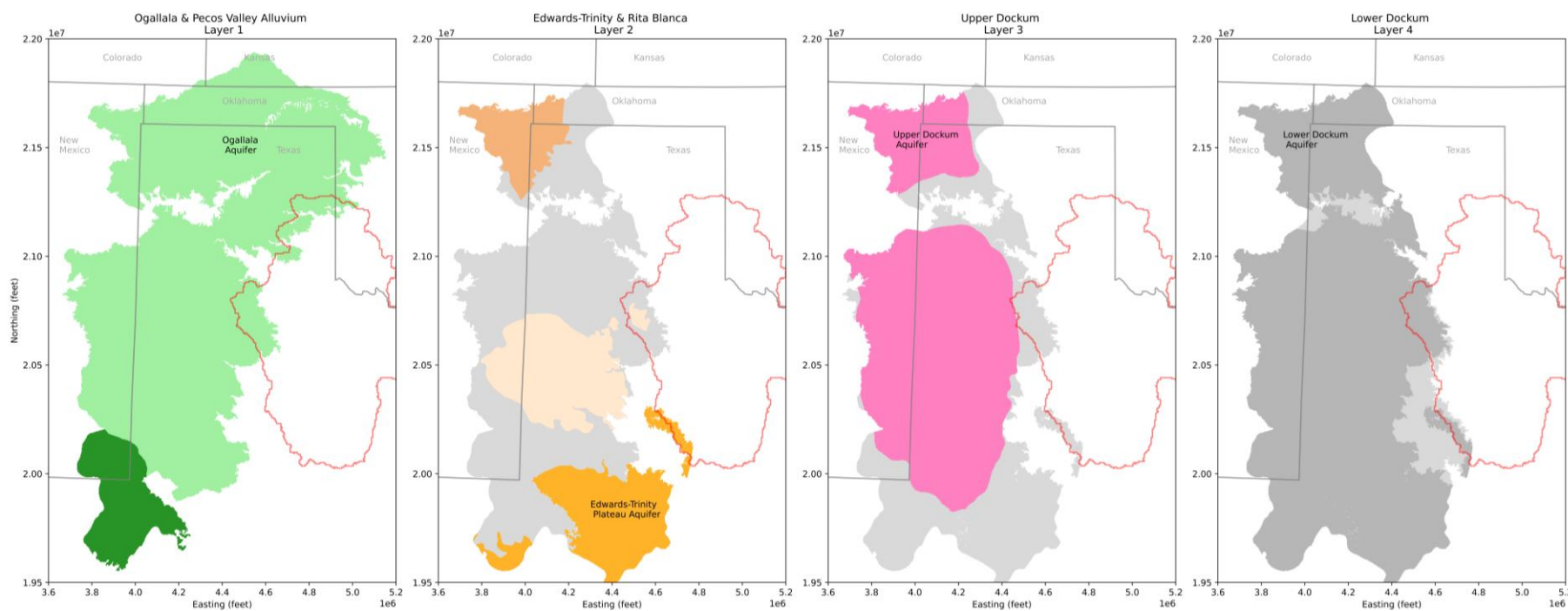


Figure 3.5-1. Aquifer Footprints from the High Plains groundwater availability model (Deeds and Jigmond, 2015; Cawthon and Wade, 2025) of the Ogallala (green) and Edwards-Trinity (Plateau) Aquifers (orange) along the northern, western, and southern groundwater availability model boundaries. Upper (pink) and Lower (grey) Dockum extents are included. Seymour and Blaine groundwater availability model extent is provided (red).

3.6 Faulting

The previous groundwater availability model developed by Ewing and others (2004) discussed minor faulting that, in part, influences regional structure of the Permian-age hydrostratigraphic units. Consistent with the previous groundwater availability model, faults were not explicitly incorporated into the conceptual model in regard to controlling inflows, outflows, and storage changes. At a regional scale, stresses and subsequent faulting that controls the strike, dip and dip direction of the Permian-age hydrostratigraphic units is included in the conceptual model structure indirectly, but faults are not explicitly incorporated. Further description of the regional stresses controlling the updated extent of the model area is described in Section 2.7 and shown in Figure 2.7-1.

4 Model overview and packages

4.1 Introduction

The code selected for the Seymour and Blaine groundwater availability model is MODFLOW 6 (Langevin and others, 2017). MODFLOW is a three-dimensional finite-difference groundwater flow model that supports a variety of boundary condition packages for simulating recharge, streams, reservoirs, and other hydrological features. MODFLOW 6 represents the latest version in the MODFLOW family of codes developed and supported by the United States Geological Survey.

The advantages of using MODFLOW 6 for this project include: (1) MODFLOW 6 incorporates the essential physics of groundwater flow, (2) it is the most widely accepted groundwater flow model in use today, (3) MODFLOW 6 is written and supported by the United States Geological Survey and is available in the public domain, (4) it is well-documented, with extensive resources available from both the United States Geological Survey and the broader scientific community (Langevin and others, 2017; Hughes and others, 2022), and (5) MODFLOW 6 has a large and active user community. Furthermore, there are numerous software available to develop MODFLOW models process the results.

To create a more modular framework that allows multiple models to be coupled more tightly, the developers of MODFLOW 6 designed a system where higher-level details that apply universally across all models (at the simulation level) are separated from the details specific to individual models (at the model level). This approach contrasts with previous versions of MODFLOW, where the model-level details were the only inputs, consisting of groupings of input text files (also called "packages") that described various components of the groundwater flow system.

Although the Seymour and Blaine groundwater availability model is a standalone model, the simulation-level configuration within MODFLOW 6 allows for enhanced flexibility with future utility. This structure provides opportunities to support more localized investigations or to integrate the model with other systems, such as climate models, thereby increasing its overall future applicability and effectiveness.

At the simulation level, configuration options such as simulation timing, the number of models included, information exchange between models, and solution methods are defined. In this case, with only a single groundwater flow model, the simulation level inputs are relatively straightforward. The main input is the simulation name file, which includes the keywords indicating that this is a single groundwater flow model and defining how it is set up in terms of time. The temporal discretization (TDIS) file is linked to the simulation name file and details the number of stress periods, period lengths, number of time steps, and time step multipliers, ensuring consistency and coherence across the simulation. The simulation level input files are listed in Table 4-1. At the model level, each model retains its own set of input packages, which describe specific components of the groundwater flow system, such as hydraulic properties, boundary conditions, and source/sink terms. Translation of the conceptual

model diagram and hydrologic processes from Figure 3.1-1 to the numerical model packages is shown on Figure 4.1-1. The input packages and their corresponding filenames are detailed in Table 4-2. The output files generated by MODFLOW 6 include water levels (HDS), water budget information (CBB), a listing of the run characteristics (LST), and specified observation output files as shown in Table 4-3. The model length unit is feet and the model time unit is days. Each individual package is introduced in the remainder of this section, along with an overview of their roles and functionalities within the overall MODFLOW 6 model.

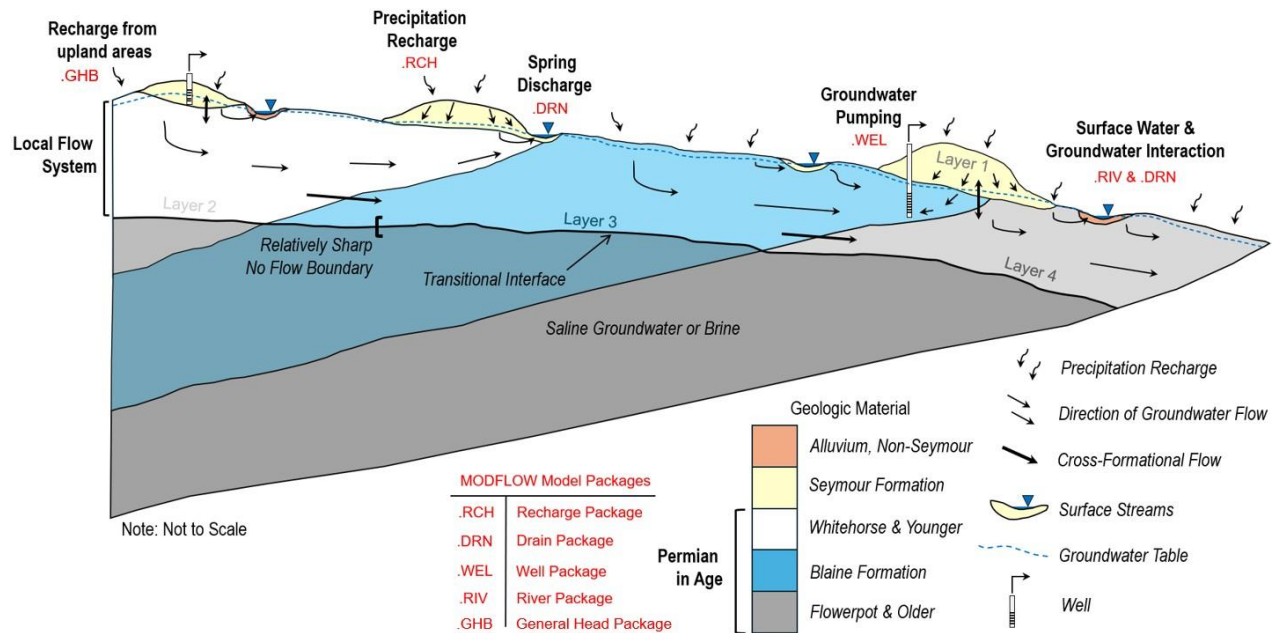


Figure 4.1-1. Conceptual model diagram with MODFLOW packages.

Table 4-1. Summary of simulation level files and file names.

File Type	Input File Name
Simulation Name File	sb.nam
Temporal Discretization	sb.tdis

Table 4-2. Summary of model input files and filenames.

File Type Abbreviation	File Type	Input File Name
DISU	Unstructured Discretization File	sb.disu
GNC	Ghost-Node-Correction Package	sb.gnc
GSF	Grid Specification File	sb.gsf
IC	Initial Conditions Package	sb.ic
NPF	Node Property Flow	sb.npf
STO	Storage Package	sb.sto
WEL	Well Package (Irrigation)	sb_lay1_pod01*.irr
WEL	Well Package (Irrigation)	sb_lay3_pod00.irr
WEL	Well Package (Municipal)	sb.muni
WEL	Well Package (Mining)	sb.mini
WEL	Well Package (Livestock)	sb.stk
WEL	Well Package (Manufacturing)	sb.mfg
WEL	Well Package (Metered)	sb.metered
WEL	Well Package (Domestic-Seymour)	sb.dom.seymour
WEL	Well Package (Domestic-Blaine)	sb.dom.blaine
WEL	Well Package (Oklahoma-All)	sb.okla
DRN	Drain Package	sb_streams.drn
DRN	Drain Package	sb_springs.drn
DRN	Drain Package	sb_pod01*_edge.drn
RCH	Recharge Package	sb.rch
RIV	River Package	sb.riv
GHB	General Head Package	sb_ogfp_north.ghb
GHB	General Head Package	sb_ogfp_south.ghb
GHB	General Head Package	sb_edtrfp.ghb
OC	Output Control	sb.oc
IMS	Iterative Model Solution	sb.ims
OBS	Observation Utility (Heads)	sb.obs
OBS	Observation Utility (Boundary Flows)	sb_ogfp_north.ghb.obs
OBS	Observation Utility (Boundary Flows)	sb_ogfp_west.ghb.obs
OBS	Observation Utility (Boundary Flows)	sb_edtrfp.ghb.obs

*Separate package included for each Seymour Aquifer pod 01 through 15

Table 4-3. Summary of model output files and filenames.

File Type	Output File Name
Binary flow file	sb.cbc
Binary head file	sb.hds
List file	sb.lst
Observation output csv – hydraulic heads	sb.head.obs.output.csv
Observation output csv – water budget	budget.csv
Observation output csv – boundary flows (ghb)	sb.ogfp_north.ghb.obs.output.csv
Observation output csv – boundary flows (ghb)	sb.ogfp_west.ghb.obs.output.csv
Observation output csv – boundary flows (ghb)	sb.edtrfp.ghb.obs.output.csv
Observation output csv – autoflow reduction	sb.metered.autoreduce.csv
Observation output csv – autoflow reduction	sb.dom.blaine.autoreduce.csv
Observation output csv – autoflow reduction	sb.dom.seymour.autoreduce.csv
Observation output csv – autoflow reduction	sb.mfg.autoreduce.csv
Observation output csv – autoflow reduction	sb.mini.autoreduce.csv
Observation output csv – autoflow reduction	sb.muni.autoreduce.csv
Observation output csv – autoflow reduction	sb.okla.autoreduce.csv
Observation output csv – autoflow reduction	sb.stk.autoreduce.csv
Observation output csv – autoflow reduction	sb_lay1_pod01*.irr.autoreduce.csv
Observation output csv – autoflow reduction	sb_lay3_pod00.irr.autoreduce.csv

*Separate output file included for each Seymour Aquifer Pod 01 through 15

4.2 Basic package

In MODFLOW 6, the basic (BAS) package is no longer used. Instead, initial head values are defined using the initial conditions (IC) package (see Section 4.7), and constant heads are specified via the time-varying specified head (CHD) package. Cells that should be permanently excluded from the simulation are managed using the IDOMAIN feature, specified in the discretization (DISU) package discussed in the following section, which also includes discussion of the extent of each model layer. There are no constant head (CHD) package cells specified in this model.

4.3 Unstructured discretization package

The unstructured discretization (DISU) package in MODFLOW 6 is used to define the model's spatial and vertical divisions for an unstructured grid. In an unstructured model space, the unstructured discretization package must contain all information for each model cell, or node, including the model cell (node) connectivity. As described in Section 3.2.3, one of the key updates to the 2004 groundwater availability model involved refining the discretization for the Seymour Aquifer. Another update included the addition of two generally Permian-in-age model layers, for a total of three Permian-age hydrostratigraphic units, to represent better the primary aquifer portion of the Blaine Aquifer. To implement this refinement and additional structural

complexity, an unstructured grid was determined to be the most appropriate as it provides the most flexibility of the MODFLOW packages defining spatial discretization best to represent the geologic structure of the system while minimizing the number of grid cells in the model.

As described in Section 3.2.3, the spatial resolution for the Seymour Aquifer formation sediments represented in layer 1 was at a scale of 1/8th mile by 1/8th mile. The Permian-age hydrostratigraphic units represented in layers 2, 3, and 4 have a spatial resolution scale of 1 mile by 1 mile where the units are present. It is important to note that all hydrostratigraphic units represented in the model domain are not laterally continuous and, in part, provided the basis for implementation of an unstructured grid. The southwest anchor point for the updated model grid is Easting: 4,438,000 United States feet, Northing: 20,024,960 United States feet. The grid's coordinate system is in feet, and, in accordance with new groundwater availability model standards set by the Texas Water Development Board. The projection used was North American Datum (NAD) 1983 TWDB GM. This decision allows for easier integration with geographic information system platforms, which widely support European Petroleum Survey Group codes, enhancing data interoperability and simplifying spatial data management.

The grid spans 238 miles in the north to south oriented y-direction and 210 miles in the west to east oriented x-direction, with no rotation applied to the grid. Aligning the grid in the north to south, absent of rotation, simplifies numerical modeling calculations, as unrotated grids avoid complications with trigonometric conversions. The spatial discretization of layer 1, representing the Seymour Aquifer formation sediments, is shown in Figure 4.3-1. Layer 1 consists of 221,409 model cells, or nodes. The spatial discretization of layers 2, 3, and 4, representing the Permian-age hydrostratigraphic units, are shown in Figure 4.3-2. In absence of consideration of the overlap in the spatial extent of layers 2, 3, and 4 as depicted in Figure 3.2-12, there are 238 rows and 210 columns at a 1-mile by 1-mile spatial resolution and a total of 25,349 cells within the active area extent (Figure 4.3-2). When considering the overlap in spatial extent of these layers, layer 2 is comprised of 10,869 nodes, layer 3 is comprised of 7,535 nodes, and layer 4 is comprised of 14,261 nodes. Collectively, this represents 32,665 nodes, with 7,316 nodes within these layers representing overlapping conditions. The spatial extents of layers 2, 3, and 4 juxtaposed over the 1 mile by 1-mile spatial resolution of the layers is displayed in Figure 4.3-3. To ensure all 254,074 model cells (nodes) communicate effectively, where necessary, there are 1,694,278 nodal connections across all model layers.

Examples visualizing the complexity of the model structure shown in Figure 3.2-12 and Figure 4.3-3 are provided by cutting two cross-sections through the constructed MODFLOW 6 numerical model using FloPy (Bakker and others, 2025). The first cross-section is a west to east cross-section cutting through the middle of the model domain at row 117 and looking north (Figure 4.3-4). The second cross-section is a south to north cross-section cutting through the middle of the model domain at column 105 and looking west (Figure 4.3-5). The cross-sections demonstrate good agreement between the conceptual model and the constructed numerical model.

Appendix A contains west to east cross-sections, facing north for all model rows.
Appendix B contains south to north cross-sections, facing west for all model columns.

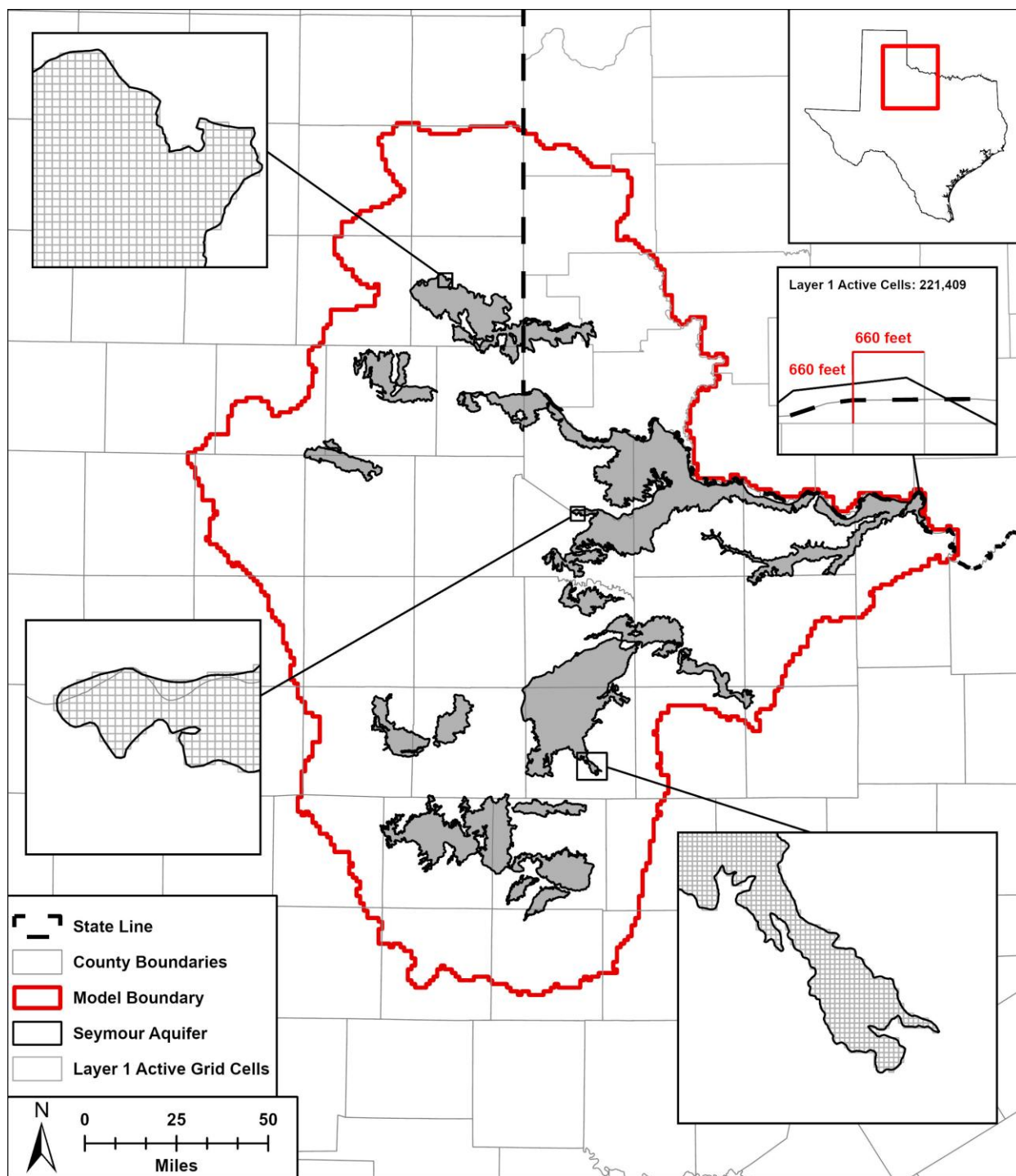


Figure 4.3-1. Active model cells (nodes) for layer 1 representing the Seymour Aquifer formation sediments.

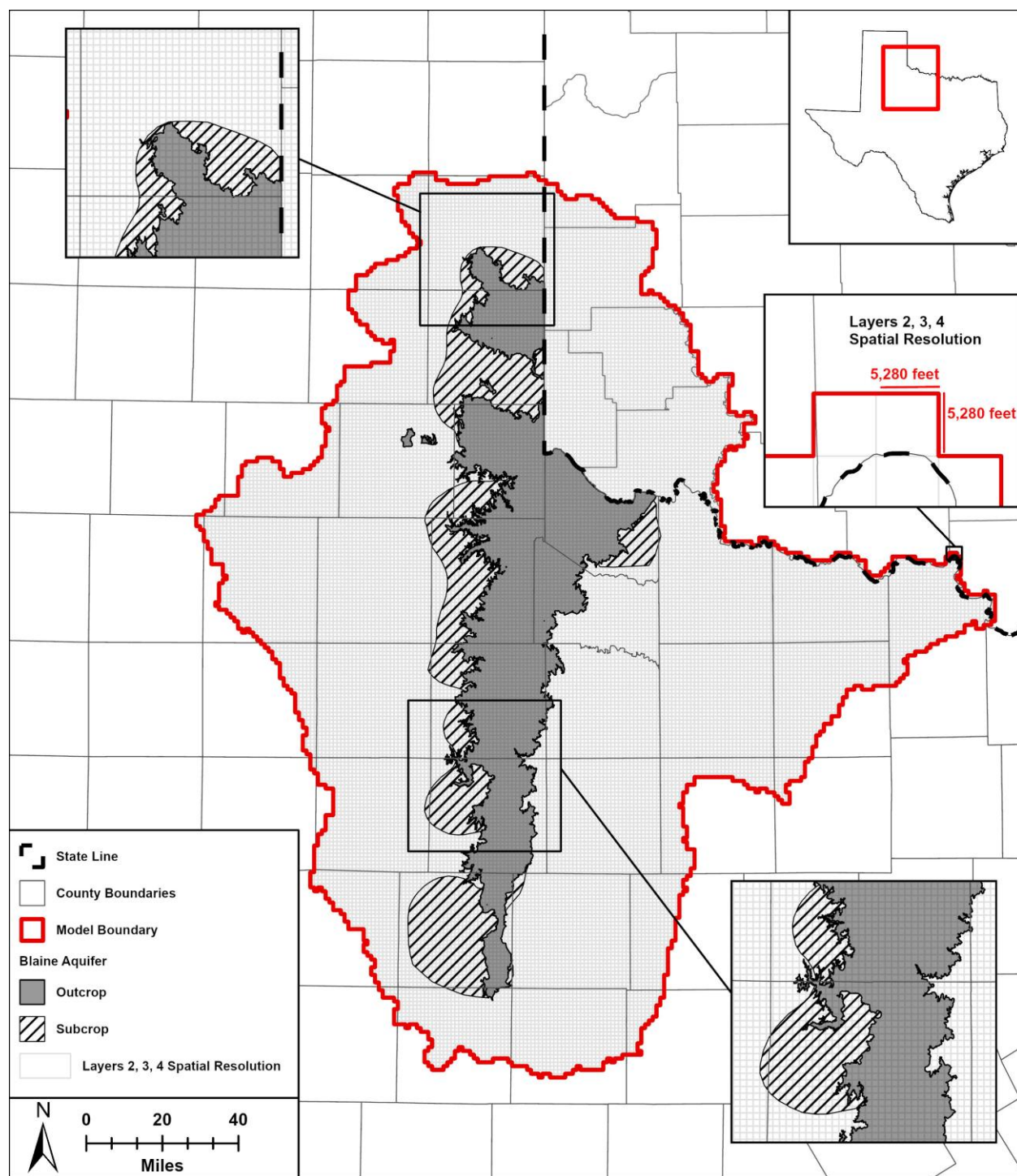


Figure 4.3-2. Generalized model cells (nodes) for layers 2, 3, and 4 representing the Permian-age hydrostratigraphic units, including the Blaine Aquifer. This figure excludes layer overlap.

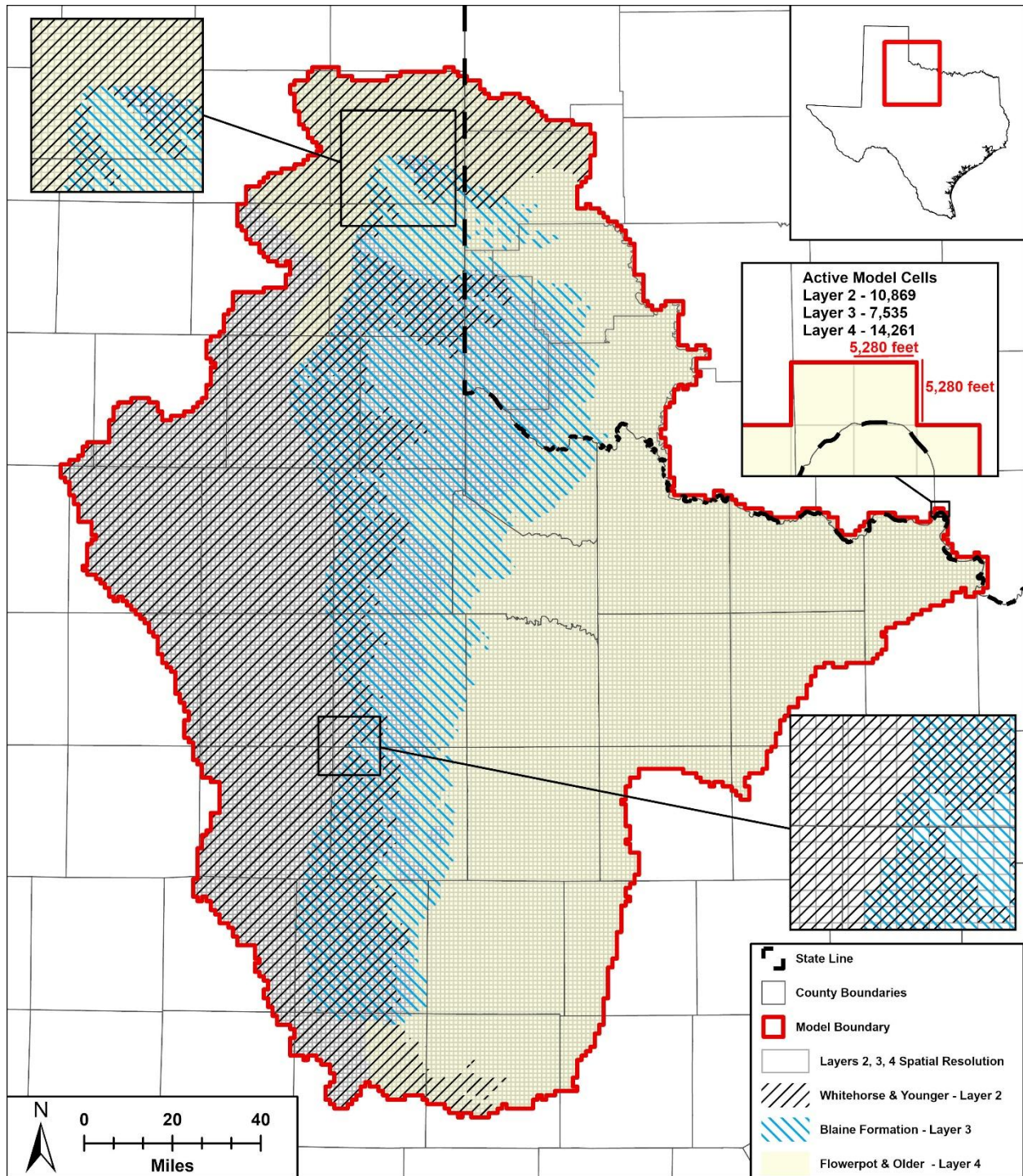


Figure 4.3-3. Detailed active model cells (nodes) for layers 2, 3, and 4 representing the Permian-age hydrostratigraphic units, including the Blaine Aquifer. This figure includes layer overlap.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

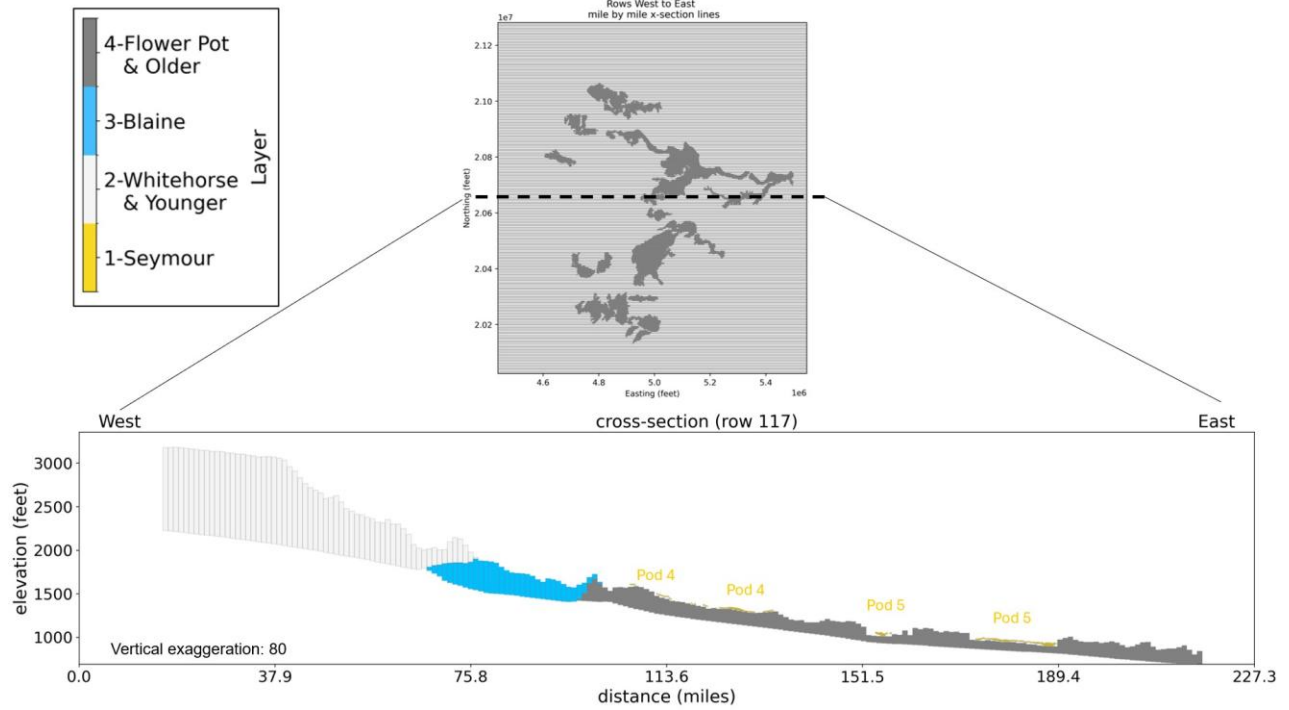


Figure 4.3-4. West to east cross-section of constructed numerical model row 117, facing north.

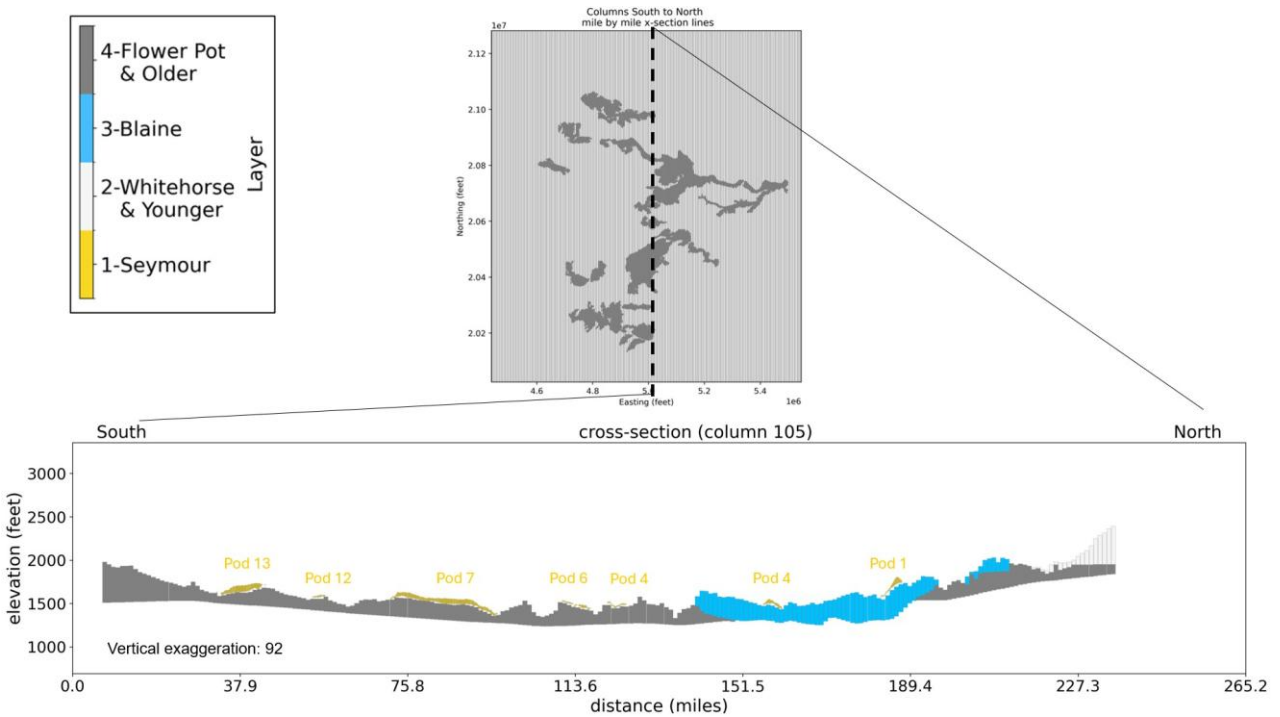


Figure 4.3-5. South to north cross-section of constructed numerical model column 105, facing west.

The top and bottom elevations in feet above mean sea level for model layer 1 representing the Seymour Aquifer formation sediments are provided in Figure 4.3-6 and Figure 4.3-7, respectively. The top and bottom elevations in feet above mean sea level for model layer 2 representing the Whitehorse and younger Permian-age hydrostratigraphic units are provided in Figure 4.3-8 and Figure 4.3-9, respectively. The top and bottom elevations in feet above mean sea level for model layer 3 representing the Blaine Aquifer formation sediments are provided in Figure 4.3-10 and Figure 4.3-11, respectively. The top and bottom elevations in feet above mean sea level for model layer 4 representing the Flowerpot shale and older Permian-age hydrostratigraphic units are provided in Figure 4.3-12 and Figure 4.3-13, respectively. Where applicable, surface elevations were calculated using the average elevation for each grid cell based on a United States Geological Survey 10-meter (32.8-foot) digital elevation model (USGS, 2019). Model base elevations for the model layers were based on well log information available from the TWDB, Submitted Driller's Report database, and Brackish Resources Aquifer Characterization Studies geophysical logs for the area and previous groundwater availability models developed by Ewing and others (2004) and Jigmond and others (2014). Further information regarding refinement of model layer basal elevations is described in Section 3.2.2.

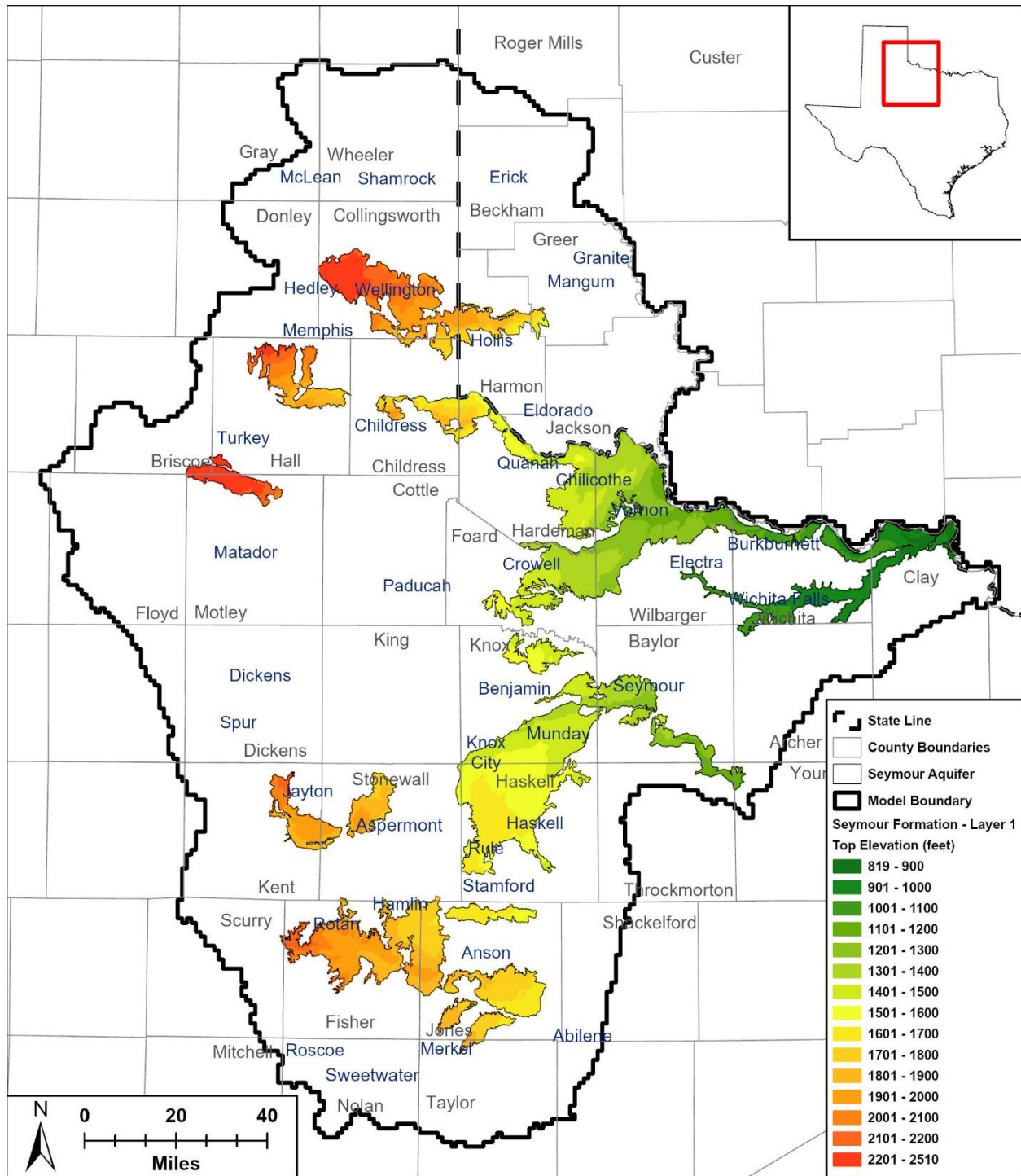


Figure 4.3-6. Model layer 1 top elevation (feet) for the Seymour Aquifer formation sediments.

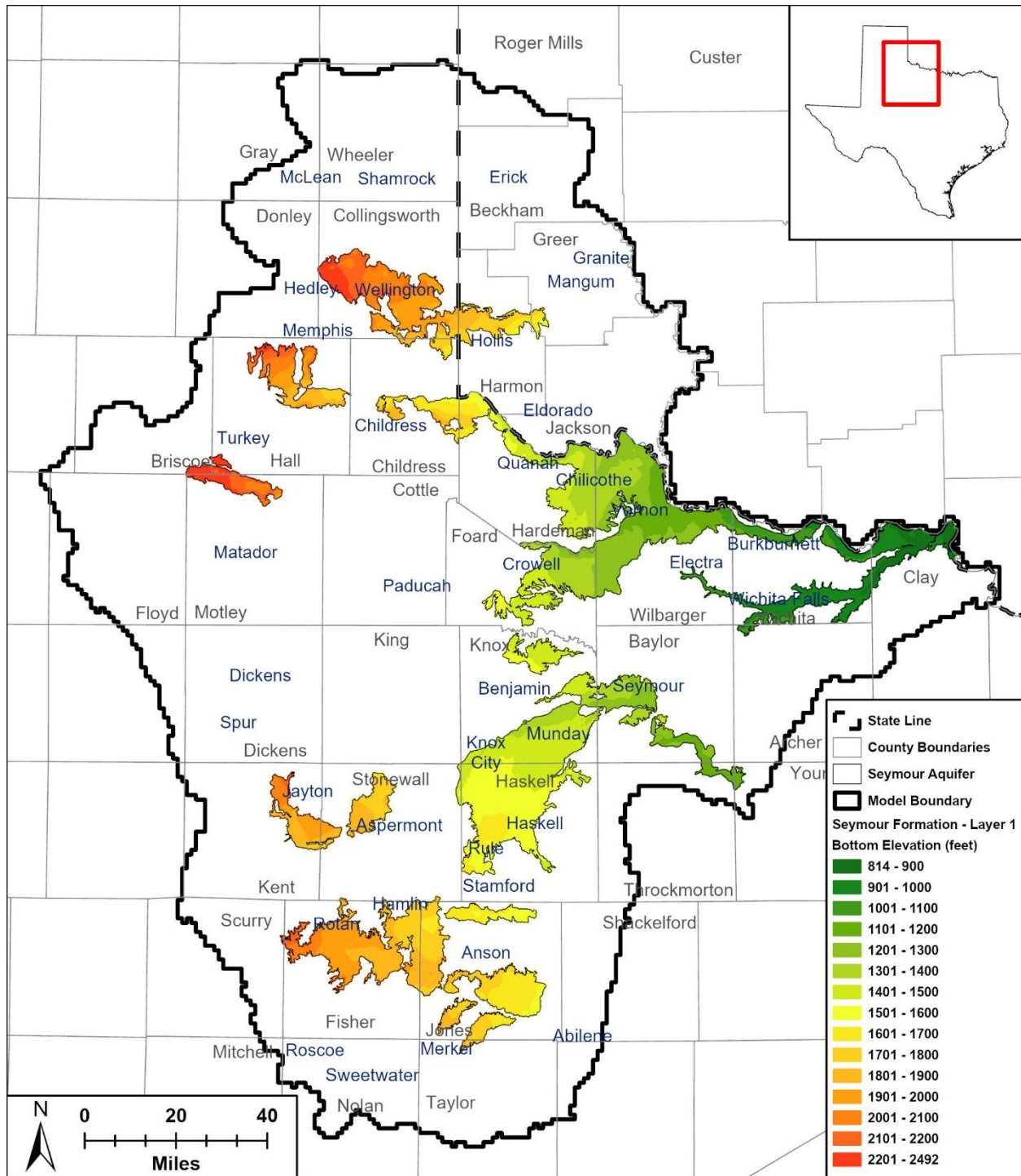


Figure 4.3-7. Model layer 1 bottom elevation (feet) for the Seymour Aquifer formation sediments.

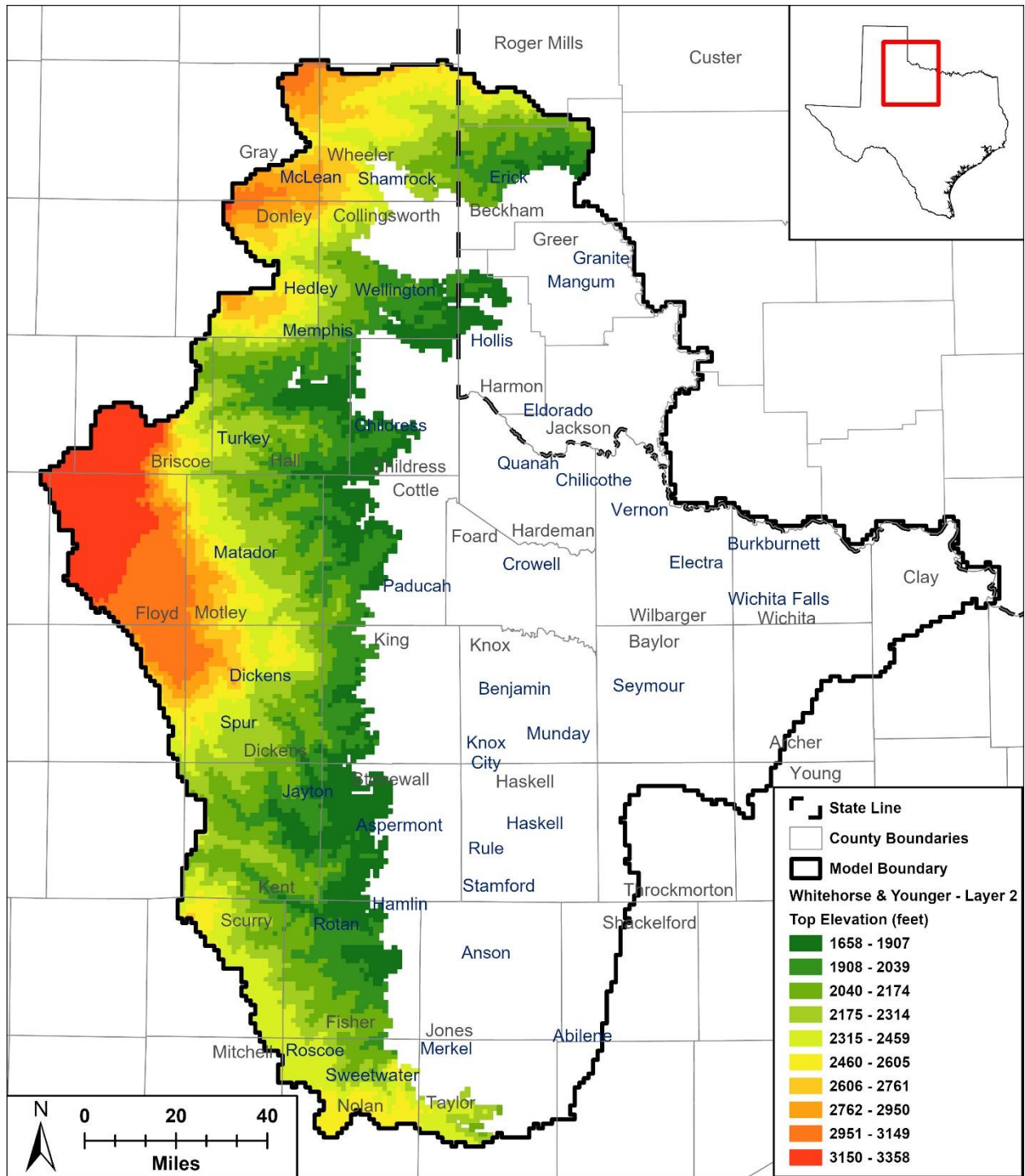


Figure 4.3-8. Model layer 2 top elevation (feet) for the Whitehorse and younger Permian-age units.

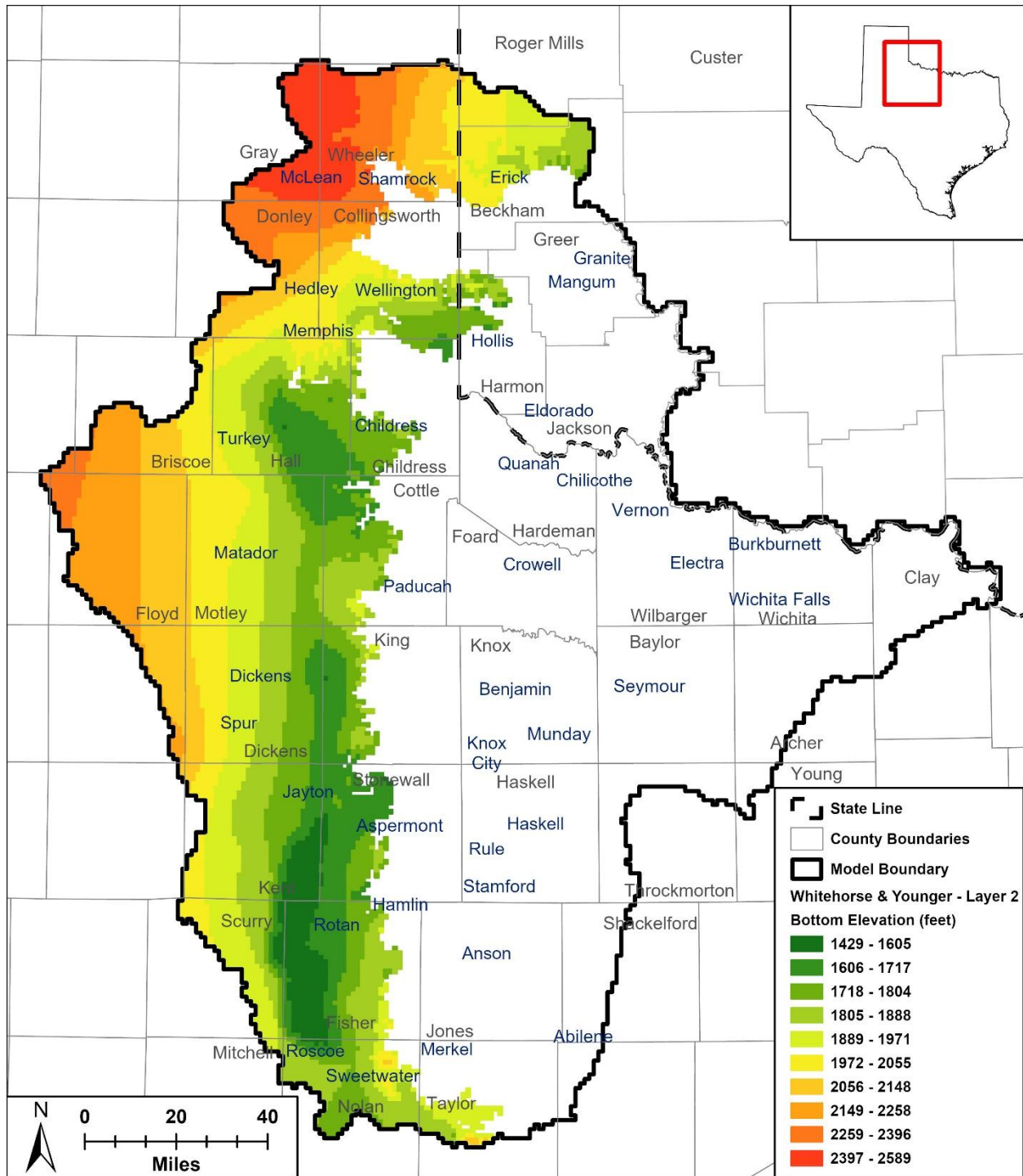


Figure 4.3-9. Model layer 2 bottom elevation (feet) for the Whitehorse and younger Permian-age units.

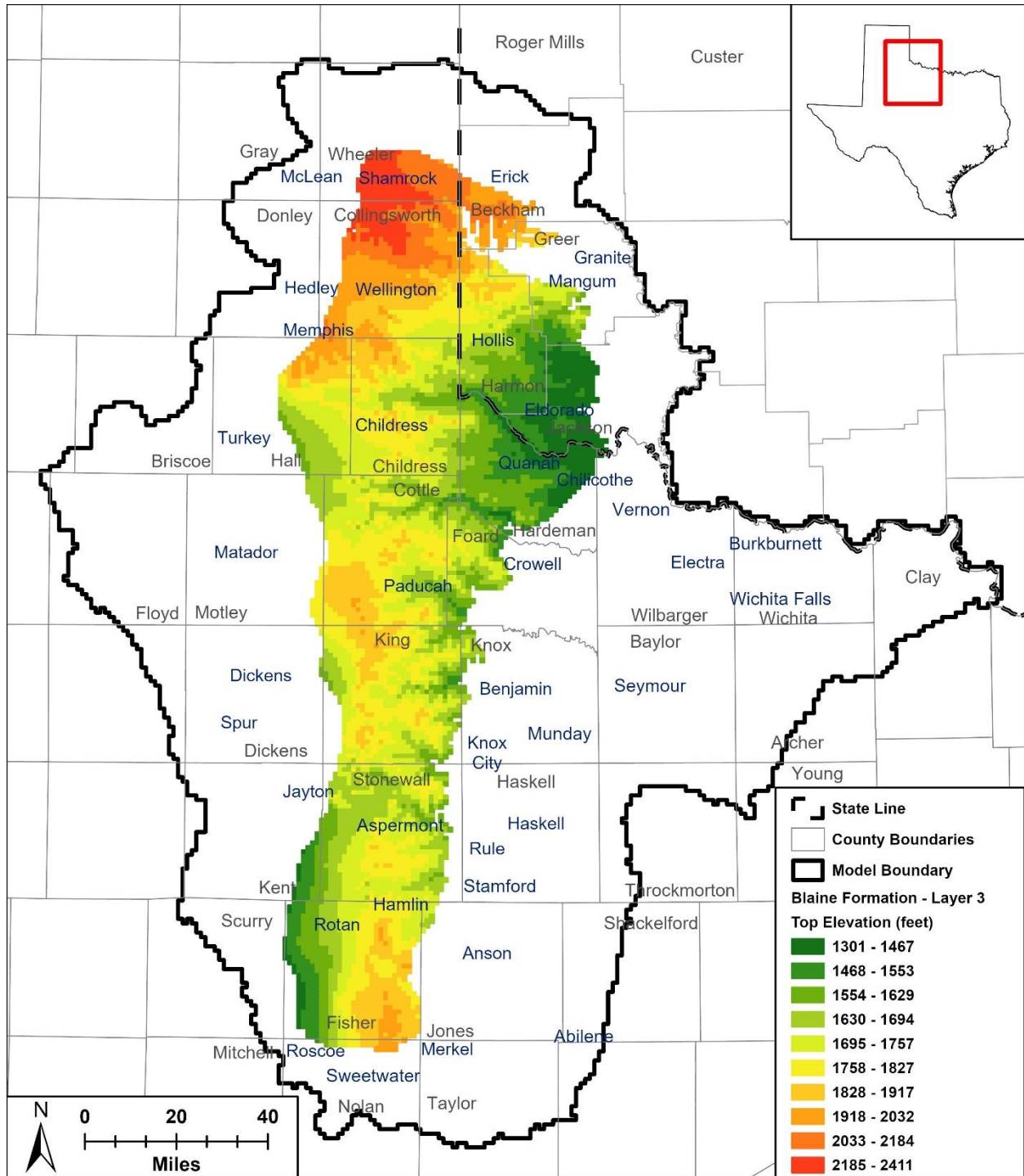


Figure 4.3-10. Model layer 3 top elevation (feet) for the Blaine formation.

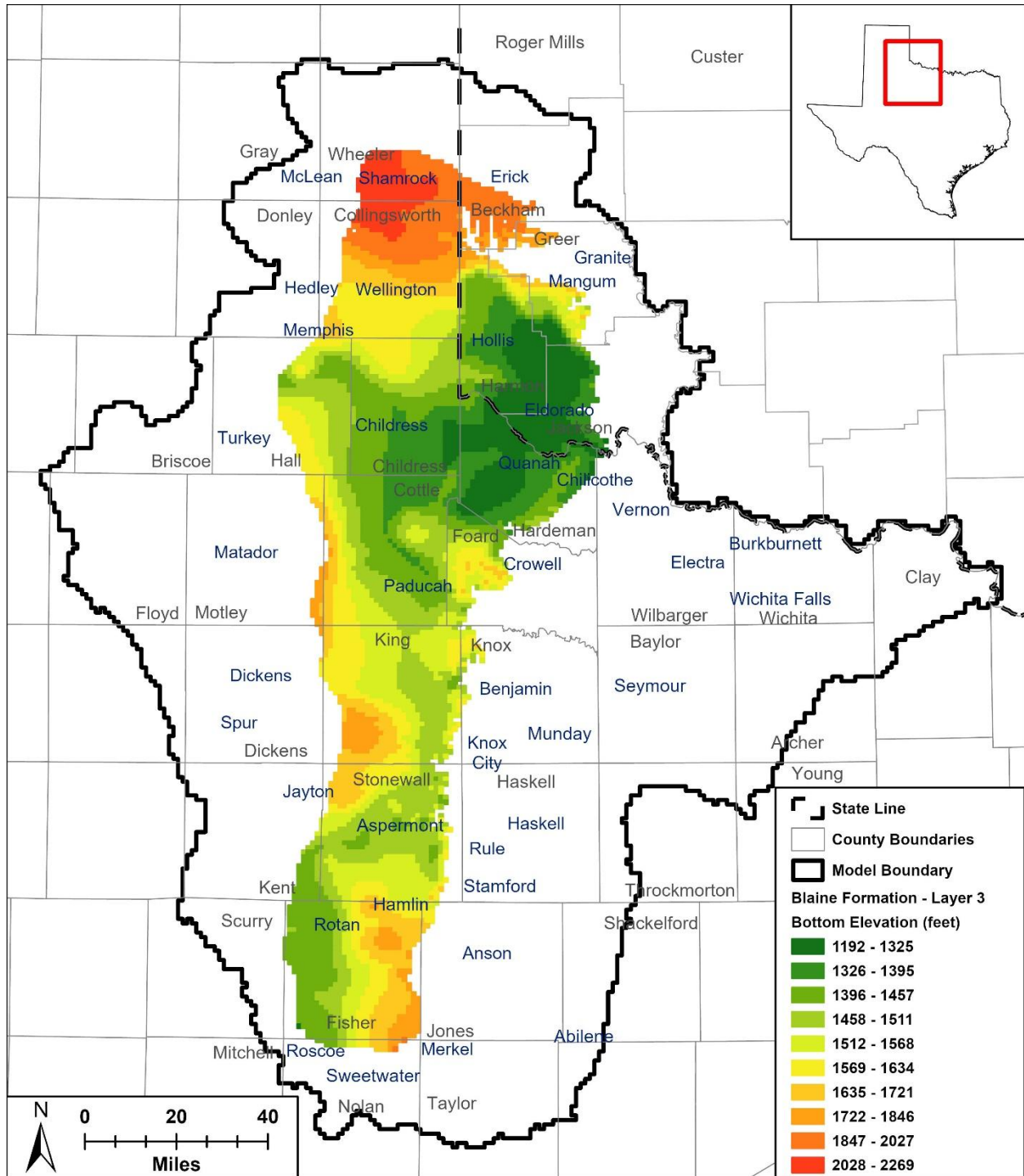


Figure 4.3-11. Model layer 3 bottom elevation (feet) for the Blaine formation.

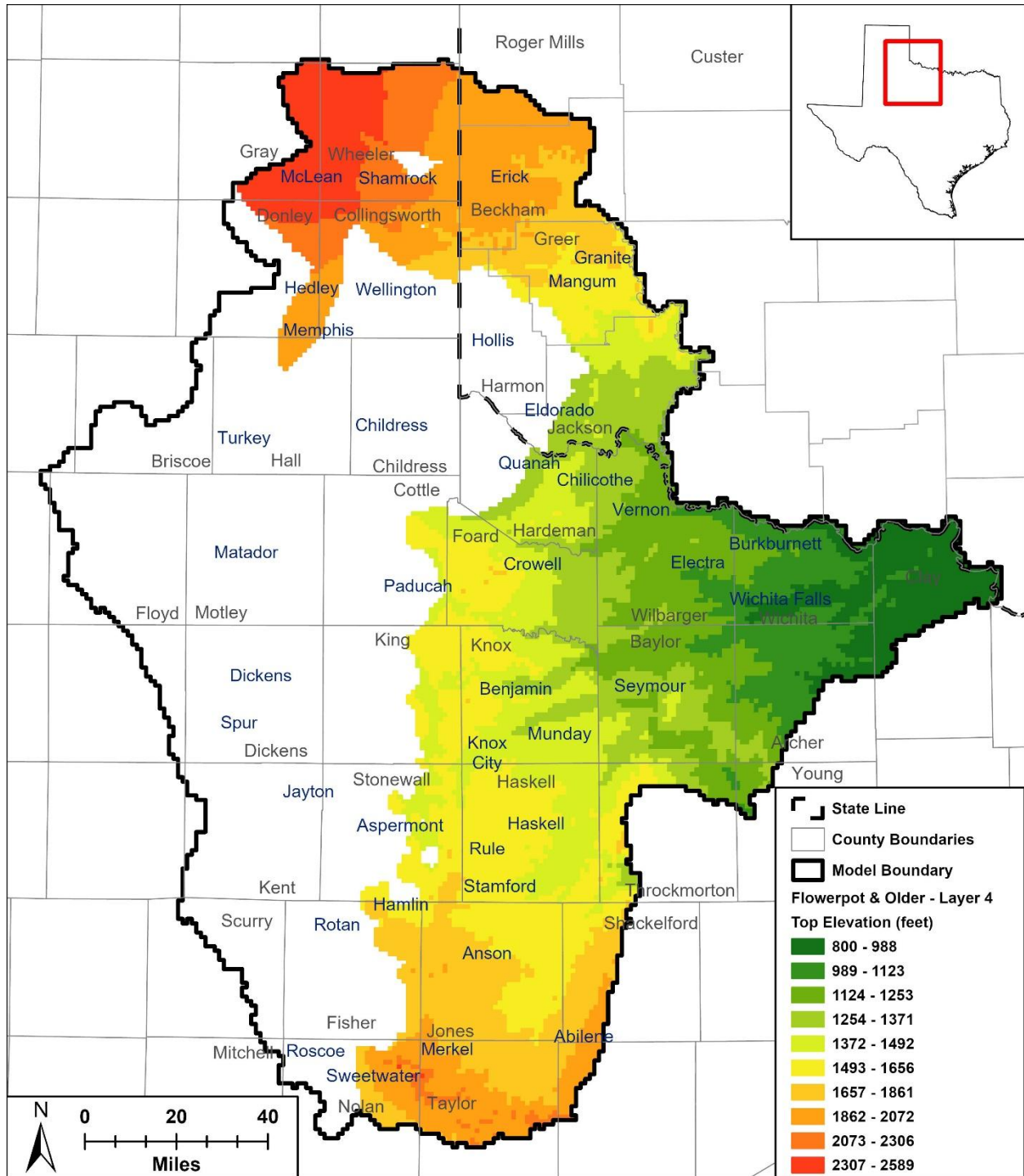


Figure 4.3-12. Model layer 4 top elevation (feet) for the Flowerpot shale and older Permian-age units.

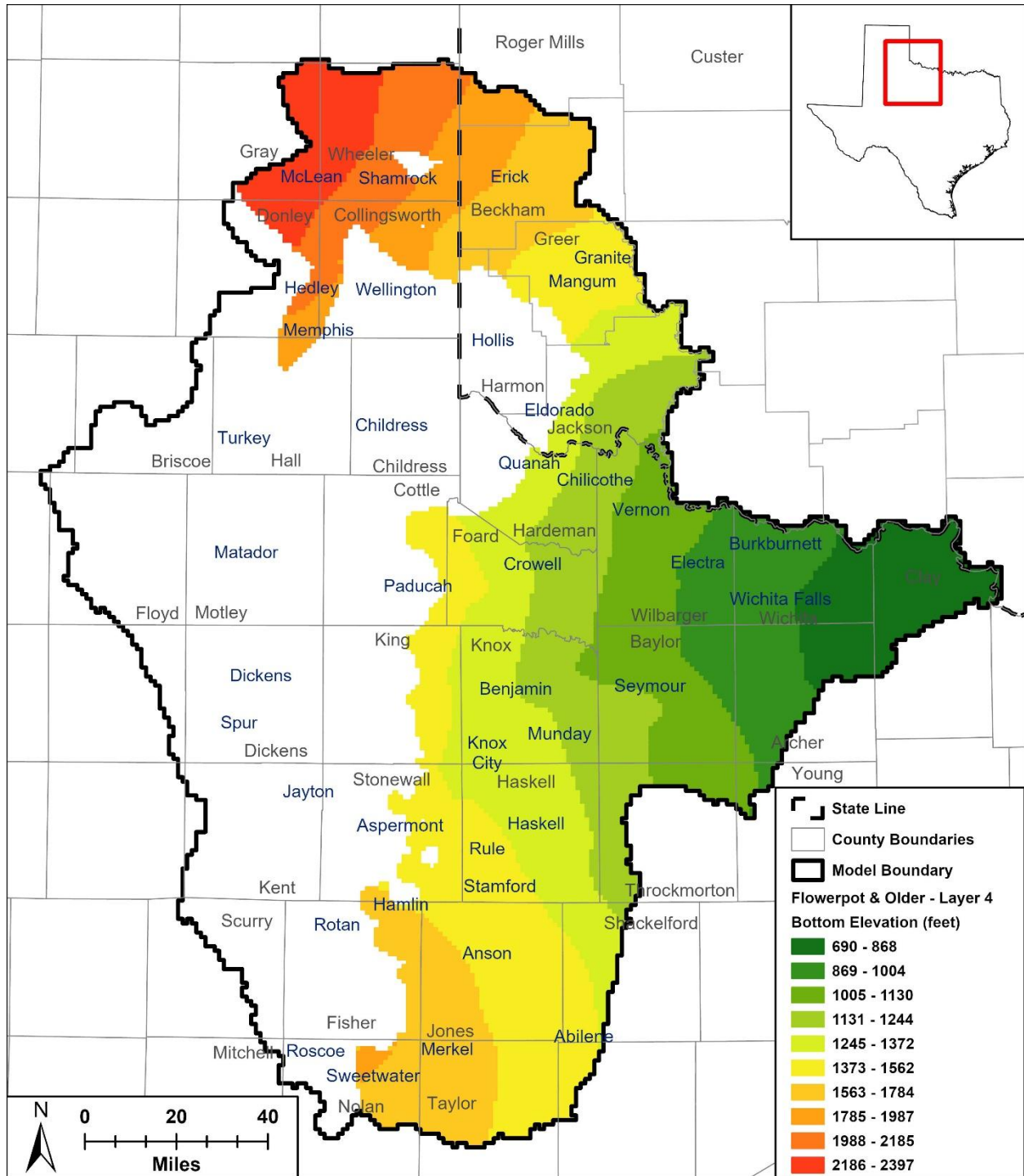


Figure 4.3-13. Model layer 4 bottom elevation (feet) for the Flowerpot shale and older Permian-age units.

4.4 Ghost node correction package

The ghost node correction (GNC) package is a common package used with MODFLOW models using unstructured model grids. This package is available for use with unstructured grids in MODFLOW 6. As stated in the MODFLOW 6 documentation, the ghost node correction is “an additional internal flow package that communicates with the node property file (NPF) package to help augment the accuracy of flow calculations for some types of numerical model gridding” (Langevin and others, 2017). This package helps minimize potential errors in flux between model nodes with different cell face sizes with the objective of maintaining local mass conservation when solving the groundwater flow equation within the control volume finite difference approximation performed during modeling. As described in Section 4.3, for the juxtaposition of modeling the Seymour Aquifer formation sediments in layer 1 with a finer resolution 1/8th mile by 1/8th mile nodal spacing over modeling the Permian-age hydrostratigraphic units in model layers 2, 3, and 4 with a coarser spatial resolution of 1-mile by 1-mile nodal spacing, the ghost node correction package becomes necessary. Specifically, the number of ghost nodes in the numerical model is equal to the number of model cells (nodes) in layer 1, which equates to 221,409 ghost nodes.

4.5 Grid specification file

The grid specification file (GSF) in MODFLOW 6 contains information defining the geometry of the numerical model grid cells (nodes) for unstructured grids. This file stores the information pertaining to each model cell (nodes) vertex in local model coordinate space. It also stores the information relevant for defining the connectivity of each model cell (node) to adjacent model cells (nodes). It contains cell vertex and connectivity information for each model cell (node) for all model layers, which is comprised of 254,074 model cells (nodes) across all model layers.

4.6 Temporal discretization package

In MODFLOW, the periods during which applied stresses (e.g., pumping) remain constant are known as stress periods. The Seymour and Blaine groundwater availability model contains a total of 122 stress periods. The first stress period is steady-state, intending to represent conditions in the aquifer before substantial anthropogenic development. Although historical data indicate some development prior to 1960, the limited availability of water level records and pumping records from 1880 to 1960 within the model domain lends itself to the assumption that this time period should be explored for use as a quasi-steady-state starting condition for the model transient historical period. This steady-state period is earlier than the steady-state period used in the previous groundwater availability model developed by Ewing and others (2004) and may need to be adjusted in time based on available data. When grounded in reasonable assumptions for the groundwater system, the quasi-steady-state starting point helps minimize drift in heads from inconsistent initial conditions during calibration of the transient historical period.

Following the steady-state stress period is a second, transient period from 1960 through 2020 with annual stress-periods. The purpose of this transitional, transient period is to represent the historical period to be used for transient model calibration, which includes stress periods 2 through 62, representing annual changes from 1960 through 2020. These transient stress periods capture the effects of changing groundwater conditions, including pumping and recharge. The historical period is followed by a 60-year predictive period that encompasses 2021 through 2080, representing annual changes from 2021 through 2080 with 60 annual stress periods. The specific time periods for each stress period are shown in Table 4-4.

Table 4-4. Summary of stress periods and durations. Steady-state = SS, Transient = TR.

Stress Period Grouping	Stress Period Begins	Stress Period Ends	Individual		Stress Period Type
			Stress Period Length (days)	Stress Period Detail	
1	-	12/31/1959	-	Pre-development	SS
2	1/1/1960	12/31/1960	366	Historical period	TR
2	1/1/1961	12/31/1961	365	Historical period	TR
2	1/1/1962	12/31/1962	365	Historical period	TR
2	1/1/1963	12/31/1963	365	Historical period	TR
2	1/1/1964	12/31/1964	366	Historical period	TR
2	1/1/1965	12/31/1965	365	Historical period	TR
2	1/1/1966	12/31/1966	365	Historical period	TR
2	1/1/1967	12/31/1967	365	Historical period	TR
2	1/1/1968	12/31/1968	366	Historical period	TR
2	1/1/1969	12/31/1969	365	Historical period	TR
2	1/1/1970	12/31/1970	365	Historical period	TR
2	1/1/1971	12/31/1971	365	Historical period	TR
2	1/1/1972	12/31/1972	366	Historical period	TR
2	1/1/1973	12/31/1973	365	Historical period	TR
2	1/1/1974	12/31/1974	365	Historical period	TR

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Individual					
Stress Period Grouping	Stress Period Begins	Stress Period Ends	Stress Period Length (days)	Stress Period Detail	Stress Period Type
2	1/1/1975	12/31/1975	365	Historical period	TR
2	1/1/1976	12/31/1976	366	Historical period	TR
2	1/1/1977	12/31/1977	365	Historical period	TR
2	1/1/1978	12/31/1978	365	Historical period	TR
2	1/1/1979	12/31/1979	365	Historical period	TR
2	1/1/1980	12/31/1980	366	Historical period	TR
2	1/1/1981	12/31/1981	365	Historical period	TR
2	1/1/1982	12/31/1982	365	Historical period	TR
2	1/1/1983	12/31/1983	365	Historical period	TR
2	1/1/1984	12/31/1984	366	Historical period	TR
2	1/1/1985	12/31/1985	365	Historical period	TR
2	1/1/1986	12/31/1986	365	Historical period	TR
2	1/1/1987	12/31/1987	365	Historical period	TR
2	1/1/1988	12/31/1988	366	Historical period	TR
2	1/1/1989	12/31/1989	365	Historical period	TR
2	1/1/1990	12/31/1990	365	Historical period	TR
2	1/1/1991	12/31/1991	365	Historical period	TR
2	1/1/1992	12/31/1992	366	Historical period	TR
2	1/1/1993	12/31/1993	365	Historical period	TR
2	1/1/1994	12/31/1994	365	Historical period	TR
2	1/1/1995	12/31/1995	365	Historical period	TR
2	1/1/1996	12/31/1996	366	Historical period	TR
2	1/1/1997	12/31/1997	365	Historical period	TR

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Individual					
Stress Period Grouping	Stress Period Begins	Stress Period Ends	Stress Period Length (days)	Stress Period Detail	Stress Period Type
2	1/1/1998	12/31/1998	365	Historical period	TR
2	1/1/1999	12/31/1999	365	Historical period	TR
2	1/1/2000	12/31/2000	366	Historical period	TR
2	1/1/2001	12/31/2001	365	Historical period	TR
2	1/1/2002	12/31/2002	365	Historical period	TR
2	1/1/2003	12/31/2003	365	Historical period	TR
2	1/1/2004	12/31/2004	366	Historical period	TR
2	1/1/2005	12/31/2005	365	Historical period	TR
2	1/1/2006	12/31/2006	365	Historical period	TR
2	1/1/2007	12/31/2007	365	Historical period	TR
2	1/1/2008	12/31/2008	366	Historical period	TR
2	1/1/2009	12/31/2009	365	Historical period	TR
2	1/1/2010	12/31/2010	365	Historical period	TR
2	1/1/2011	12/31/2011	365	Historical period	TR
2	1/1/2012	12/31/2012	366	Historical period	TR
2	1/1/2013	12/31/2013	365	Historical period	TR
2	1/1/2014	12/31/2014	365	Historical period	TR
2	1/1/2015	12/31/2015	365	Historical period	TR
2	1/1/2016	12/31/2016	366	Historical period	TR
2	1/1/2017	12/31/2017	365	Historical period	TR
2	1/1/2018	12/31/2018	365	Historical period	TR
2	1/1/2019	12/31/2019	365	Historical period	TR
2	1/1/2020	12/31/2020	366	Historical period	TR

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Individual					
Stress Period Grouping	Stress Period Begins	Stress Period Ends	Stress Period Length (days)	Stress Period Detail	Stress Period Type
3	1/1/2021	12/31/2021	365	Predictive period	TR
3	1/1/2022	12/31/2022	365	Predictive period	TR
3	1/1/2023	12/31/2023	365	Predictive period	TR
3	1/1/2024	12/31/2024	366	Predictive period	TR
3	1/1/2025	12/31/2025	365	Predictive period	TR
3	1/1/2026	12/31/2026	365	Predictive period	TR
3	1/1/2027	12/31/2027	365	Predictive period	TR
3	1/1/2028	12/31/2028	366	Predictive period	TR
3	1/1/2029	12/31/2029	365	Predictive period	TR
3	1/1/2030	12/31/2030	365	Predictive period	TR
3	1/1/2031	12/31/2031	365	Predictive period	TR
3	1/1/2032	12/31/2032	366	Predictive period	TR
3	1/1/2033	12/31/2033	365	Predictive period	TR
3	1/1/2034	12/31/2034	365	Predictive period	TR
3	1/1/2035	12/31/2035	365	Predictive period	TR
3	1/1/2036	12/31/2036	366	Predictive period	TR
3	1/1/2037	12/31/2037	365	Predictive period	TR
3	1/1/2038	12/31/2038	365	Predictive period	TR
3	1/1/2039	12/31/2039	365	Predictive period	TR
3	1/1/2040	12/31/2040	366	Predictive period	TR
3	1/1/2041	12/31/2041	365	Predictive period	TR
3	1/1/2042	12/31/2042	365	Predictive period	TR
3	1/1/2043	12/31/2043	365	Predictive period	TR

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Individual					
Stress Period Grouping	Stress Period Begins	Stress Period Ends	Stress Period Length (days)	Stress Period Detail	Stress Period Type
3	1/1/2044	12/31/2044	366	Predictive period	TR
3	1/1/2045	12/31/2045	365	Predictive period	TR
3	1/1/2046	12/31/2046	365	Predictive period	TR
3	1/1/2047	12/31/2047	365	Predictive period	TR
3	1/1/2048	12/31/2048	366	Predictive period	TR
3	1/1/2049	12/31/2049	365	Predictive period	TR
3	1/1/2050	12/31/2050	365	Predictive period	TR
3	1/1/2051	12/31/2051	365	Predictive period	TR
3	1/1/2052	12/31/2052	366	Predictive period	TR
3	1/1/2053	12/31/2053	365	Predictive period	TR
3	1/1/2054	12/31/2054	365	Predictive period	TR
3	1/1/2055	12/31/2055	365	Predictive period	TR
3	1/1/2056	12/31/2056	366	Predictive period	TR
3	1/1/2057	12/31/2057	365	Predictive period	TR
3	1/1/2058	12/31/2058	365	Predictive period	TR
3	1/1/2059	12/31/2059	365	Predictive period	TR
3	1/1/2060	12/31/2060	366	Predictive period	TR
3	1/1/2061	12/31/2061	365	Predictive period	TR
3	1/1/2062	12/31/2062	365	Predictive period	TR
3	1/1/2063	12/31/2063	365	Predictive period	TR
3	1/1/2064	12/31/2064	366	Predictive period	TR
3	1/1/2065	12/31/2065	365	Predictive period	TR
3	1/1/2066	12/31/2066	365	Predictive period	TR

Individual					
Stress Period Grouping	Stress Period Begins	Stress Period Ends	Stress Period Length (days)	Stress Period Detail	Stress Period Type
3	1/1/2067	12/31/2067	365	Predictive period	TR
3	1/1/2068	12/31/2068	366	Predictive period	TR
3	1/1/2069	12/31/2069	365	Predictive period	TR
3	1/1/2070	12/31/2070	365	Predictive period	TR
3	1/1/2071	12/31/2071	365	Predictive period	TR
3	1/1/2072	12/31/2072	366	Predictive period	TR
3	1/1/2073	12/31/2073	365	Predictive period	TR
3	1/1/2074	12/31/2074	365	Predictive period	TR
3	1/1/2075	12/31/2075	365	Predictive period	TR
3	1/1/2076	12/31/2076	366	Predictive period	TR
3	1/1/2077	12/31/2077	365	Predictive period	TR
3	1/1/2078	12/31/2078	365	Predictive period	TR
3	1/1/2079	12/31/2079	365	Predictive period	TR
3	1/1/2080	12/31/2080	366	Predictive period	TR

4.7 Initial conditions package

In MODFLOW 6, the initial conditions (IC) package is used to specify the starting hydraulic head values for the simulation. This package defines the initial state of the groundwater system, which can influence the groundwater availability model's behavior during subsequent simulation periods.

For the Seymour and Blaine aquifer system groundwater availability model, the initial head values for all layers were developed from the same initial hydraulic head conditions used in the previous groundwater availability model developed by Ewing and others (2004). For layer 1 specifically, the initial condition hydraulic head values from layer 1 in the 2004 groundwater availability model were used to calculate the initial saturated thickness for the Seymour Aquifer. Then the saturated thickness was interpolated using the “Topo to Raster” tool in ArcGIS Pro and mapped to the updated Seymour Aquifer layer 1 model grid. The same approach was used for the Permian-age hydrostratigraphic units in layers 2, 3, and 4 to calculate initial hydraulic head

conditions using the initial condition hydraulic heads from layer 2 in the previous groundwater availability model and mapped to the updated model grid. Using the initial condition from the previous groundwater availability model helps simplify model setup and provides a reasonable starting point for solving the initial steady-state stress period within the simulation. The initial hydraulic heads for the Seymour formation in model layer 1 are provided in Figure 4.7-1. The initial hydraulic heads for the Permian-age hydrostratigraphic units in model layers 2, 3, and 4 are provided in Figure 4.7-2.

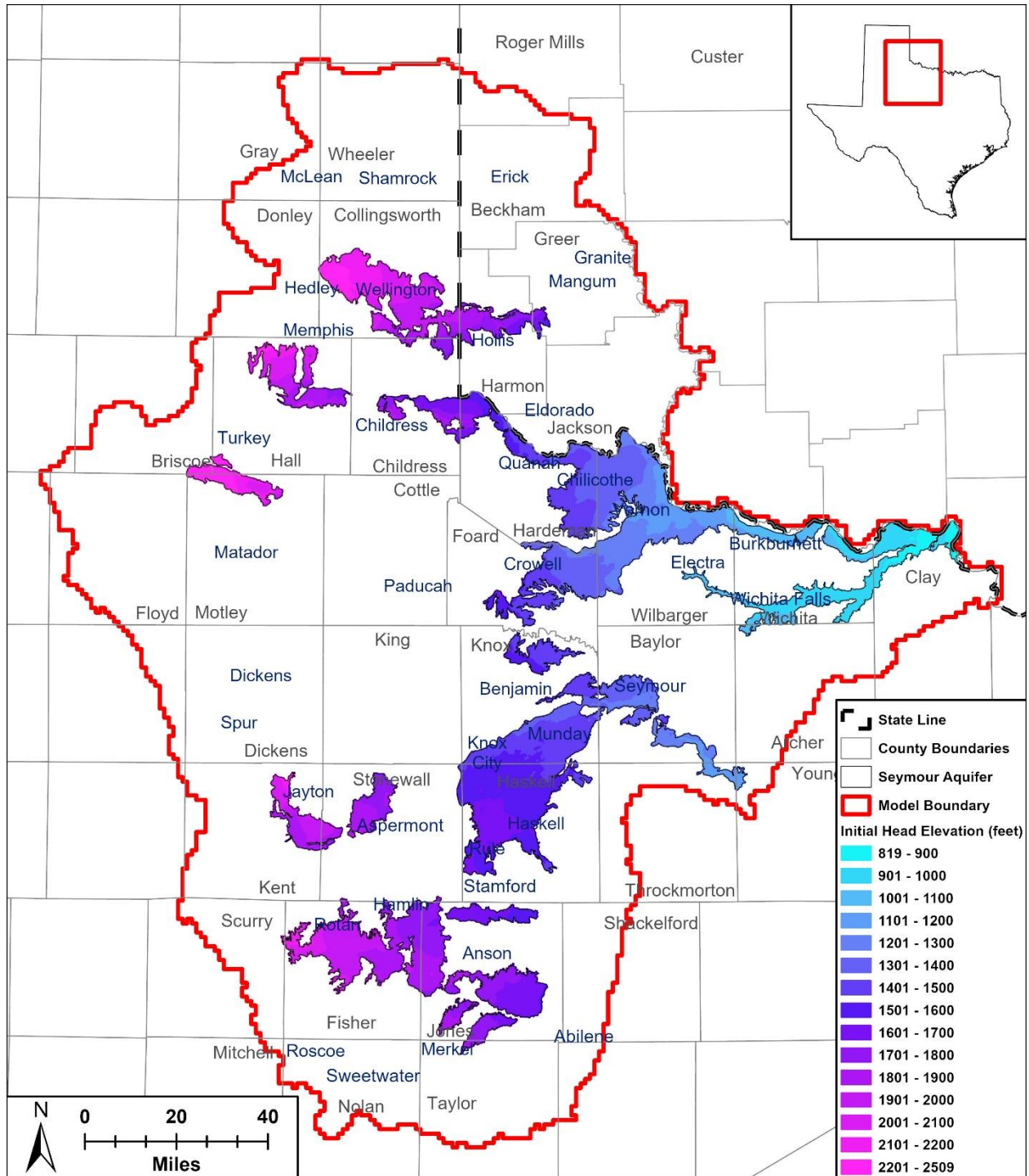


Figure 4.7-1. Initial hydraulic heads for the Seymour formation in model layer 1.

Texas Water Development Board Contract Number 2448302843
 Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

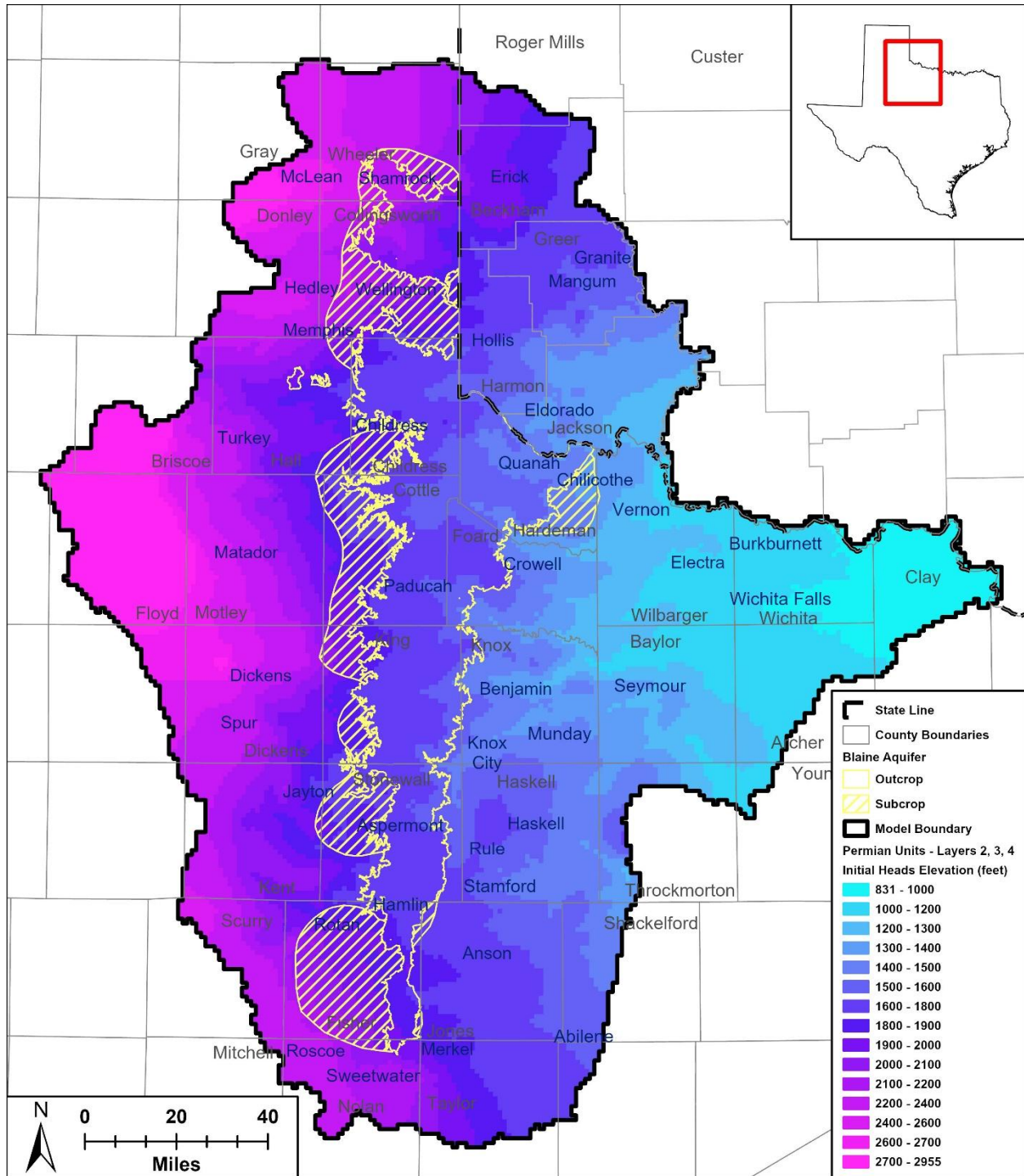


Figure 4.7-2. Initial hydraulic heads for the Permian-age hydrostratigraphic units in model layers 2, 3, and 4.

4.8 Node-property flow package

The node property flow (NPF) package has replaced the layer property flow (LPF) package from previous versions of MODFLOW. In the node property flow package, aquifer properties necessary for calculating hydraulic conductance are specified. In this package, both the vertical and horizontal hydraulic conductivities are set. Both vertical and horizontal hydraulic conductivities are defined.

Hydraulic conductivity is a measure of the ease with which groundwater can flow through an aquifer expressed in units of length per time (e.g., feet per day). Higher hydraulic conductivity indicates that the aquifer will allow more water movement under the same hydraulic gradient.

Prior to model calibration, the following horizontal and vertical hydraulic conductivities were assumed during initial model testing to keep the model saturated for each model layer as presented in Table 4-5. Isotropy was assumed in the horizontal hydraulic conductivities between the x and y directions. The ratio of horizontal hydraulic conductivities to the vertical hydraulic conductivity was 3,000, which was assumed to have the same spatial distribution. These initial parameters will change substantially during model calibration and include spatial variability. The initial horizontal hydraulic conductivity distributions for layers 1, 2, 3, and 4 are provided in Figure 4.8-1, Figure 4.8-2, Figure 4.8-3, and Figure 4.8-4, respectively.

MODFLOW 6 uses the node property flow package to calculate intercell conductance values, manage cell wetting and drying, and incorporate Newton-Raphson terms for intercell flow expressions. Unlike earlier versions where the confined or convertible designation was layer-based, the node property flow package allows individual cells to be designated as either confined or convertible. This feature may be explored during future model calibration of transient conditions if challenges in calibration arise requiring switching of cells from unconfined to confined storage following significant recharge events. If challenges sourced from this do manifest, model layers may be allowed to transition dynamically between confined and unconfined states based on groundwater conditions.

Table 4-5. Summary of mean initial hydraulic conductivity values to be refined during model calibration.

Model Layer	Horizontal Hydraulic Conductivity (feet/day)	Vertical Hydraulic Conductivity (feet/day)	Horizontal : Vertical Hydraulic Conductivity (unitless)
1	106.8	3.6E-2	3,000
2	1.6	5.3E-4	3,000
3	4.6	1.5E-3	3,000
4	1.0	3.3E-4	3,000

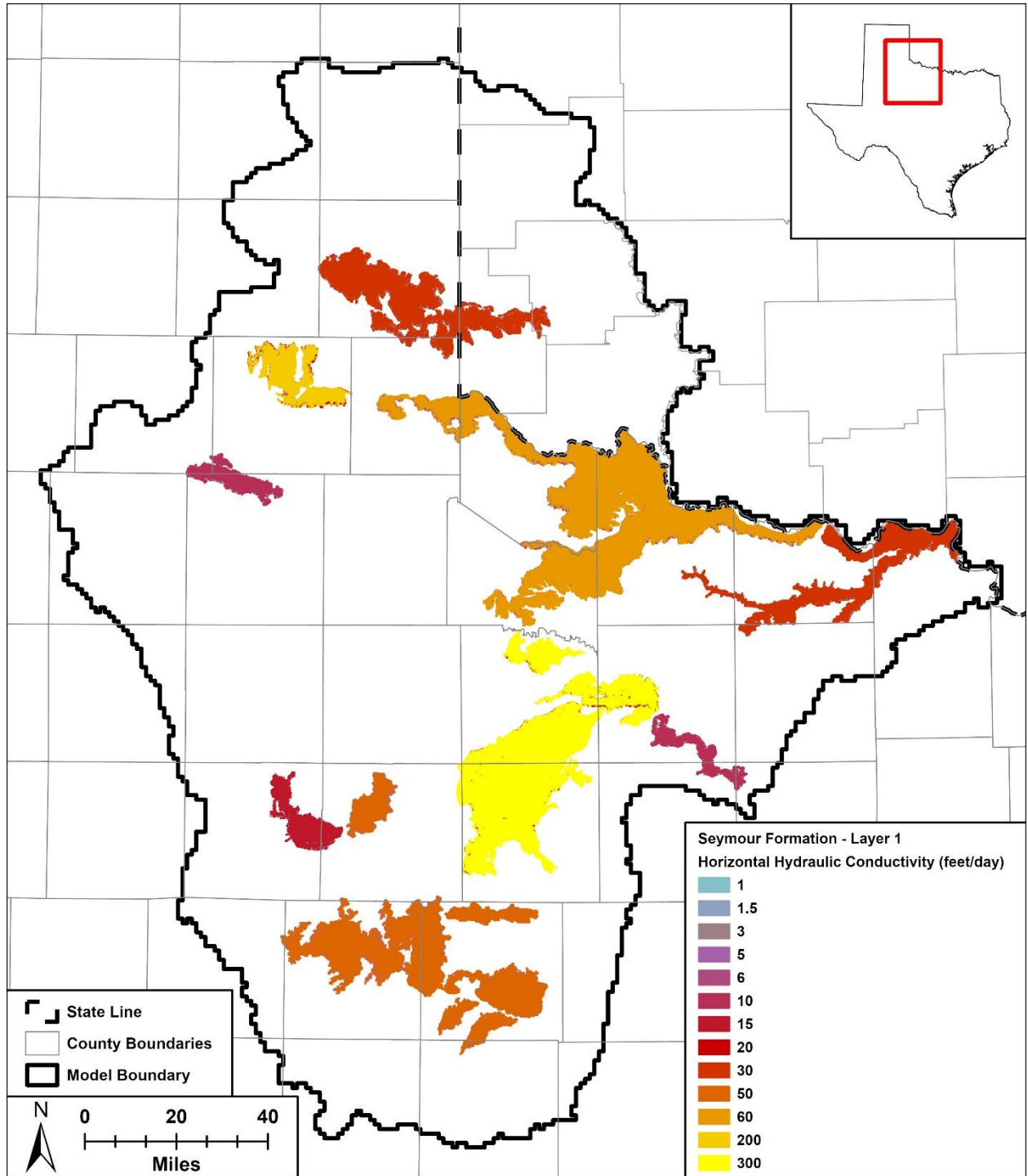


Figure 4.8-1. Model layer 1 initial horizontal hydraulic conductivity distribution (feet per day).

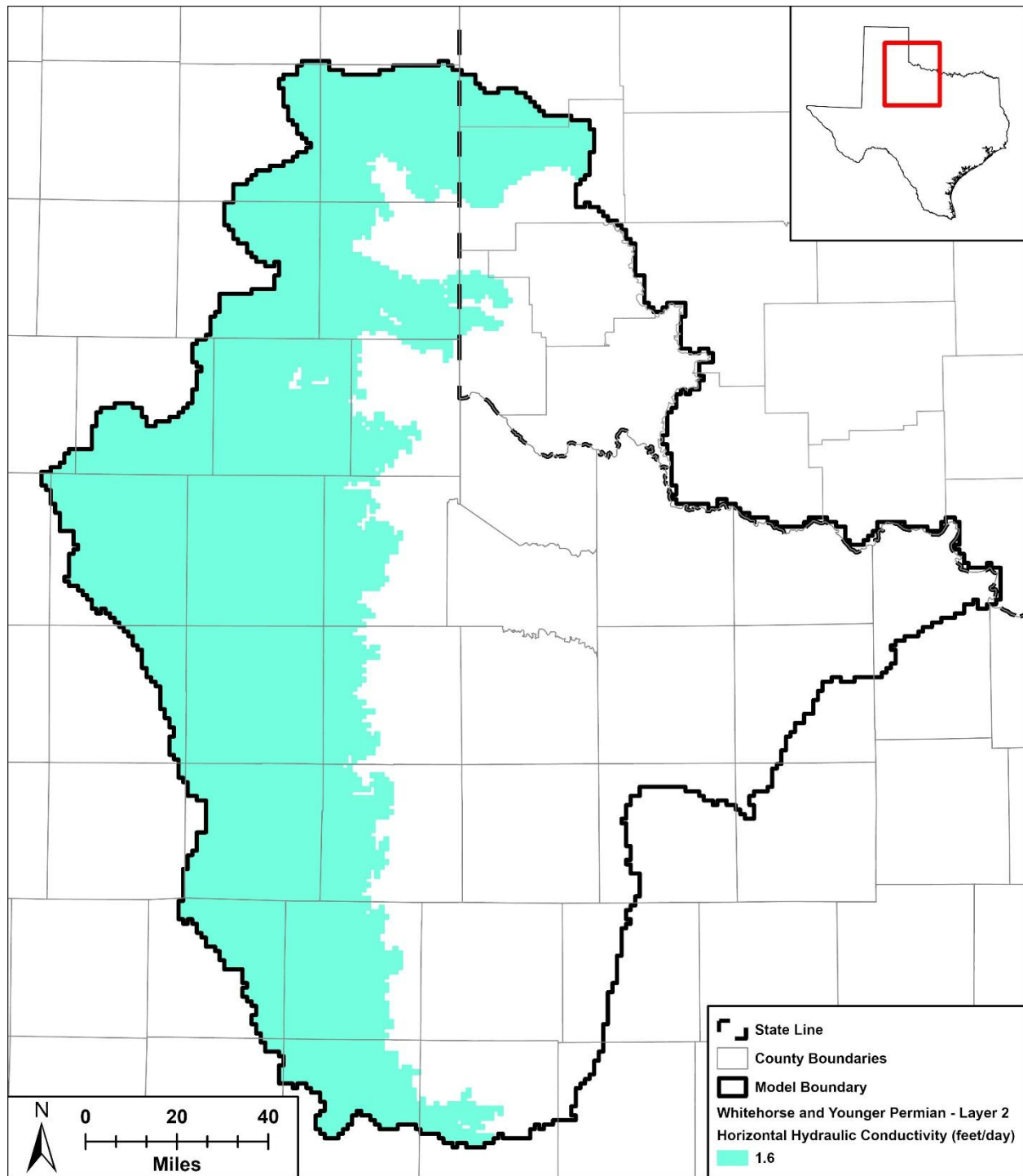


Figure 4.8-2. Model layer 2 initial horizontal hydraulic conductivity distribution (feet per day).

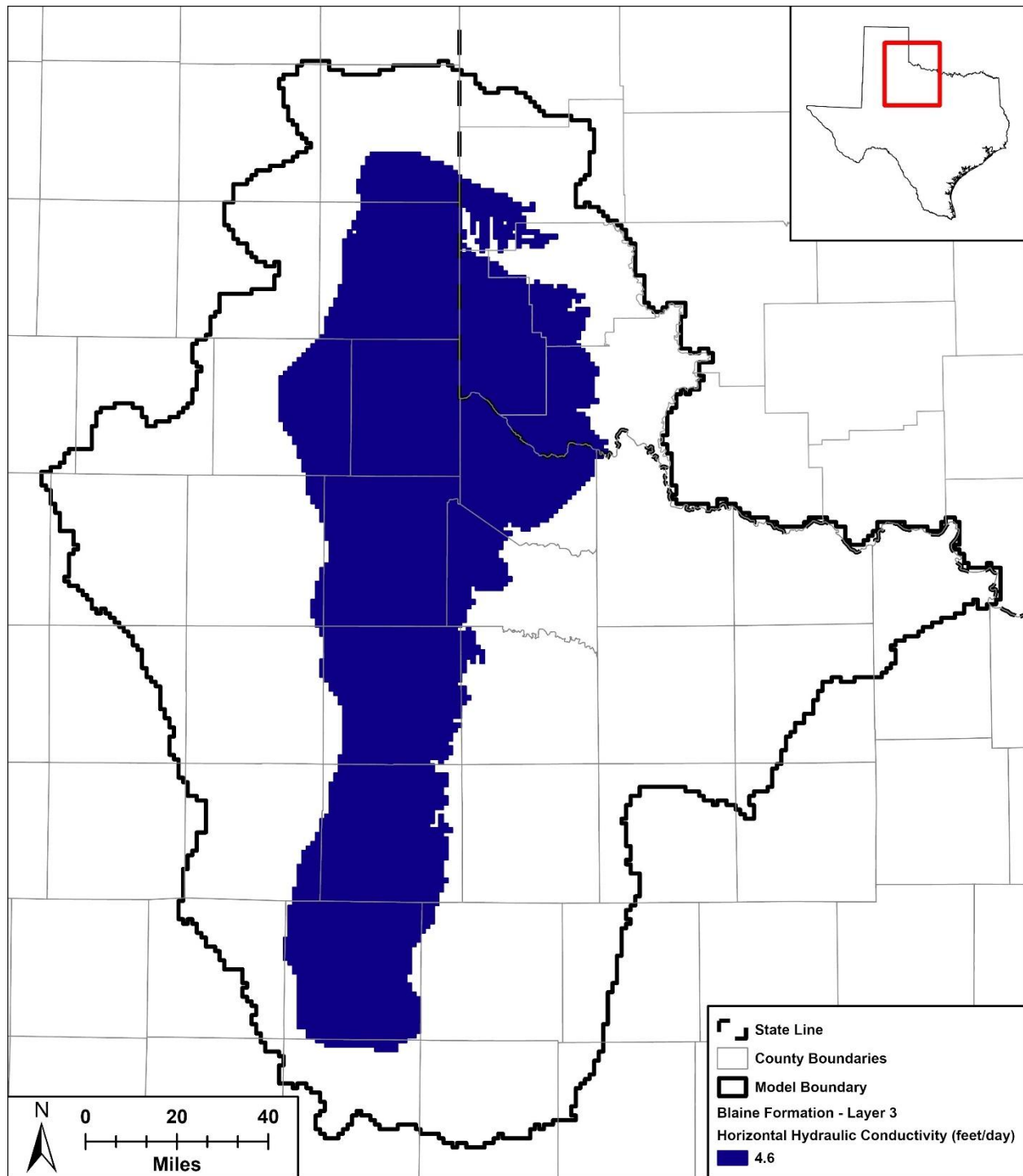


Figure 4.8-3. Model layer 3 initial horizontal hydraulic conductivity distribution (feet per day).

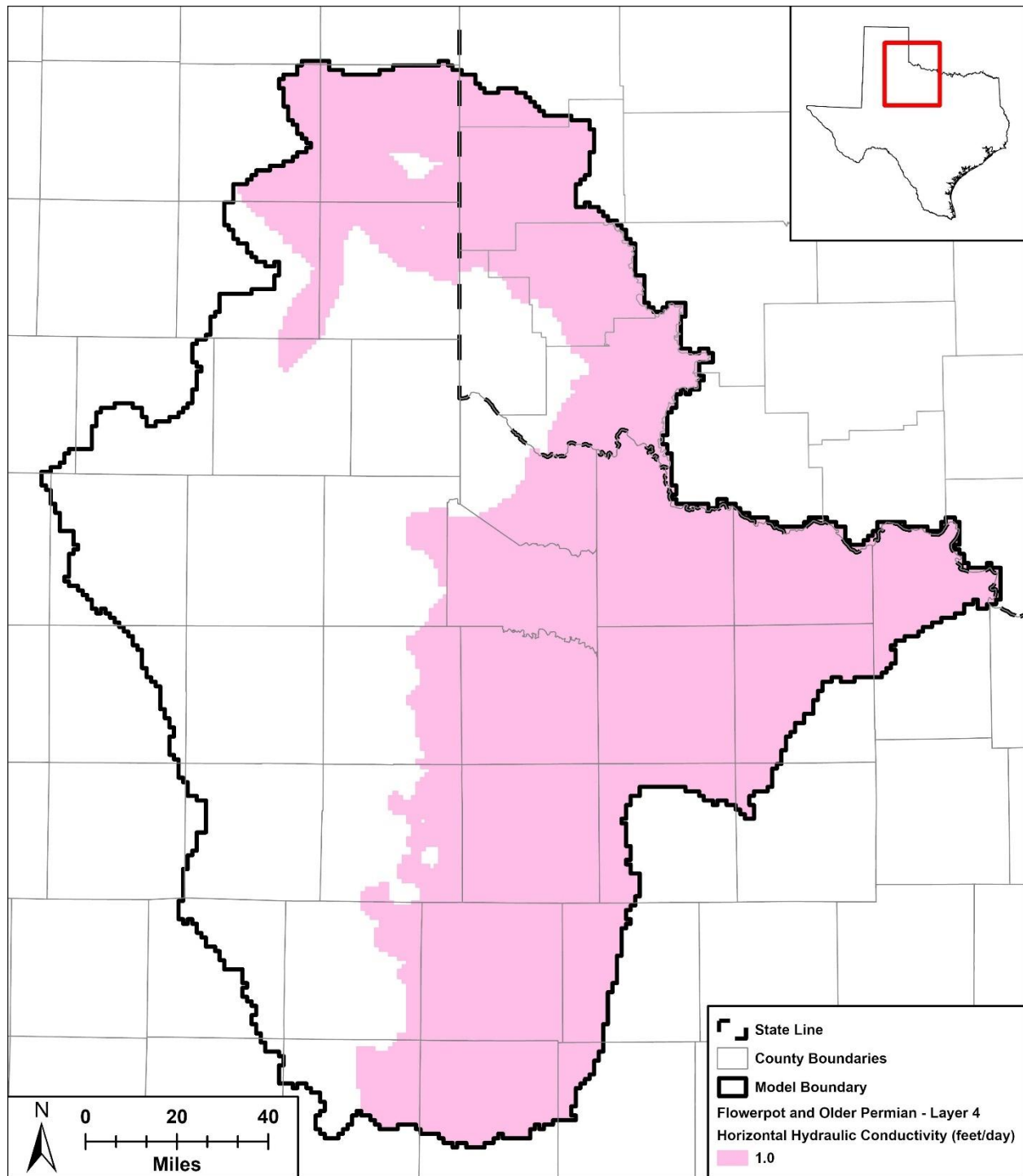


Figure 4.8-4. Model layer 4 initial horizontal hydraulic conductivity distribution (feet per day).

4.9 Storage package

In MODFLOW 6, storage properties such as storativity, specific storage and specific yield are specified using the storage (STO) package. This represents a shift from previous versions of MODFLOW, where these properties were defined within the Layer Property Flow (LPF), Block-Centered Flow (BCF), and Upstream Weighting (UPW) Packages. The storage package in MODFLOW 6 allows for more precise and flexible definition of these properties, enhancing the model's ability to simulate groundwater storage dynamics accurately.

For the steady-state simulation—where changes in storage are zero—storativity, specific yield and specific storage values for all layers in the groundwater availability model are not considered in the solving of the groundwater flow equation. They are considered for the transient stress periods; the following initial values for specific yield and specific storage values were assumed based on the previous groundwater availability model developed by Ewing and others (2004) and the literature for initial model testing as presented in Table 4-6. Each layer's respective value is assumed to be constant; however, this will change during model calibration.

Table 4-6. Summary of mean initial storage properties to be refined during model calibration.

Model Layer	Unit	Confining Condition	Specific Yield, (unitless, -)	Specific Storage, (feet ⁻¹)
1	Seymour	Unconfined	0.14	-
2	Whitehorse and Younger Permian	Variable	0.15	1E-5
3	Blaine	Variable	0.15	1E-5
4	Flowerpot and Older Permian	Variable	0.15	1E-5

The storage package was set-up using MODFLOW 6's "STORAGECOEFFICIENT" and "SS_CONFINED_ONLY" options. The latter option specifies that compressible storage is calculated only when a cell is convertible and the simulated head is greater than or equal to the top of the cell (Langevin and others, 2017). All cells are defined as convertible. Specific storage values are only defined in the Permian model layers in areas where the units were not outcropping. Storativity values at these locations were calculated using the hydrostratigraphic unit thickness multiplied by the specific storage value. For the Permian model layers and the Seymour pods that are outcropping, storativity values were fixed at a value of one-(1) to mitigate physically unrealistic flooding behavior simulated by the flow model when outcropping model cells are flooded during the simulation periods. The spatial distributions and relative magnitudes of specific storage and specific yield will be refined during model calibration of the transient stress periods. These values are crucial for simulating accurately the response of the groundwater system to changes in recharge and discharge conditions, ensuring that the model can capture the temporal and spatial variations in groundwater storage.

4.10 Well package

The MODFLOW 6 Groundwater Flow Well package is used to simulate groundwater production focused on the Seymour and Blaine aquifers, with minor amounts of pumping in the model attributed to other Permian units in connection with the Seymour and Blaine aquifers. Groundwater in the study area supports various uses but, for this study, groundwater pumping was conceptually categorized into unique use types. Conceptual use types were preserved as separate pumping packages within the Texas spatial footprint of the model, where the pumping use types within the Oklahoma footprint were all considered but consolidated into one representative aggregate pumping package in the model. Additionally, within the Texas footprint, metered data were available from Rolling Plains, Panhandle, and Mesquite groundwater conservation districts, which were explicitly incorporated into model as a separate pumping package. The appreciable use types incorporated with the metered data were primarily irrigation along with some municipal. These categories help categorize the analysis of groundwater pumping impacts across different sectors and account for the varying levels of uncertainty associated with each use type. For example, irrigation demand can fluctuate significantly from year to year, depending on the number of irrigated acres, as well as weather factors such as temperature and rainfall. In contrast, domestic and municipal water use is more predictable, with relatively stable demand over time and across locations, leading to a higher degree of confidence in estimating their pumping volumes. There are nine-(9) types of well packages included in the model representing the following;

1. Irrigation (Texas)
2. Municipal (Texas)
3. Mining (Texas)
4. Industrial/Manufacturing (Texas)
5. Rural, domestic for the Seymour Aquifer (Texas)
6. Rural, domestic for the Blaine Aquifer (Texas)
7. Livestock (Texas)
8. Metered (Texas)
9. Oklahoma, All Use Types (Oklahoma)

As irrigation pumping makes up the vast majority of pumping in the model, the irrigation package was portioned into separate irrigation packages for each Seymour pod and the Blaine Aquifer. Explanation of the methods used to estimate the annual volumes and spatial distributions of groundwater pumping estimates for each use type and respective well packages are provided in the following subsections.

4.10.1 Rural and domestic estimates

As described in Section 3.4, rural and domestic pumping estimates for the Seymour and Blaine aquifers were included in the numerical model, spanning the time period from 1960 to 2020. These estimates were developed from U.S. Census Bureau population data at the block and county levels. Block-level data, offering the finest resolution, were available for the 1990, 2000, 2010, and 2020 census years. For interim years, county-level annual population estimates were downscaled to block-level resolution using linearly interpolated spatial distributions based on the decadal block data. In areas where the study region partially overlapped a county, the block-level data were used to calculate a representative proportion of the county population. These proportions were also linearly interpolated for interim years. For years prior to 1990, the within-county block-level population distribution was held constant at the 1990 pattern, with county totals scaled by annual population estimates.

Census tracts, representing an intermediate resolution between blocks and counties, were not used in this analysis. These spatial distributions, combined with annual county-level population estimates, provided refined temporal and spatial population inputs for the model.

To convert population data into groundwater pumping estimates, the population density for each cell was calculated based on the distribution of people within the corresponding census blocks. The United States Department of Agriculture defines rural areas as open countryside with population densities less than 500 people per square mile. A threshold value of 500 people per square mile was used to distinguish rural from urban areas, ensuring accurate attribution of rural domestic water use. Per capita use rates were determined based on historical studies and were assumed to increase stepwise over time (Table 4-7). These studies suggest that, between 1980 and 2020, per capita use is constant at 100 gallons per person per day. Prior to 1980, 70 and 75 gallons per capita per day were used, for 1960-1969 and 1970-1979, respectively. The pumping estimates were made using the assumption that all rural domestic water use is supplied by groundwater from the aquifer outcropping in each location.

Table 4-7. Rural domestic assumed per capita use rate.

Year	Assumed Per Capita Use (gallons per day)
1960-1969	70
1970-1979	75
1980-2020	100

This methodology allowed for detailed calculation of rural domestic groundwater use on a cell-by-cell basis, incorporating both population growth and changes in water demand over the model period. For 1960 through 1979, the per-cell domestic pumping was generated by holding the 1980 pumping spatial distribution fixed and scaling it by the population change relative to 1980. The total annual groundwater pumping for rural domestic use was thus derived for each year from 1960 through 2020, reflecting spatial and temporal variations in water use across the model

domain. The initial prescribed, Texas-specific domestic pumping rates for the Seymour and Blaine aquifers across the entire model are shown in Figure 4.10-1. The initial prescribed, Texas-specific domestic pumping rates for the Seymour Aquifer across the entire model by county is shown in Figure 4.10-2. The initial prescribed, Texas-specific domestic pumping rates for the Blaine Aquifer across the entire model by county is shown in Figure 4.10-3. The initial prescribed, Texas-specific domestic pumping rate spatial distribution for the Seymour and Blaine aquifers across the entire model for 1980, 2000, and 2020 are shown in Figure 4.10-4, Figure 4.10-5, and Figure 4.10-6, respectively.

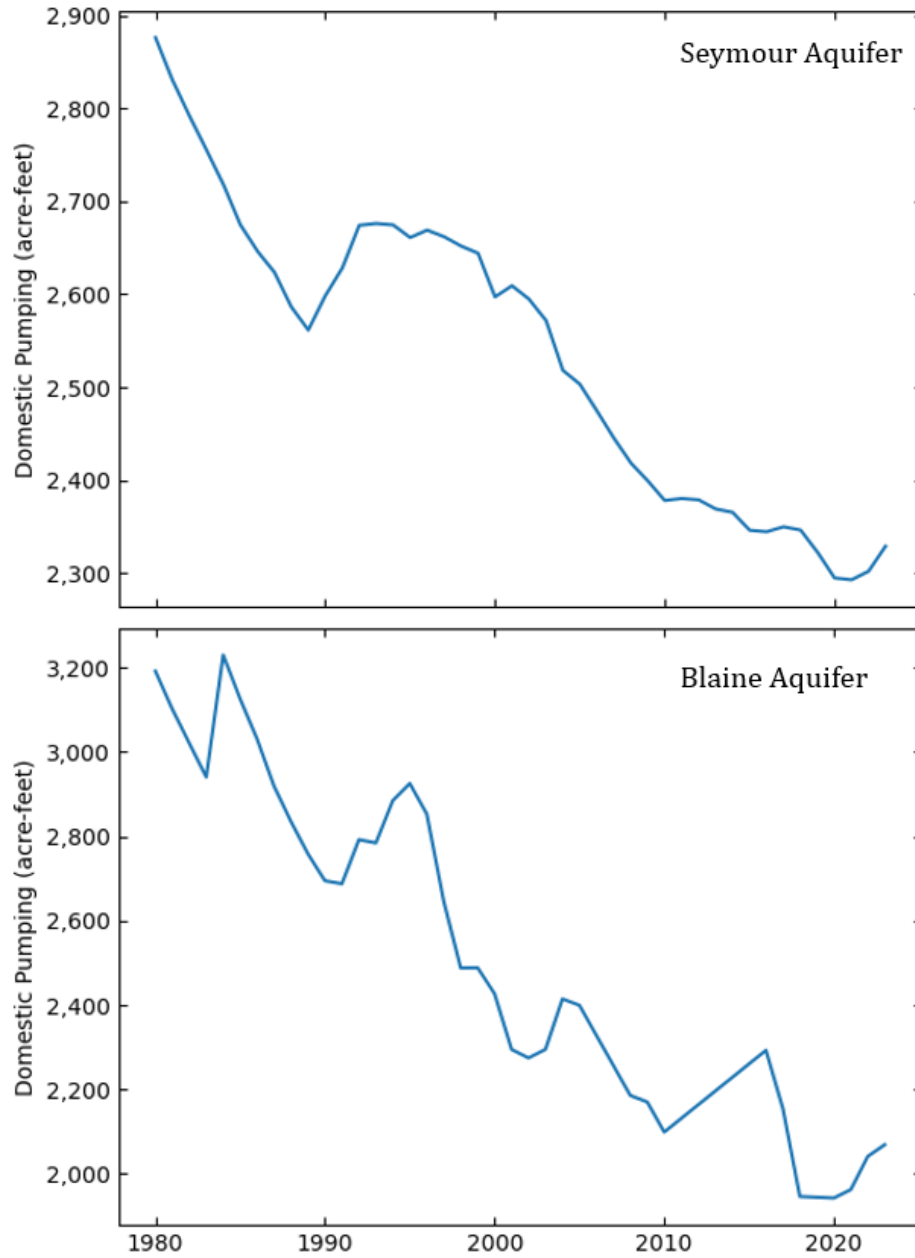


Figure 4.10-1. Initial Prescribed Texas domestic pumping rates (in acre-feet per year) for the Seymour and Blaine aquifers.

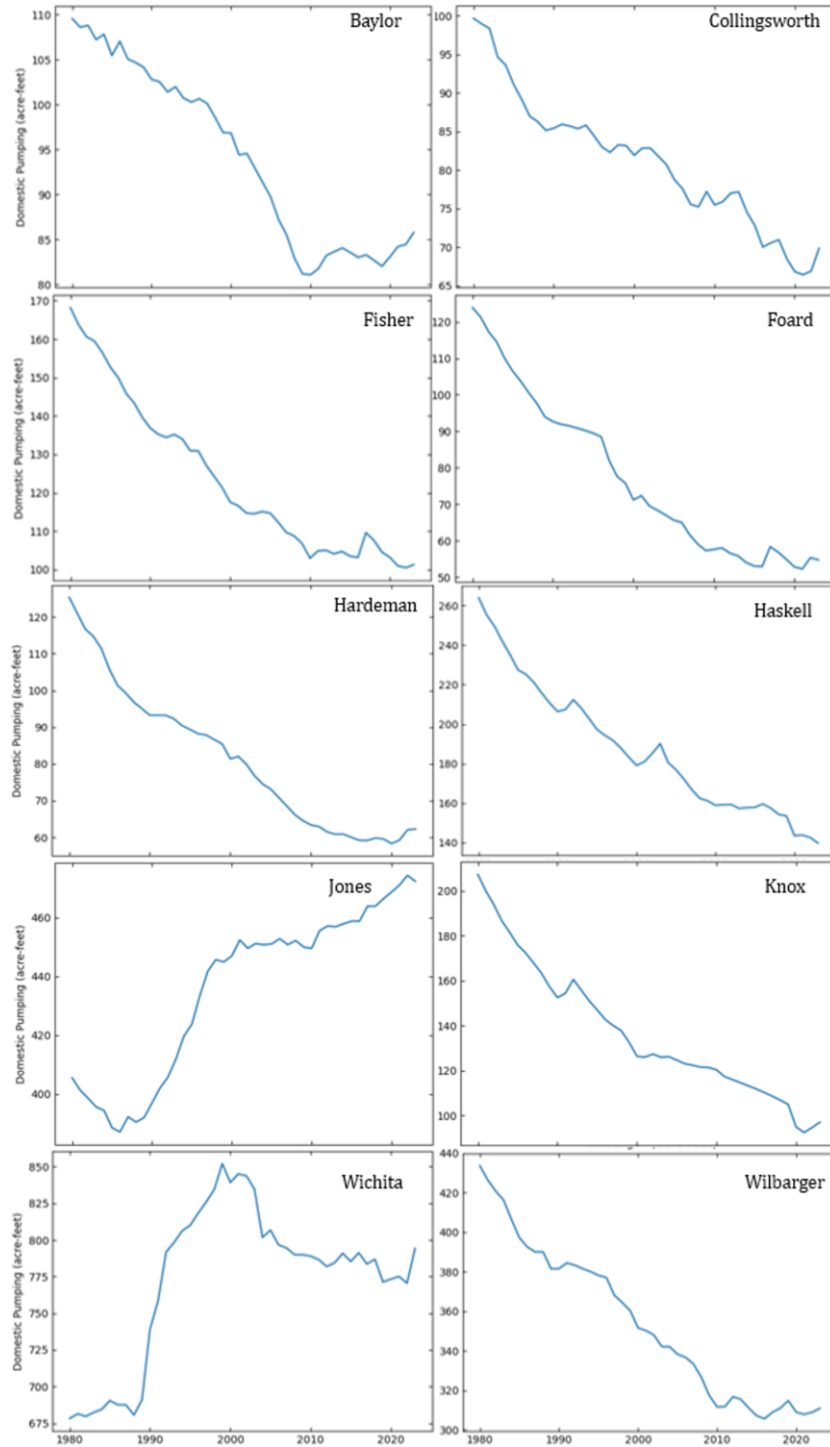


Figure 4.10-2. Initial Prescribed Texas domestic pumping rates (in acre-feet per year) for the Seymour Aquifer for counties with greater than 100 acre-feet per year rates. Archer, Briscoe, Childress, Clay, Donley, Hall, Kent, King, Motley, Scurry, Stonewall, Taylor, Throckmorton, and Young counties had less than 100 acre-feet per year rates across all time periods.

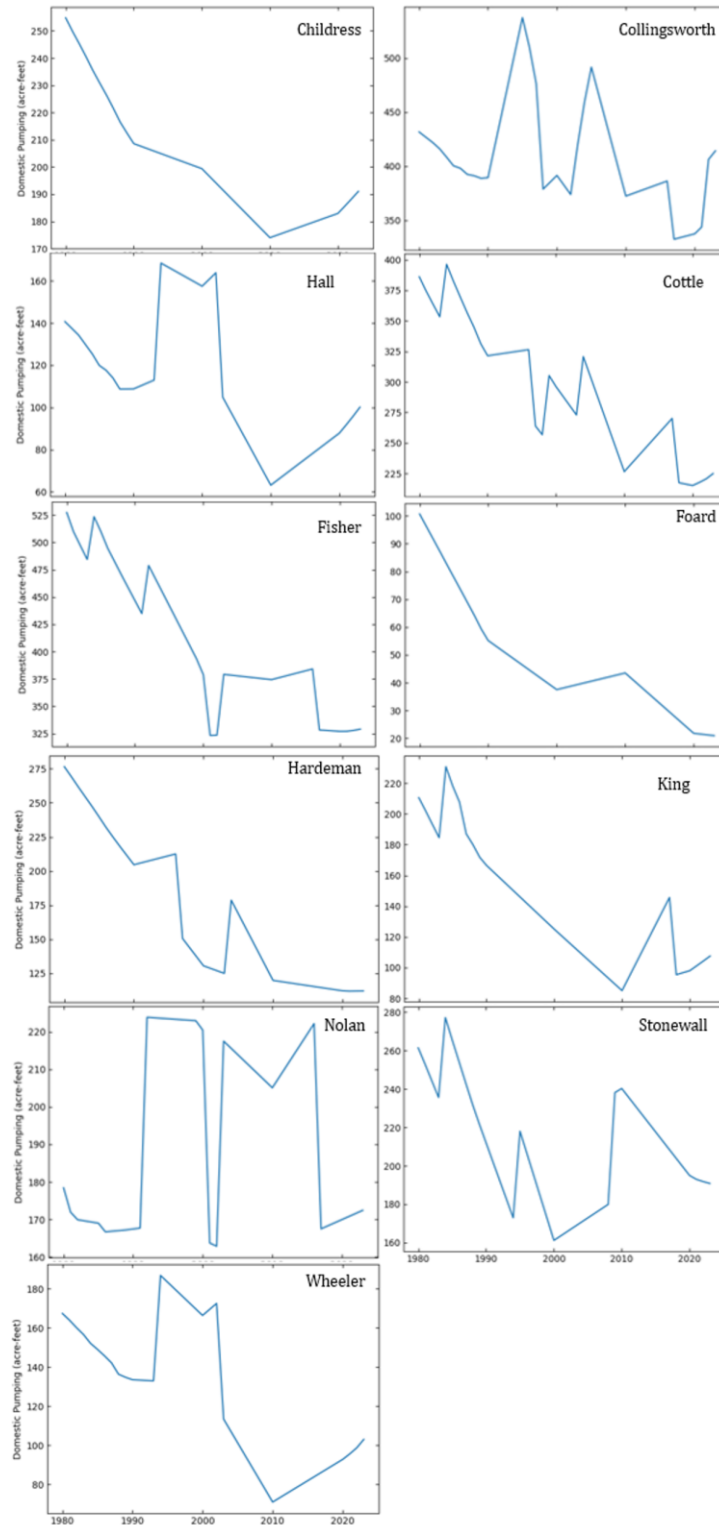


Figure 4.10-3. Initial Prescribed Texas domestic pumping rates (in acre-feet per year) for the Blaine Aquifer for counties with greater than 100 acre-feet per year rates. Dickens, Jones, Kent, Knox, Motley, Scurry, and Wilbarger counties had less than 100 acre-feet per year rates across all time periods.

Texas Water Development Board Contract Number 2448302843
 Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

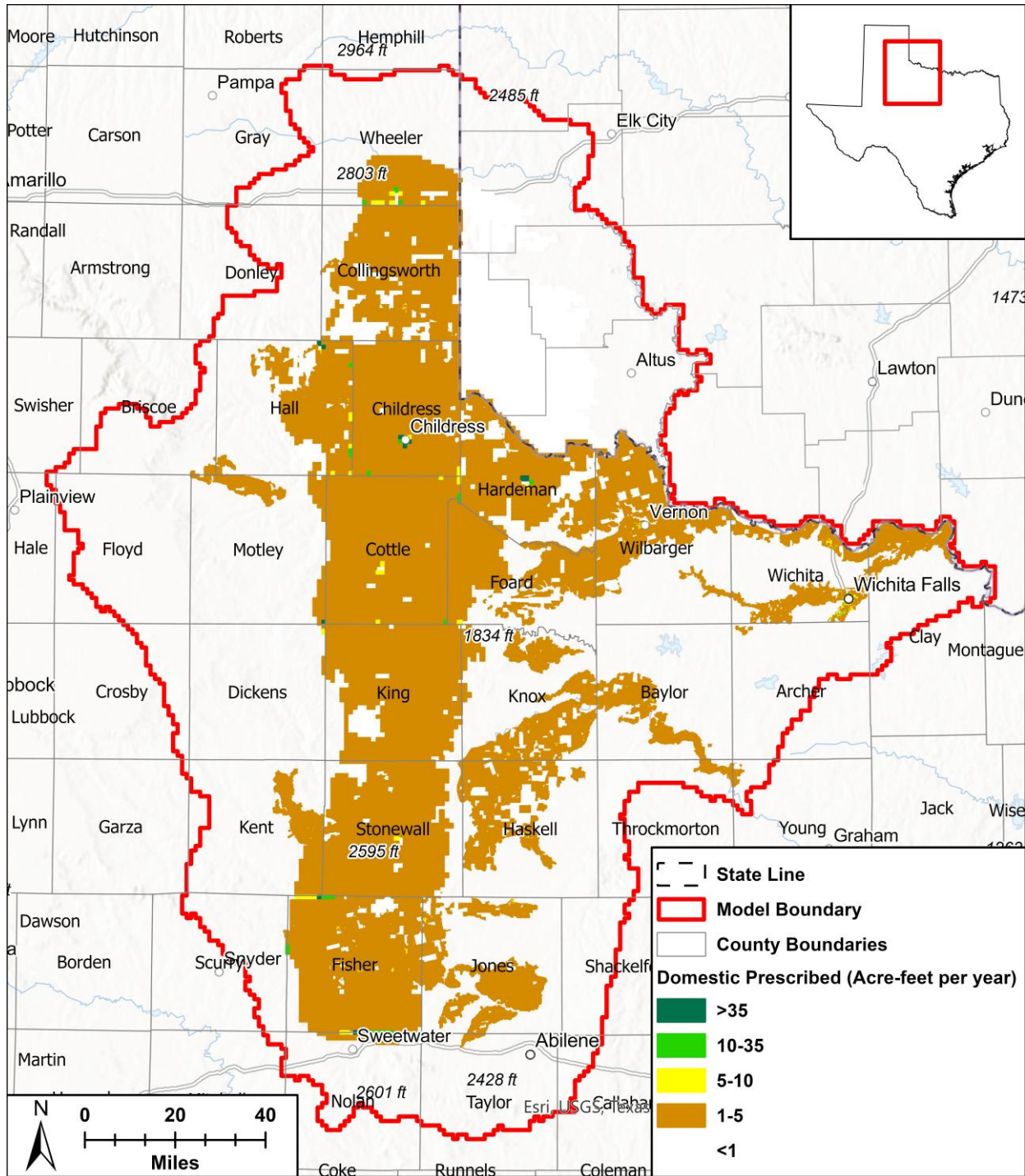


Figure 4.10-4. Initial Prescribed Texas domestic pumping rates (in acre-feet per year) in 1980 within the Seymour and Blaine Groundwater Availability Model.

Texas Water Development Board Contract Number 2448302843
 Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

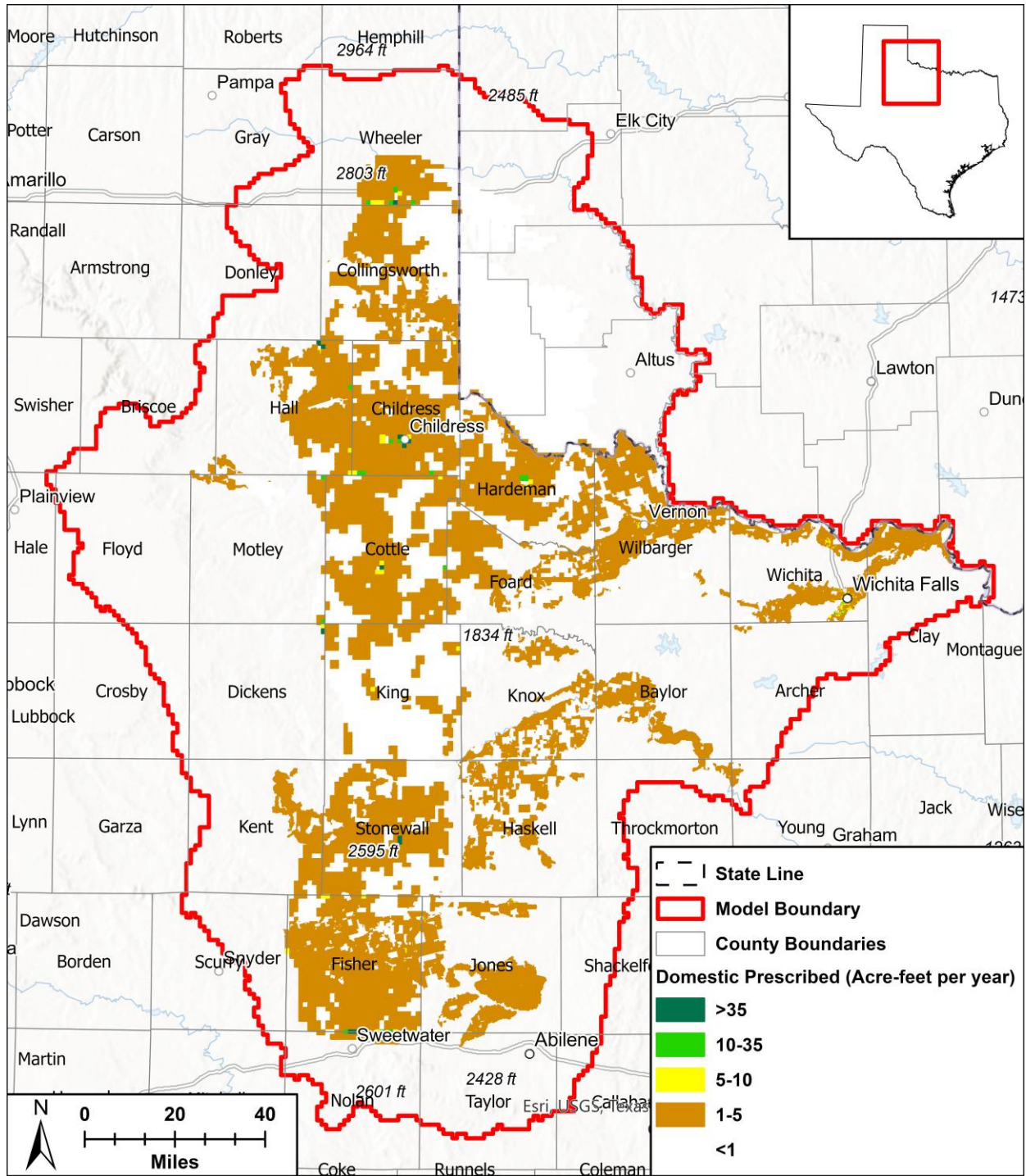


Figure 4.10-5. Initial Prescribed Texas domestic pumping rates (in acre-feet per year) in 2000 within the Seymour and Blaine Groundwater Availability Model.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

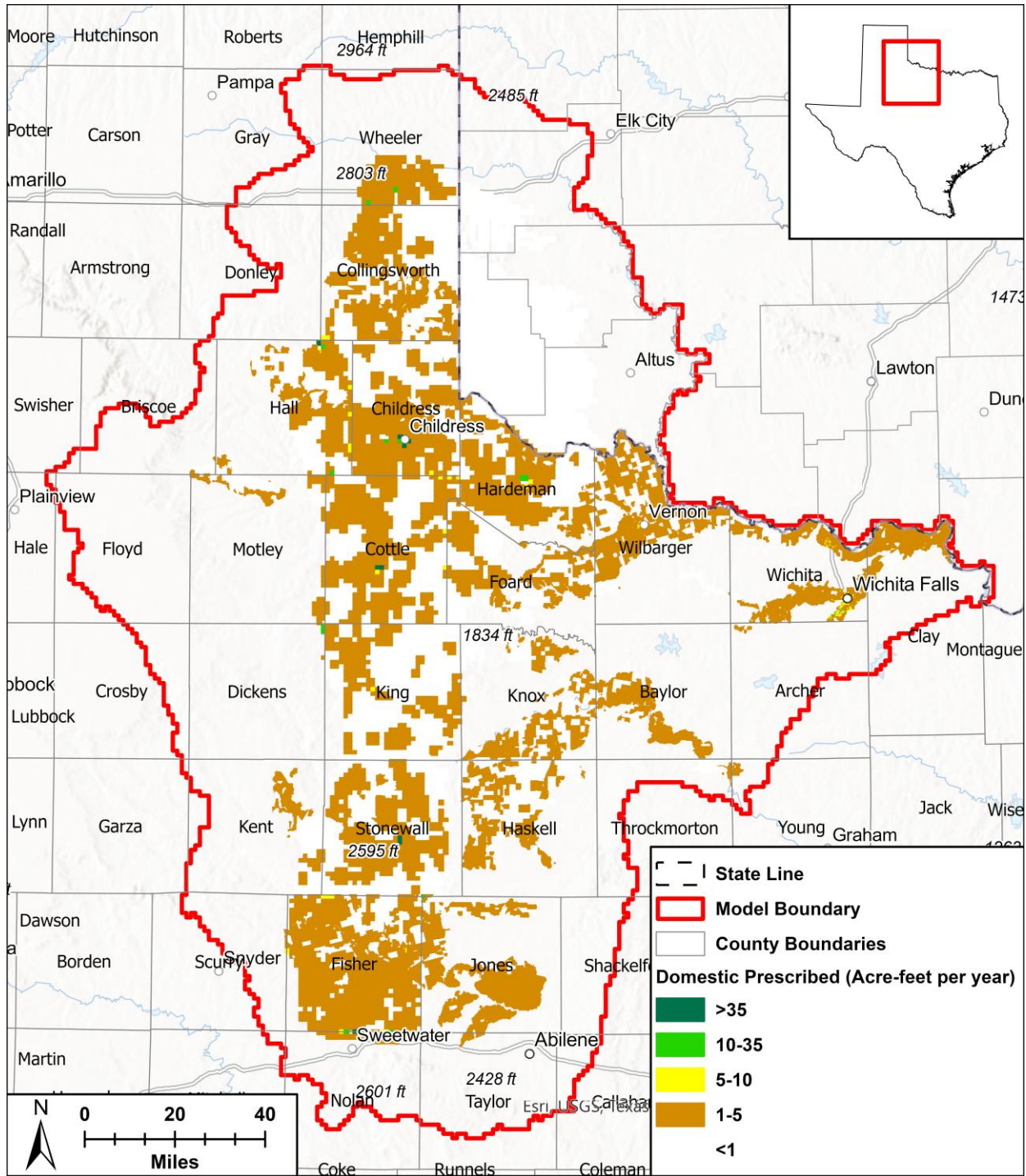


Figure 4.10-6. Initial Prescribed Texas domestic pumping rates (in acre-feet per year) in 2020 within the Seymour and Blaine Groundwater Availability Model.

As expected, delineation of urban and rural areas within the Seymour and Blaine aquifer footprints exhibited variable spatiotemporal distributions. Urban and rural spatiotemporal variability was leveraged for spatial distribution of non-domestic use pumping types, when necessary, to distribute pumping volume estimates in a representative region of the model domain.

4.10.2 Historical pumping estimates for non-domestic use types

Estimates of historical pumping from 1974, 1980, and from 1984 to 2020 for municipal, manufacturing/industrial, mining, power generation, irrigation, and livestock water use categories were obtained from the Texas Water Development Board (TWDB, 2025b). In the model, manufacturing/industrial and power generation pumping volumes were consolidated into a single "manufacturing" well package (sb.mfg) for simulation purposes. These estimates were developed to support state water planning and the TWDB Groundwater Modeling program. Pumping estimates for 1981–1983 were interpolated linearly between 1980 and 1984. Values for 1975–1979 were interpolated between 1974 and 1980, and 1960–1973 were set equal to 1974.

Pumping for manufacturing/industrial, power generation, mining, livestock, irrigation, and municipal uses was distributed among wells with corresponding reported use types, and the volumes were proportionally allocated based on the reported or estimated well yields. Figure 4.10-7 and Figure 4.10-8 show the number of wells by use type in each county across the model study area, while Figure 4.10-9 depicts the spatial distribution of non-domestic pumping wells throughout the model area and by aquifer.

When well yield data were unavailable in the TWDB or Submitted Drillers Reports databases, yields were estimated using a multiple linear regression model relating well diameter, well depth, and reported yield. The analysis was performed separately for each use type and aquifer footprint to assess consistency among construction characteristics and yield (Figure 4.10-10 and Figure 4.10-11).

Correlations in the Seymour Aquifer are weaker and more variable, reflecting its shallow, heterogeneous deposits. The strength of these correlations is described using the coefficient of determination (R^2), with values closer to 1 representing stronger relationships. Livestock wells show the strongest relationship ($R^2 = 0.70$) with yield increasing with both diameter and depth, while irrigation and municipal wells exhibit lower correlations ($R^2 = 0.34$ – 0.38). There were insufficient data points to develop a regression for mining wells. Overall, well diameter exerts a stronger control on yield than depth, consistent with localized transmissive zones and variable completion practices. Regression results for the Blaine Aquifer indicate moderate to strong correlations between yield and the explanatory variables. Irrigation wells show the highest correlation ($R^2 = 0.75$), with both diameter and depth contributing positively to yield. Mining wells display a moderate correlation ($R^2 = 0.62$), dominated by casing diameter, while livestock wells show a weaker relationship ($R^2 = 0.28$). There were insufficient data points to develop a regression for municipal wells.

Despite variation across use types, yields generally increase with both well depth and diameter. Although regression-based yields may overestimate some wells, they provide a consistent initial framework for allocating pumping where measured data are lacking, with uncertainty addressed in model calibration (see Chapter 5).

Pumping volumes were allocated to the model grid using a hierarchical approach designed to honor reported well capacities while ensuring all reported pumping is preserved in the model. For each (aquifer, county, use type, year) combination, the prescribed pumping volume was first distributed among active wells of the corresponding use type in the county, with each well's allocation proportional to its capacity (estimated yield) and clipped at that capacity. When the prescribed pumping volume exceeded the aggregate capacity of these wells — that is, when the proportional allocation would have required individual wells to pump beyond their estimated yields — the unallocated remainder was distributed uniformly across grid cells associated with the aquifer of interest. Cells were classified as rural or urban based on census data, and remainder pumping was assigned to rural cells for irrigation, stock, and mining uses, and to urban cells for municipal and manufacturing uses. In counties where no active wells of a given use type were present in the master well dataset for a given year, the full prescribed pumping volume was distributed in the same manner across rural or urban cells of the aquifer. In the limited cases where no rural or urban cells were available for the (aquifer, county) combination, the prescribed pumping was distributed uniformly across all active aquifer cells within the county. This hierarchical approach ensures mass conservation of the reported county-level pumping volumes throughout the model domain.

Pumping volumes associated with individual wells were assigned to their corresponding grid cells. Vertically, the allocation of well pumping volumes to specific aquifers was determined using total well depth, as detailed well screen information was limited. Wells less than 250 feet deep were assigned to the aquifer present at 80 percent of the well depth (e.g., a well with a depth of 100 feet would be assigned to the aquifer located 80 feet below the surface). For wells deeper than 250 feet, the aquifer unit located 50 feet above the bottom of the well was used to ensure that the well was most likely associated with the aquifer it screened.

Texas Water Development Board Contract Number 2448302843
 Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

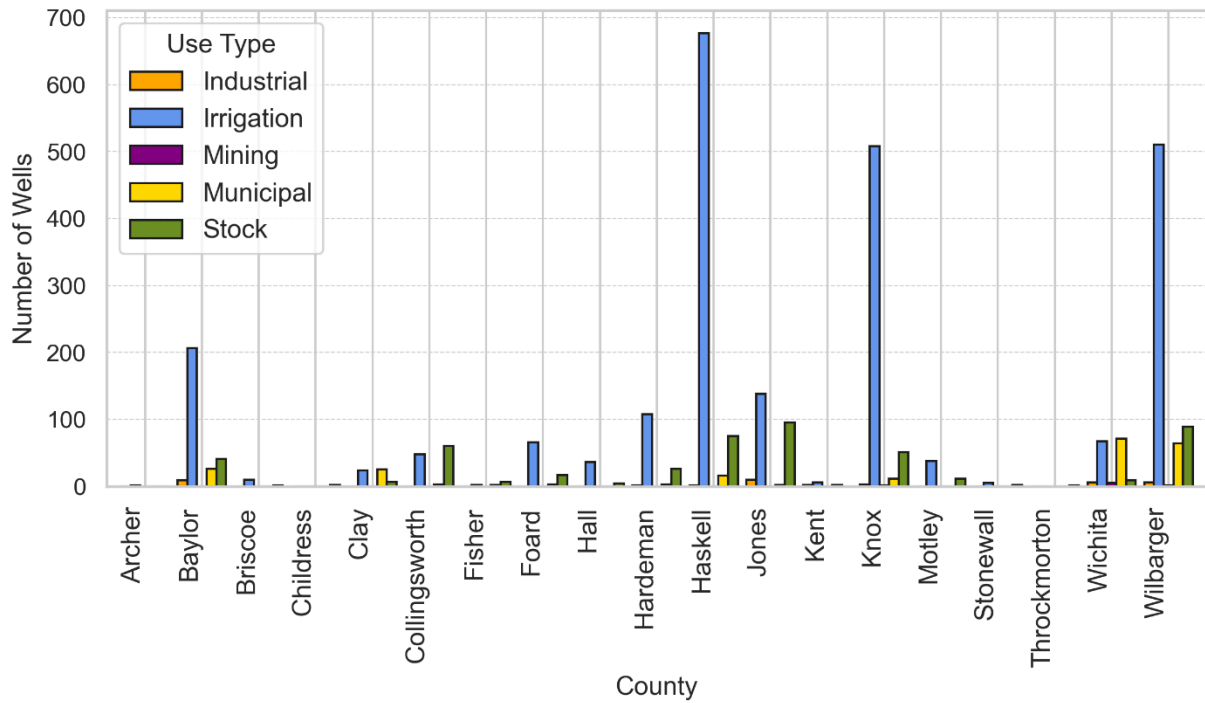


Figure 4.10-7. Number of non-domestic wells by county and water use type in the Seymour Aquifer.

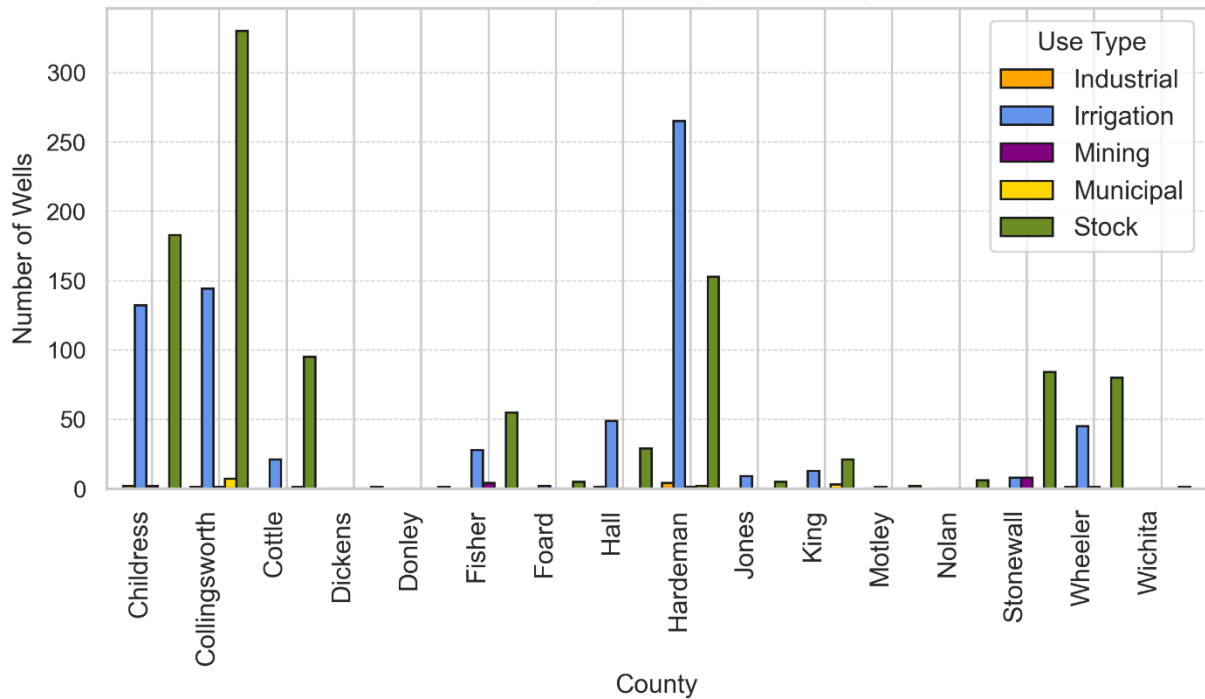


Figure 4.10-8. Number of non-domestic wells by county and water use type in the Blaine Aquifer.

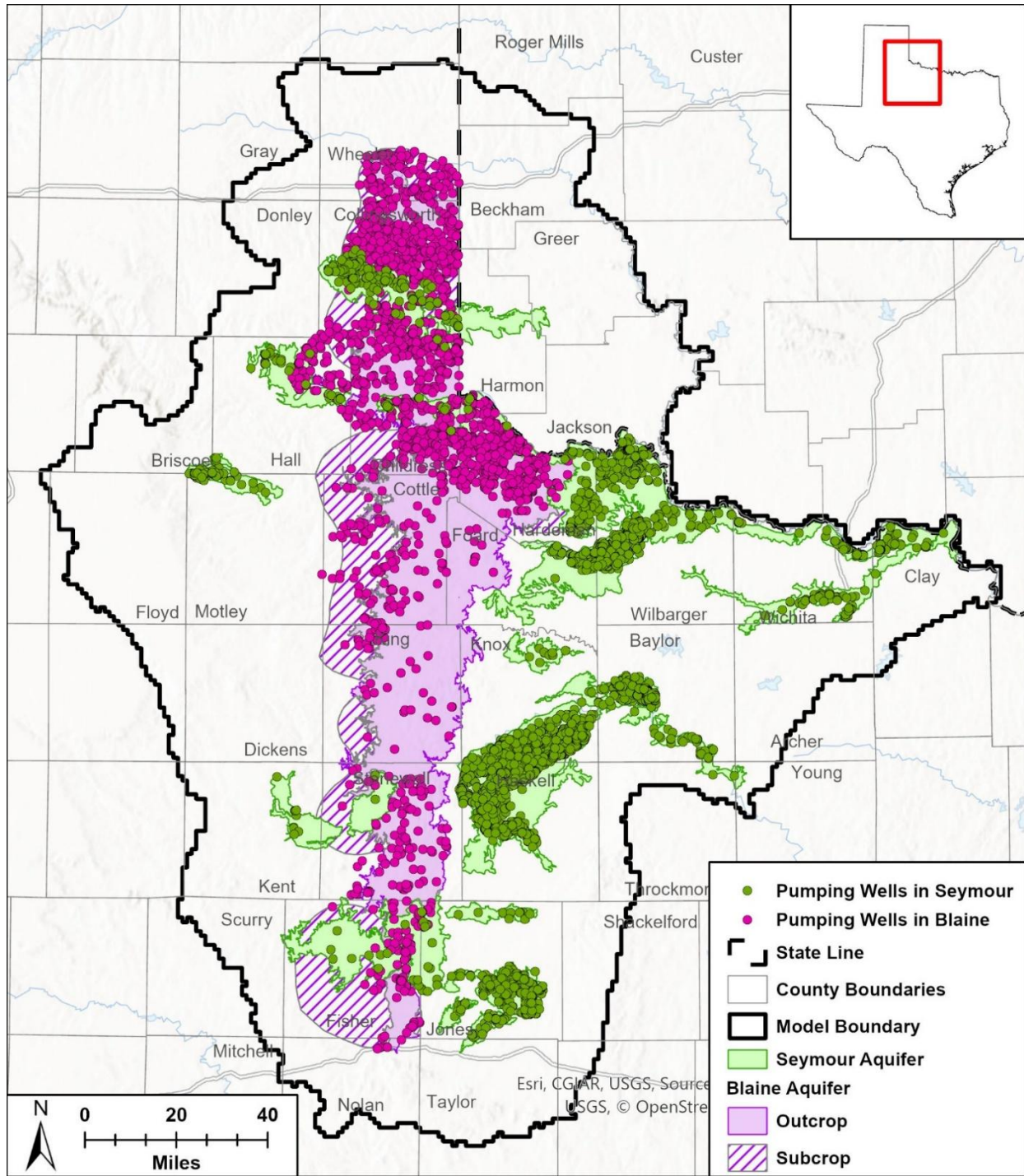
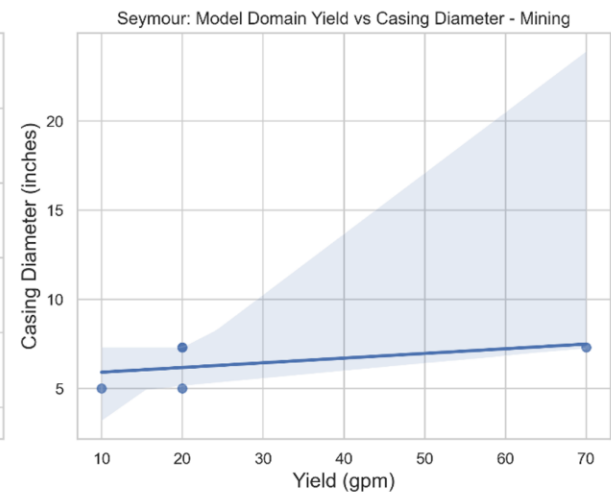
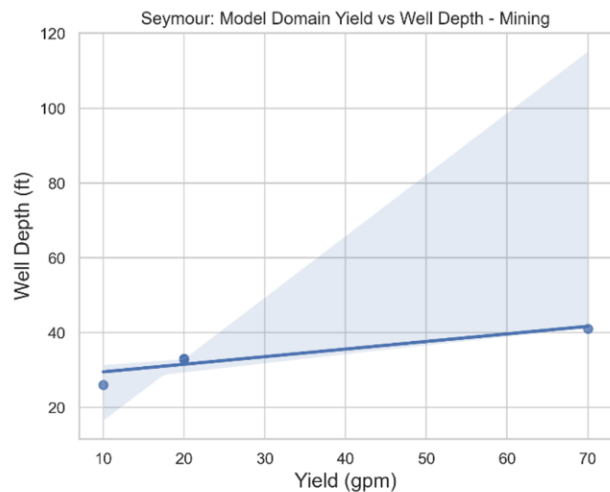
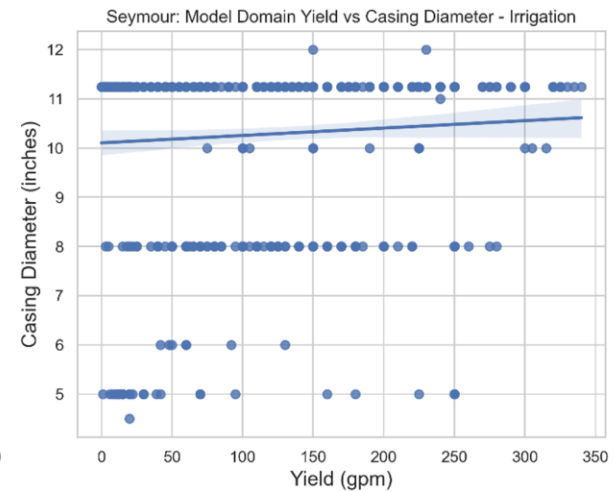
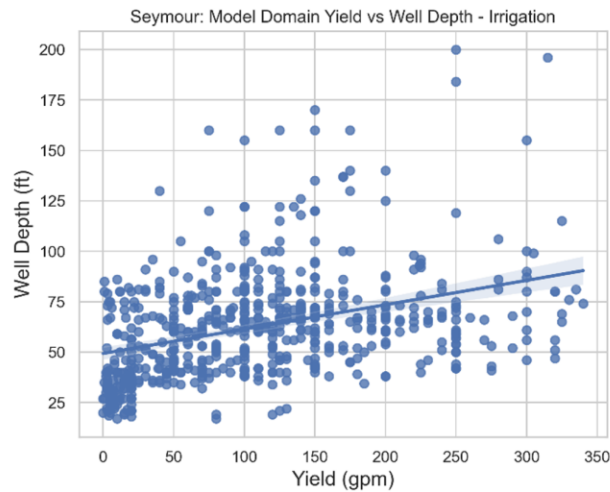
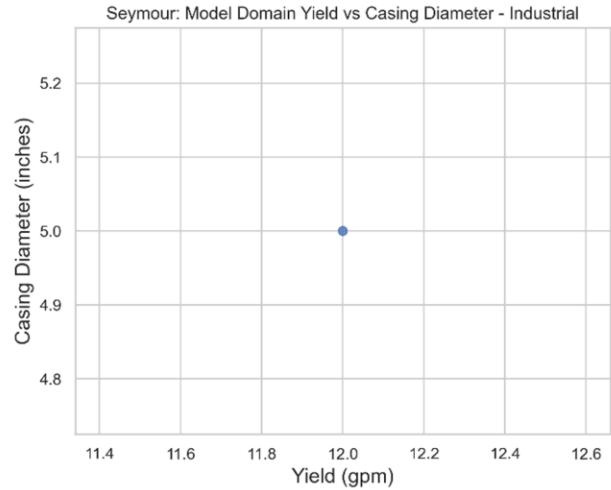
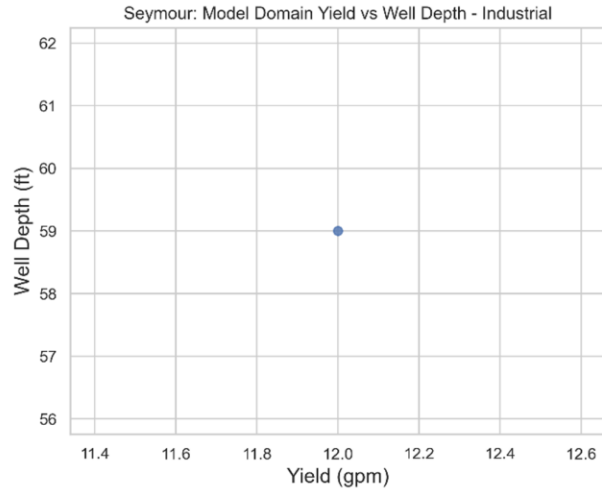
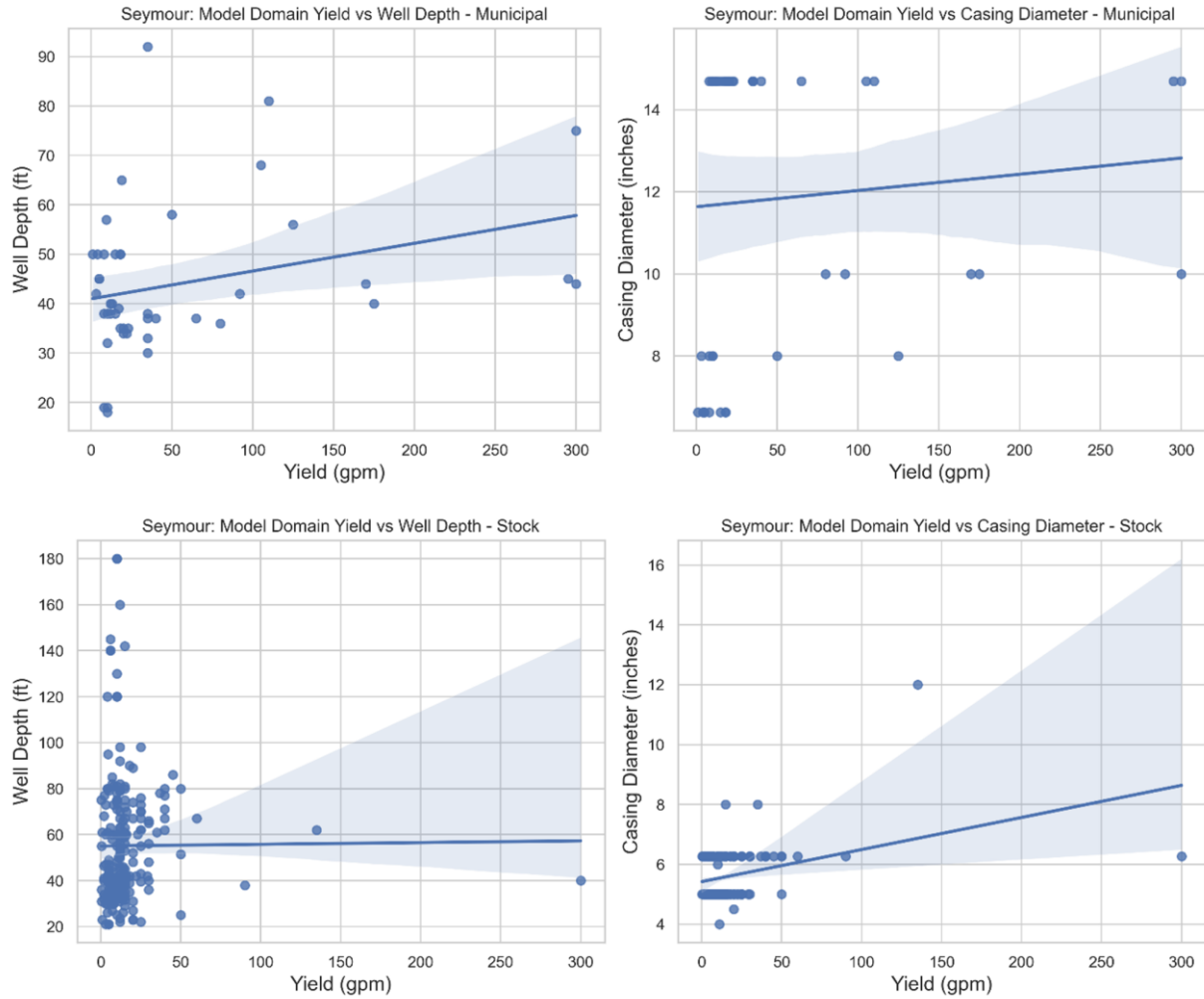


Figure 4.10-9. Non-domestic use wells within the Seymour and Blaine Groundwater Availability Model.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers



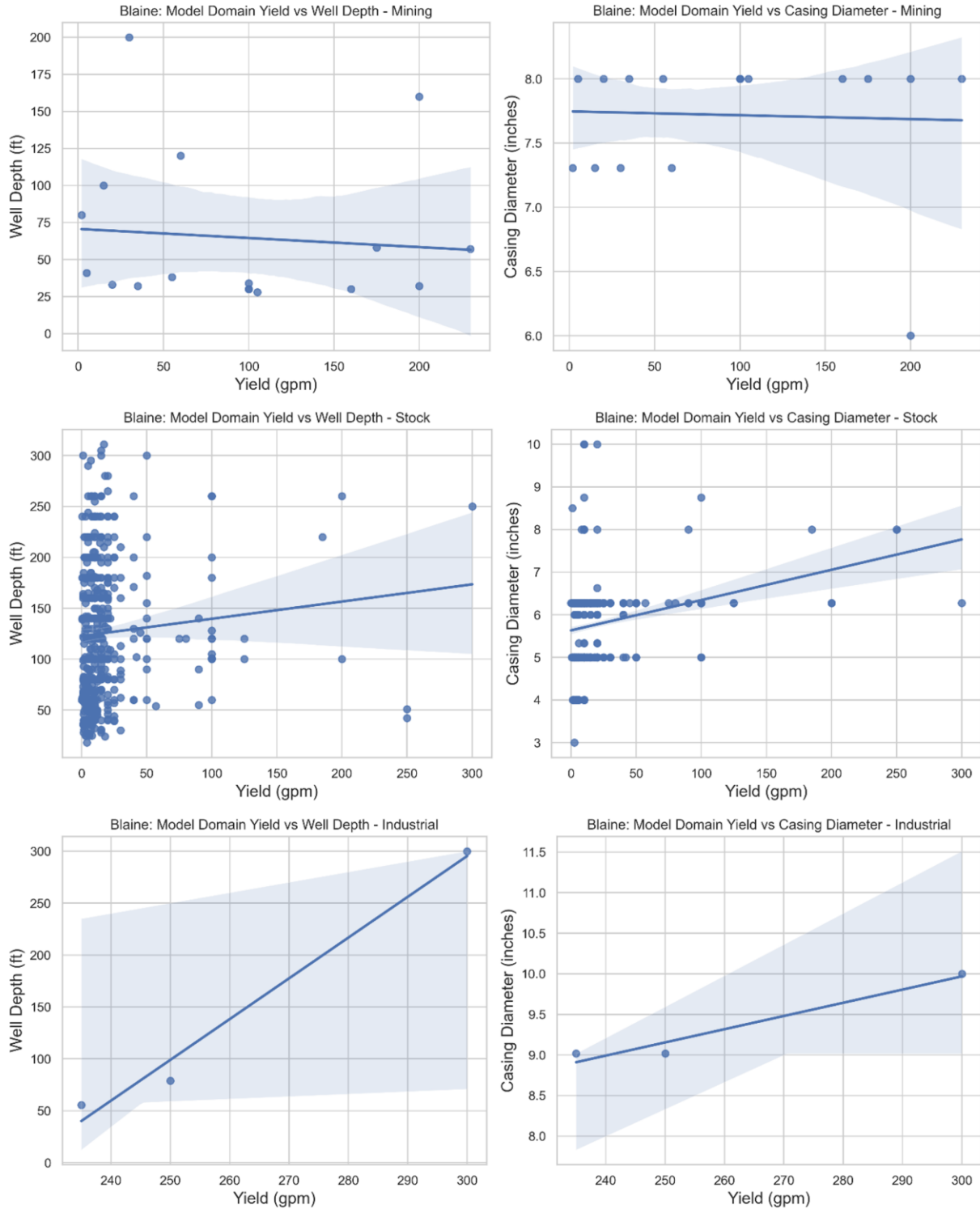
Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

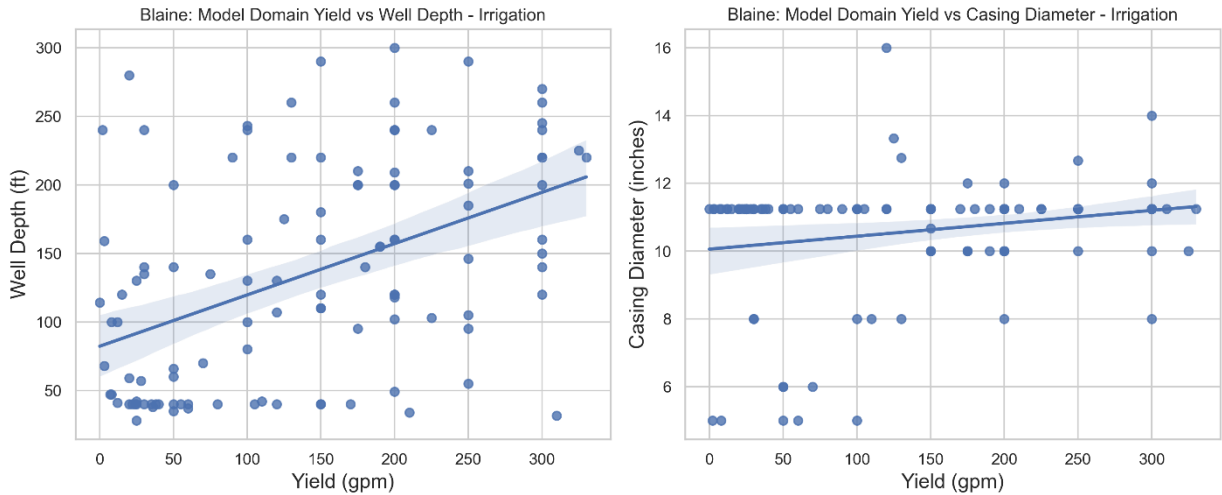


Note: ft = feet, gpm = gallons per minute

Figure 4.10-10. Well depth versus yield and yield versus casing diameter for non-domestic well use in the Seymour Aquifer.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers





Note: ft = feet, gpm = gallons per minute

Figure 4.10-11. Well depth versus yield and yield versus casing diameter for non-domestic well use in the Blaine Aquifer.

4.10.3 Metered pumping estimates

Accurate metered pumping data are the best estimates for estimating groundwater pumping. Metered data from 2004 to 2023 were graciously provided by three-(3) groundwater conservation districts; Rolling Plains, Mesquite, and Panhandle.

Metered data were available in Seymour Pods one-(1), two-(2), three-(3), four-(4), seven-(7); the Blaine Aquifer; and other Permian units and covered primarily irrigation pumping but also included a minor amount of municipal pumping. Data were incorporated explicitly as a separate pumping package. Where metered pumping data were available outside the Seymour and the Blaine footprint, they were assigned to the shallowest underlying Permian unit in the model. Over ninety-(90) percent of the metered data available were before 2020, which were all able to be incorporated into the model. Spatially, the model can accommodate one-hundred-(100) percent of the metered data, but temporally nine-(9) percent of the data covered 2020 to 2023, which were not included in the calibration model. Minor refinements to the estimates were made where units were variable for consistency. Other pumping packages were updated based on the metered data to reduce double counting the same pumping. Table 4-8 provides a general summary of the available metered data.

Table 4-8. General Summary of Available Metered Data. ⁽¹⁾Data from Mesquite Groundwater Conservation District. ⁽²⁾Data from Panhandle Groundwater Conservation District. ⁽³⁾Data from Rolling Plains Groundwater Conservation District.

Source	Temporal Range	Aquifers	Type
Mesquite GCD ⁽¹⁾	2018-2022 (Temporally Sparse)	Seymour, Blaine, Not Specified	Irrigation, Municipal
Panhandle GCD ⁽²⁾	2015-2022 (Temporally Variable)	Seymour, Blaine, Permian	Irrigation
Rolling Plains GCD ⁽³⁾	2004-2023 (Temporally Sparse)	Seymour	Irrigation, Municipal

The raw spatial distributions as provided and respective aquifer assignments for the metered data through the modeled period of 2020 for the calibration model are shown in Figure 4.10-12.

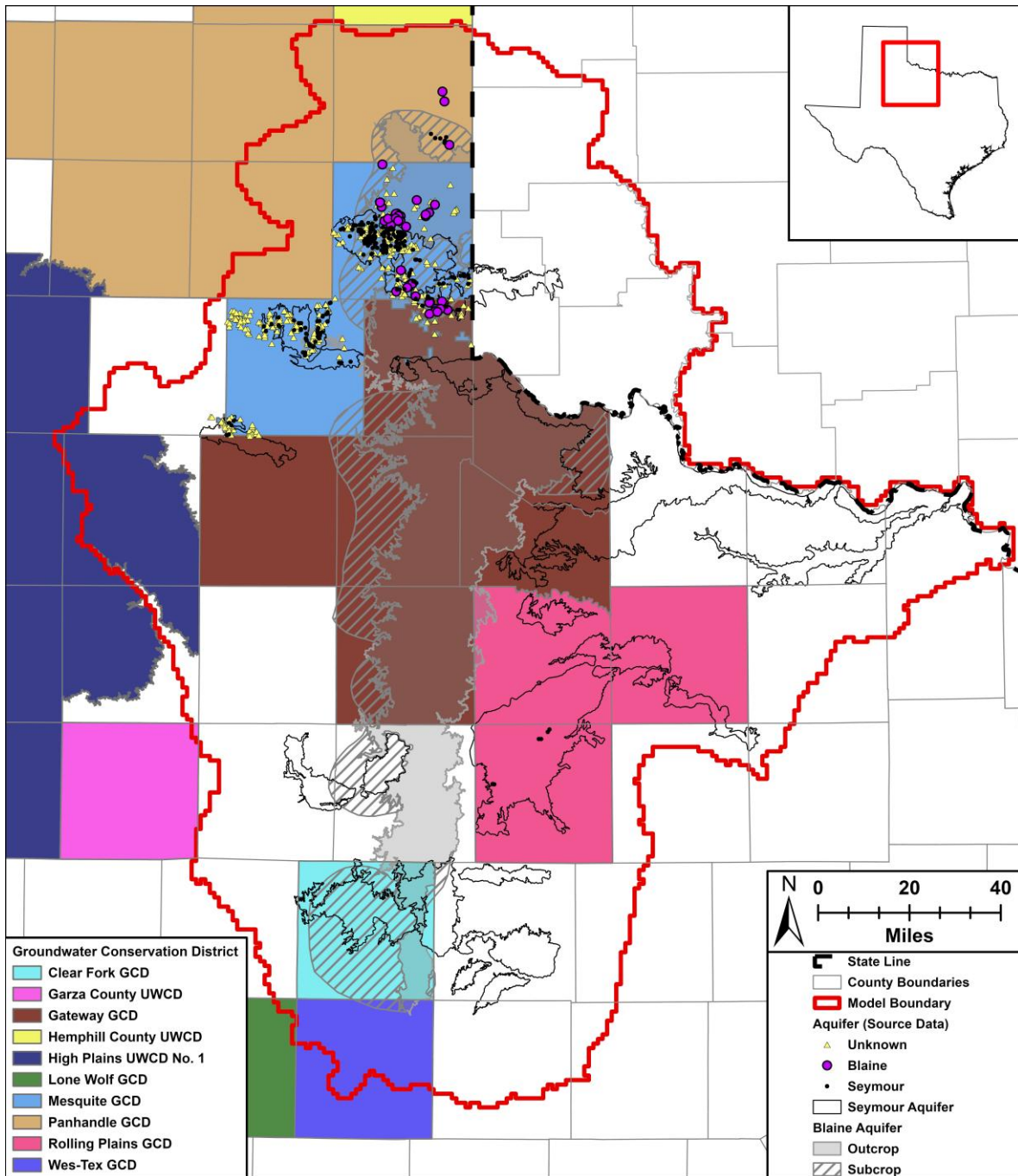


Figure 4.10-12. Spatial distributions and aquifer assignments for the metered data through the historical simulation period.

Metered pumping volumes summarized by county for the available data through 2020 are given in Figure 4.10-13. These were explicitly used as prescribed inputs for pumping input files for the groundwater availability model update.

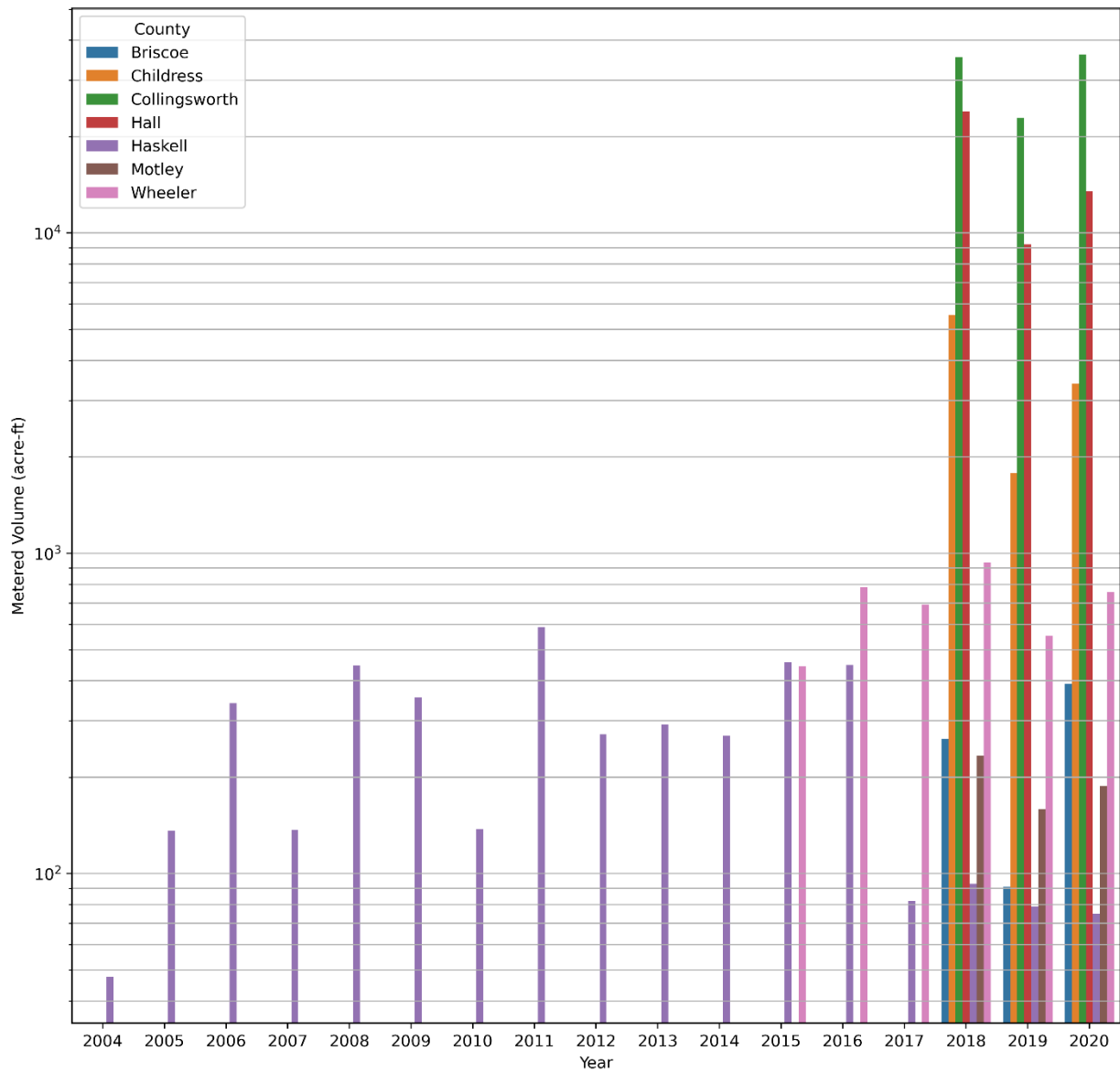


Figure 4.10-13. Metered pumping volumes (acre-feet) summarized by county for the historical simulation period.

The translation of the raw data to the numerical model layering is shown in Figure 4.10-14. Aquifer assignments were made where the metered lacked aquifer assignments or did not align with the modeled extent of the Seymour pods.

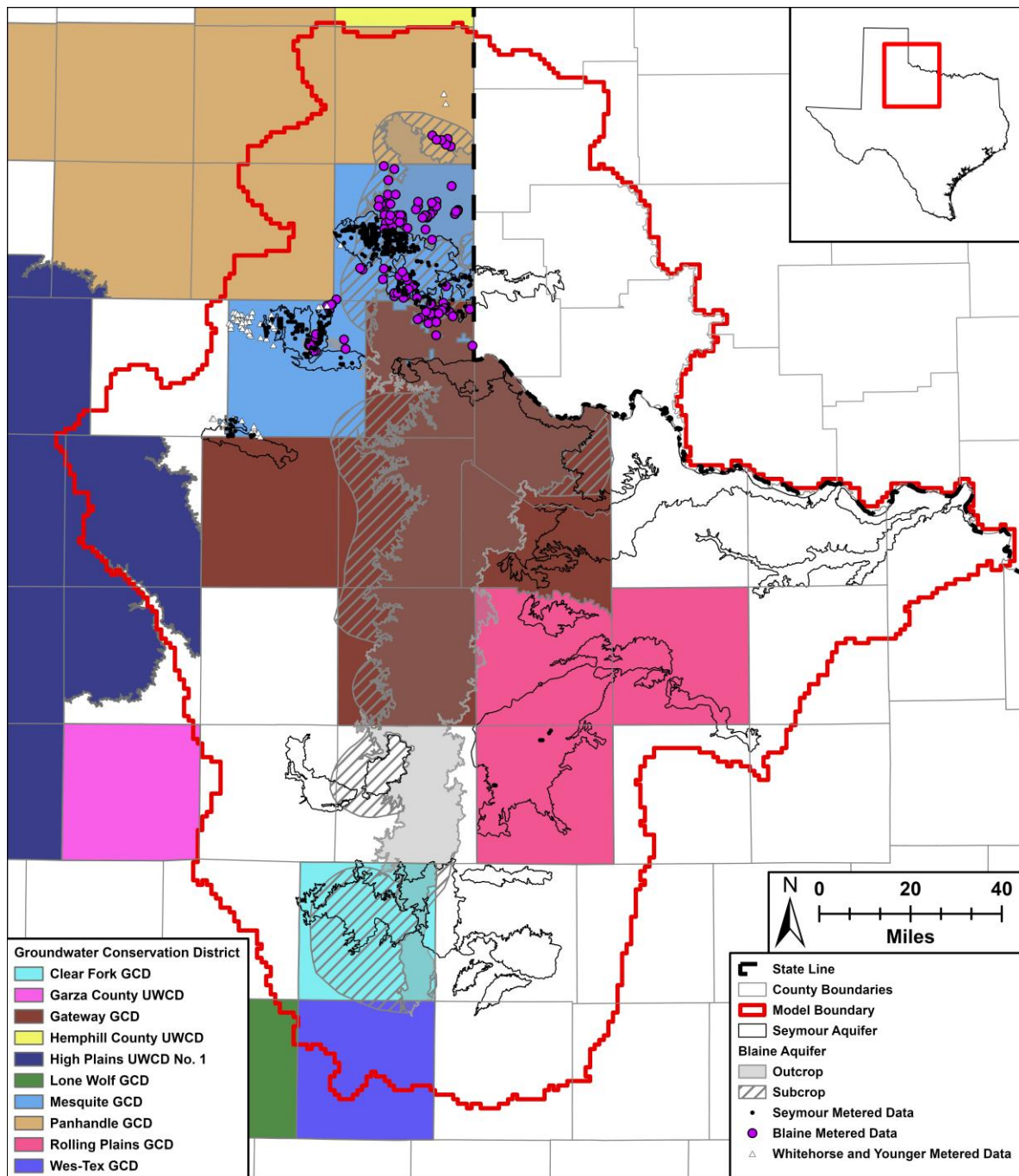


Figure 4.10-14. Spatial distribution of metered data by aquifer.

Temporal pumping volumes transcribed to the model hydrostratigraphic units for the available metered data used in development of the metered pumping package are provided in Figure 4.10-15.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

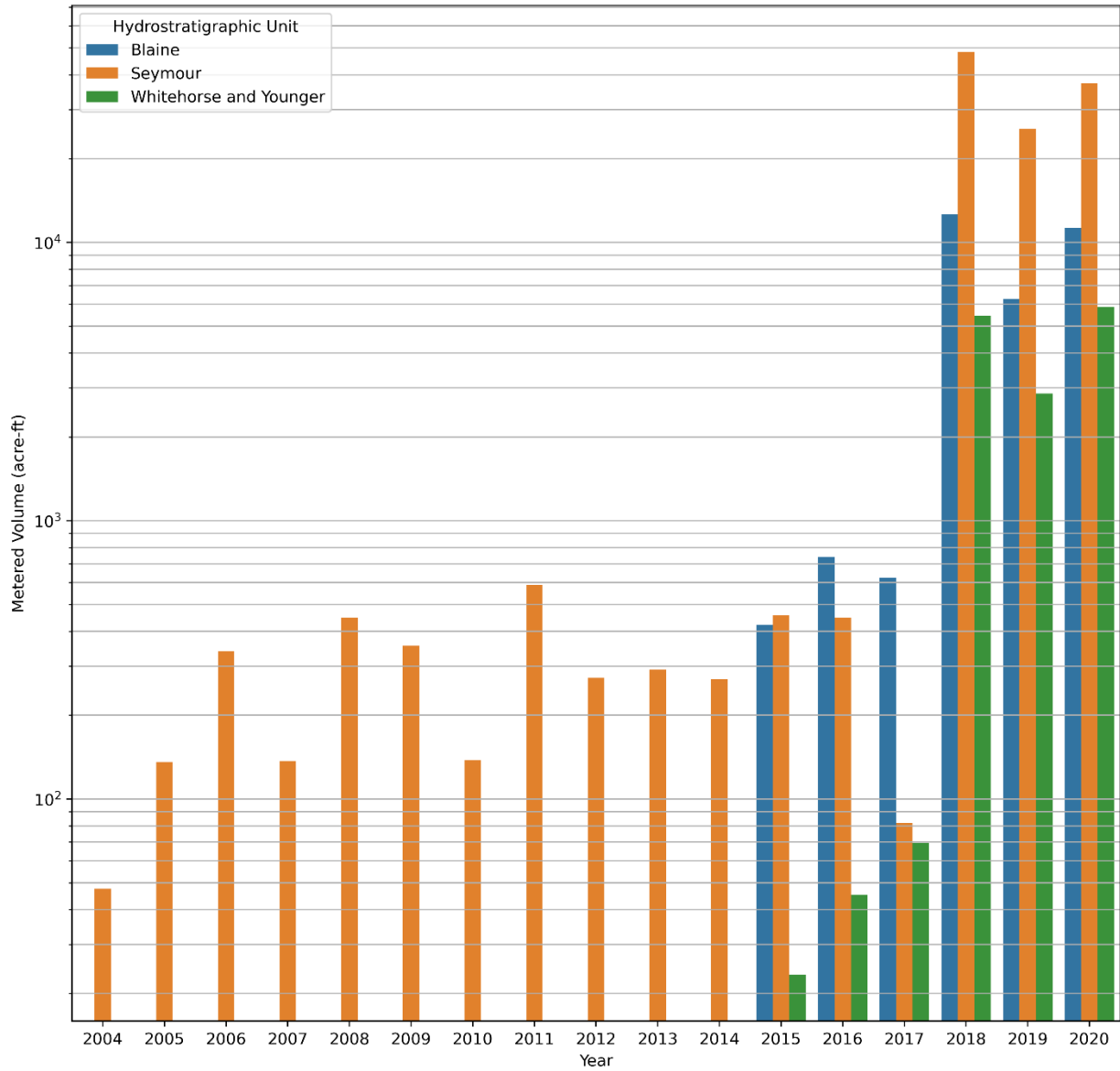


Figure 4.10-15. Temporal pumping volumes (acre-feet) transcribed to the model hydrostratigraphic units (hsu) for the available metered data used in development of the metered pumping package.

A temporal breakdown of the modeled metered pumping data for the Seymour pods from the available data is provided in Figure 4.10-16.

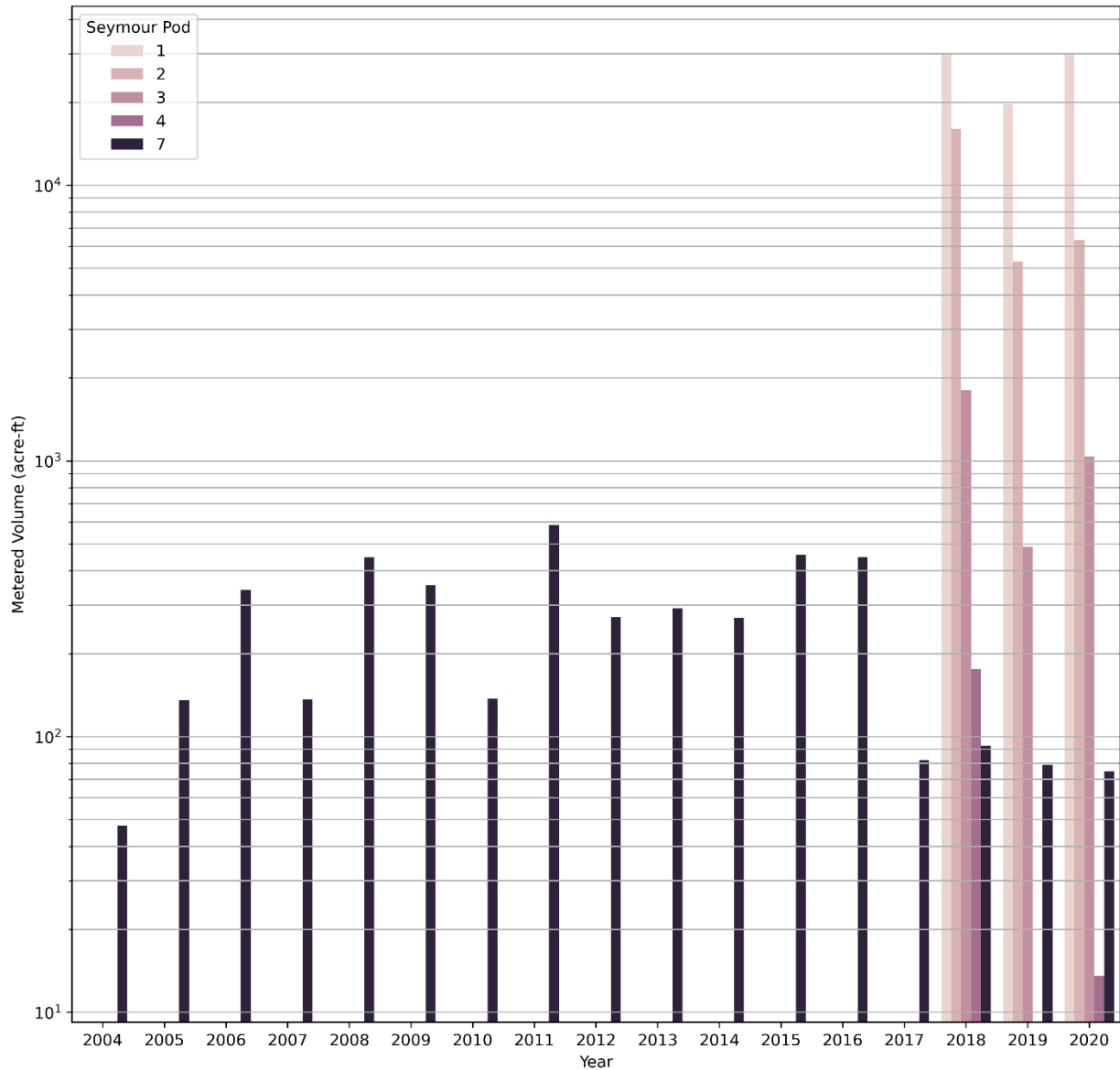


Figure 4.10-16. Temporal breakdown of the modeled metered pumping data (acre-feet) for the Seymour pods from the available data.

A temporal breakdown of metered data by use type is shown in Figure 4.10-17.

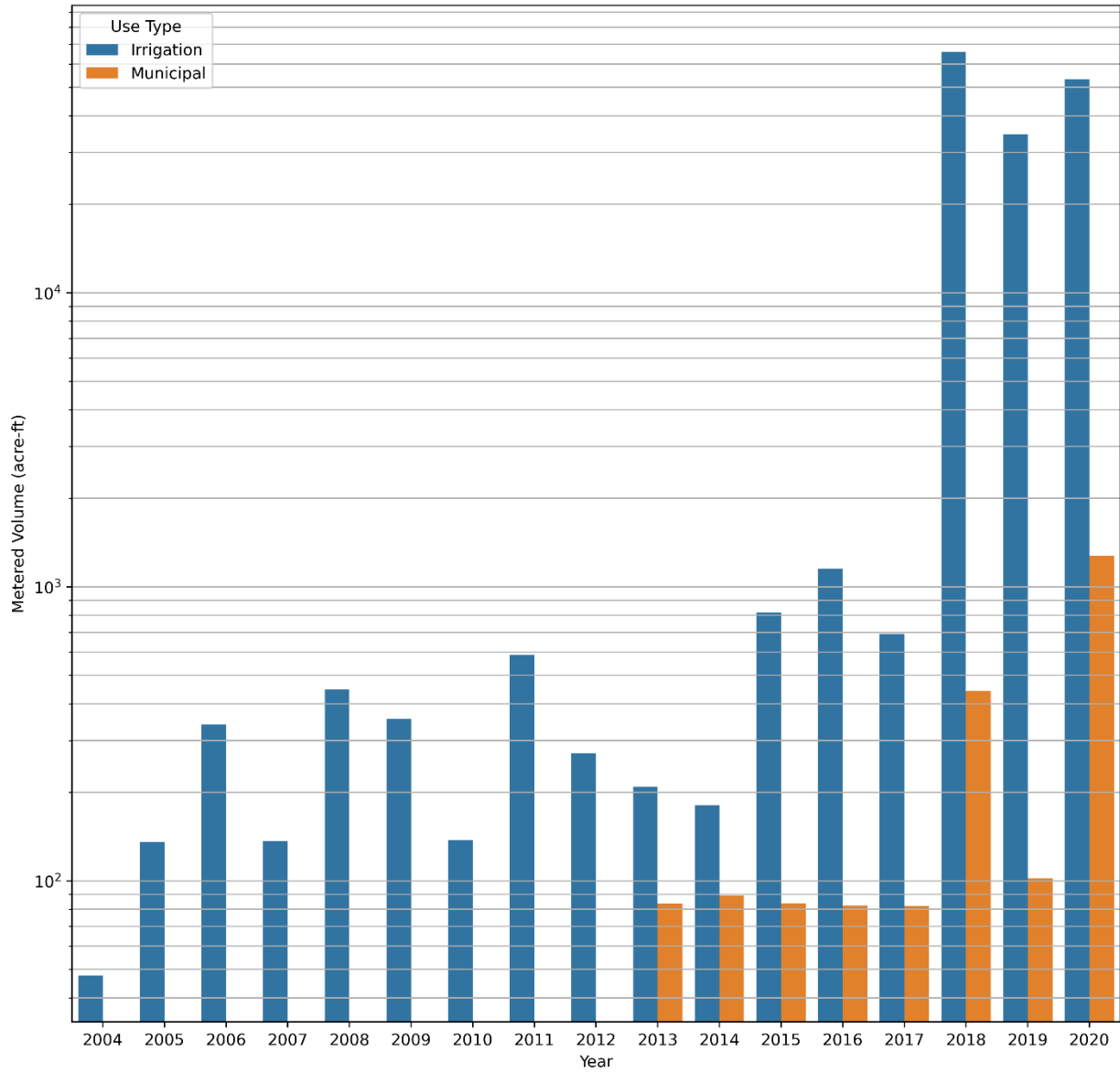


Figure 4.10-17. Temporal breakdown of metered data (acre-feet) by use type.

4.10.4 Oklahoma pumping estimates

Pumping estimates for the state of Oklahoma were a secondary focus for the groundwater availability model update but were included, as they are an important component of the water budget for the Blaine Aquifer and for Seymour pods one-(1) and four-(4), which either extend into Oklahoma or closely border the state line. The estimates for pumping in Oklahoma were developed directly from the estimates from the previous 2004 groundwater availability model that covered 1975 to 1999. Assumptions were made to infill time periods 1960 to 1975 and 1999 to 2020 based on the pumping estimates available from the 2004 groundwater availability model. The prescribed pumping for 1960 through 1974 was assumed to be equal to prescribed pumping in 1975 from the previous 2004 groundwater availability model in both magnitude and spatial distribution. The same assumption was made for extending Oklahoma pumping from 2000 through 2020 with 1999 pumping magnitude and spatial distribution from the previous groundwater availability model (Ewing and others, 2004). Use types were not discretized into separate packages as was done for the pumping within Texas for simplicity.

4.10.5 Spatial redistribution of prescribed pumping

There is considerable uncertainty in the source information in initial pumping estimates at the county level for each use type based on limitations in spatially assigning the estimates to appropriate wells based on the available data in publicly available databases. These uncertainties and limitations were highlighted with the initial model response where substantial autoflow reductions were observed in regions of the model that were not aligned with the conceptual understanding of pumping estimates. To provide a better starting point for the pumping reductions to align better with the conceptual understanding of the pumping estimates, the preliminary spatial distributions of prescribed pumping estimates for each use type were redistributed based on steady-state saturated aquifer thickness simulated by the model across all time periods for all use types. Prescribed pumping was redistributed to locations of the model with a minimum of six-(6) feet of saturated thickness. The minimum thickness was selected based on initial testing of model response while keeping continuity with prescribed pumping estimates consistent before and after redistribution both at the county and hydrostratigraphic unit levels.

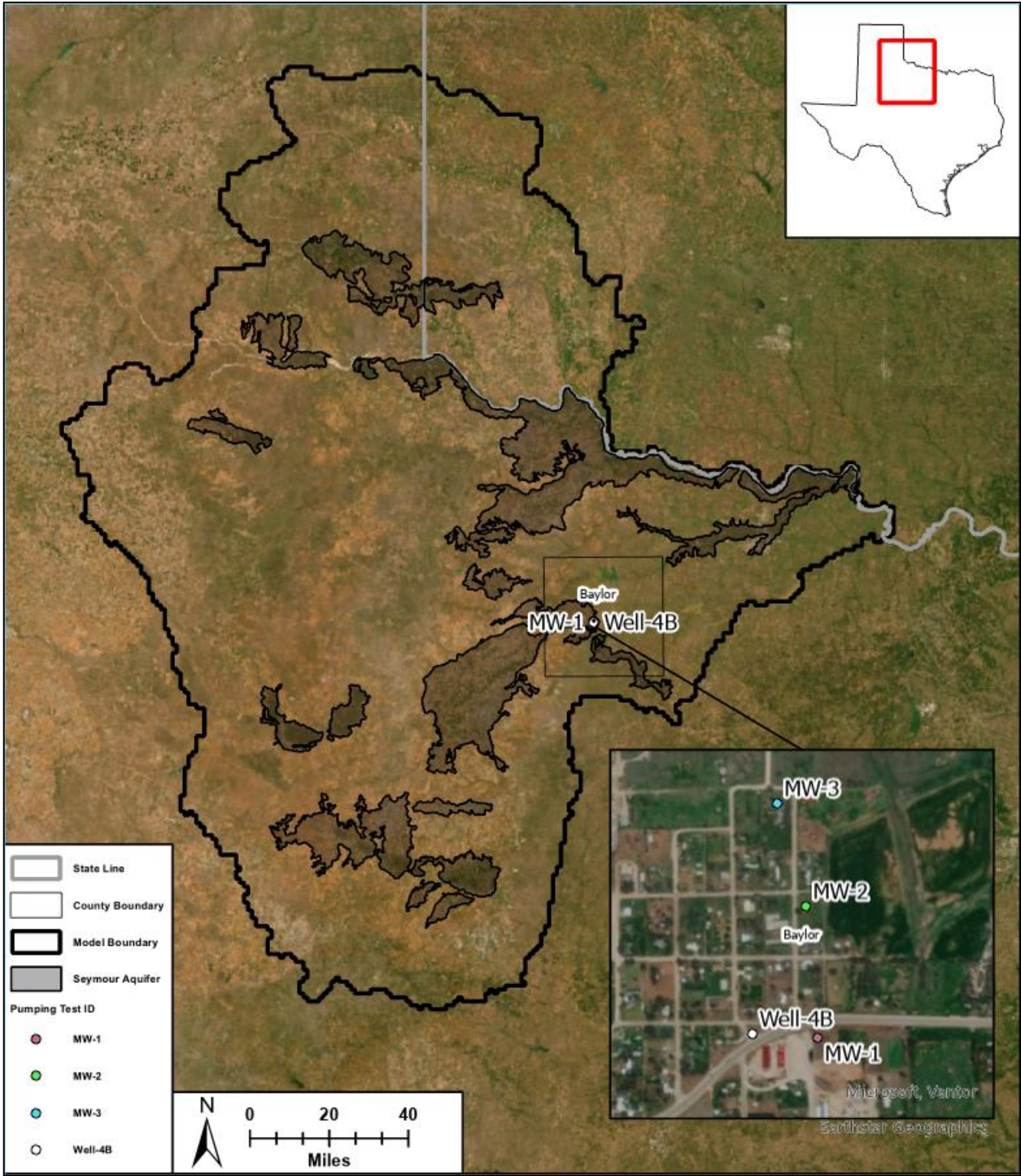
4.10.6 Autoflow reduction settings

MODFLOW 6 has autoflow reduction capability settings in the well (WEL) package. This reduction prevents wells from extracting water when available saturated thickness becomes too low, simulating the natural decline in production as water levels drop. Typically, autoflow reductions of pumping are based on a ratio (percent) of the remaining cell thickness as an explicit input. This functionality can become limiting in regional models where model cell thickness is highly variable and there are thin, highly productive intervals as is observed in some locations of the Seymour Aquifer with basal gravel units. To accommodate these better, Joseph Hughes (INTERA) developed an auto flow reduction length-based input instead of ratio-based unit and incorporated it into the main branch of MODFLOW-6 github repository that is

publicly available. The autoflow reduction length setting was used for all well (WEL) packages in the model with a reduction length specification of five-(5) feet. Given the relatively thin and spatially variable saturated thickness of the Seymour formation pods, reductions in pumping were anticipated and addressed as a conceptual constraint during calibration (see Section 5.2.2).

4.10.7 Aquifer testing data

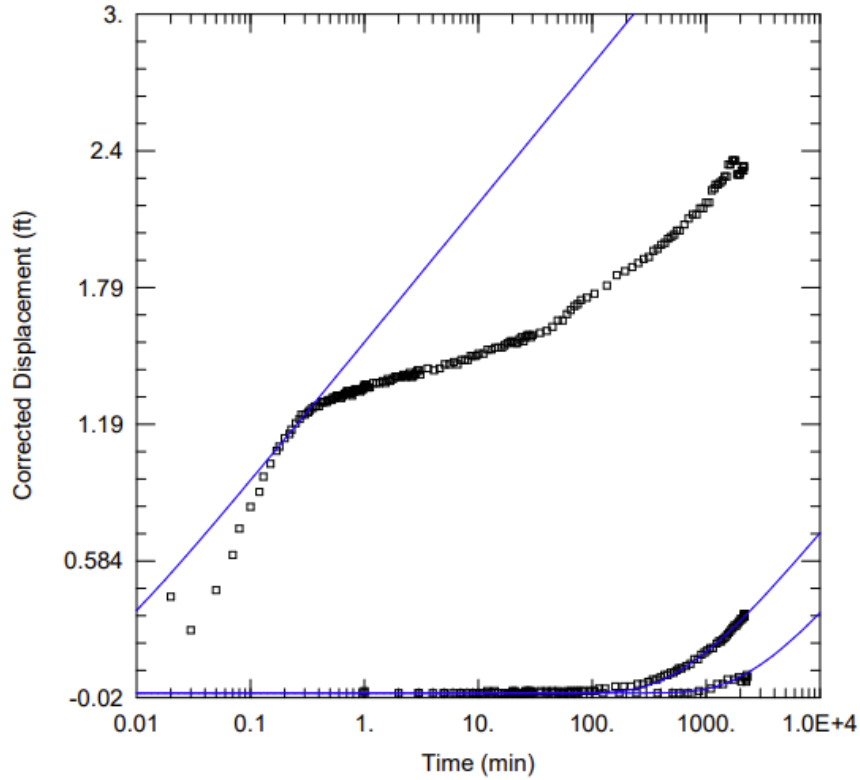
Rolling Plains Groundwater Conservation District provided high-quality aquifer testing data from testing one of the City of Seymour's old production wells, Well 4B, in the northeast extent of Seymour Pod 7. The test included multiple observation wells at varying distances for the aquifer testing. The production well has an open hole completion with cement casing down to 36 feet below ground surface, approximately to the base of the Seymour Aquifer. The aquifer test duration was 36 hours at a constant rate of approximately 230 gallons per minute. The test was completed in 2024 and also collected recovery data after the pumping period reached completion. Water levels were collected at the testing well and all of the monitoring wells. The estimated specific capacity of the well is 92 gallons per minute per foot of drawdown. Figure 4.10-18 displays the location of the wells used in the aquifer testing.



Note: ID = identification, MW = monitoring well

Figure 4.10-18. City of Seymour aquifer testing data locations in 2024.

Aquifer testing analysis to estimate aquifer properties was completed by Rolling Plains Groundwater Conservation District using AQTESOLV software (Duffield, 2007). Collecting water levels during testing at both the testing and monitoring wells facilitates a platform to estimate aquifer transmissivity and storage properties of the Seymour Aquifer. Using the saturated thickness of the aquifer and the estimated transmissivity, a hydraulic conductivity can be estimated. Estimated hydraulic conductivity and specific yield from the aquifer testing will be compared to the estimated model parameters from the automated model calibration as an independent check. The observed data collected during the aquifer testing is also used as an independent performance reference to understand how the calibrated model may perform in the area of the aquifer test. Fits from the aquifer testing analysis and respective estimated aquifer properties provided by Rolling Plains Groundwater Conservation District for the Seymour Aquifer from the testing are summarized in Figure 4.10-19 and Table 4-9.



WELL TEST ANALYSIS					
Data Set: C:\...\Seymour 4B.aqt			Time: 12:19:56		
Date: 02/02/26					
WELL DATA					
Pumping Wells			Observation Wells		
Well Name	X (ft)	Y (ft)	Well Name	X (ft)	Y (ft)
4B	1738151	7264414	4B	1738151	7264414
			MW-1	1738521	7264380
			MW-2	1738465	7265114
SOLUTION					
Aquifer Model: Unconfined			Solution Method: Theis		
T = 9.897E+4 gal/day/ft			S = 0.1092		
Kz/Kr = 0.197			b = 20. ft		

Note: ft = feet, gal/day/ft = gallons per day per foot, min = minutes

Figure 4.10-19. City of Seymour aquifer testing data analysis provided by Rolling Plains Groundwater Conservation District.

Table 4-9. City of Seymour aquifer testing results for estimation of aquifer properties.

Aquifer Parameter Estimated	Value
Transmissivity (feet ² day ⁻¹)	13,230
Hydraulic Conductivity (feet day ⁻¹)	662
Saturated Thickness (feet)	20
Storage Coefficient (unitless)	0.11
Hydraulic Conductivity Anisotropy Ratio, Kz:Kh (unitless)	0.2

4.11 Drain package

The MODFLOW drain (DRN) package was employed to simulate groundwater outflow to generally intermittent streams and rivers and to springs and seeps in hydraulic connection with the Seymour and Blaine aquifer system. This package is essential for managing groundwater levels and preventing flooding conditions within the model area. Intermittent streams flow only during certain times of the year when there is sufficient rain or groundwater flow. Because groundwater dynamics are the focus of this model, it was important to capture the interactions between groundwater and intermittent streams, which will be represented with the drain package. Streams and rivers as delineated and characterized by the National Hydrography Dataset Plus High Resolution were used as the foundation from which the drain package and also the river package were developed and are shown in Figure 4.11-1. The river package will be discussed in Section 4.14. The intent of the base drain package is to represent intermittent streams and rivers generally within the model domain using stream order bounding as an initial starting point that may be refined during model calibration.

As an initial starting point to be refined during model calibration, a stream order of three through five for the streams and rivers defined in the National Hydrography Dataset Plus High Resolution was used as the delineation for the base drain package as shown in Figure 4.11-2. Initial bed conductance for the base drain package was calculated using the channel lengths available from the National Hydrography Dataset Plus High Resolution for each individual drain cell representing rivers and streams. Values for the hydraulic conductivity for the bed, stream width, and stream length were assumed to estimate a reasonable bed conductance that will be refined during model calibration. The drain elevations correspond to the ground surface elevation of the grid. United States Geological Survey high-resolution (10-meter) surface elevation data were used to define elevations for the drains with minimum elevations, calculated at the grid cell level. The implementation of the drain package in the Seymour and Blaine aquifer groundwater availability model is crucial for simulating groundwater outflow through natural drainage features accurately. By adjusting drain locations and conductance values during model calibration, the model effectively prevents flooding and ensures a realistic representation of the groundwater system. The number of grid cells (nodes) in the model for the base drains is 12,928. There are 5,823 of those cells (nodes) in layer 1 within the Seymour formation active sediments and the 7,104 cells (nodes) in layers 2, 3, and 4 within the Permian-age hydrostratigraphic units. The model cells (nodes) included in the base drain model package and the included boundary condition elevations are shown in Figure 4.11-3.

Where other boundary conditions were already defined in the model, for example river boundary or general head boundary, drain package cells were removed to avoid over definition of system boundary conditions in the same spatial location.

A separate drain package was developed specifically to represent the springs mapped within the model domain as described in report section 2.6 for more efficient mass balance tracking in MODFLOW 6. There are 703 unique instances of springs mapped within the model domain. The number of unique grid cells (nodes) in the model for the spring drains is 497. There are 118 of those spring cells (nodes) in layer 1 within the Seymour formation active sediments and there are 379 spring cells (nodes) in layers 2, 3, and 4 within the Permian-age hydrostratigraphic units. The drain elevations representing springs were defined using the same approach used in the base drain package; however, a vertical offset of 15 feet was added to avoid artificial communication between modeled boundary conditions after initial testing. The initial conductance components were not calculated using channel lengths from the National Hydrography Dataset Plus High Resolution but were based on a reasonable starting point based on previous modeling experience not to inhibit flows with high resistance. The conductance was not modified during model calibration as spring elevations were focused on explicitly as opposed to spring flows. The model cells (nodes) included in the spring drain model package and the included boundary condition elevations are shown in Figure 4.11-1.

Perimeter drains were included for each of the fifteen-(15) Seymour Aquifer pods to accommodate seepage at the edges. The initial conductance components were not calculated using channel lengths from the National Hydrography Dataset Plus High Resolution. The conductance values were based on a reasonable starting point based on previous modeling experience not to inhibit flows with high resistance and thus were not modified during model calibration. The edge drain elevations were set at 5 feet above the top of each model cell. The model cells (nodes) representing the edge drain boundary conditions for each Seymour pod are shown in Figure 4.11-5 and contain a total of 28,353 cells in layer 1.

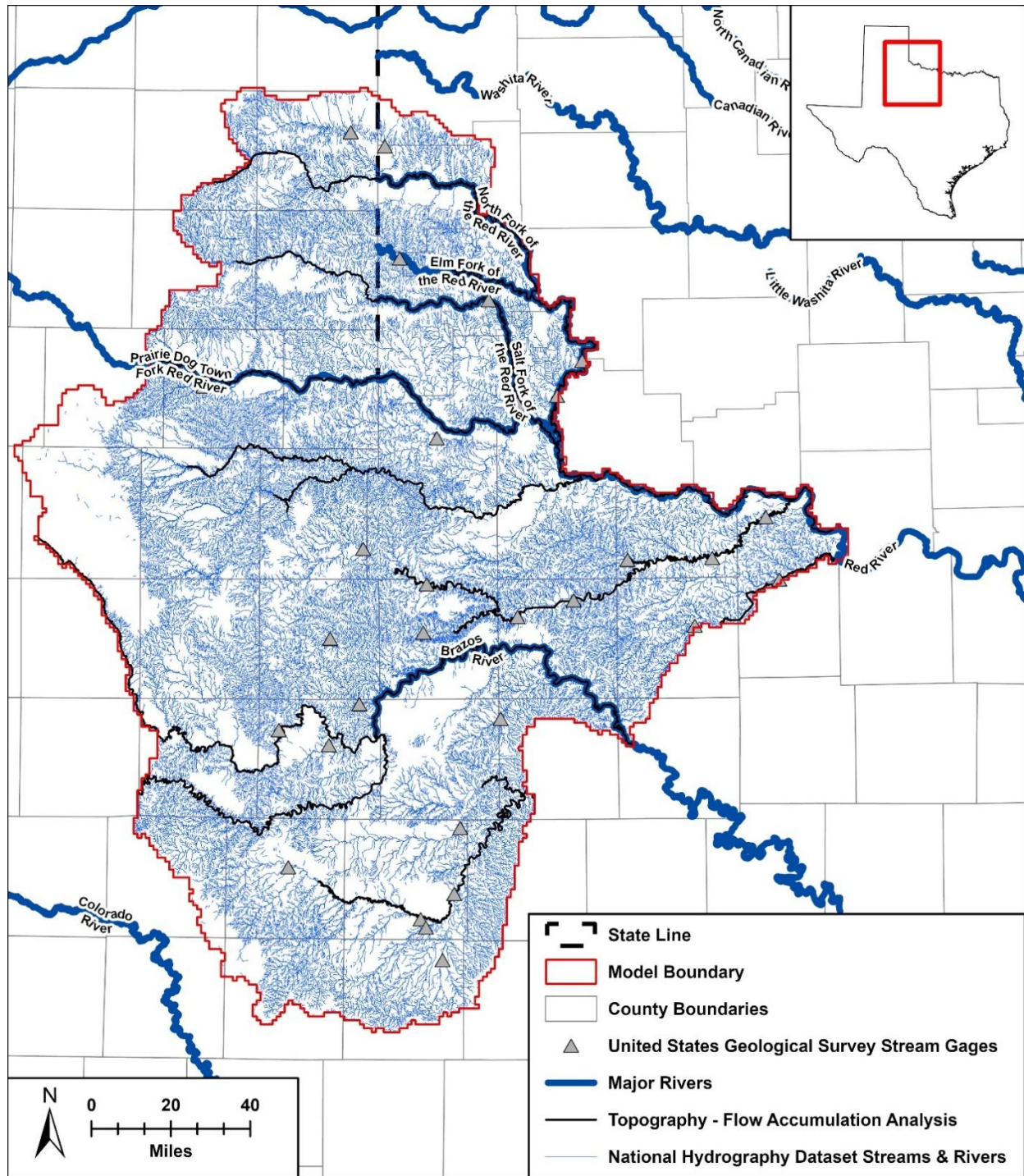


Figure 4.11-1. Locations of major rivers and perennial and intermittent streams in the outcrop areas based on National Hydrography Dataset Plus High Resolution.

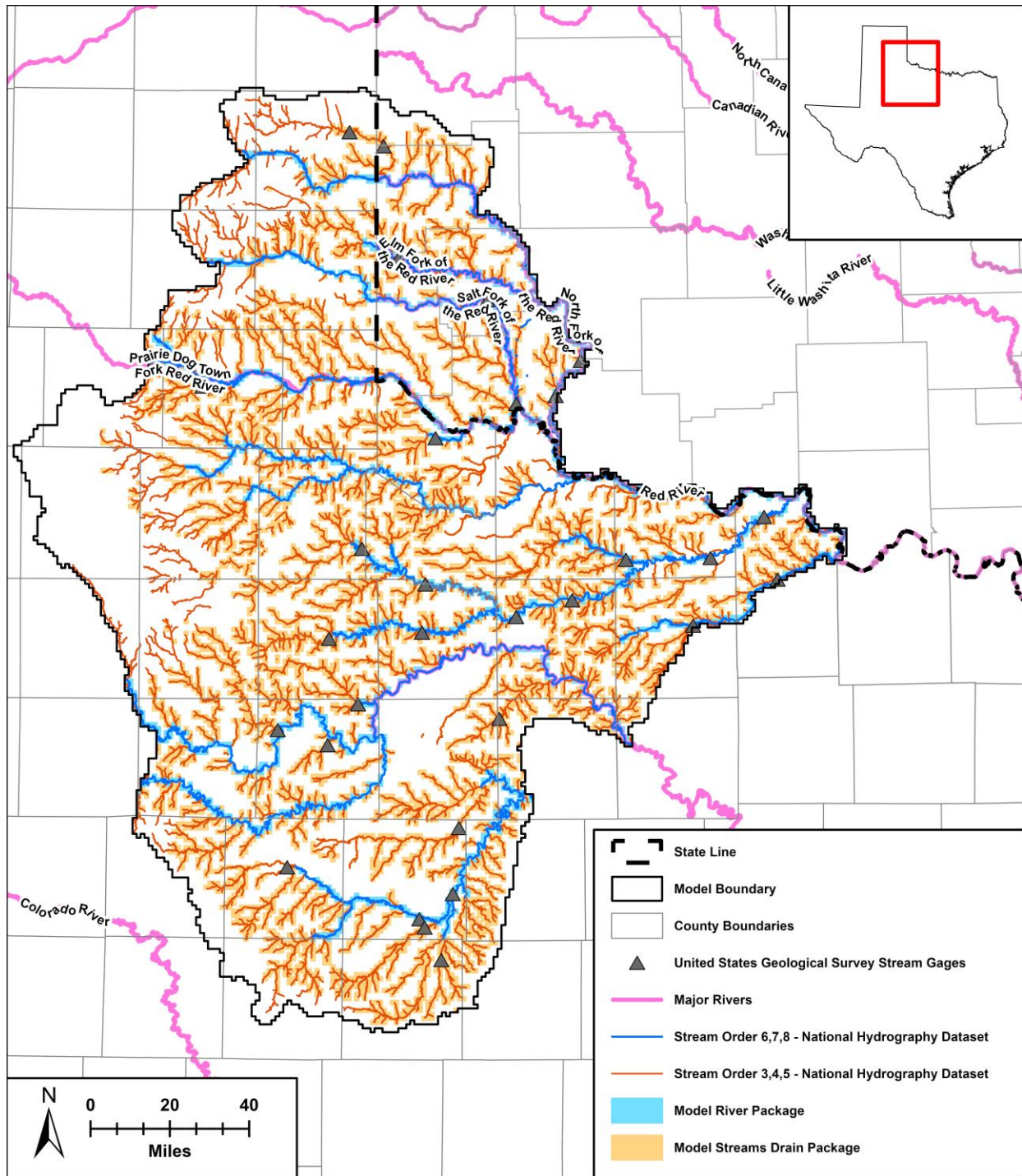


Figure 4.11-2. Delineation of river and drain model packages based on the National Hydrography Dataset Plus High Resolution.

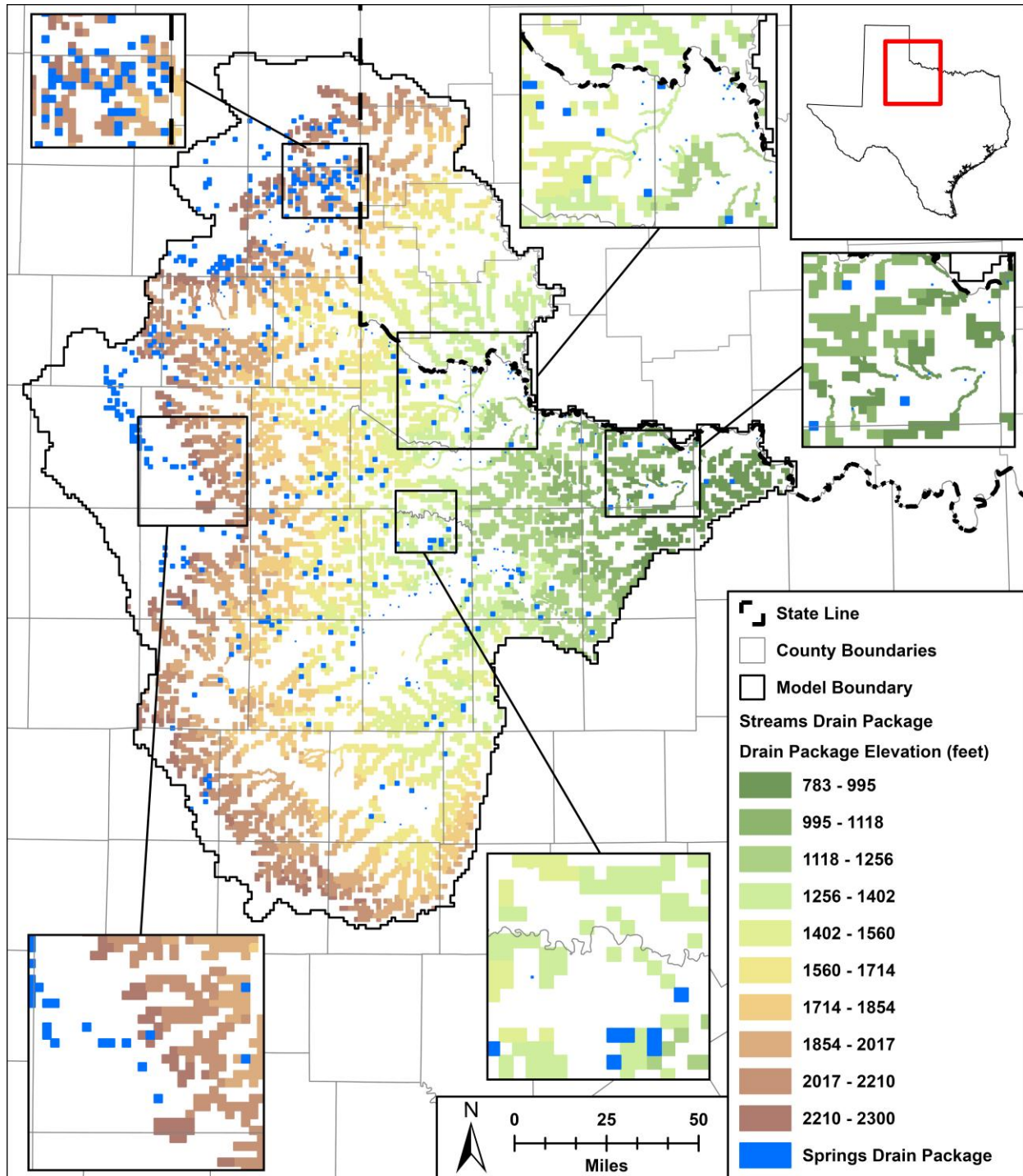


Figure 4.11-3. Location of drain cells representing ephemeral and intermittent streams in the model domain. Drain package cells in blue represent springs and seeps.

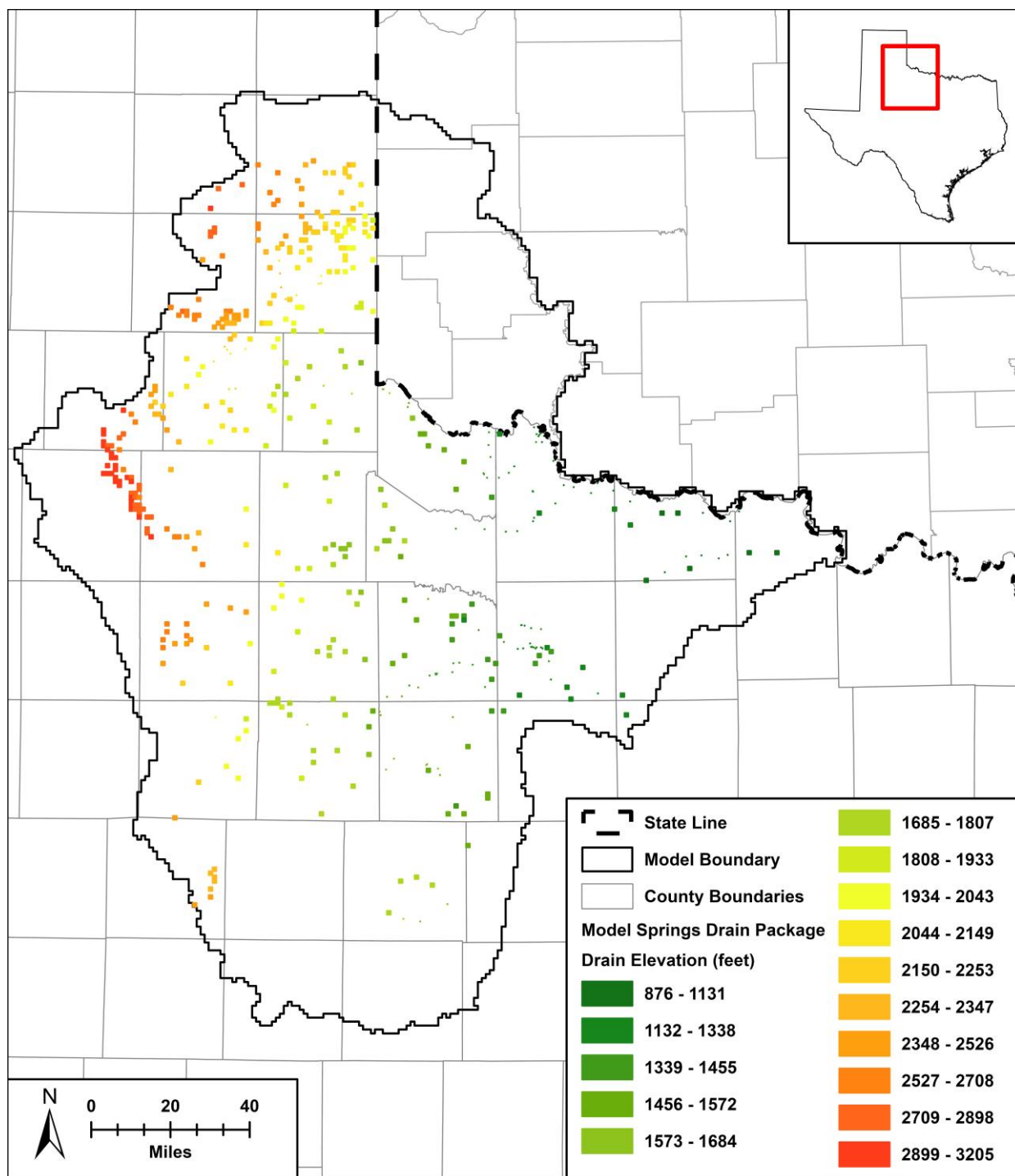


Figure 4.11-4. Location of drain package cells representing springs and seeps mapped in the model domain.

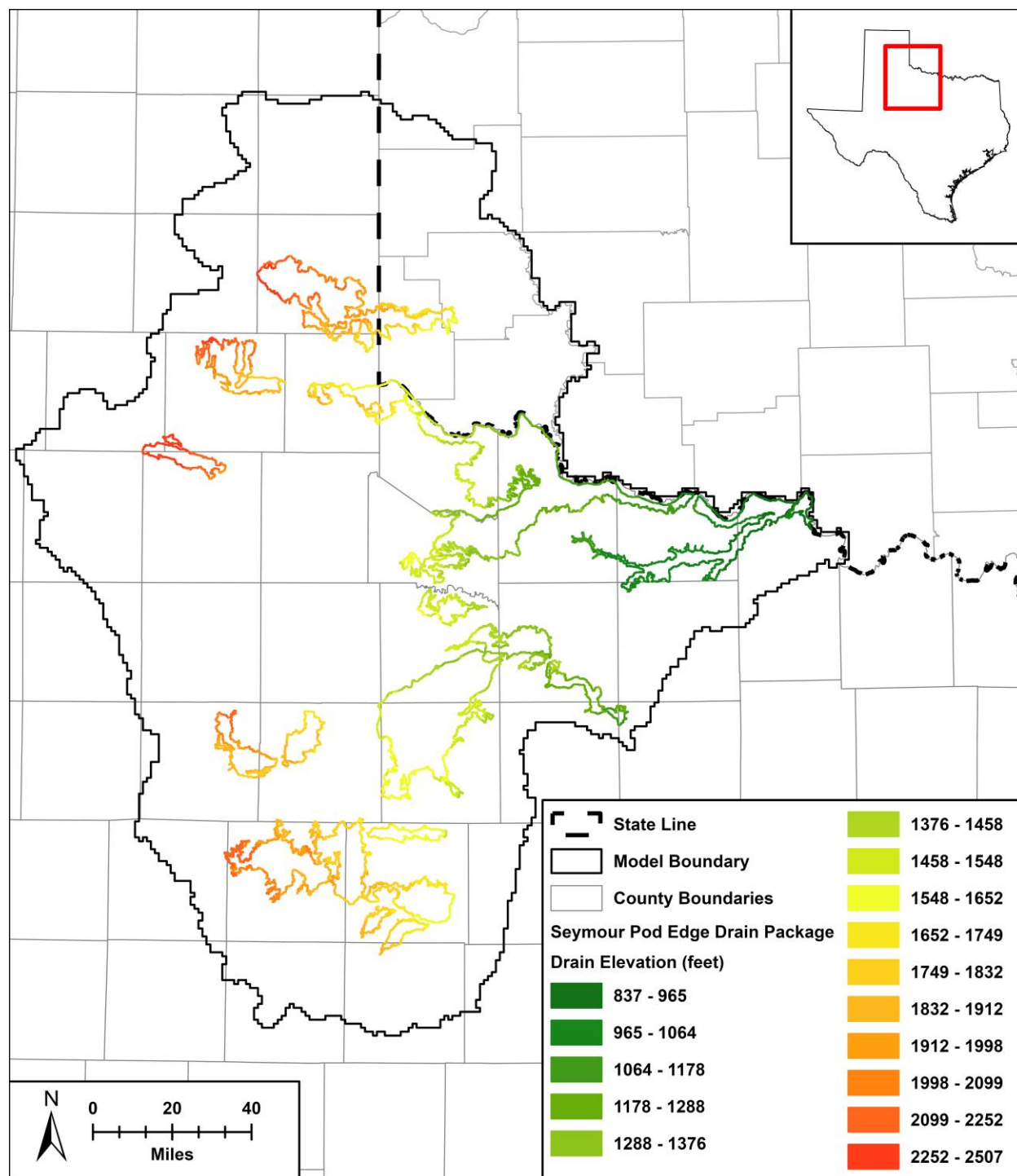


Figure 4.11-5. Location of drain package cells representing Seymour pod perimeter edge drains included as additional representation of seeps.

4.12 General-head boundary package

The MODFLOW general-head boundary (GHB) package was utilized in the updated groundwater availability model. The general-head boundary package was constructed explicitly from the High Plains Aquifer Groundwater Availability Model. The High Plains Aquifer groundwater availability model was originally developed in 2015 (Deeds and Jigmond, 2015), but was recently updated by the Texas Water Development Board to extend the simulated time of the model forward to understand more recent system dynamics (Cawthon and Wade, 2025). As described previously in the conceptual modeling section (Chapter 3), spring flows and recharge from hydrogeologic units overlying the Permian hydrostratigraphic units primarily in the western, but also northern and southern extents of the groundwater availability model update, are important contributions to the water budget.

General head boundaries were defined in the groundwater availability model update for the Seymour and Blaine groundwater availability model where the Ogallala Aquifer to the western and northern extents overlapped with the High Plains Aquifer groundwater availability model and where the Edwards-Trinity (Plateau) overlapped in the southern extent. Each of these three-(3) footprints were developed as separate general-head boundary packages to improve tracking of inflows and outflows, respectively. The general-head boundary package explicitly defines head and conductance values for each model cell. The head definitions for all cells in the groundwater availability model update were temporally variable on an annual basis and defined based on the simulated heads directly from the High Plains Aquifer groundwater availability model update (Cawthon and Wade, 2025). The conductance was defined by an initial calculation using the initial vertical hydraulic conductivity of the underlying Permian hydrogeologic unit, the model cell width and length, and an assumed representative thickness of 1 foot. This assumption was merely a starting point as the conductance was indirectly calibrated during the automated calibration process. The vertical conductivity used in the general-head boundary conductance calculation was directly tied to the calibrated vertical hydraulic conductivity of the underlying Permian unit.

The described overlap of the Ogallala and Edwards-Trinity (Plateau) modeled footprints in the High Plains Aquifer groundwater availability model with the model extent in the groundwater availability model update, along with some cross-sections to highlight simulated water levels in the updated High Plains Aquifer groundwater availability model from 2020, is provided in Figure 4.12-1.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

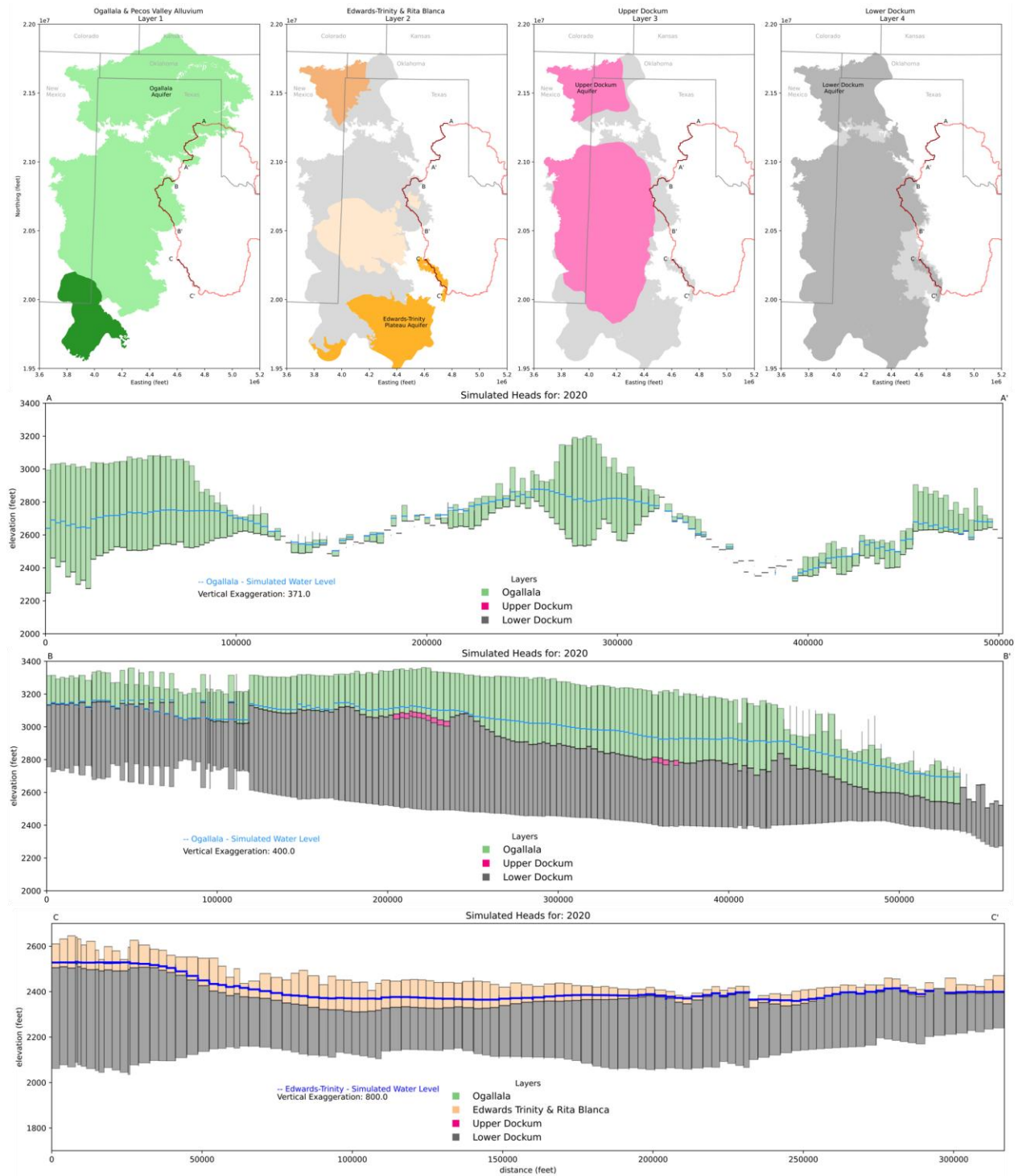


Figure 4.12-1. Overlap of the Ogallala and Edwards-Trinity (Plateau) Aquifer footprints in the High Plains Aquifer groundwater availability model (Deeds and Jigmond, 2015; Cawthon and Wade, 2025) with the Seymour and Blaine groundwater availability model extent in red (top panel) and cross-sections of 2020 simulated water levels in the updated High Plains Aquifer Groundwater Availability Model.

The modeled extent of the general head boundaries in the groundwater availability model update is shown in Figure 4.12-2. Where the Ogallala Aquifer overlies the Permian hydrostratigraphic units in the groundwater availability model update, the Ogallala simulated heads were used from the updated High Plains Aquifer System Groundwater Availability Model, and Edwards-Trinity (Plateau) simulated heads were used where it overlies Permian hydrostratigraphic units. The outcropping Permian hydrostratigraphic unit in the groundwater availability model update was used for the definition of the general head boundaries. At locations where both general head boundary cells and drain cells representing ephemeral and intermittent streams—or river cells representing perennial streams and rivers—could be defined, the general head boundary footprint was updated not to conflict with the existing boundary conditions.

Texas Water Development Board Contract Number 2448302843
 Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

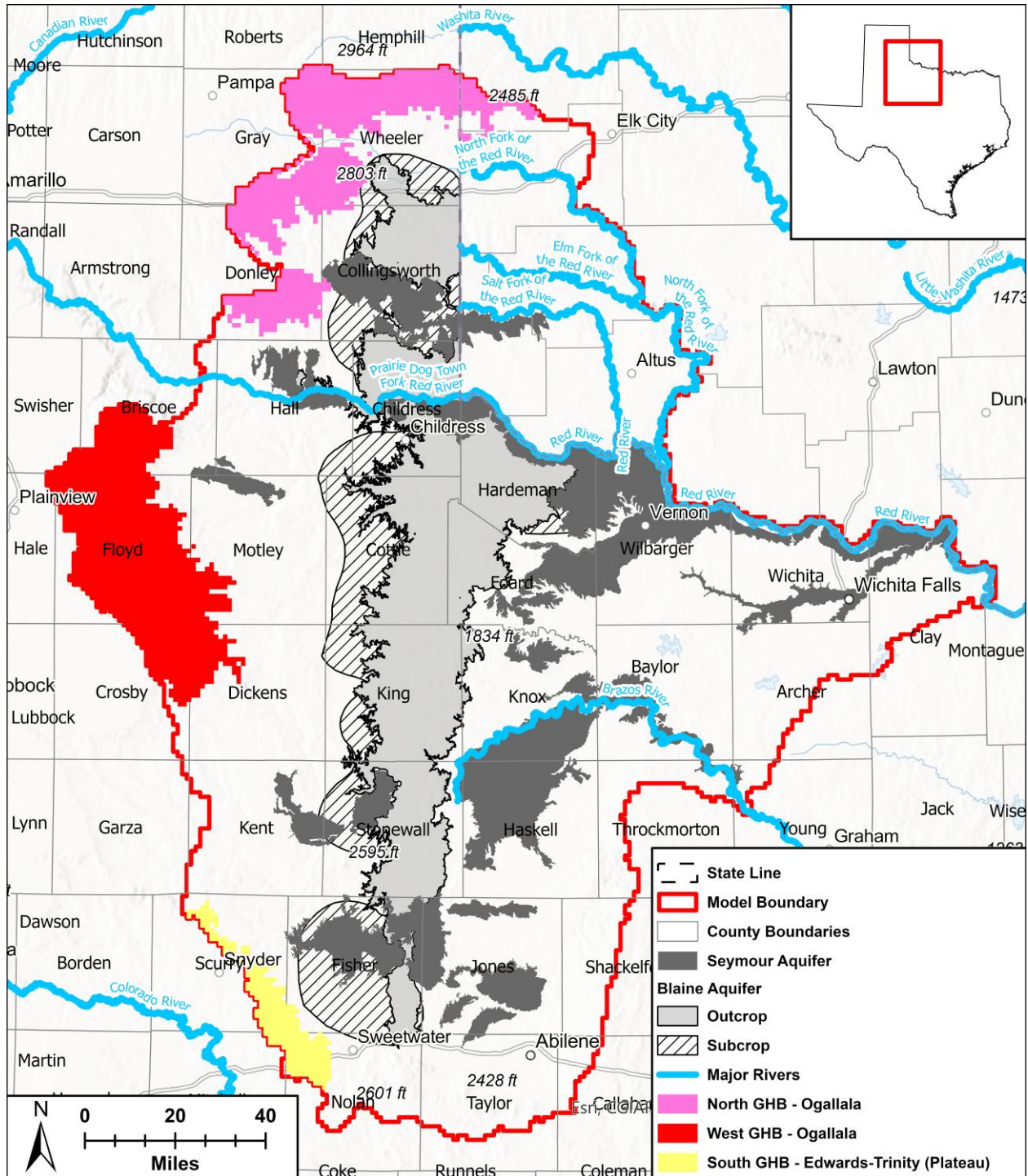


Figure 4.12-2. Modeled extent of the general head boundaries (GHB) in the groundwater availability model update.

4.13 Recharge package

The MODFLOW recharge (RCH) package was used to simulate groundwater recharge in the model (Table 4-2). The initial recharge estimates for all model layers with model cells (nodes) exposed at ground surface were informed by multiple different data sources. The initial model recharge estimates for all layers were subsequently refined during model calibration in both spatial distribution and magnitude. The data sources that informed the initial recharge estimates include: (1) annual precipitation estimates for the model domain from Parameter-elevation Regressions on Independent Slopes Model (PRISM) developed by the PRISM Climate Group at Oregon State University (PRISM Climate Group, 2025), (2) previous groundwater availability model steady-state recharge rates developed in Ewing and others (2004) and Jigmond and others (2014), (3) recharge rates described in Section 3.5, specifically in Table 3-2, and (4) preliminary steady-state model runs and iterating on initial hydraulic parameters and spatial recharge distribution to keep the Seymour formation aquifer sediments saturated and minimally flooded. This iteration included a supplemental routine applied along the lateral margins of the Seymour Aquifer pods, where the digitized aquifer boundary and the 10-meter digital elevation model are locally inconsistent; recharge in these cells was assigned at the rate required to maintain saturation. The annual recharge estimates from the PRISM dataset for years 1980 to 2023 were developed from monthly precipitation records. The average spatial distribution of precipitation over this 43-year period, shown in Figure 2.3-9, serves as a reference to constrain reasonable steady-state recharge estimates as model calibration progresses.

Initial groundwater recharge rates for the steady-state period to be refined during model calibration for model layer 1 representing the Seymour Aquifer formation sediments are shown in Figure 4.13-1. Initial groundwater recharge rates for the steady-state period to be refined during model calibration for model layers 2, 3, and 4 representing the Permian-age formation sediments are shown in Figure 4.13-2. Note the higher relative groundwater recharge in the Seymour formation aquifer sediments as compared to the surrounding Permian-age formation sediments. This is consistent with the conceptual understanding of recharge for these different hydrostratigraphic units as described in the literature.

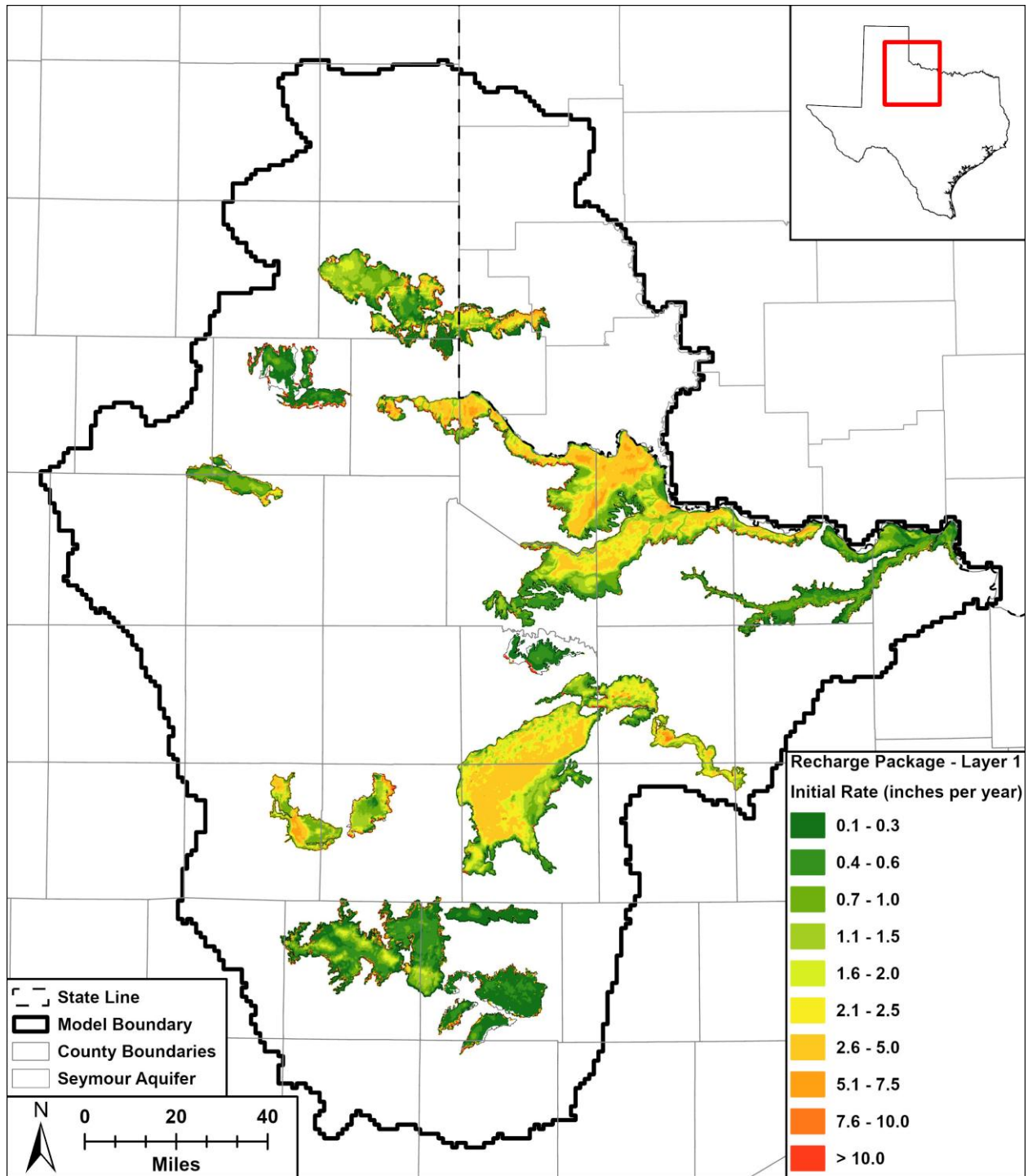


Figure 4.13-1. Initial model recharge values in inches per year in the recharge model package for model layer 1 representing the Seymour formation aquifer sediments.

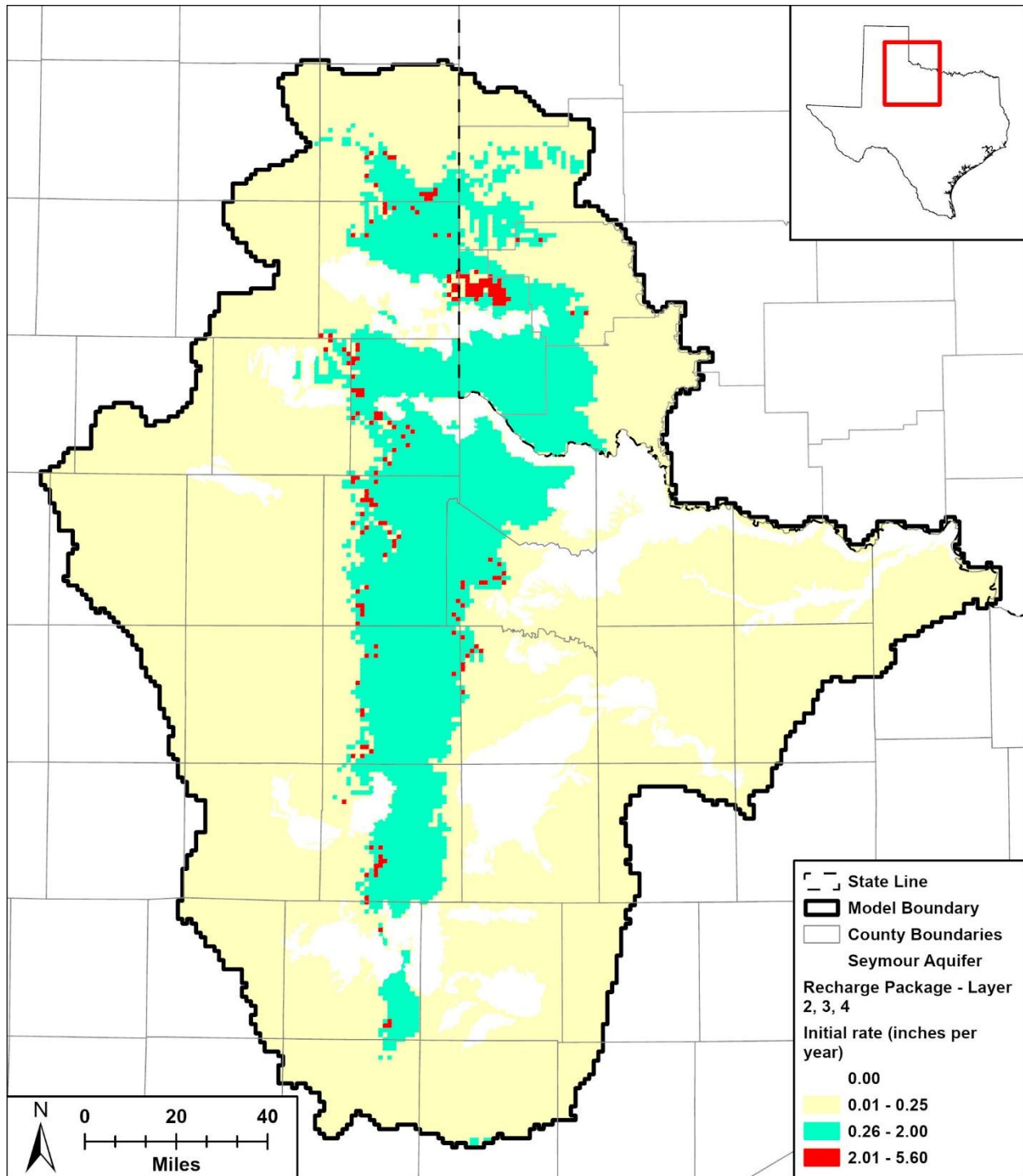


Figure 4.13-2. Initial model recharge values in inches per year in the recharge model package for model layers 2, 3, and 4 representing the Permian-age hydrostratigraphic units.

4.14 River package

The MODFLOW river (RIV) package was used to simulate the exchange of groundwater with major (perennial) rivers and reservoirs within the model. Unlike the drain package used for relatively smaller, intermittent streams and creeks, the river package allows both recharge and discharge to/from surface water. Perennial streams flow continuously throughout the year, fed by groundwater and/or consistent surface runoff.

As an initial starting point to be refined during model calibration, a stream order of six or greater for the streams and rivers defined in the National Hydrography Dataset Plus High Resolution was used as the delineation for the base river package as shown in Figure 4.11-2. Anthropogenic structures were filtered out of the river package delineation, specifically feature codes of 33601, representing canals and ditches, and 42813, representing pipelines. Initial bed conductance for the river package was calculated using the channel lengths available from the National Hydrography Dataset Plus High Resolution for each individual river cell representing rivers and streams. Values for the hydraulic conductivity for the bed, stream width, bed thickness, and stream length were assumed to estimate a reasonable bed conductance. Hydraulic conductivity of the streambed will be refined during model calibration. The river package bed-top elevations correspond to the ground surface elevation of the grid. United States Geological Survey high-resolution (10-meter) surface elevation data were used to define elevations for the riverbed-top with minimum elevations, calculated at the grid cell level. By adjusting river package locations and conductance values during model calibration, the model effectively prevents flooding and ensures a realistic representation of the groundwater system. The number of grid cells (nodes) in the model for the river model package is 5,033. There are 3,202 of those cells (nodes) in layer 1 within the Seymour formation active sediments and there are 1,831 cells (nodes) in layers 2, 3, and 4 within the Permian-age hydrostratigraphic units. The model cells (nodes) included in the river model package and the included boundary condition elevations are shown in Figure 4.14-1. The package definitions are not temporally variable.

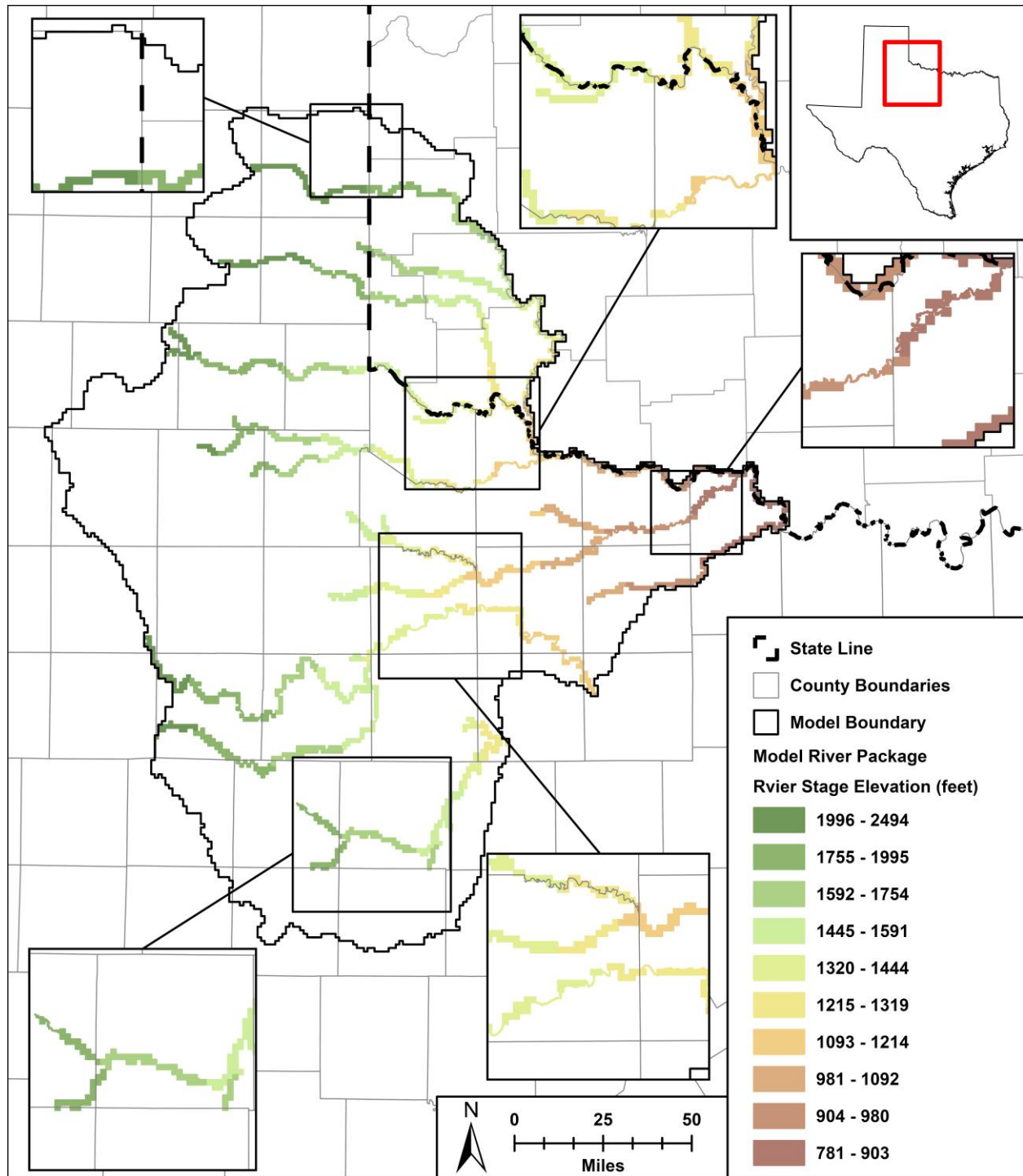


Figure 4.14-1. Location of river package cells in the model domain.

4.15 Evapotranspiration package

The evapotranspiration (ET) package was not included in the updated groundwater availability model for the Seymour and Blaine aquifer system. Hydraulics that could be represented with the evapotranspiration package are considered in other model boundary conditions (e.g., riparian evapotranspiration is represented in the cells with river and drain boundary conditions) for efficiency and reasonable model run times.

4.16 Output control file

The MODFLOW output control (OC) package determines when water level and water budget information are saved to disk during the simulation. In this setup, the output control file is configured to save these results at the end of each stress period, specifically at the end of the pre-development period and annually from 1960 to 2080. The output control file will be structured to save cell-by-cell flux and heads for each model stress period. When multiple timesteps exist within a transient stress period, the final timestep cell-by-cell flux and head information will be saved. Budget files will be saved in the non-compact format.

4.17 Solver

The MODFLOW 6 iterative model solution (IMS) package was used to solve the system of groundwater equations that determine the hydraulic head at each node. For this simulation, the Newton-Raphson linearization scheme was employed due to its robustness and effectiveness in handling the complexities that arise from drying and rewetting portions of the simulation domain (Langevin and others, 2017).

The solver parameters were generally set according to the recommendations for moderately complex problems as described in the MODFLOW 6 input/output manual (Langevin and others, 2017). The biconjugate gradient stabilized (BiCGSTAB) linear accelerator was utilized to solve the system of equations, whether symmetric systems arising from confined flow or asymmetric systems from the Newton-Raphson formulation for unconfined flow.

The solver complexity was set to COMPLEX for the model. The nonlinear (outer) head closure criterion for convergence was set to an outer maximum number of iterations of 2500. The linear (inner) head change criterion for convergence was set to 0.25 foot with an inner maximum of 2500 iterations. The residual closure criterion of 0.1 cubic feet per day and linear (outer) head change criterion for convergence of 0.001 feet were not modified from default values. These solver criteria settings will be refined during model calibration. Relaxation of the solver criteria may be necessary due to the complexities of keeping the saturated portions of the Seymour Aquifer saturated in the model.

4.18 Observation utility

The observation (OBS) utility in MODFLOW 6 allows selected simulated values to be written to output files at each time step, making them readily available for post-processing without reading the binary model output. The model includes four

observation packages: one tracking simulated hydraulic heads at monitoring well locations, and one for each of the three general-head boundary packages (Edwards-Trinity (Plateau), Ogallala North, and Ogallala West) tracking simulated boundary flows, written to "sb_edtrfp.ghb.obs.output.csv," "sb_ogfp_north.ghb.obs.output.csv," and "sb_ogfp_west.ghb.obs.output.csv," respectively. All packages utilizing the OBS utility are detailed in Table 4-3.

The head observations are written to "sb.head.obs.output.csv" and were intentionally built from the complete compiled water-level dataset, prior to calibration-target screening, so that simulated hydrographs are available at every well with a measured water level. The file therefore reports simulated heads at 3,369 well locations: the 3,190 weighted head-target locations (2,400 in the Seymour Aquifer and 790 in the Blaine Aquifer), 137 wells excluded from calibration because their measured water levels fall below the model bottom, and 42 wells whose measurements could not be assigned to an annual model stress period — either because they post-date the calibration period or because the well's only measurement falls more than six months from the nearest stress-period date. Simulated heads at spring target locations are not included in this file; spring heads are evaluated from the spring drain package budget output.

5 Model calibration and results

Most groundwater availability models are numerical models designed to simulate steady-state conditions before development, transient conditions post-anthropogenic development, and predictive future scenarios for groundwater planning purposes. Historically, most groundwater availability models have been developed using a standard approach that typically involves the following steps:

1. Develop a conceptual model incorporating key features, events, and processes.
2. Construct a numerical model based on the conceptual framework.
3. Calibrate the model by adjusting parameters to minimize the misfit between model outputs and historical observations.
4. Use the calibrated parameters in the predictive model to generate a single estimate of future groundwater system conditions.

This standard method produces a single set of simulation results to represent possible future groundwater system conditions, but it does not provide a measure of reliability in that estimate. Even though ad hoc sensitivity analyses may be conducted by changing parameter values to evaluate how predictions respond to uncertainty in key parameters, this process does not give an explicit estimate of prediction uncertainty, nor does it respect the plausible range of post-calibration parameter values or the correlation between post-calibration parameter values. Given the significant uncertainties in the Seymour and Blaine groundwater system, discussed in previous sections and summarized in the Model Limitations (Chapter 7), it becomes challenging for decision makers to assess the reliability of a single prediction made by a calibrated groundwater model. This limitation reduces the value of modeling to support decision-making related to groundwater resource planning in Texas (Doherty and Moore, 2020).

In developing the Seymour and Blaine groundwater availability model, INTERA followed the standard workflow but incorporated a probabilistic approach to account better for uncertainty. The probabilistic approach is based on a Bayesian framework, where probable but uncalibrated parameter fields are updated with observed data to improve parameter distributions to estimate current conditions and predictive uncertainty. Bayes' Theorem is a fundamental principle in probability theory that describes how to update the probability of a hypothesis, i.e., parameter set, based on new evidence (Bayes, 1763; Bishop, 2006). Mathematically, it is expressed in Equation 5-1 as:

$$P(\theta|D) = \frac{P(D|\theta)P(\theta)}{P(D)} \quad (\text{Equation 5-1})$$

where:

$P(\theta|D)$ = is the posterior probability of the model parameters (θ) given the observed data D

$P(D|\theta)$ = is the likelihood, representing the probability of observing D given a specific model parameter θ

$P(\theta)$ = is the prior probability of model parameters, θ , based on previous knowledge or assumptions

$P(D)$ = is the marginal likelihood, ensuring proper normalization

The additional steps in this probabilistic approach are outlined below and discussed in detail in the following subsections:

1. Construct a numerical model based on the conceptual framework:
 - Parameterize model inputs to represent known sources of uncertainty explicitly in the calibration process; parameterization used a combination of observed data and conceptual understanding.
 - Develop statistical parameter distributions that describe the plausible range of model inputs and the expected correlation between these inputs using geostatistics, collectively referred to as the “Prior.”
 - Generate/draw an ensemble of uncalibrated parameter sets (referred to as “the Prior parameter ensemble”) using the defined parameter values and distributions.
 - Evaluate the prior parameter ensemble by running each parameter set in the ensemble through the MODFLOW 6 Groundwater Flow model.
 - Adjust the parameterization and/or Prior so that the simulation results from the prior parameter ensemble better align with the observed groundwater system states.
2. Calibrate the model to historical groundwater system state observations:
 - Apply an iterative algorithm to the Prior ensemble, which adjusts the parameter sets to minimize the misfit between the historical groundwater level observations and corresponding simulated quantity while also respecting conceptual information. This process yields an updated, history-matched parameter ensemble known as “the Posterior” parameter ensemble, where each parameter set in this ensemble acceptably reproduces historical groundwater level observations when evaluated in the Groundwater Flow model.
 - The Posterior parameter ensemble was refined further by evaluating each parameter set’s model fit, ensuring each parameter set contained values

were reasonable, and confirming that the resulting model's behavior aligned with the conceptual model.

3. Simulate future groundwater conditions:

- Models are often structured with the final stress period aligning with the end of history matching, while predictive runs are conducted separately using initial conditions from the last or averaged final stress periods. Here, we include a 60-year predictive period (2021 – 2080), transitioning directly from history matching (1960-2020) in one continuous model run. The predictive period is developed from average conditions of the last five-(5) years (2016 – 2020), estimated from the history matching. The predictive period does not inform calibration; it serves as a quality assurance check to ensure predictive trends remain consistent with historical behavior under average conditions.

This probabilistic approach resulted in an ensemble of calibrated models (arising from the Posterior parameter ensemble), where each calibrated model reflects different assumptions and has distinct parameter values and varies in how closely they match observed characteristics of the aquifers. From this ensemble, INTERA selected the single model that aligned with the conceptual model and represented the median of the posterior distribution as the groundwater availability model to be used as the baseline for regional planning, such that this model is centered with respect to parameter uncertainty.

To execute this probabilistic approach, INTERA utilized PESTPP, a suite of programs that retains much of PEST's original functionality while adding the capability to incorporate known sources of uncertainty explicitly within the history matching process. Specifically, INTERA leveraged the PESTPP Iterative Ensemble Smoother for history matching (Section 5.2). This tool enables model inputs to be sampled randomly based on probability distribution functions informed by data and expert knowledge for each parameter defined in the Prior.

The following subsections describe (1) the calibration procedure INTERA used to generate a prior ensemble of plausible but uncalibrated models and (2) how that prior ensemble was transformed into a posterior ensemble of calibrated models and the process for selecting a single model from this ensemble to represent the Seymour and Blaine groundwater availability model.

5.1 Model parameterization and the prior

The numerical groundwater availability model developed in this update builds upon and expands on the frameworks previously developed in the groundwater availability model for the Seymour Aquifer system developed by Ewing and others (2004); a conceptual and numerical model refinement developed in Jones and others (2012) and Jigmond and others (2014) for the Seymour Aquifer in Haskell, Knox and Baylor counties; and a Brackish Aquifer Characterization Study for the Blaine Aquifer in North-Central Texas developed by Finch and others (2016). These reports provided

the conceptual framework and much of the data used to inform prior parameter distributions, as well as to account for the expected variability inherent in the data.

In the steps outlined in the previous section, defining the Prior parameter distribution is one of the most critical steps, and, when done effectively, the history-matching process becomes more of a refinement or "polishing" step. The Python package pyEMU was used to create a PESTPP control file, along with the necessary model interface files.

Adjustable parameters were defined to include recognized sources of uncertainty in the input datasets to the MODFLOW 6 Groundwater Flow Model. The parameters were conceptualized as multipliers applied to the initial model input datasets. In this way, the values in the initial MODFLOW 6 Groundwater Flow model are preserved, and the quantities that are estimated during calibration are departures from these initial datasets. The upper and lower bounds for these adjustable parameters are a key part of the Prior parameter distribution and reflect the expected uncertainty of the underlying model properties at various spatial and temporal scales. These adjustable parameters are shown in Table 5-1 through Table 5-8, along with their types, bounds, and initial values.

Adjustable parameters in the Seymour and Blaine groundwater availability model are parameterized using two distinct adjustment types: constant and pilot point. Each type serves a unique role in defining how parameter values are distributed and varied across the model domain:

- **Constant:** This adjustment type is straightforward and ideal when a uniform adjustment is needed for the entire model, a specific layer, or a boundary condition. A constant parameter can be thought of as a way to shift the mean of the entire property. Constants can be assigned as either multipliers or additive scalars. Multipliers scale values by a fixed factor (e.g., doubling or halving), while additive scalars shift values up or down by a constant amount. Constant multipliers were applied to nearly every adjustable parameter, effectively scaling properties when the most probable value significantly deviated from initial values.
- **Pilot Points:** This adjustment type uses a set of uniformly spaced points to create a spatially variable, continuous field for parameter distribution at a spatial scale greater than the grid resolution of the model. In essence, pilot points allow us to represent broad-scale heterogeneity explicitly. Pilot points allow flexibility in modeling heterogeneity by enabling parameter values to vary continuously between defined locations. The spatial correlation of these points is governed by a geostatistical structure, which ensures that the parameter field respects expected spatial continuity. Pilot points are particularly effective when prior knowledge of the study area's spatial variability can inform the parameter distribution, adding a layer of expert-guided refinement to the model.

Parameterization type is fairly consistent for a parameter group across all layers of the model with the exception of layer 1 representing the Seymour Aquifer. To align

the numerical model with the conceptual understanding of the system better, layer 1 was parametrized on a pod-by-pod basis to more accurately represent hydrogeologic variability.

As shown in Table 5-1 through Table 5-8, adjustable parameters generally use one or both of the adjustment types. This approach offers flexibility to capture parameter variability while applying control through specified lower and upper bounds, as well as ultimate lower and upper bounds listed in Table 5-1 through Table 5-8. The lower and upper bounds constrain the constant and pilot point multipliers, while the ultimate bounds define the minimum and maximum allowable values for the actual parameter. These constraints ensure that parameters remain within realistic ranges.

Using the specified parameter bounds and geostatistical information, a parameter ensemble of 70 unique parameter sets (or “realizations”) was drawn, which collectively formed the prior parameter ensemble. These realizations were sampled such that they respect the set parameter bounds and have patterns of spatial heterogeneity that are not implausible. However, each realization in the prior parameter ensemble is “uncalibrated” in that, when evaluated with the Groundwater Flow model, the resulting groundwater levels do not honor the historic groundwater level observations very well. This approach assesses uncertainties in model parameters and outputs within a Bayesian uncertainty framework (Fienen and others, 2013), requiring a Prior informed by expert knowledge and prior modeling results. Model outputs from the Prior were then evaluated and compared to provide insights into model behavior and parameter sensitivities before moving into history matching.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

**Table 5-1. Parameter information for defining prior parameter distributions of Horizontal Hydraulic Conductivity (feet per day).
Constant Multiplier = CN, Pilot Point Multiplier = PP.**

Hydro-stratigraphic Unit	Pod / Layer	PP	CN	PP Spacing (feet)	PP Lower Bound	PP Upper Bound	CN Lower Bound	CN Upper Bound	Ultimate Lower Bound	Ultimate Upper Bound	Minimum Initial Value	Maximum Initial Value
Seymour	1 / 1	x	x	10,560	0.31	3.33	0.5	2	0.465	199.8	3	30
Seymour	2 / 1	x	x	10,560	0.31	3.33	0.5	2	3.1	1,332	20	200
Seymour	3 / 1	x	x	10,560	0.31	3.33	0.5	2	0.155	66.6	1	10
Seymour	4 / 1	x	x	10,560	0.31	3.33	0.5	2	0.93	399.6	6	60
Seymour	5 / 1	x	x	10,560	0.31	3.33	0.5	2	0.465	199.8	3	30
Seymour	6 / 1	x	x	10,560	0.15	5	0.25	4	1.125	6000	30	300
Seymour	7 / 1	x	x	10,560	0.31	3.33	0.5	2	4.65	1998	30	300
Seymour	8 / 1	x	x	10,560	0.15	5	0.25	6	0.0375	300	1	10
Seymour	9 / 1	x	x	10,560	0.31	3.33	0.5	2	0.2325	99.9	1.5	15
Seymour	10 / 1	x	x	10,560	0.15	5	0.25	4	0.1875	1000	5	50
Seymour	11 / 1	x	x	10,560	0.31	3.33	0.5	2	0.775	333	5	50
Seymour	12 / 1	x	x	10,560	0.31	3.33	0.5	2	0.775	333	5	50
Seymour	13 / 1	x	x	10,560	0.31	3.33	0.5	2	0.775	333	5	50
Seymour	14 / 1	x	x	10,560	0.31	3.33	0.5	2	0.775	333	5	50
Seymour	15 / 1	x	x	10,560	0.31	3.33	0.5	2	0.775	333	5	50
Whitehorse and Younger	- / 2	x	x	52,800	0.31	3.33	0.5	2	0.248	10.656	1.6	1.6
Blaine	- / 3	x	x	52,800	0.31	3.33	0.5	2	0.713	30.636	4.6	4.6
Flowerpot and Older	- / 4	x	x	52,800	0.31	3.33	0.5	2	0.155	6.66	1	1

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

**Table 5-2. Parameter information for defining prior parameter distributions of Vertical Hydraulic Conductivity (feet per day).
Constant Multiplier = CN, Pilot Point Multiplier = PP.**

Hydro-stratigraphic Unit	Pod / Layer	PP	CN	PP Spacing (feet)	PP Lower Bound	PP Upper Bound	CN Lower Bound	CN Upper Bound	Ultimate Lower Bound	Ultimate Upper Bound	Minimum Initial Value	Maximum Initial Value
Seymour	1 / 1	x	x	10,560	0.5	2	0.625	1.5	0.000155	0.0666	0.001	0.01
Seymour	2 / 1	x	x	10,560	0.5	2	0.625	1.5	0.0010338 5	0.444222	0.00667	0.0667
Seymour	3 / 1	x	x	10,560	0.5	2	0.625	1.5	0.000051615	0.0221778	0.000333	0.00333
Seymour	4 / 1	x	x	10,560	0.5	2	0.625	1.5	0.00031	0.1332	0.002	0.02
Seymour	5 / 1	x	x	10,560	0.5	2	0.625	1.5	0.000155	0.0666	0.001	0.01
Seymour	6 / 1	x	x	10,560	0.5	2	0.625	1.5	0.000375	2	0.01	0.1
Seymour	7 / 1	x	x	10,560	0.5	2	0.625	1.5	0.00155	0.666	0.01	0.1
Seymour	8 / 1	x	x	10,560	0.5	2	0.625	1.5	1.25E-05	0.0666	0.000333	0.00333
Seymour	9 / 1	x	x	10,560	0.5	2	0.625	1.5	0.0000775	0.0333	0.0005	0.005
Seymour	10 / 1	x	x	10,560	0.5	2	0.625	1.5	6.25E-05	0.3334	0.001667	0.01667
Seymour	11 / 1	x	x	10,560	0.5	2	0.625	1.5	0.000258385	0.1110222	0.001667	0.01667
Seymour	12 / 1	x	x	10,560	0.5	2	0.625	1.5	0.000258385	0.1110222	0.001667	0.01667
Seymour	13 / 1	x	x	10,560	0.5	2	0.625	1.5	0.000258385	0.1110222	0.001667	0.01667
Seymour	14 / 1	x	x	10,560	0.5	2	0.625	1.5	0.000258385	0.1110222	0.001667	0.01667
Seymour	15 / 1	x	x	10,560	0.5	2	0.625	1.5	0.000258385	0.1110222	0.001667	0.01667
Whitehorse and Younger	- / 2	x	x	52,800	0.5	2	0.625	1.5	8.27E-05	0.003551998	0.000533333	0.000533333
Blaine	- / 3	x	x	52,800	0.5	2	0.625	1.5	0.000237615	0.01020978	0.001533	0.001533
Flowerpot and Older	- / 4	x	x	52,800	0.5	2	0.625	1.5	0.000051615	0.00221778	0.000333	0.000333

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Table 5-3. Parameter information for defining prior parameter distributions of Specific Yield (-). Constant Multiplier = CN, Pilot Point Multiplier = PP.

Hydro-stratigraphic Unit	Pod / Layer	PP	CN	PP Spacing (feet)	PP Lower Bound	PP Upper Bound	CN Lower Bound	CN Upper Bound	Ultimate Lower Bound	Ultimate Upper Bound	Minimum Initial Value	Maximum Initial Value
Seymour	1 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.01	0.22	0.14	0.14
Seymour	2 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.01	0.22	0.14	0.14
Seymour	3 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.01	0.22	0.14	0.14
Seymour	4 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.01	0.22	0.14	0.14
Seymour	5 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.01	0.22	0.14	0.14
Seymour	6 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.01	0.22	0.14	0.14
Seymour	7 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.01	0.22	0.14	0.14
Seymour	8 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.01	0.22	0.14	0.14
Seymour	9 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.1	0.22	0.14	0.14
Seymour	10 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.01	0.22	0.14	0.14
Seymour	11 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.01	0.22	0.14	0.14
Seymour	12 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.01	0.22	0.14	0.14
Seymour	13 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.01	0.22	0.14	0.14
Seymour	14 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.01	0.22	0.14	0.14
Seymour	15 / 1	x	x	10,560	0.31	3.33	0.25	1.25	0.01	0.22	0.14	0.14
Whitehorse and Younger	- / 2	x	x	52,800	0.31	3.33	0.25	1.25	0.01	0.22	0.15	0.15
Blaine	- / 3	x	x	52,800	0.31	3.33	0.25	1.25	0.01	0.22	0.15	0.15
Flowerpot and Older	- / 4	x	x	52,800	0.31	3.33	0.25	1.25	0.01	0.22	0.15	0.15

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Table 5-4. Parameter information for defining prior parameter distributions of Storativity (-). Constant Multiplier = CN, Pilot Point Multiplier = PP.

Hydro-stratigraphic Unit	Pod / Layer	PP	CN	PP Spacing (feet)	PP Lower Bound	PP Upper Bound	CN Lower Bound	CN Upper Bound	Ultimate Lower Bound	Ultimate Upper Bound	Minimum Initial Value	Maximum Initial Value
Whitehorse and Younger	- / 2	x	x	52,800	0.1	10	0.25	4	4.88E-06	0.22	0.00019506	0.0060627
Blaine	- / 3	x	x	52,800	0.1	10	0.25	4	1.25E-06	0.22	0.00005	0.005379
Flowerpot and Older	- / 4	x	x	52,800	0.1	10	0.25	4	5.00E-06	0.22	0.0002	0.0050991

Table 5-5. Parameter information for defining prior parameter distributions of River Conductance (feet squared per day). Constant Multiplier = CN, Pilot Point Multiplier = PP.

Hydro-stratigraphic Unit	Package / Layer	PP	CN	PP Spacing (feet)	PP Lower Bound	PP Upper Bound	CN Lower Bound	CN Upper Bound	Ultimate Lower Bound	Ultimate Upper Bound	Minimum Initial Value	Maximum Initial Value
Seymour	RIV / 1	x	x	10,560	0.2	10	0.5	5	3.603	1,252,508.5	36.03	25,050.17
Whitehorse and Younger	RIV / 2	x	x	52,800	0.2	10	0.5	5	79.865	32,112,044.5	798.65	642,240.89
Blaine	RIV / 3	x	x	52,800	0.2	10	0.5	5	1,731.47	25,146,155	17,314.7	502,923.1
Flowerpot & Older	RIV / 4	x	x	52,800	0.2	10	0.5	5	192.921	19,793,129	1,929.21	395,862.58

Table 5-6. Parameter information for defining prior parameter distributions of Streams Drain Conductance (feet squared per day). Constant Multiplier = CN, Pilot Point Multiplier = PP.

Hydro-stratigraphic Unit	Package / Layer	PP	CN	PP Spacing (feet)	PP Lower Bound	PP Upper Bound	CN Lower Bound	CN Upper Bound	Ultimate Lower Bound	Ultimate Upper Bound	Minimum Initial Value	Maximum Initial Value
Seymour	DRN / 1	x	x	10,560	0.2	10	0.5	5	0.144	1,376,558	1.44	27,531.16
Whitehorse and Younger	DRN / 2	x	x	52,800	0.2	10	0.5	5	0.417	22,190,055.5	4.17	443,801.11
Blaine	DRN / 3	x	x	52,800	0.2	10	0.5	5	21.519	14,358,560.5	215.19	287,171.21
Flowerpot and Older	DRN / 4	x	x	52,800	0.2	10	0.5	5	0.731	19,206,496.5	7.31	384,129.93

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Table 5-7. Parameter information for defining prior parameter distributions of Recharge (feet per day). Constant Multiplier = CN, Pilot Point Multiplier = PP, Steady-State = SS, Transient = TR.

Description	Pod / Layer	PP	CN	PP Spacing feet	PP Lower Bound	PP Upper Bound	CN Lower Bound	CN Upper Bound	Ultimate Lower Bound	Ultimate Upper Bound	Minimum Initial Value	Maximum Initial Value
SS Dampening Factor (-)	1-15 / 1-4		x				1.00E-06	1	1.00E-06	1	1	1
TR Dampening Factor (-)	1-15 / 1-4		x				0.1	4	0.25	1	0.25	0.25
SS Recharge Factor (-)	1 / 1		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	2 / 1		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	3 / 1		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	4 / 1		x				0.5	2	0.5	2	1	1
SS Recharge Factor (-)	5 / 1		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	6 / 1		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	7 / 1		x				0.5	2	0.5	2	1	1
SS Recharge Factor (-)	8 / 1		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	9 / 1		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	10 / 1		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	11 / 1		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	12 / 1		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	13 / 1		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	14 / 1		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	15 / 1		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	- / 2		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	- / 3		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge Factor (-)	- / 4		x				0.666667	1.5	0.666667	1.5	1	1
SS Recharge (ft per day)	- / 2	x	x	52,800	0.31	3.33	0.25	5	1.00E-08	1.00E-02	7.13E-07	4.56E-05
SS Recharge (ft per day)	- / 3	x	x	52,800	0.31	3.33	0.25	5	1.00E-08	1.00E-02	1.35E-06	8.67E-05
SS Recharge (ft per day)	- / 4	x	x	52,800	0.31	3.33	0.25	5	1.00E-08	1.00E-02	7.13E-07	4.56E-05

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Table 5-8. Parameter information for defining prior parameter distributions of Pumping. Constant Multiplier = CN. Pumping parameter information ranges for pod and layer combinations defined with unique temporal configurations and bounds to reflect pod-specific data considerations (as described in Section 5.3.1, Pumping). Pod / Layer: 1-15 Seymour pods / 2-4 Permian Layers, Layer 2 = Whitehorse and Younger, Layer 3 = Blaine.

Description	Pod / Layer	Temporal Discretization	CN	Time Period Start	Time Period End	Temporal Correlation Length (Years)	CN Lower Bound	CN Upper Bound	Initial Value
Irrigation Factor (-)	1-2,4-5, 7-8, 11-15 / 3	Annual	x	1960	1975	15	0.5	1.4	1
Irrigation Factor (-)	1-2,4-5, 7-8, 11-15 / 3	Annual	x	1976	2020	15	0.75	1.25	1
Irrigation Factor (-)	3 / -	Annual	x	1960	1975	15	1	1.4	1
Irrigation Factor (-)	3 / -	Annual	x	1976	2020	15	1	1.25	1
Irrigation Factor (-)	9 / -	Annual	x	1960	1969	15	1	1.5	1.25
Irrigation Factor (-)	9 / -	Annual	x	1970	1975	15	0.4	1.5	1.0
Irrigation Factor (-)	9 / -	Annual	x	1976	2000	15	0.25	1.5	0.8
Irrigation Factor (-)	9 / -	Annual	x	2001	2020	15	0.75	1.25	1
Irrigation Factor (-)	6,10 / -	Annual	x	1960	2020	15	0.5	1.5	1
Metered Factor (-)	1,2,3,4,7 / 2,3	Annual	x	2004	2020	15	0.85	1.15	1
Municipal Factor (-)	1-15 / 3	Annual	x	1960	1975	15	0.5	1.4	1
Municipal Factor (-)	1-15 / 3	Annual	x	1976	2020	15	0.75	1.25	1
Manufacturing Factor (-)	1-15 / 3	Annual	x	1960	1975	15	0.5	1.4	1
Manufacturing Factor (-)	1-15 / 3	Annual	x	1976	2020	15	0.75	1.25	1
Mining Factor (-)	1-15 / 3	Annual	x	1960	1975	15	0.5	1.4	1
Mining Factor (-)	1-15 / 3	Annual	x	1976	2020	15	0.75	1.25	1
Domestic Factor (-)	1-15 / 3	Annual	x	1960	1975	15	0.5	1.4	1
Domestic Factor (-)	1-15 / 3	Annual	x	1976	2020	15	0.75	1.25	1
Livestock Factor (-)	1-15 / 3	Annual	x	1960	1975	15	0.5	1.4	1
Livestock Factor (-)	1-15 / 3	Annual	x	1976	2020	15	0.75	1.25	1
Oklahoma All Factor (-)	1-15 / 3	Annual	x	1960	1975	15	0.5	1.4	1
Oklahoma All Factor (-)	1-15 / 3	Annual	x	1976	2020	15	0.75	1.25	1

5.2 History matching

In groundwater availability models, the primary goal is often to predict groundwater levels, or "heads," which indicate changes in the groundwater system over time and are crucial for water resource planning. This modeling approach focuses on generating predictions that simulate a response to specific management decisions. When a numerical model is built for this purpose, incorporating uncertainties in model parameters such as hydraulic properties and stress factors (e.g., locations and magnitudes of past and future water use) explicitly into the modeling analysis is an important consideration, so that reliability in the simulated response to possible management decisions can be conveyed to water resource managers and stakeholders.

Unlike traditional methods, which use a single calibrated parameter set for predictive simulations (and therefore lack the reliability context), a stochastic groundwater modeling approach seeks to generate many well-calibrated but unique parameter sets (known as an ensemble). When each of these sets is run through the model and the results are collated, collectively, they produce a range of potential outcomes, allowing for probability-based predictions after matching historical observations.

To facilitate this, INTERA used PESTPP Iterative Ensemble Smoother (White, 2018), which implements the iterative ensemble smoother algorithm (Chen and Oliver, 2013). PESTPP Iterative Ensemble Smoother uses an ensemble of parameter realizations and therefore naturally provides a stochastic result. PESTPP Iterative Ensemble Smoother is highly efficient in high-dimensional settings, making it ideal for models with a large number of adjustable parameters. Unlike the deterministic Gauss-Levenberg-Marquardt algorithm, which requires a full Jacobian matrix of derivatives, PESTPP Iterative Ensemble Smoother estimates the Jacobian empirically from an ensemble of parameter values, significantly reducing computational demands. For instance, the Seymour and Blaine model, with 9720 parameters, required only 70 model runs per iteration of the algorithm, as a result of this ensemble approach.

5.2.1 Observation targets

Observation targets used in the automated calibration process were primarily composed of observed groundwater levels in wells and spring elevations in the form of water level observations through the history matching period, where the direct observation types were used explicitly. Conceptual model constraints were included in the automated calibration process as well. Specifically, AUTOFLOW reduction targets on pumping were included to guide the model ensembles so that realizations were penalized for parameter combinations that resulted in higher degrees of AUTOFLOW reduction of irrigation pumping in some of the more productive Seymour pods.

Baseflows were estimated based on available United States Geological Survey stream gage data in the model that appeared to have minimal influence from anthropogenic controls (e.g., releases large reservoirs). After investigation of stream gage data, baseflow estimates, and initial model response during the automated

calibration, it became clear that characterizing baseflow was much more complex, and there was a low degree of confidence in the baseflow targets relative to the other observation groups. During initial model calibration, including the baseflow targets as weighted observations produced artifacts in the head and spring matches that were inconsistent with conceptual understanding. As a result, baseflow targets were not retained in the final calibration dataset. Drawdown targets were also evaluated for inclusion in the calibration. However, they provided limited additional information beyond what was already captured by the observed groundwater level time series, as drawdowns are inherently derived from those same measurements. Consequently, their contribution to the objective function was minimal, and they were not retained in the final calibration dataset.

The observed groundwater level time series consists of point measurements, representing the hydrologic conditions at a particular time and space. To scale the point measurements to an annual average based on the groundwater model's temporal resolution, a rolling average of the measurements was calculated. A rolling average is a statistical method that calculates trends over a particular period and smooths out high frequency fluctuations. For the water level measurements, a rolling average period of 181 days (0.5 year) was used. Appendix C contains figures of point measurements and their rolling average for each observation location.

Observation noise was represented explicitly through a stochastic observation ensemble so the calibration could account for measurement and process uncertainty rather than fitting a single deterministic target set. In practice, noise realizations are generated from the observed values (and a temporal correlation for high-frequency transient groundwater levels). PESTPP-Iterative Ensemble Smoother then conditions parameter updates against this noisy ensemble to help prevent overfitting to individual observations, thus producing a more realistic residual structure and yielding posterior uncertainty that better reflects uncertainty in both data and model response.

Steady-state and transient groundwater elevation targets

Observed groundwater levels were the primary source of calibration targets for the model. Groundwater level data used for both steady-state and transient calibration were obtained from the Texas Water Development Board and the Oklahoma Water Resources Board groundwater databases. Given the limited availability of data, all available water level information was considered; however, priority was given to wells with longer and more complete records. Only measurements classified as publishable in the TWDB groundwater database and without remarks indicating potential impacts from pumping were included in the calibration dataset.

The steady-state model represents conditions prior to development of the aquifer system, which was considered to be prior to 1960. Selection of water level measurements representative of predevelopment conditions is a challenge for most groundwater modeling studies because aquifers are never truly in steady-state conditions, especially in locations where domestic and non-domestic pumping is prevalent. To approximate these conditions for the Seymour and Blaine aquifers, the first measurement collected on or before January 1, 1960, for each well was selected

from the available groundwater level record and used as the steady-state target. Wells without a qualifying pre-1960 measurement were excluded from the steady-state observation dataset.

After removal of 25 targets below the model bottom, a total of 574 steady-state groundwater elevation targets were retained for the Seymour Aquifer and 154 were retained for the Blaine Aquifer. In comparison, after removal of 541 targets below the model bottom, 8,079 transient groundwater elevation targets at 2,392 locations were retained in the Seymour Aquifer and 4,516 targets at 789 locations were retained in the Blaine Aquifer. Because the steady-state simulation provides the initial heads for the transient simulation, early-time transient observations provide an additional constraint on the steady-state calibration. The locations of the groundwater elevation targets are presented in Figure 5.2-1. Table 5-9 summarizes the target locations by whether each has steady-state targets, transient targets, or both.

Steady-state and transient groundwater elevation targets were grouped by pod if in the Seymour Aquifer. Transient targets were subdivided further into high-frequency and low-frequency wells. High-frequency designation was assigned to wells with more than five measurements and a record length of at least five years, while all other wells were designated as low-frequency. High-frequency observations were given the greatest weight in the objective function because they provide longer records and more reliable trends for calibration. If a Seymour pod did not contain any high-frequency targets, then the low-frequency targets were given the greatest weight for said pod. This weighting strategy directed the Iterative Ensemble Smoother to prioritize fitting these observations relative to other targets.

A total of 35 observation groups were used to classify groundwater elevation observations, allowing a flexible weighting scheme within the calibration process based on data confidence and modeling priorities. Table 5-10 lists groundwater elevation observation groupings and the number of water level observations in each group, broken down by pod, model layer, and observation type.

Table 5-9. Number of groundwater elevation target locations by target type.

Aquifer	Steady-state target only	Steady-state and transient targets	Transient target only	Total target locations
Seymour	8	566	1,826	2,400
Blaine	1	153	636	790
Total	9	719	2,462	3,190

**Table 5-10. Number of groundwater elevation observations by observation type, layer and pod.
Layer 1 = Seymour pods and Layer 3 = Blaine.**

Layer¹	Pod	High Frequency Transient	Low Frequency Transient	Steady-State
1	1	547	19	1
1	2	138	13	
1	3	158	83	14
1	4	1905	1180	187
1	5	132	65	5
1	6	-	110	-
1	7	1,855	952	334
1	8	-	14	-
1	9	71	10	-
1	10	-	5	-
1	11	8	24	-
1	12	4	26	4
1	13	364	338	29
1	14	-	20	-
1	15	-	38	-
3	-	3,707	809	154
Total		8,889	3,706	728

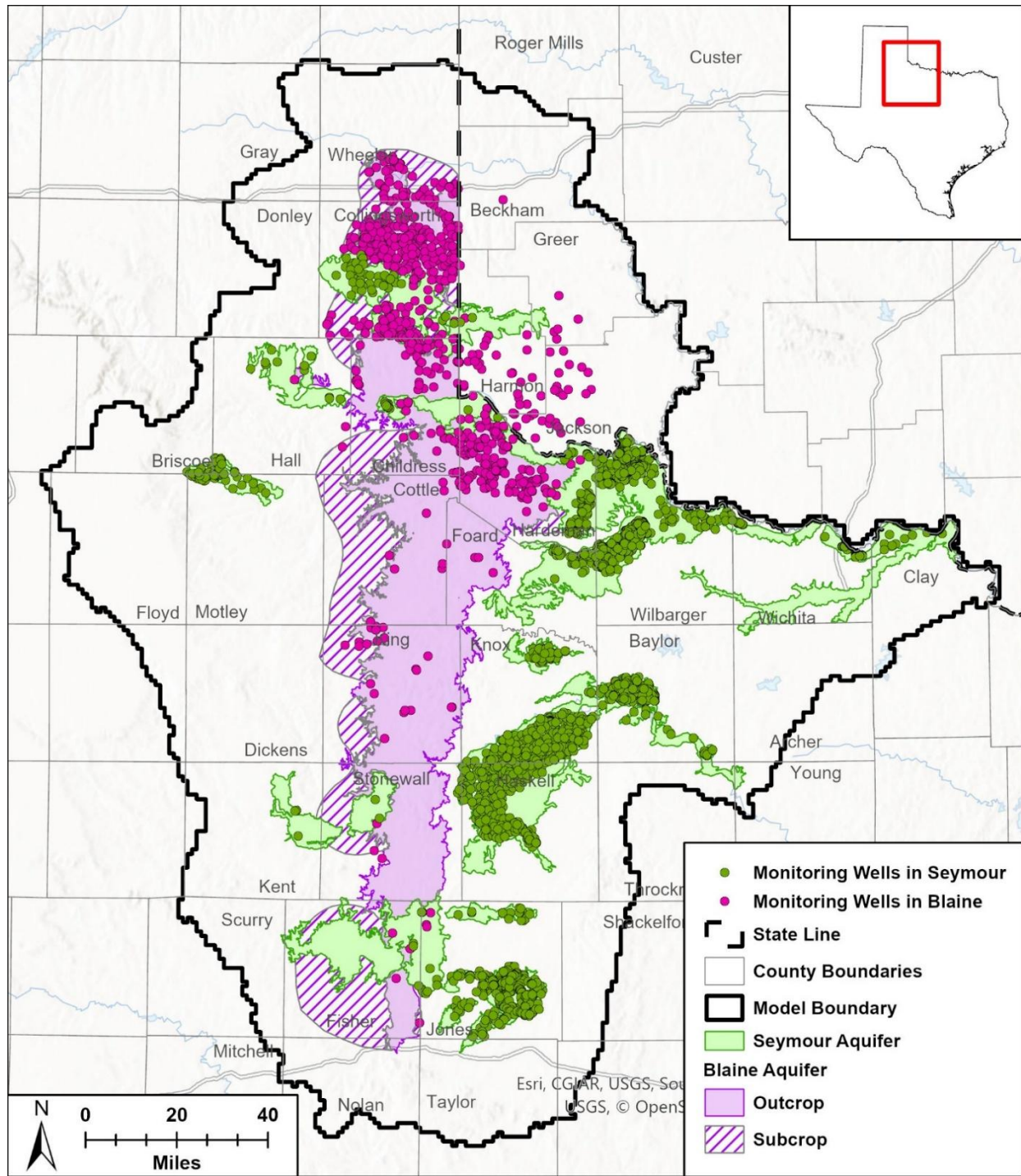


Figure 5.2-1. Groundwater monitoring wells in the Seymour and Blaine aquifers.

Spring head targets

Spring head targets were included to provide an additional calibration constraint on groundwater–surface water interactions. These targets represent observed hydraulic head elevations at spring locations and help constrain simulated heads in areas where groundwater discharge is expected to occur. All spring elevations simulated with the model, including those used for explicit calibration targets, were cut-in 15 feet from surface elevation to accommodate limitations with the coarser spatial discretization of the model cells relative to the smaller spatial footprint of springs and seeps. Spring drain elevations were not adjusted during the automated calibration process.

The spatial distribution of both weighted and unweighted spring head observations included in the calibration is shown in Figure 5.2-2. Weighted spring head observations were included as direct calibration targets. Unweighted spring head observations were retained in the observation dataset but assigned zero weight and therefore did not contribute to the objective function. These observations lacked temporal information; in most cases, only the occurrence of a spring at a given location was known, rather than the timing or frequency of discharge. As a result, they were not appropriate for use as direct calibration targets but were retained for evaluation purposes in the calibration process. A total of 132 weighted spring head observations were used as direct calibration targets.

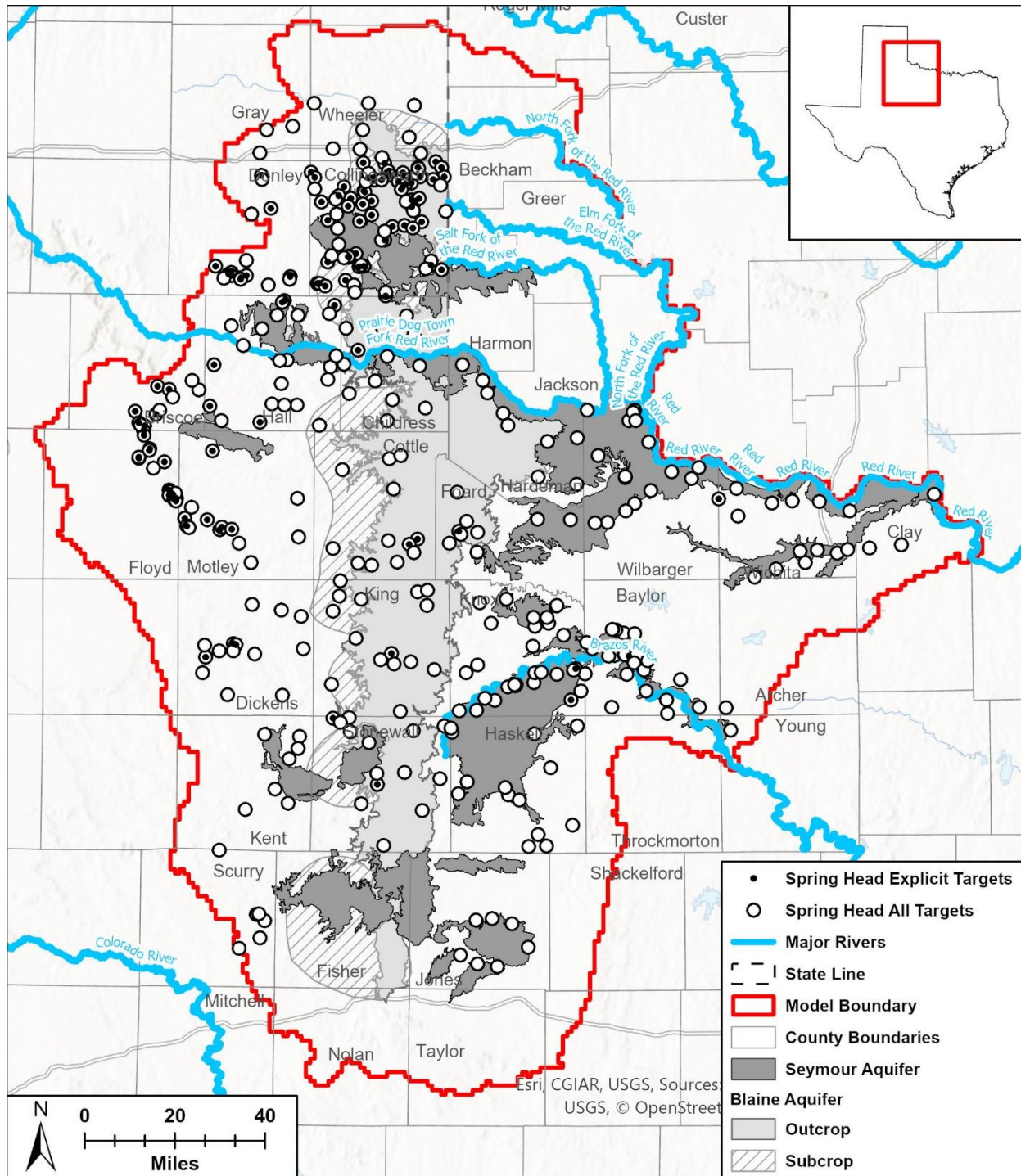


Figure 5.2-2 Spring head calibration targets.

5.2.2 Conceptual model constraints on calibration

In addition to measured data, other controls on calibration were implemented based on conceptual understanding of the Seymour and Blaine aquifers. These controls on calibration were enforced more qualitatively than the measured water levels and spring head targets but are no less important and ensure the calibrated model was in harmony with expert knowledge related to the hydrologic behavior of the Seymour and Blaine aquifers.

PESTPP Iterative Ensemble Smoother has the ability to set inequality constraints, where simulated outcomes are penalized if they exceed or fall below a specified threshold condition. The inequality constraint groups described as follows further refine calibrated parameters to simulate conditions more aligned with the conceptual model. These “soft” or qualitative observations help calibrate the groundwater model for its ultimate use as a water management tool.

AUTOFLOW reduction-based targets

Pumping in the model was represented using the WEL package. Within this package, an AUTOFLOW reduction option was enabled to track when simulated withdrawals were hydraulically infeasible and therefore reduced (see report section 4.10.6).

AUTOFLOW reduction targets focused on irrigation pumping, the major contribution to total pumping in the model. Two complementary AUTOFLOW diagnostics were extracted at each irrigation pumping cell and stress period: (1) the requested pumping and (2) reduced pumping. Requested pumping is the prescribed withdrawal rate, whereas reduced pumping represents the portion of that prescribed pumping that MODFLOW 6 could not pump under simulated conditions. These diagnostics were aggregated to five-year intervals to reduce observation redundancy and emphasize long-term behavior rather than short-term fluctuations.

AUTOFLOW-based targets were developed for irrigation wells only, because irrigation is the dominant pumping component in the Seymour Aquifer and because tracking all pumping categories temporally and spatially would have created an excessively large observation ensemble dataset, leading to infeasible run times. Targets were organized by pod and layer to support consistent weighting and localized evaluation of pumping feasibility. In the Seymour Aquifer, reduction targets focused on the highest-contribution pods (1, 3, 4, 7, 11, and 13), which retained the most informative constraints while considering observation ensemble size.

In calibration, requested-pumping diagnostics were retained for reference with zero weight. Reduced-pumping diagnostics were implemented as less-than inequality constraints, with penalties applied when simulated reductions exceeded 50 percent of requested pumping. This approach complements groundwater level calibration by discouraging calibrated parameter combinations that match heads primarily through unrealistic reduction of irrigation withdrawals.

Localizer

A rule-based localization matrix was implemented during calibration to impose conceptual-model constraints on how observations inform parameter updates. Under this framework, each observation group was allowed to inform only physically consistent parameter groups. This approach reduced compensation during calibration from spurious parameter correlation, improved interpretability of parameter updates, and kept inversion behavior aligned with known hydrogeologic controls.

The localization matrix was constructed at the observation-group by parameter-group level. Core features of the matrix include:

- Recharge damping factors (steady-state and transient) are globally informed by all observation groups, reflecting their role as system-wide scaling factors.
- Pod-based Seymour recharge multipliers (one per Seymour pod) are constrained to their matching pod-based hydraulic head observations, while Permian recharge base multipliers for Layers 2, 3, and 4 are globally informed by all observation groups.
- Seymour hydraulic properties (horizontal and vertical hydraulic conductivity, and specific yield) are parameterized at the pod level and are informed only by hydraulic head observations from their corresponding pod. Hydraulic properties for Layers 2, 3, and 4 are globally informed by all observation groups, a deliberate relaxation that produced a better calibration fit.
- Stream drain and river conductance parameters for Layer 1 are informed only by Seymour pod hydraulic head observations. Stream drain and river conductance parameters for Layers 2, 3, and 4 are globally informed by all observation groups.
- Spring head observations are allowed to inform all parameter groups.
- Pod-specific irrigation pumping parameters (one per Seymour pod and one for the Blaine) are informed only by hydraulic head observations from their corresponding pod. Metered pumping is informed by hydraulic head observations in the pods where metered wells exist. All other non-irrigation pumping categories (municipal, domestic for Seymour and Blaine separately, manufacturing, mining, livestock, and Oklahoma) are informed by all pod-based hydraulic head observations, reflecting their distribution across the model domain.
- For Pods 8, 10, 12, 14, and 15, all parameter groups assigned to these pods are informed only by the hydraulic head observations from that same pod. This pod-specific constraint was applied to these data-poor pods to prevent parameter updates from being driven by observations outside the pod. This produced a more stable and physically consistent calibration fit than a broader localization approach.

- For Pod 3, parameter groups assigned to this pod were instead informed by all observation groups. This broader localization was applied because observations within Pod 3 alone were insufficient to constrain the calibration adequately.
- AUTOFLOW reduction targets (inequality constraints described in Section 5.2.2, AUTOFLOW reduction-based targets) are restricted to their matching pod-based irrigation pumping parameters for the principal Seymour pods (1, 3, 4, 7, 11, and 13). For pods 1, 3, 4, and 7, AUTOFLOW targets additionally inform the metered pumping parameters, and for Pod 1 they also inform the Oklahoma pumping parameter.

5.3 Calibrated results

When calibrating the model using PESTPP Iterative Ensemble Smoother, the resulting parameter ensembles are recorded during every history-matching iteration as well as the objective function or phi. The objective function quantifies the residual between simulated and observed values multiplied by their respective weights. Observation weighting was based on observation groups. A summary of observation groups and their percent weighting is listed in Table 5-11.

The weighting scheme is one of the most adaptive and influential components of the calibration process, as it allows for prioritization of observations based on their importance to key physical processes in the model. Throughout calibration, multiple weighting strategies were tested and refined until a balance was achieved between minimizing misfits and maintaining consistency with the conceptual understanding of the system.

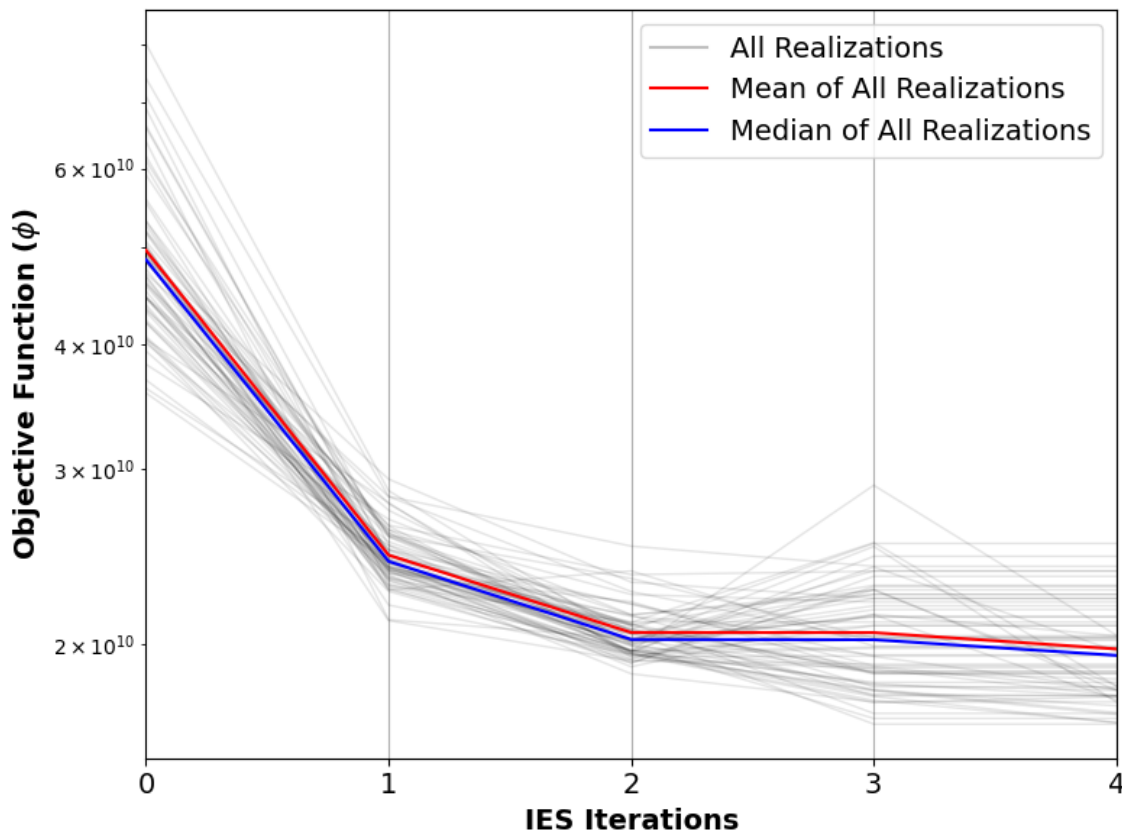
Table 5-11 summarizes the observation groups, their assigned weighting as a percentage of total phi, and the number of weighted observations contributing to each group. Weighting percentages were also based off the quality of the observation group type. For example, “high frequency” is a groundwater elevation grouping of high-quality groundwater level data. This was given a high weighting because of the data quality and the importance of accurately simulating groundwater levels throughout the model domain.

By refining the weighting scheme through iterative testing, the final calibration effectively captured the dominant hydrogeologic processes while avoiding undue influence from uncertain or overly sensitive parameters, ensuring a model that remains both stable and representative of system behavior.

Table 5-11. Table of observation groups and their percent weighting when calculating the objective function. AUTOFLOW irrigation pumping reduction counts reflect individual irrigation cell by stress-period records used as weighted inequality constraints; groundwater elevation and spring head counts reflect individual measurements used as weighted calibration targets.

Observation Group	Type	Preferred % of Total Phi	Number of Weighted Observations
tr-hds.lofreq.lay3.pod00	groundwater level	0.01%	809
tr-hds.lofreq.lay1.pod15	groundwater level	1.68%	38
tr-hds.lofreq.lay1.pod14	groundwater level	2.68%	20
tr-hds.lofreq.lay1.pod13	groundwater level	0.01%	338
tr-hds.lofreq.lay1.pod12	groundwater level	0.01%	26
tr-hds.lofreq.lay1.pod11	groundwater level	0.10%	24
tr-hds.lofreq.lay1.pod10	groundwater level	4.47%	5
tr-hds.lofreq.lay1.pod09	groundwater level	0.10%	10
tr-hds.lofreq.lay1.pod08	groundwater level	4.47%	14
tr-hds.lofreq.lay1.pod07	groundwater level	0.01%	952
tr-hds.lofreq.lay1.pod06	groundwater level	4.47%	110
tr-hds.lofreq.lay1.pod05	groundwater level	0.01%	65
tr-hds.lofreq.lay1.pod04	groundwater level	0.01%	1,180
tr-hds.lofreq.lay1.pod03	groundwater level	0.10%	83
tr-hds.lofreq.lay1.pod02	groundwater level	0.01%	13
tr-hds.lofreq.lay1.pod01	groundwater level	0.01%	19
tr-hds.hifreq.lay3.pod00	groundwater level	17.05%	3,707
tr-hds.hifreq.lay1.pod13	groundwater level	4.45%	364
tr-hds.hifreq.lay1.pod12	groundwater level	1.93%	4
tr-hds.hifreq.lay1.pod11	groundwater level	5.45%	8
tr-hds.hifreq.lay1.pod09	groundwater level	3.61%	71
tr-hds.hifreq.lay1.pod07	groundwater level	8.65%	1,855
tr-hds.hifreq.lay1.pod05	groundwater level	1.95%	132
tr-hds.hifreq.lay1.pod04	groundwater level	8.65%	1,905
tr-hds.hifreq.lay1.pod03	groundwater level	5.25%	158
tr-hds.hifreq.lay1.pod02	groundwater level	4.25%	138
tr-hds.hifreq.lay1.pod01	groundwater level	4.25%	547
ss-hds.lay3.pod00	groundwater level	1.26%	154
ss-hds.lay1.pod13	groundwater level	1.26%	29
ss-hds.lay1.pod12	groundwater level	1.26%	4
ss-hds.lay1.pod07	groundwater level	1.26%	334
ss-hds.lay1.pod05	groundwater level	1.26%	5
ss-hds.lay1.pod04	groundwater level	1.26%	187
ss-hds.lay1.pod03	groundwater level	2.26%	14
ss-hds.lay1.pod01	groundwater level	0.84%	1
sh	spring heads	1.00%	132
less_than_autof_red_lay1_pod13	irrigation pumping reduction	0.79%	77,584
less_than_autof_red_lay1_pod11	irrigation pumping reduction	0.79%	154,206
less_than_autof_red_lay1_pod07	irrigation pumping reduction	0.79%	464,984
less_than_autof_red_lay1_pod04	irrigation pumping reduction	0.79%	669,279
less_than_autof_red_lay1_pod03	irrigation pumping reduction	0.79%	37,632
less_than_autof_red_lay1_pod01	irrigation pumping reduction	0.79%	104,148

Figure 5.3-1 shows the reduction in the objective function for each history-matching iteration. The objective function, or phi values, decrease in a log-linear manner during iterations 0 (prior) to iteration 3, but the rate of decrease is notably lower between iterations 3 and 4, indicating that the misfit is not likely to improve much with additional iterations. The observed behavior in phi highlights, in part, the quality of data sources used to inform model parameter initialization in the prior ensemble and showcases the concept of deploying PESTPP Iterative Ensemble Smoother as a calibration polishing tool. The parameter ensemble generated in iteration 3 was chosen as the posterior parameter ensemble. The posterior parameter ensemble and its resulting simulated outputs are discussed in detail in the following subsections.



Note: IES = Iterative Ensemble Smoother

Figure 5.3-1. Phi reduction for every iteration of calibration. The objective Function (Φ) is the sum of squared weighted residuals.

5.3.1 Calibrated parameters

Through the calibration (or history-matching) process, the prior parameter ensemble is adjusted to improve alignment with both observation data and conceptual model expectations, producing the posterior parameter ensemble. These parameter adjustments, or “updates,” lead to a reduction in parameter uncertainty, which in turn decreases predictive uncertainty. While some parameters may exhibit significant

shifts between their prior versus posterior distributions, others may remain largely unchanged. For these parameters, the observed data provided little or no information regarding what value is most likely, and therefore calibration was unable to reduce uncertainty.

There are 66 parameter realizations in the posterior ensemble. The reduction from 70 prior to 66 posterior realizations reflects routine attrition as realizations are progressively dropped based on numerical convergence and statistical phi criteria across iterations, well within the range typical for ensemble-based calibrations of regional groundwater models. All posterior realizations are calibrated to observations and represent potential, equally likely configurations of hydrologic properties and historical stresses in the Seymour and Blaine aquifers. While it is important to analyze the entire posterior parameter ensemble, the realization with minimum introduced heterogeneity is recommended to be used for deterministic runs of the Seymour and Blaine groundwater availability model when water management decisions are desired. This realization, labeled the “base realization” in PESTPP Iterative Ensemble Smoother, starts the calibration process from the initial parameter values defined in Chapter 4, which represent the best prior estimates before calibration updates are applied. During calibration, parameter values of all realizations are updated, but the base realization represents the central tendency of the posterior parameter distribution; or, in other words, a realization centrally located within the distribution and not an outlier of the distribution.

Spatial plots of each parameter type from the posterior base realization follow, accompanied by tabular summary statistics and violin plots. These violin plots visually represent data distribution by combining a boxplot and a density plot, showing both the range and concentration of values across different quantiles of the ensemble. The prior distribution is represented by the gray violin, while the posterior distribution appears as a transparent blue violin. The wider shape of the prior violin indicates a greater spread and higher uncertainty in values. If the corresponding posterior distribution is much narrower, this indicates that the property was more conditioned by calibration. However, if the posterior distribution is not substantially different from the prior, this indicates the property was not as informed by calibration. Each violin plot includes quantile markers representing key statistical breakpoints in the ensemble distribution:

- 0th percentile (minimum value)
- 25th percentile (first quartile, lower bound of most values)
- 50th percentile (median, central tendency of the ensemble)
- 75th percentile (third quartile, upper bound of most values)
- 100th percentile (maximum value)

Hydraulic conductivity and anisotropy

Horizontal hydraulic conductivity and vertical hydraulic conductivity were parameterized to accommodate the distinct hydrogeologic characters of the Seymour Aquifer and the underlying Permian units. In the Seymour Aquifer (layer 1), horizontal hydraulic conductivity and vertical hydraulic conductivity were parameterized at the pod scale, with each of the 15 Seymour pods assigned its own pod-scale constant multiplier and a set of spatially distributed pilot point multipliers, reflecting the isolated pod geometry of the aquifer and the heterogeneous depositional character of the Quaternary material across pods. In the three Permian units (layers 2 through 4), horizontal hydraulic conductivity and vertical hydraulic conductivity were parameterized using a single formation-scale constant multiplier and spatially distributed pilot point multipliers applied across each layer's full extent, consistent with the more laterally continuous character of the Permian stratigraphy and the lower density of horizontal hydraulic conductivity and vertical hydraulic conductivity information available for these deeper units. Vertical hydraulic conductivity was parameterized independently from horizontal hydraulic conductivity rather than through a prescribed anisotropy ratio, allowing the vertical anisotropy ratio (vertical hydraulic conductivity/horizontal hydraulic conductivity) to emerge as a derived quantity reflecting the relative calibration response of each property. Because the vertical anisotropy ratio captures the hydraulically meaningful relationship between the two properties, calibration results are presented below in terms of horizontal hydraulic conductivity and the vertical anisotropy ratio; posterior vertical hydraulic conductivity summary statistics by layer are provided in Table 5-15 for reference.

The single site-specific estimate of hydraulic properties available within the model domain, the City of Seymour Well 4B multi-well aquifer test (Table 4-9), served as an independent check on the calibrated parameters (see Comparison with City of Seymour Aquifer Test Data at the end of this section). Calibration bounds were applied to both formation-scale constant multipliers and pilot point multipliers, with ultimate upper and lower bounds constraining calibrated values within hydrogeologically reasonable ranges drawn from the prior conceptualization, which was based on literature values and regional understanding of the aquifer system. Parameter information for defining the prior distributions of horizontal hydraulic conductivity and vertical hydraulic conductivity is provided in Table 5-1 and Table 5-2, respectively.

Posterior horizontal hydraulic conductivity distributions for the Seymour Aquifer (Figure 5.3-2 and Figure 5.3-3) show a consistent reduction in posterior spread relative to the prior across nearly all pods, indicating that horizontal hydraulic conductivity in layer 1 was well informed by calibration. The direction of the calibration shift varies by pod: posterior medians shift downward relative to the prior in Pods 2, 6, and 15; remain near the prior median in Pods 1, 5, 11, 12, 13 and 14; and shift upward relative to the prior in Pods 3, 4, 7, 8, 9, and 10. Posterior values remain within prescribed parameter bounds across all pods, indicating that calibrated results are hydrogeologically reasonable.

Pod-level variability in posterior horizontal hydraulic conductivity is substantial and reflects the heterogeneous depositional character of the Seymour Formation across the model domain, where sediments grade laterally from clay and silt to coarse sand and gravel, with a basal coarse-grained section present where the aquifer overlies buried Permian channels (Ewing and others, 2004). Pod 7, encompassing the Haskell-Knox-Baylor area, exhibits the highest calibrated horizontal hydraulic conductivity values, with a posterior median near approximately 500 feet per day, and simultaneously exhibits one of the tightest posterior distributions of any layer 1 pod, reflecting the large observation count supporting Pod 7 (3,141 observations per Table 5-10) and consistent with its relatively large and sustained irrigation pumping record. Most remaining pods calibrate to posterior medians in the approximate range of 10 to 90 feet per day, with Pod 6 and 10 calibrating higher at approximately 125 and 220 feet per day, respectively. Pods 9 and 10 show posteriors sitting largely above the prior with minimal 25th–75th percentile overlap, while Pods 11 and 12 show posteriors that closely track the prior with little narrowing — both patterns indicate weakly informed calibration, and values in these four pods should be interpreted with caution. More broadly, each of pods 6, 8, 9, 10, 11, 12, 14, and 15 is supported by fewer than 150 groundwater elevation observations (Table 5-10), compared to between 150 and approximately 3,300 observations in pods 1, 2, 3, 4, 5, 7, and 13. Calibrated horizontal hydraulic conductivity values for these data-poor pods should therefore be interpreted with appropriate caution, with pods 9 through 12 warranting the greatest caution.

For the Permian units, posterior horizontal hydraulic conductivity distributions are shown in Figure 5.3-4. The Blaine Aquifer exhibits substantial narrowing of the posterior relative to the prior across all quantiles, with posterior values tightly constrained around a median near 4 to 5 feet per day and spanning approximately 2 to 20 feet per day, reflecting strong conditioning of Blaine horizontal hydraulic conductivity by the head observations included as calibration targets. Layers 2 and 4 received no direct conditioning from head observations but nevertheless show clear posterior narrowing relative to the prior, driven by indirect conditioning. Layers 2 and 4 calibrated to similar overall ranges of approximately 0.4 to 4 feet per day, but the Flowerpot and Older Permian returned the lowest horizontal hydraulic conductivity values of all four model layers, with a base realization median of approximately 0.8 foot per day compared to approximately 2.8 feet per day for the Whitehorse and Younger Permian. Summary statistics for horizontal hydraulic conductivity by layer and pod from the posterior ensemble are provided in Table 5-12, and summary statistics for the base realization by layer are provided in Table 5-14.

The spatial distribution of calibrated horizontal hydraulic conductivity for each model layer for the base realization is shown in Figure 5.3-5 through Figure 5.3-8. In the Seymour Aquifer (Figure 5.3-5), the highest horizontal hydraulic conductivity values are concentrated in the larger pods with greater saturated thicknesses and active pumping histories, consistent with the conceptual understanding that thicker sections of the aquifer overlie buried channels incised within the underlying Permian units and contain a greater proportion of coarse basal sand and gravel (Ewing and others, 2004; Jones and others, 2012). The spatial pattern is notably discontinuous, reflecting

the isolated pod geometry of the Seymour Aquifer. The Whitehorse and Younger Permian unit (Figure 5.3-6) shows a low horizontal hydraulic conductivity field (0.5 to 5.5 feet per day) across its active extent in the western portion of the model domain, with the lowest values concentrated at the northern and southern margins of the layer's extent and the highest values forming a broad central band. The Blaine Aquifer (Figure 5.3-7) exhibits the highest horizontal hydraulic conductivity values (up to approximately 21 feet per day) in the central portion of the aquifer with values decreasing both to the north and to the south, where minimum horizontal hydraulic conductivity reaches approximately 2 feet per day. The Flowerpot and Older Permian unit (Figure 5.3-8) exhibits the lowest horizontal hydraulic conductivity values of all four layers, generally below 1.5 feet per day across most of the domain, with the lowest values concentrated through the central portion of the layer's extent and somewhat higher values (up to approximately 4 feet per day) along the northern and southern margins.

Posterior vertical anisotropy ratio (vertical hydraulic conductivity/horizontal hydraulic conductivity) distributions for the Seymour Aquifer (Figure 5.3-9 and Figure 5.3-10) show reduction in posterior spread relative to the prior across most pods, with the strongest narrowing observed in Pods 1, 3, 4, and 7. Across all Seymour pods, posterior anisotropy ratios are concentrated in the range of approximately 10^{-4} to 10^{-3} , indicating strong predominance of horizontal over vertical flow within the Seymour formation. Posterior medians remain near the prior in Pods 1, 3, 5 and 11, shift upward relative to the prior in Pods 2, 6, 13, 14 and 15; and shift downward in Pods 4, 7, 8, 9, 10, and 12. For the data-poor pods (Pods 6, 8, 9, 10, 11, 12, 14, and 15), calibrated anisotropy ratios should be interpreted with the same caution noted for horizontal hydraulic conductivity, particularly for Pods 9 through 12.

For layers 2 through 4 (Figure 5.3-11), all three Permian units exhibit substantial posterior narrowing relative to the prior across all quantiles, with posteriors tightly constrained around layer-specific medians. The base realization medians are approximately 1.5×10^{-4} for the Whitehorse and Younger Permian unit (layer 2), approximately 4×10^{-4} for the Flowerpot and Older Permian unit (layer 4), and approximately 5×10^{-4} for the Blaine Aquifer (layer 3), consistent with the Blaine Aquifer exhibiting somewhat less pronounced vertical anisotropy than the bounding Permian units. Posterior values remain well within the 10^{-4} to approximately 2×10^{-3} range across all three layers. Summary statistics for anisotropy ratios by layer and pod are provided in Table 5-13, and base realization statistics by layer are provided in Table 5-16.

The spatial distribution of calibrated anisotropy ratios for the base realization is shown in Figure 5.3-12 through Figure 5.3-15. In the Seymour Aquifer (Figure 5.3-12), anisotropy ratios range from approximately 3×10^{-5} to 1.4×10^{-3} , with the lowest values generally associated with the highest horizontal hydraulic conductivity areas of Pod 7 and the eastern Seymour pods. Because the vertical anisotropy ratio is a derived quantity, these low values reflect the strong upward calibration shift in horizontal hydraulic conductivity in those pods relative to the more modest shift in vertical hydraulic conductivity. The Whitehorse and Younger Permian unit (Figure 5.3-13)

spans approximately 4×10^{-5} to 1.7×10^{-3} , with the lowest values concentrated across the central portion of the layer and higher values along the northern and southern margins. The Blaine Aquifer (Figure 5.3-14) spans approximately 1.0×10^{-4} to 2.0×10^{-3} , with the lowest ratios in the central portion of the aquifer, corresponding spatially to the zone of highest horizontal hydraulic conductivity in the Blaine, and higher ratios toward the southern outcrop margin. The Flowerpot and Older Permian unit (Figure 5.3-15) spans approximately 8×10^{-5} to 1.6×10^{-3} , with the highest anisotropy ratios in the northeastern portion of the domain, and the lowest values through a central column and the southern extent. Across all four layers, the calibrated anisotropy ratios indicate strongly horizontal flow regimes, with horizontal hydraulic conductivity exceeding vertical hydraulic conductivity by approximately two to four orders of magnitude throughout the model domain.

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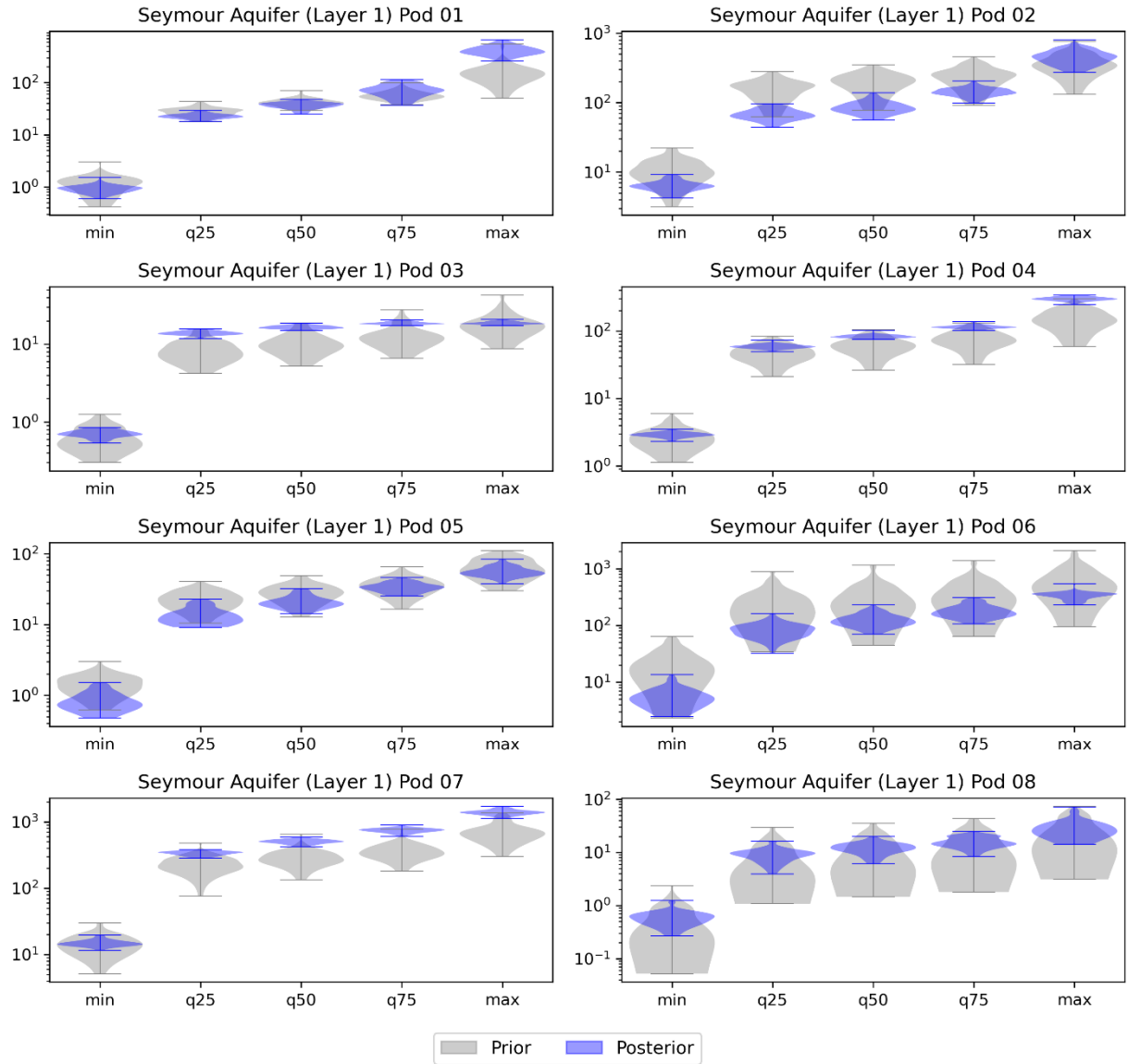


Figure 5.3-2. Violin plots showing the prior and posterior parameter ensembles for horizontal hydraulic conductivity for pods 1 through 8 in the Seymour Aquifer. Values are in percent (x axis) and feet per day (y axis).

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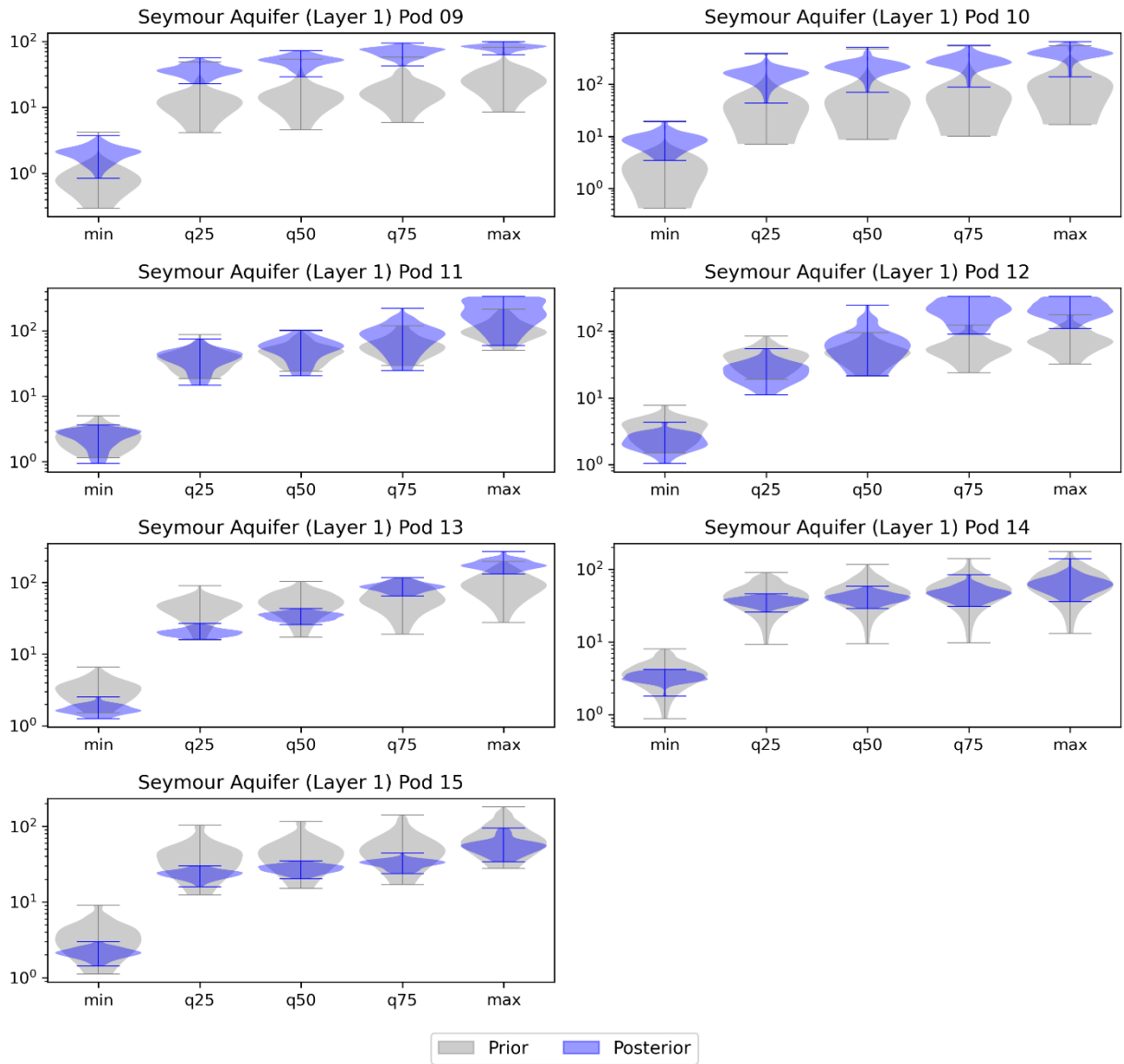


Figure 5.3-3. Violin plots showing the prior and posterior parameter ensembles for horizontal hydraulic conductivity for pods 9 through 15 in the Seymour Aquifer. Values are in percent (x axis) and feet per day (y axis).

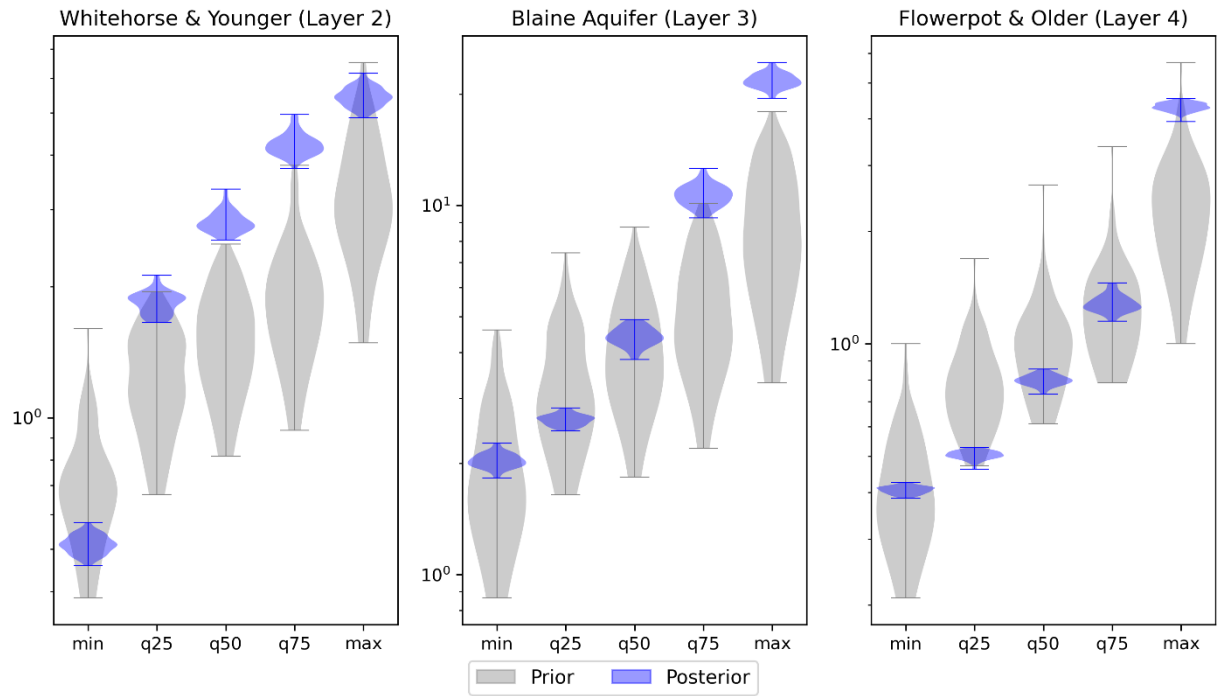


Figure 5.3-4. Violin plots showing the prior and posterior parameter ensembles for horizontal hydraulic conductivity for model layers 2 through 4. Values are in percent (x axis) and feet per day (y axis).

Table 5-12. Horizontal hydraulic conductivity statistics by layer and pod for the posterior parameter ensemble. Values are in feet per day. Layer 1 = Seymour Pods, Layer 3 = Blaine.

Layer	Pod	Average	Standard Deviation	Minimum	25th Percentile	Median	75th Percentile	Maximum
1	1	2.48E+01	1.19E+01	5.93E-01	1.63E+01	2.31E+01	3.13E+01	9.41E+01
1	2	1.20E+02	8.30E+01	4.23E+00	6.77E+01	8.93E+01	1.47E+02	8.10E+02
1	3	1.58E+01	3.34E+00	5.33E-01	1.40E+01	1.67E+01	1.83E+01	2.07E+01
1	4	9.41E+01	5.09E+01	2.28E+00	5.88E+01	8.30E+01	1.15E+02	3.38E+02
1	5	2.42E+01	1.29E+01	4.77E-01	1.33E+01	2.19E+01	3.35E+01	8.42E+01
1	6	1.42E+02	7.48E+01	2.49E+00	8.70E+01	1.25E+02	1.86E+02	5.42E+02
1	7	5.72E+02	3.00E+02	1.16E+01	3.36E+02	5.03E+02	7.46E+02	1.70E+03
1	8	1.33E+01	6.49E+00	2.68E-01	8.94E+00	1.22E+01	1.63E+01	7.22E+01
1	9	5.27E+01	2.07E+01	8.33E-01	3.62E+01	5.17E+01	6.95E+01	9.98E+01
1	10	2.37E+02	1.12E+02	3.44E+00	1.59E+02	2.24E+02	3.05E+02	6.67E+02
1	11	7.83E+01	6.79E+01	9.37E-01	3.72E+01	5.69E+01	9.00E+01	3.33E+02
1	12	1.17E+02	1.03E+02	1.04E+00	2.79E+01	7.14E+01	2.00E+02	3.33E+02
1	13	5.71E+01	4.74E+01	1.26E+00	2.07E+01	3.45E+01	8.54E+01	2.68E+02
1	14	4.22E+01	1.27E+01	1.80E+00	3.51E+01	4.03E+01	4.80E+01	1.38E+02
1	15	2.85E+01	8.19E+00	1.42E+00	2.31E+01	2.76E+01	3.26E+01	9.45E+01
3	—	7.16E+00	5.75E+00	1.83E+00	2.63E+00	4.44E+00	1.07E+01	2.44E+01

Table 5-13. Vertical anisotropy ratio (vertical hydraulic conductivity/horizontal hydraulic conductivity) statistics by layer and pod for the posterior parameter ensemble. Values are unitless. Layer 1 = Seymour Pods, Layer 3 = Blaine.

Layer	Pod	Average	Standard Deviation	Minimum	25th Percentile	Median	75th Percentile	Maximum
1	1	4.24E-04	2.45E-04	5.41E-05	2.52E-04	3.67E-04	5.30E-04	2.53E-03
1	2	6.01E-04	3.59E-04	4.42E-05	3.06E-04	5.53E-04	8.13E-04	2.52E-03
1	3	3.53E-04	1.13E-04	1.52E-04	2.65E-04	3.34E-04	4.19E-04	1.08E-03
1	4	2.62E-04	1.71E-04	3.72E-05	1.51E-04	2.22E-04	3.16E-04	1.63E-03
1	5	5.12E-04	3.46E-04	6.31E-05	2.58E-04	4.06E-04	6.74E-04	2.96E-03
1	6	7.31E-04	4.10E-04	1.26E-04	4.29E-04	6.39E-04	9.30E-04	4.42E-03
1	7	2.18E-04	1.46E-04	2.47E-05	1.05E-04	1.78E-04	2.98E-04	1.35E-03
1	8	2.65E-04	1.57E-04	3.75E-05	1.54E-04	2.24E-04	3.31E-04	1.79E-03
1	9	1.14E-04	6.97E-05	2.55E-05	7.11E-05	9.55E-05	1.33E-04	1.16E-03
1	10	9.90E-05	5.91E-05	1.93E-05	5.95E-05	8.34E-05	1.20E-04	6.01E-04
1	11	3.63E-04	2.54E-04	2.31E-05	1.88E-04	3.05E-04	4.68E-04	2.95E-03
1	12	2.81E-04	2.92E-04	1.57E-05	4.61E-05	1.68E-04	4.41E-04	1.90E-03
1	13	5.36E-04	3.74E-04	3.83E-05	1.97E-04	4.81E-04	7.79E-04	2.25E-03
1	14	4.26E-04	1.45E-04	1.03E-04	3.24E-04	4.14E-04	5.00E-04	1.19E-03
1	15	5.86E-04	2.15E-04	1.05E-04	4.33E-04	5.55E-04	7.10E-04	1.80E-03
3	—	6.21E-04	4.59E-04	7.37E-05	2.37E-04	4.98E-04	8.70E-04	2.23E-03

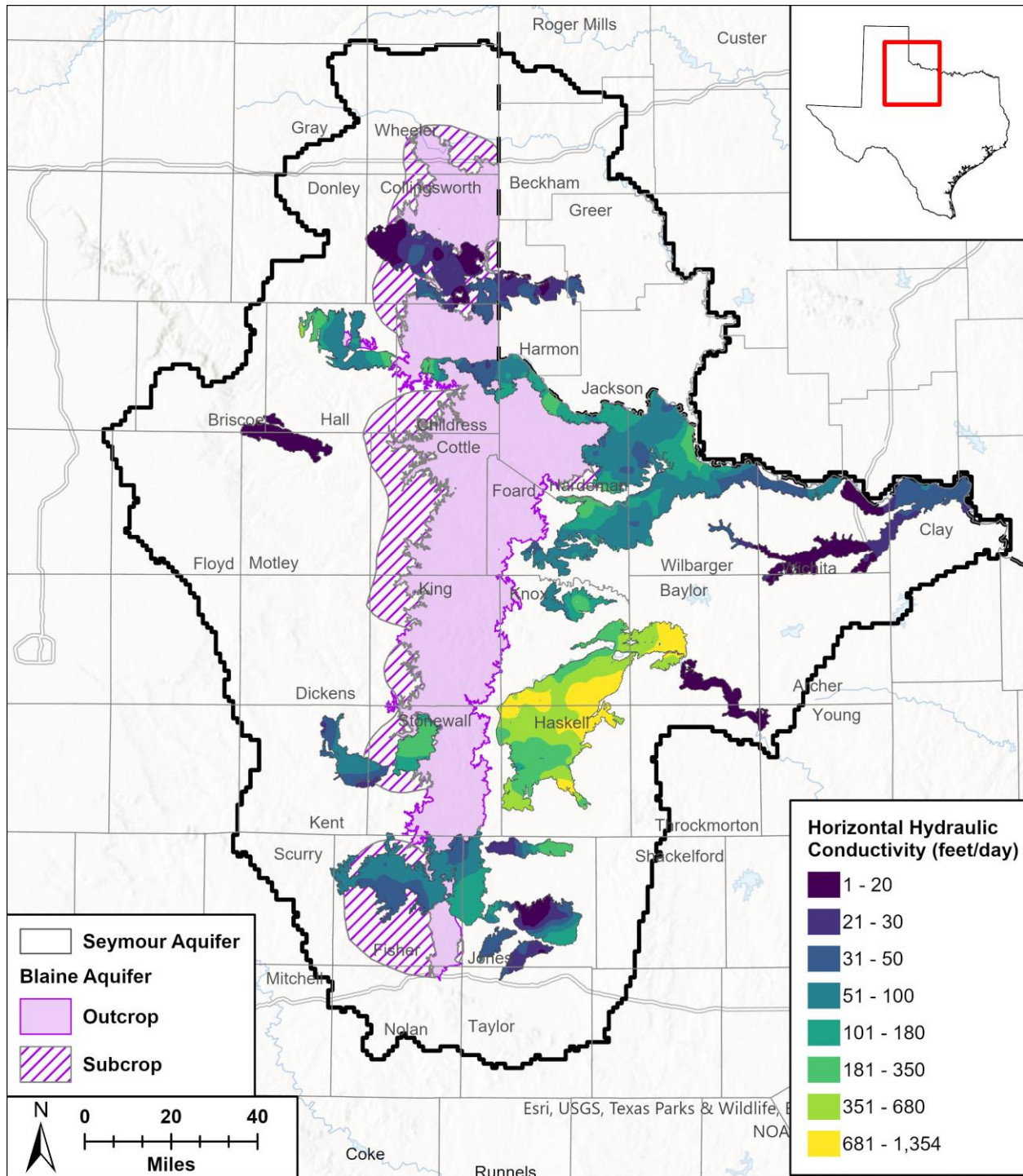


Figure 5.3-5. Calibrated horizontal hydraulic conductivity (in feet per day) for layer 1, the Seymour Aquifer.

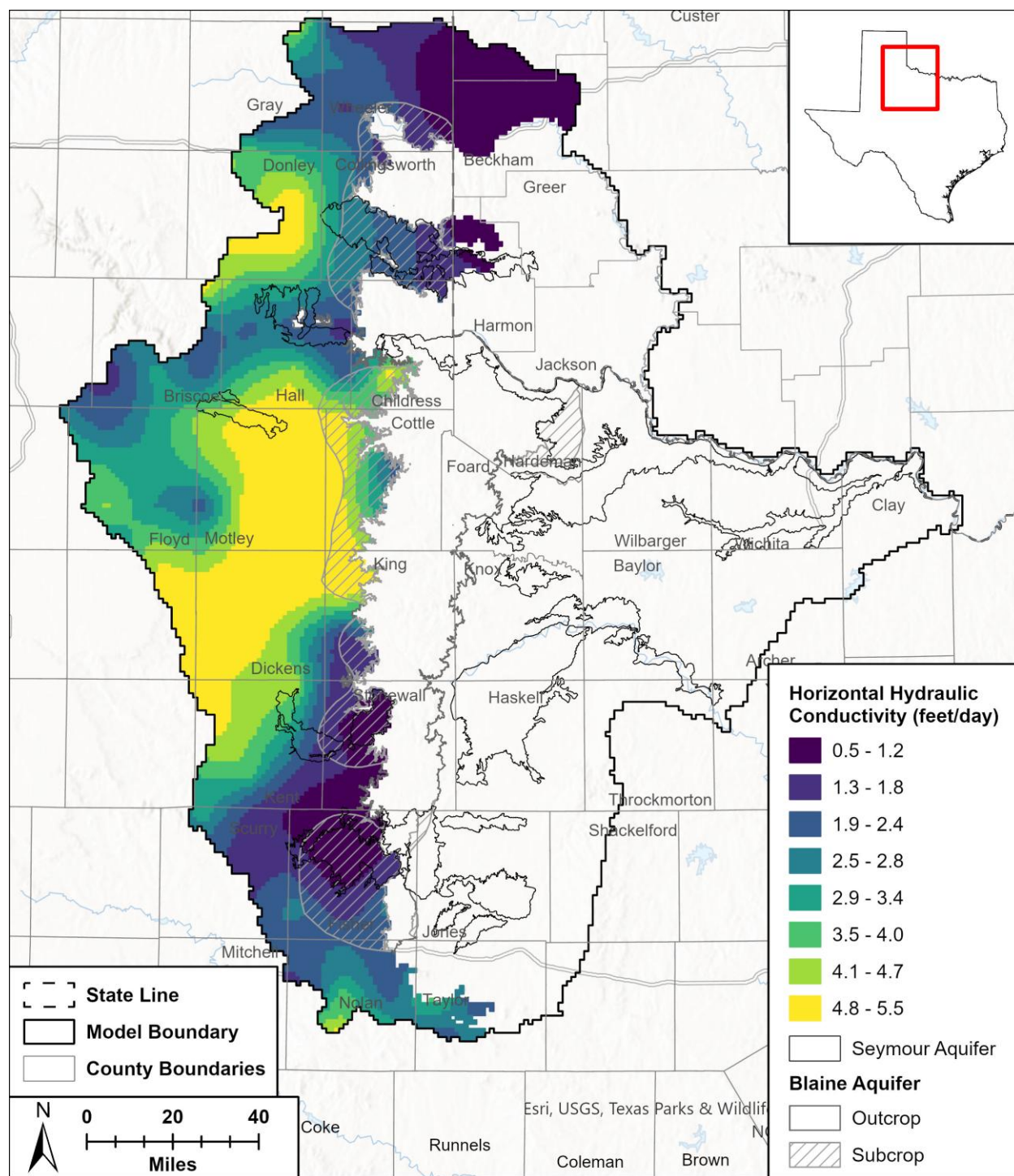


Figure 5.3-6. Calibrated horizontal hydraulic conductivity (in feet per day) for layer 2, the Whitehorse and Younger Permian Units.

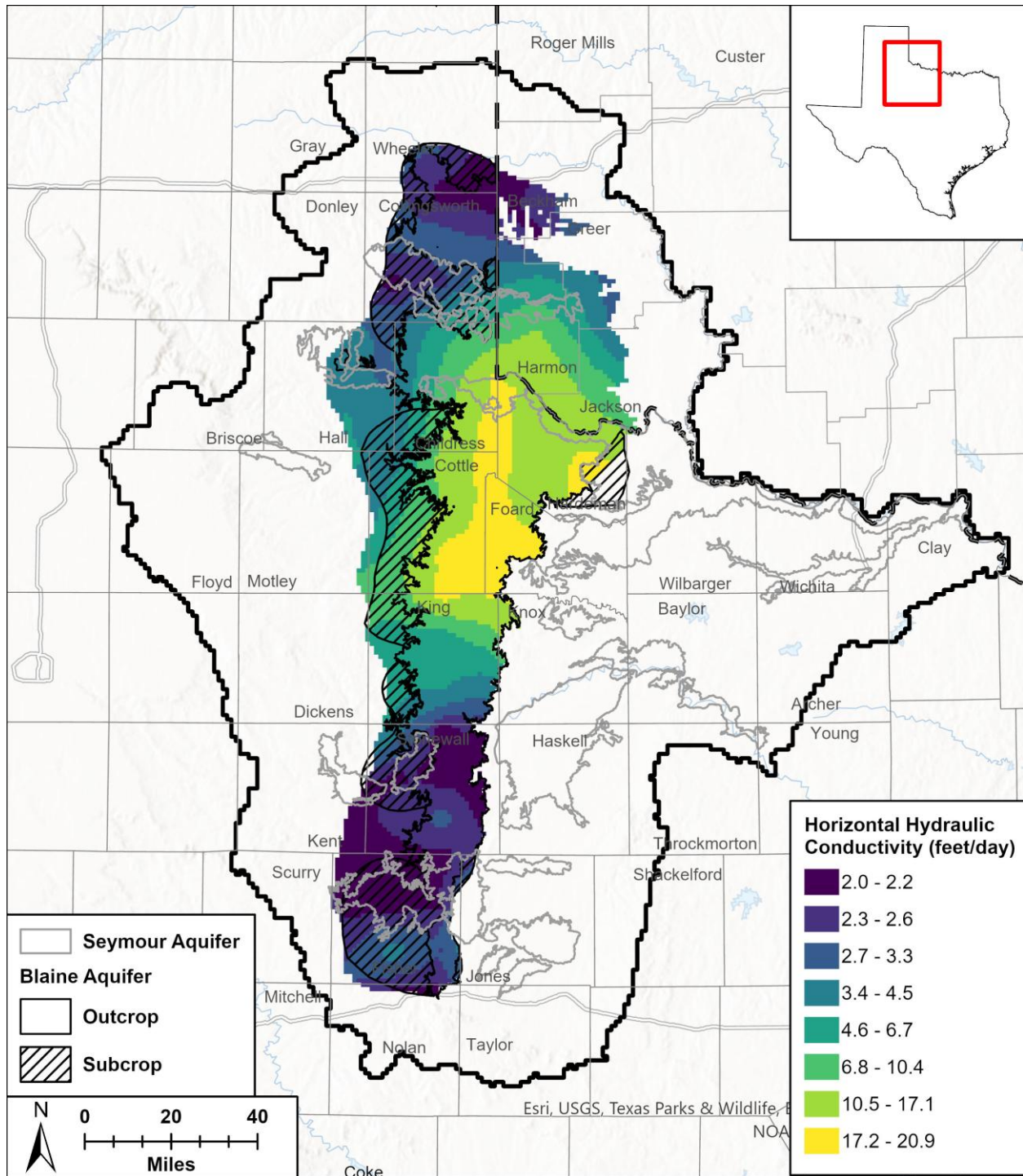


Figure 5.3-7. Calibrated horizontal hydraulic conductivity (in feet per day) for layer 3, the Blaine Aquifer.

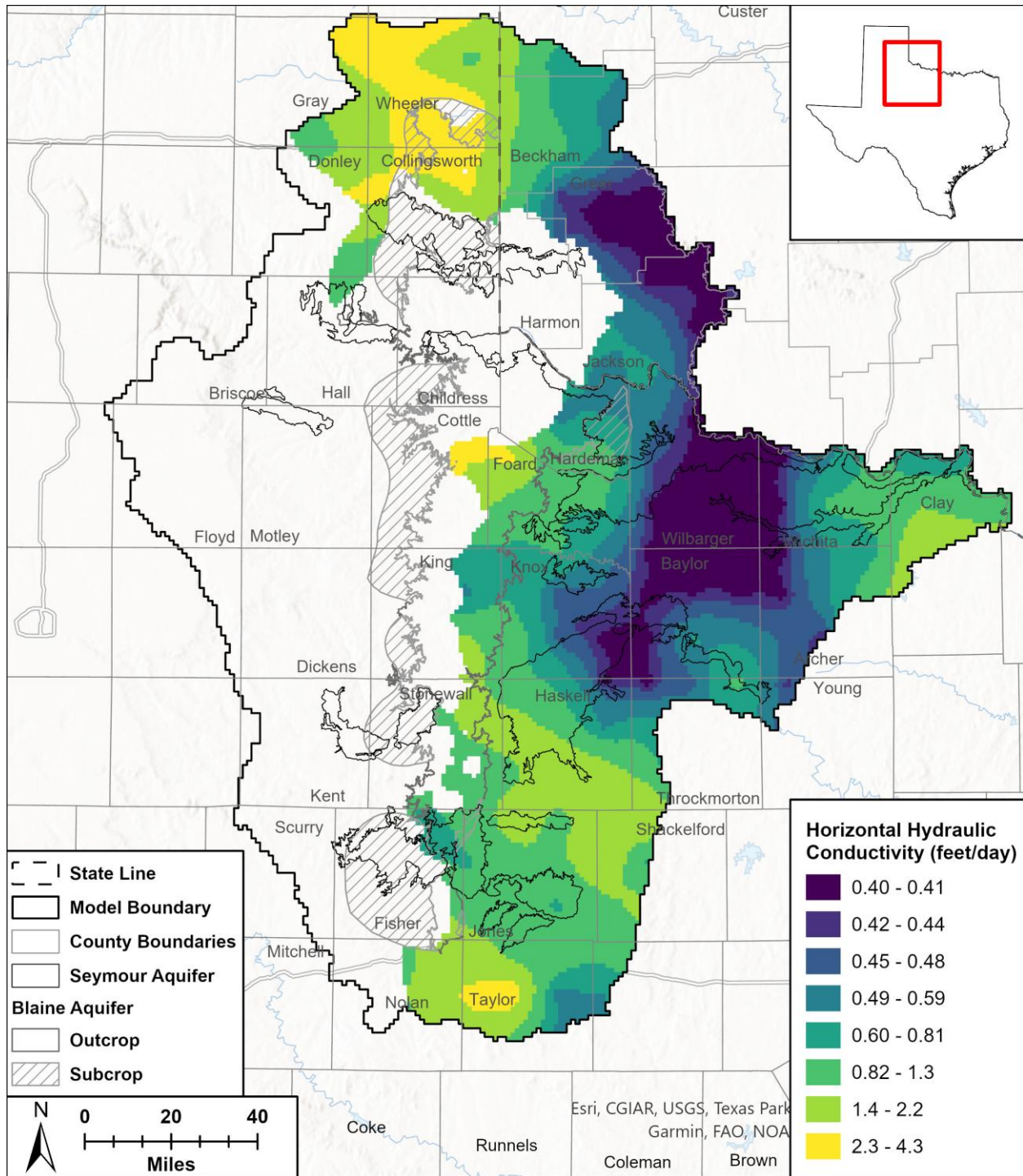


Figure 5.3-8. Calibrated horizontal hydraulic conductivity (in feet per day) for layer 4, the Flowerpot and Older Permian Units.

Table 5-14. Calibrated base realization horizontal hydraulic conductivity (feet per day) by model layer. Layer 1 = Seymour pods, Layer 2 = Whitehorse and Younger, Layer 3 = Blaine, Layer 4 = Flowerpot and Older.

Layer	mean	median	minimum	maximum	1st Percentile	5th Percentile	25th Percentile	75th Percentile	95th Percentile	99th Percentile
1	172.14	69.54	0.61	1,353.43	6.73	13.24	33.93	183.98	747.37	1,135.04
2	3.00	2.78	0.52	5.48	0.58	0.77	1.91	4.22	5.42	5.48
3	6.92	4.30	1.95	20.93	1.97	2.02	2.51	10.40	18.46	19.77
4	1.01	0.82	0.40	4.26	0.40	0.40	0.49	1.29	2.40	3.44

Table 5-15. Calibrated base realization vertical hydraulic conductivity (feet per day) by model layer. Layer 1 = Seymour pods, Layer 2 = Whitehorse and Younger, Layer 3 = Blaine, Layer 4 = Flowerpot and Older.

Layer	mean	median	minimum	maximum	1st Percentile	5th Percentile	25th Percentile	75th Percentile	95th Percentile	99th Percentile
1	3.19E-02	1.80E-02	2.27E-04	1.68E-01	2.06E-03	4.57E-03	1.07E-02	4.62E-02	9.87E-02	1.22E-01
2	4.67E-04	3.96E-04	2.26E-04	9.06E-04	2.26E-04	2.26E-04	2.64E-04	6.23E-04	8.96E-04	9.05E-04
3	2.61E-03	2.53E-03	1.25E-03	4.02E-03	1.32E-03	1.53E-03	1.94E-03	3.29E-03	3.76E-03	3.94E-03
4	3.64E-04	3.22E-04	1.97E-04	7.84E-04	1.97E-04	1.98E-04	2.35E-04	4.49E-04	6.87E-04	7.64E-04

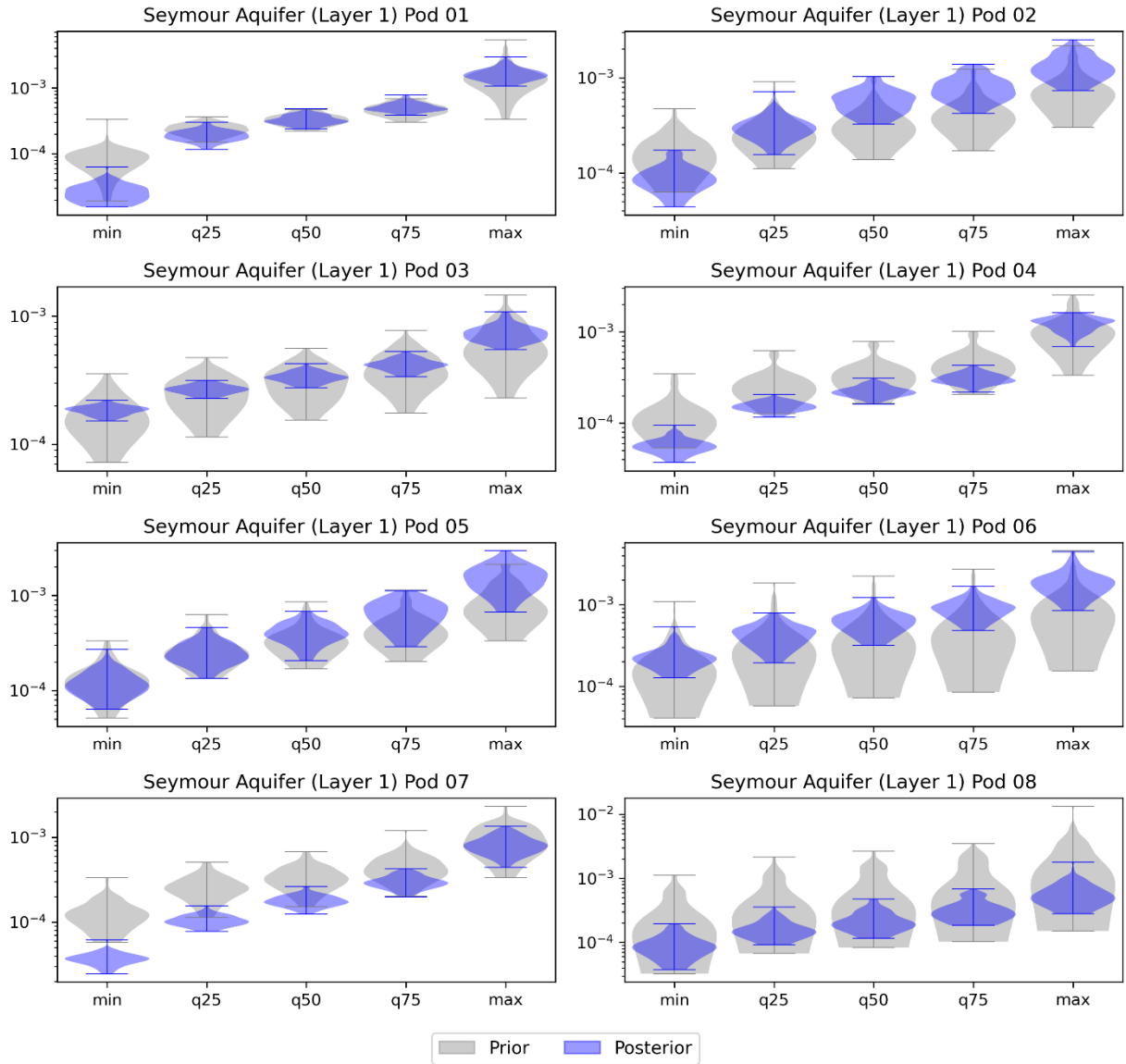


Figure 5.3-9. Violin plots showing the prior and posterior parameter ensembles for vertical anisotropy ratios (vertical hydraulic conductivity/horizontal hydraulic conductivity) for pods 1 through 8 in the Seymour Aquifer. Quantile values are in percent.

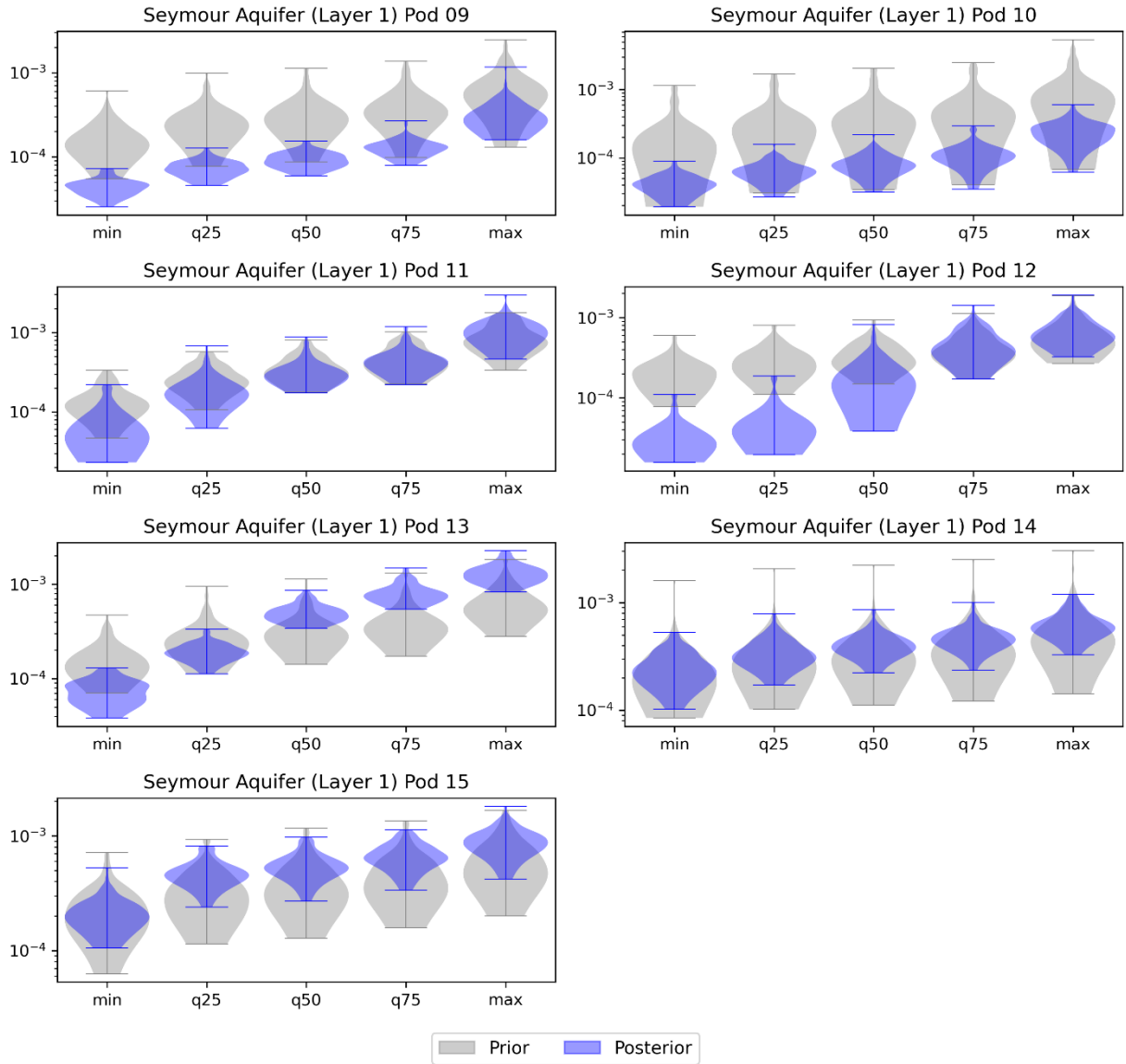


Figure 5.3-10. Violin plots showing the prior and posterior parameter ensembles vertical anisotropy ratios (vertical hydraulic conductivity/horizontal hydraulic conductivity) for pods 9 through 15 in the Seymour Aquifer. Quantile values are in percent.

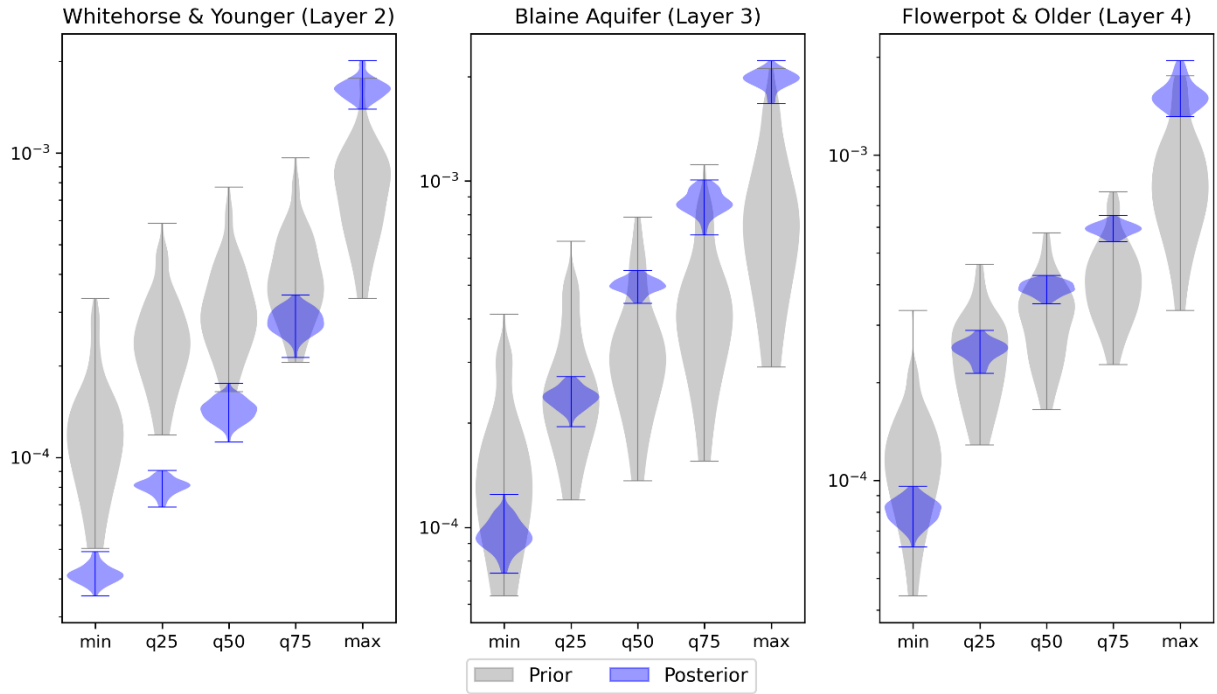


Figure 5.3-11. Violin plots showing the prior and posterior parameter ensembles vertical anisotropy ratios (vertical hydraulic conductivity/horizontal hydraulic conductivity) for model layers 2 through 4. Quantile values are in percent.

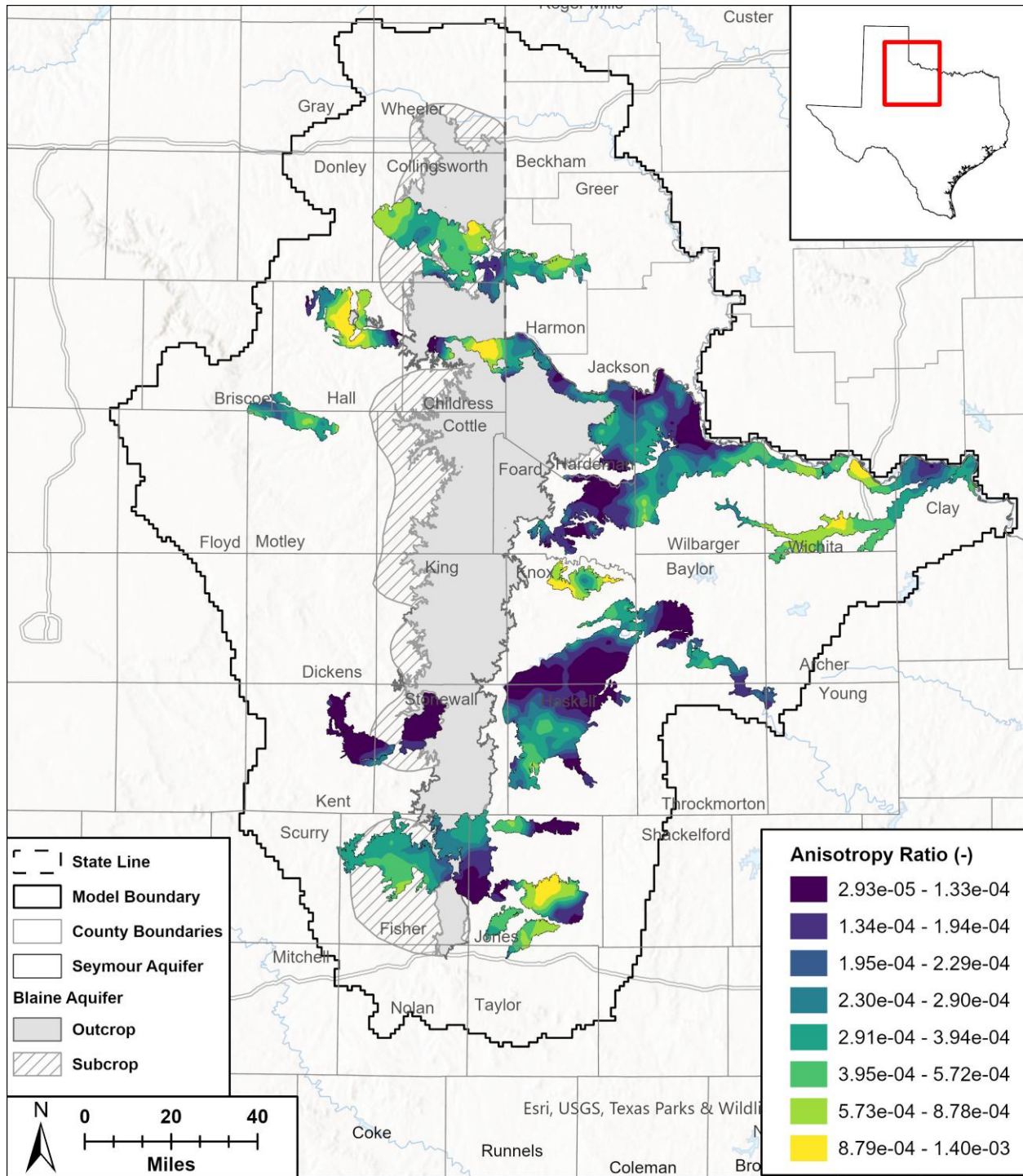


Figure 5.3-12. Calibrated vertical anisotropy ratio (vertical hydraulic conductivity/horizontal hydraulic conductivity) for layer 1, the Seymour Aquifer.

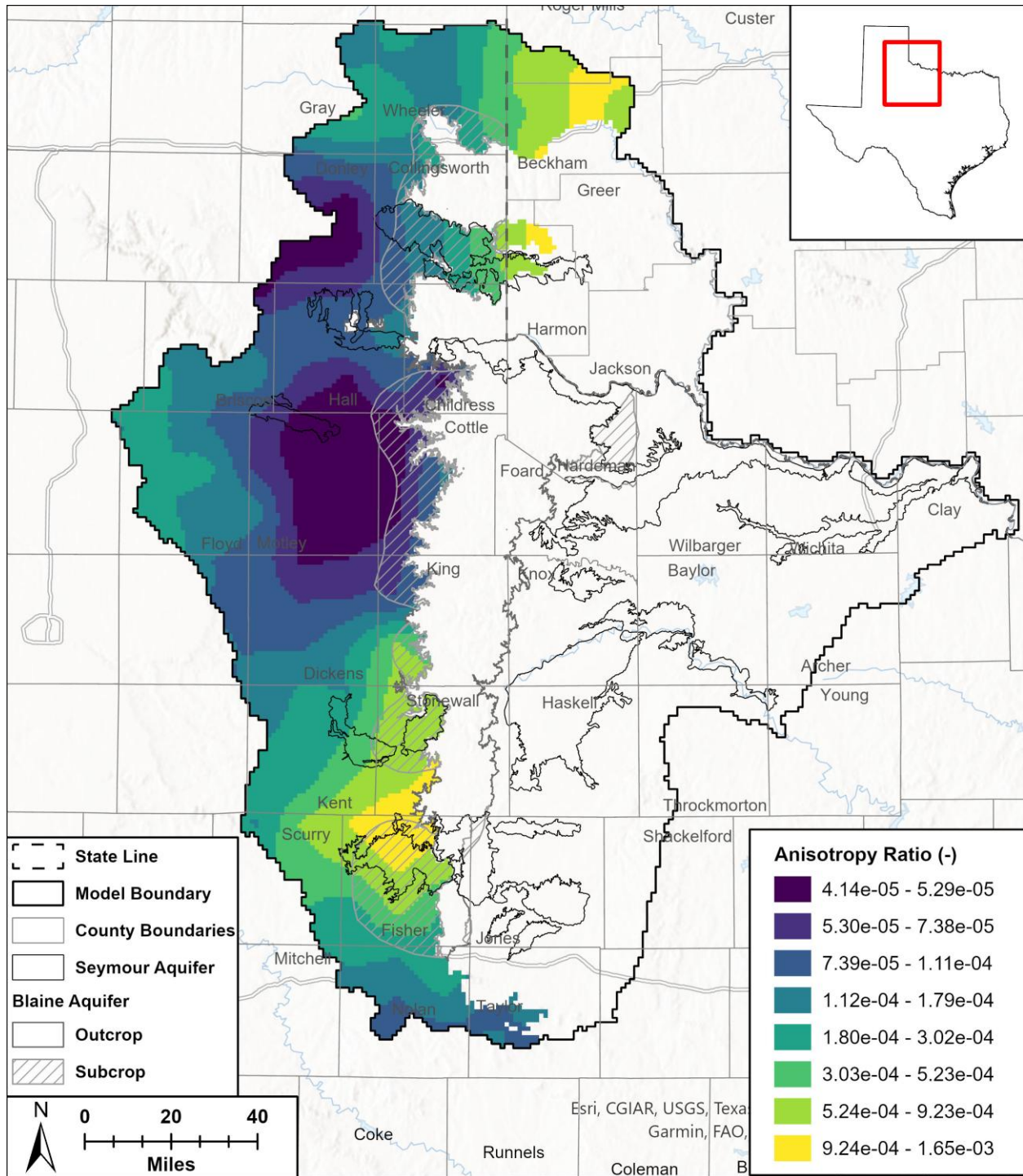


Figure 5.3-13. Calibrated vertical anisotropy ratio (vertical hydraulic conductivity/horizontal hydraulic conductivity) for layer 2, the Whitehorse and Younger Permian Units.

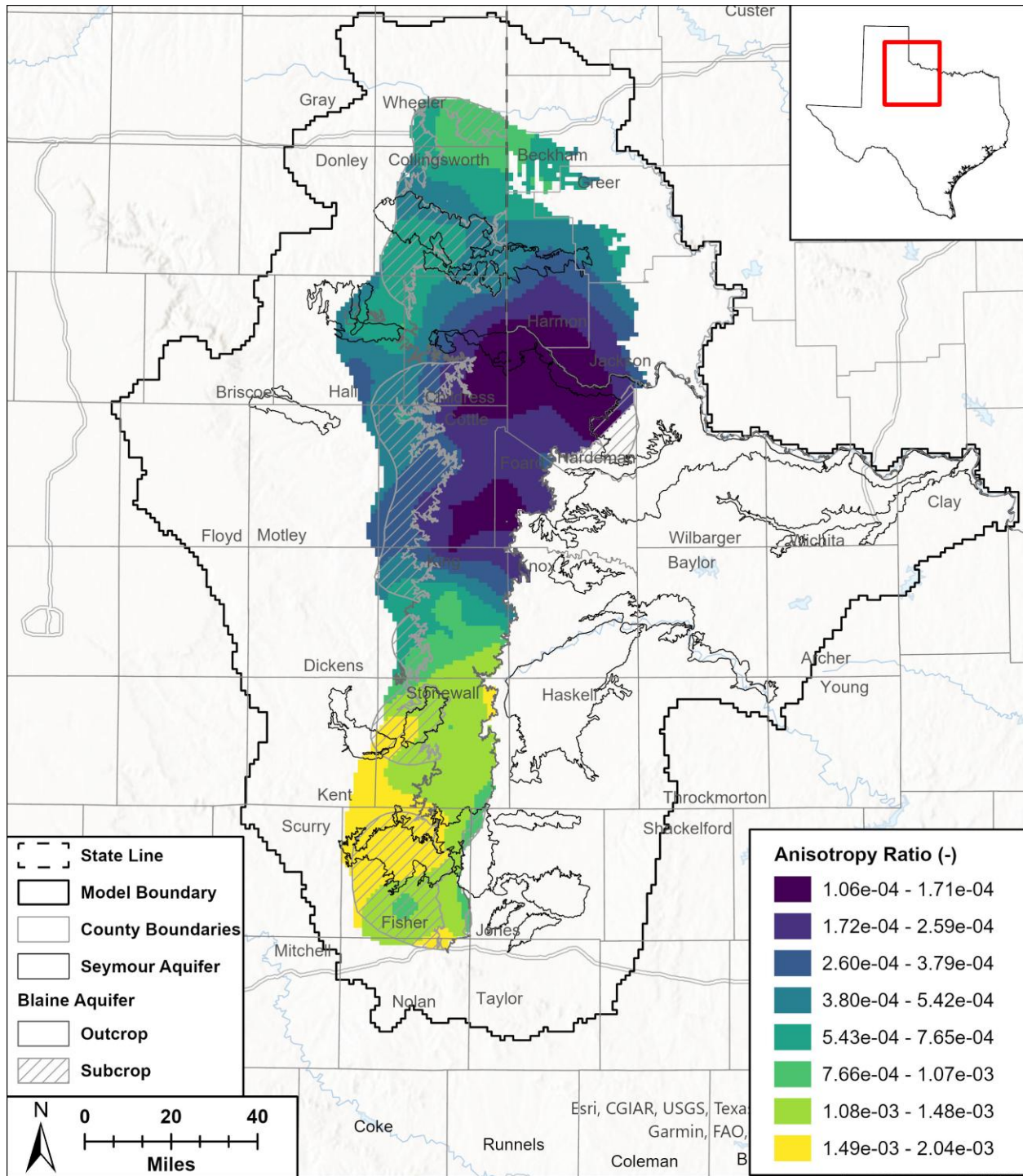


Figure 5.3-14. Calibrated vertical anisotropy ratio (vertical hydraulic conductivity/horizontal hydraulic conductivity) for layer 3, the Blaine Aquifer.

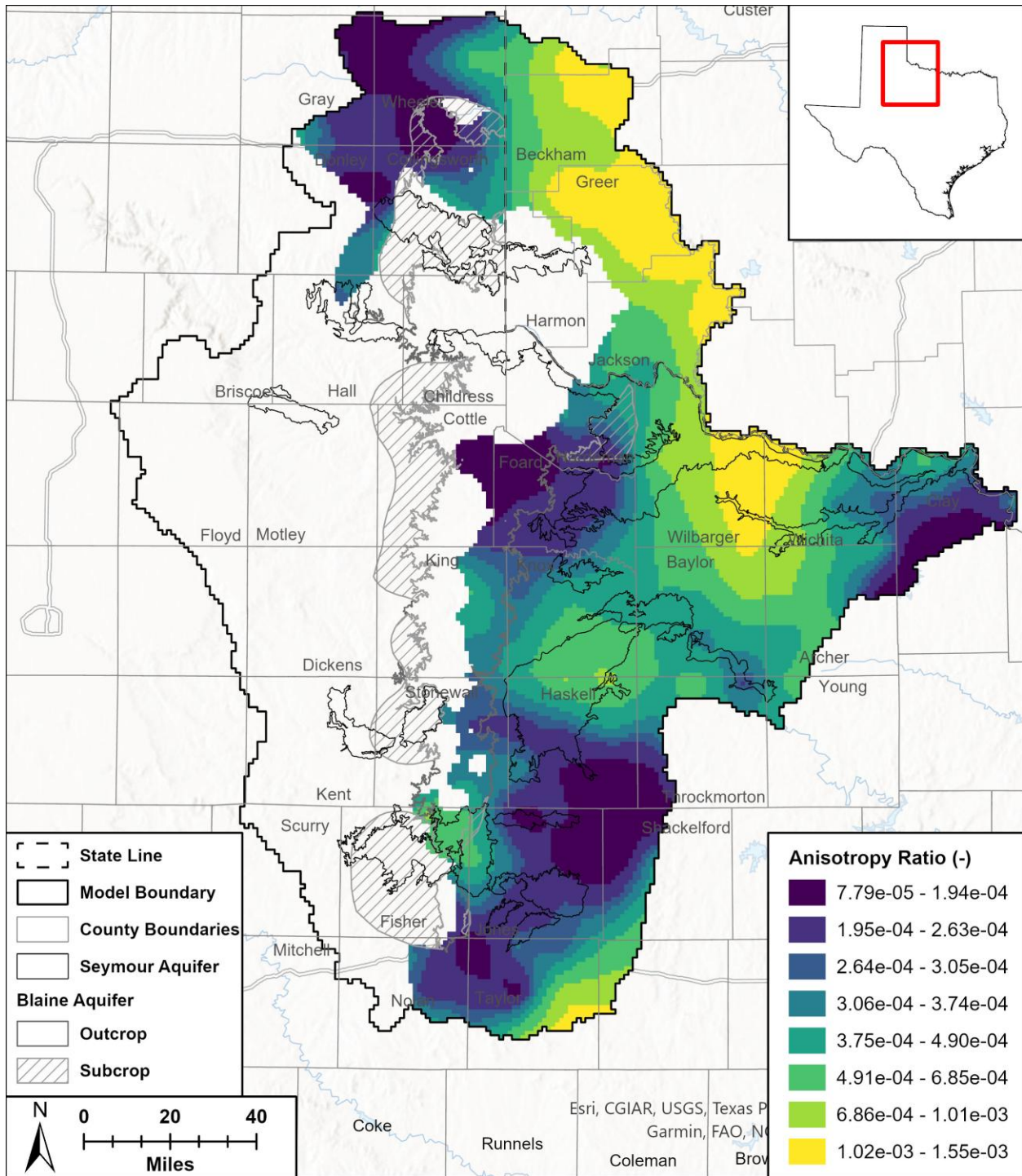


Figure 5.3-15. Calibrated vertical anisotropy ratio (vertical hydraulic conductivity/horizontal hydraulic conductivity) for layer 4, the Flowerpot and Older Permian Units.

Table 5-16. Calibrated base realization vertical anisotropy ratio, vertical hydraulic conductivity to horizontal hydraulic conductivity (-) by layer. Layer 1 = Seymour pods, Layer 2 = Whitehorse and Younger, Layer 3 = Blaine, Layer 4 = Flowerpot and Older.

Layer	mean	median	minimum	maximum	1st Percentile	5th Percentile	25th Percentile	75th Percentile	95th Percentile	99th Percentile
1	3.19E-04	2.70E-04	2.93E-05	1.40E-03	5.08E-05	7.70E-05	1.60E-04	3.99E-04	7.88E-04	1.07E-03
2	2.47E-04	1.45E-04	4.14E-05	1.65E-03	4.20E-05	4.49E-05	8.16E-05	2.75E-04	8.60E-04	1.15E-03
3	6.53E-04	5.06E-04	1.06E-04	2.04E-03	1.26E-04	1.44E-04	2.43E-04	9.32E-04	1.70E-03	1.95E-03
4	4.79E-04	3.87E-04	7.79E-05	1.55E-03	1.16E-04	1.55E-04	2.48E-04	5.96E-04	1.14E-03	1.33E-03

Specific yield and storativity

Storativity and specific yield were parameterized to represent groundwater storage and release processes across the hydrostratigraphic framework of the model. Direct field measurements of aquifer storage properties within the model domain are limited to the single aquifer test in the Seymour Aquifer (Table 4-9), which was withheld from calibration as an independent check on the calibrated parameters (see Comparison with City of Seymour Aquifer Test Data at the end of this section); prior parameter ranges were therefore defined from literature values and regional conceptual understanding. Parameter information for the prior distributions of specific yield and storativity is provided in Table 5-3 and Table 5-4, respectively.

The single site-specific estimate of hydraulic properties available within the model domain, the City of Seymour Well 4B multi-well aquifer test (Table 4 9), served as an independent check on the calibrated parameters (see Comparison with City of Seymour Aquifer Test Data at the end of this section).

Specific yield was parameterized across all four model layers as all model layers were defined as convertible. In the Seymour Aquifer, specific yield was parameterized at the pod scale, with each of the 15 Seymour pods assigned its own pod-scale constant multiplier and spatially distributed pilot point multipliers, mirroring the pod-scale parameterization applied to horizontal and vertical hydraulic conductivity. In the three Permian units, specific yield was parameterized using a single formation-scale constant multiplier and spatially distributed pilot point multipliers applied across each layer's extent. Storativity was parameterized in the Permian unit layers 2, 3, and 4 because storage behavior in the outcropping Seymour Aquifer is generally dominated more by unconfined conditions. For the three Permian units, storativity was parameterized using a single formation-scale constant multiplier and spatially distributed pilot point multipliers, identical in structure to the specific yield parameterization for those layers. Calibration of storativity was allowed only in Permian units that were subcropping or overlain by other hydrostratigraphic units in the model. Calibration bounds allowed storativity and specific yield to vary within hydrogeologically reasonable ranges, with ultimate bounds on storativity spanning several orders of magnitude to accommodate the wide range of confined storage behavior possible across the Permian section.

Posterior specific yield distributions for the Seymour Aquifer are shown in Figure 5.3-16 through Figure 5.3-17. Most Seymour pods calibrate to posterior medians in the approximate range of 0.10 to 0.20, with consistent reduction in posterior spread relative to the prior for the well-observed pods. Pods 6, 8, 10, 11, 12, 14, and 15 show posterior distributions that remain close to the prior with minimal narrowing, consistent with the sparse observation record available to inform calibration for these data-poor pods (discussed in earlier sections). For the three Permian units, posterior specific yield distributions are shown in Figure 5.3-18. The Blaine Aquifer calibrates to a posterior median near 0.22, with the upper percentiles of the posterior pinned at the prior upper bound of 0.22 (Table 5-17); this indicates that calibration was driving toward higher specific yield in the Blaine and that the prior

upper bound was binding for a substantial portion of the ensemble. In contrast, the Whitehorse and Younger Permian and the Flowerpot and Older Permian exhibit substantially lower posterior medians, near 0.13 and 0.14 respectively, with their upper percentiles less constrained by the upper bound.

Posterior storativity distributions for the three Permian units are shown in Figure 5.3-19. All three Permian layers exhibit substantial narrowing of posterior storativity relative to the prior, indicating that calibration extracted meaningful information about confined storage behavior through the transient head response to historical stresses, even in the absence of direct storage observations. Posterior medians for the three Permian units fall in the approximate range of 2×10^{-4} to 7×10^{-4} , with the Flowerpot and Older Permian calibrating to the lowest median storativity (approximately 2×10^{-4}) and the Blaine Aquifer to the highest (approximately 7×10^{-4}). Summary statistics for specific yield and storativity for the base realization are provided in Table 5-17 and Table 5-18, respectively.

The spatial distribution of calibrated specific yield for each model layer for the base realization is shown in Figure 5.3-20 through Figure 5.3-23. In the Seymour Aquifer (Figure 5.3-20), specific yield values range from approximately 0.04 to 0.22 and exhibit substantial heterogeneity within individual pods rather than a coherent inter-pod gradient, consistent with the conceptual model of isolated pods containing internally variable alluvial deposits. The Whitehorse and Younger Permian (Figure 5.3-21) exhibits large areas near the upper bound of approximately 0.22 concentrated across the central portion of the layer's extent and lower values (approximately 0.05 to 0.10) concentrated in the northern and southern margins. The Blaine Aquifer (Figure 5.3-22) calibrates to values near the upper bound of 0.22 across most of the aquifer extent, with a low-specific-yield band (approximately 0.08 to 0.12) running through the central-western portion of the aquifer and a small additional low-value localized region in the northern subcrop. The Flowerpot and Older Permian (Figure 5.3-23) exhibits the lowest specific yield values across the northern portion of the layer's extent and along a central column, while the highest values (approaching the upper bound of 0.22) are concentrated across the eastern and southern portions of the layer.

The spatial distribution of calibrated storativity for the Permian units for the base realization is shown in Figure 5.3-24 through Figure 5.3-26. In the Whitehorse and Younger Permian (Figure 5.3-24), storativity is shown only in the subcrop areas of the model where the layer is confined and ranges from approximately 5×10^{-5} to 5×10^{-3} , with the highest values concentrated in the southernmost subcrop and lower values distributed across the central and northern subcrop areas. The Blaine Aquifer (Figure 5.3-25) exhibits storativity values ranging from approximately 5×10^{-6} to 6×10^{-3} , with the highest values concentrated in the northern portion of the aquifer and in localized parts of the southern extent, and the lowest values dominating the central portion of the aquifer. The Flowerpot and Older Permian (Figure 5.3-26) displays the most heterogeneous storativity distribution, with values ranging from approximately 8×10^{-6} to 6×10^{-3} and a spatial pattern in which higher values cluster in the southern

extent and along an eastern band, while lower values dominate the northern portion of the layer.

Because storage parameters are only indirectly constrained by the historical head record, estimates of groundwater in storage or recoverable volumes in the Seymour and Blaine aquifers should be interpreted with appropriate caution.

Comparison with City of Seymour Aquifer Test Data

The calibrated hydraulic properties for Pod 7 in the Seymour Aquifer were compared against the City of Seymour Well 4B aquifer test results presented in Table 4-9 as an example of an independent check on the calibration. Pod 7 contains the test location and is one of the most data-rich pods in the model, supporting a meaningful comparison between locally measured aquifer properties and regionally calibrated model parameters. The comparison is between point-scale test values at a single well screen and posterior ensemble statistics aggregated across all model cells comprising Pod 7, and consistency between the two should be interpreted in that context.

The calibrated Pod 7 median horizontal hydraulic conductivity for the posterior ensemble of approximately 503 feet per day is in the same order of magnitude as the aquifer test estimate of 662 feet per day (Table 5-12). Calibrated specific yield in Pod 7 for the posterior ensemble (median 0.12) is similar to the aquifer test storage coefficient of 0.11 for Well 4B. These two comparisons indicate that the regionally calibrated Pod 7 properties are consistent with the independent field-scale aquifer test for the dominant controls on horizontal flow and storage.

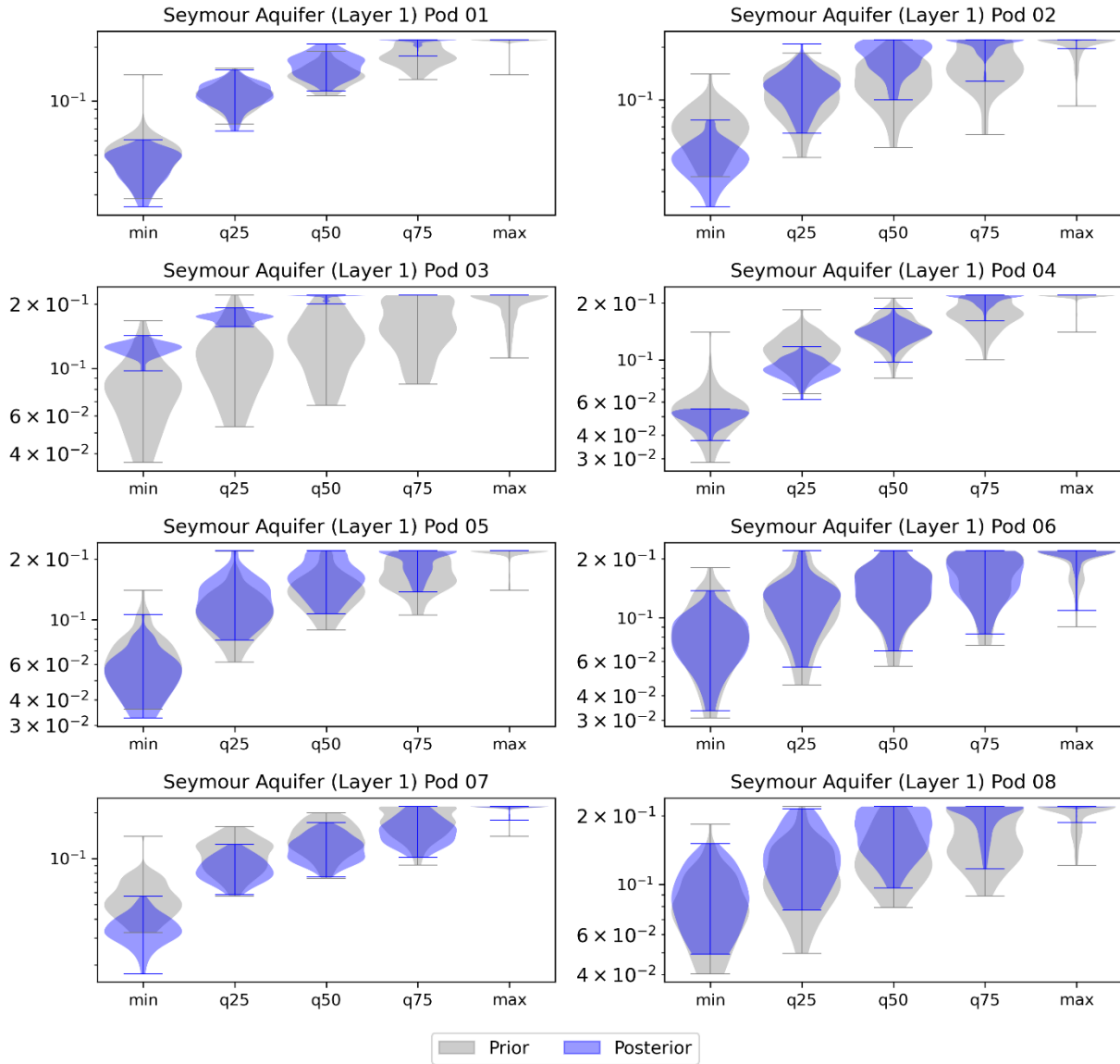


Figure 5.3-16. Specific yield prior (gray) versus posterior (blue) violin plots for pods 1 through 8 in the Seymour Aquifer. Specific yield values are unitless (y axis). Values on the x-axis are percentages.

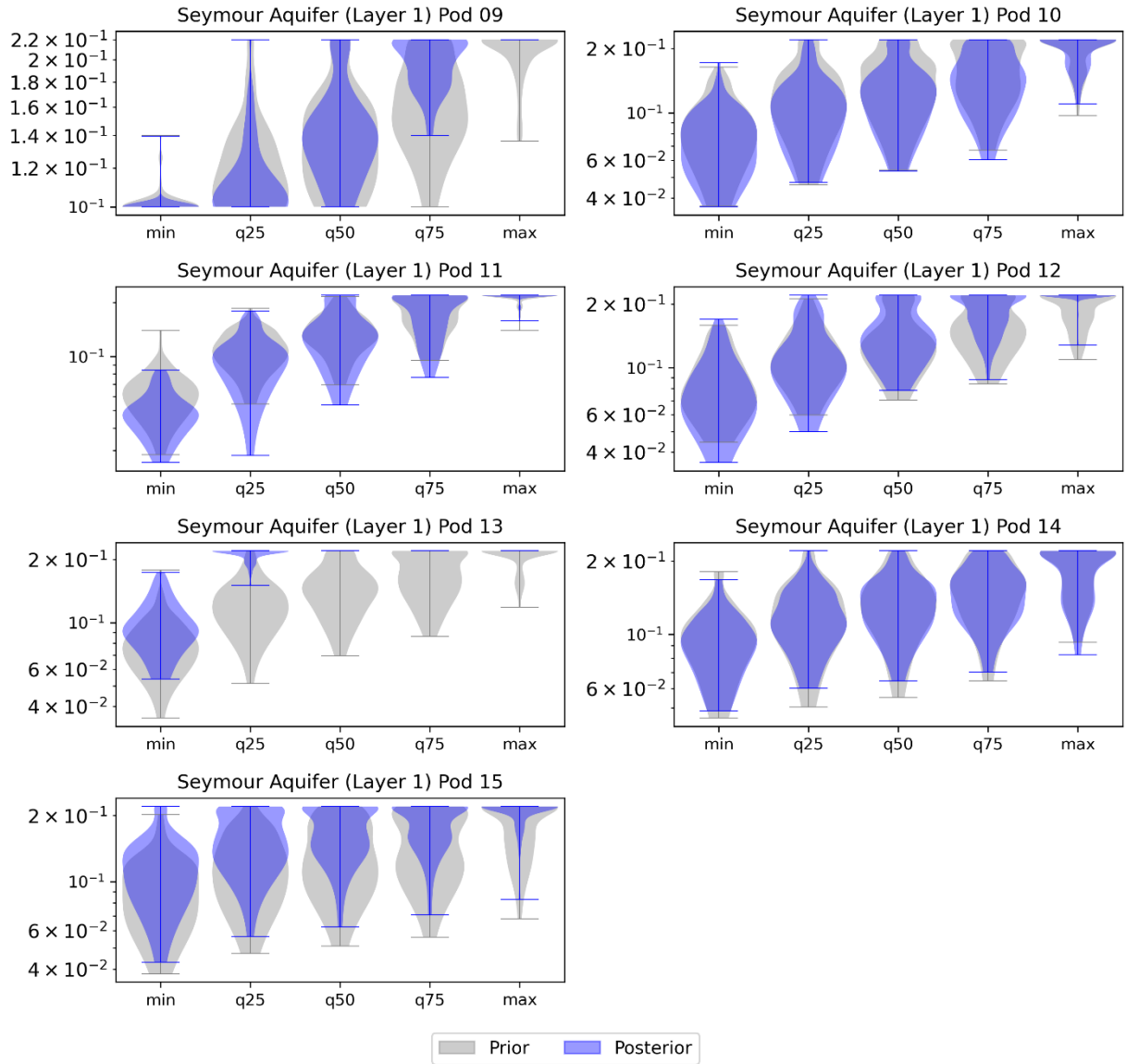


Figure 5.3-17. Specific Yield prior (gray) versus posterior (blue) violin plots for pods 9 through 15 in the Seymour Aquifer. Specific yield values are unitless (y axis). Values on the x-axis are percentages.

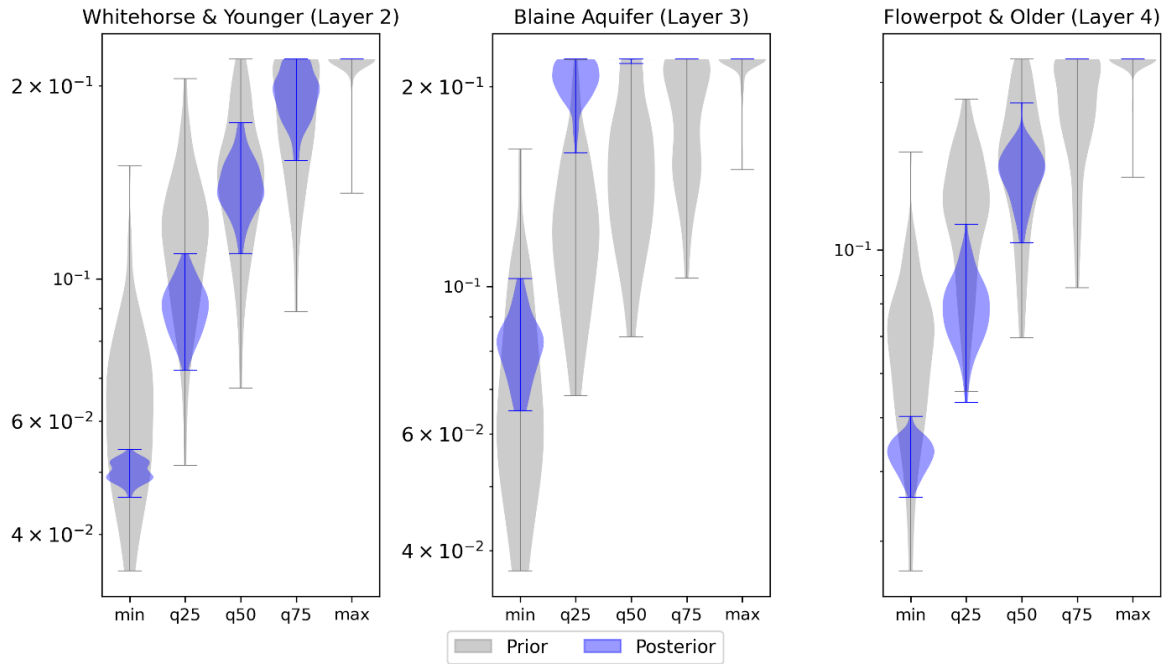


Figure 5.3-18. Specific Yield prior (gray) versus posterior (blue) violin plots for model layers 2 through 4. Specific yield values are unitless (y axis). Values on the x-axis are percentages.

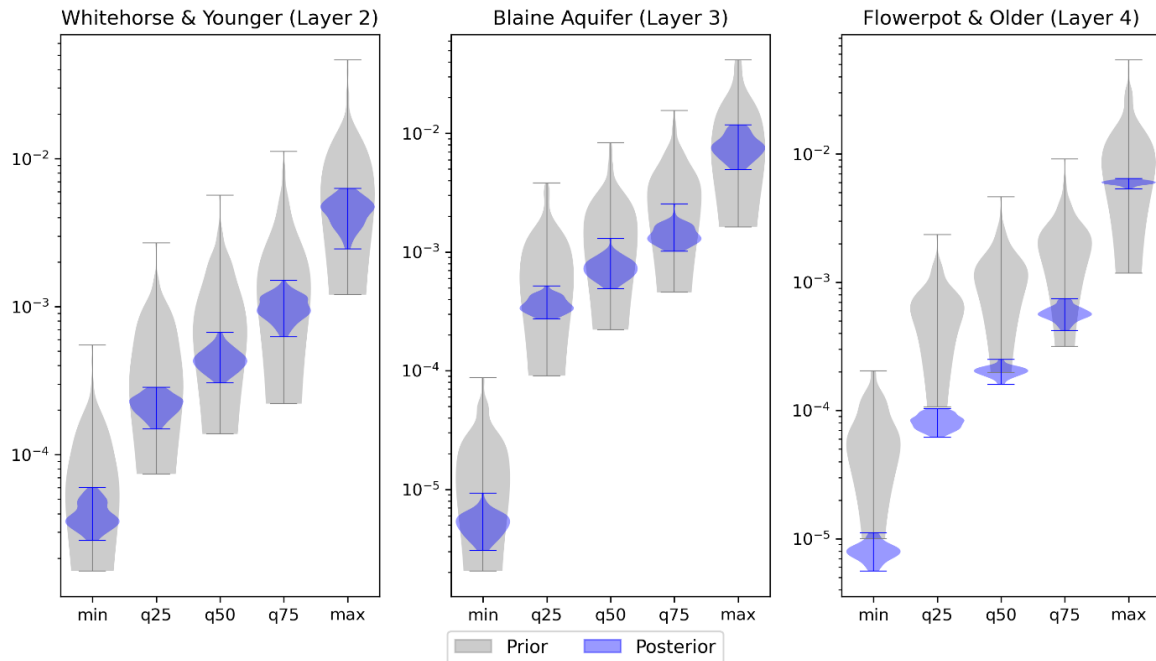


Figure 5.3-19. Storativity prior (gray) versus posterior (blue) violin plots. Storativity values are unitless (y axis). Values on the x-axis are percentages.

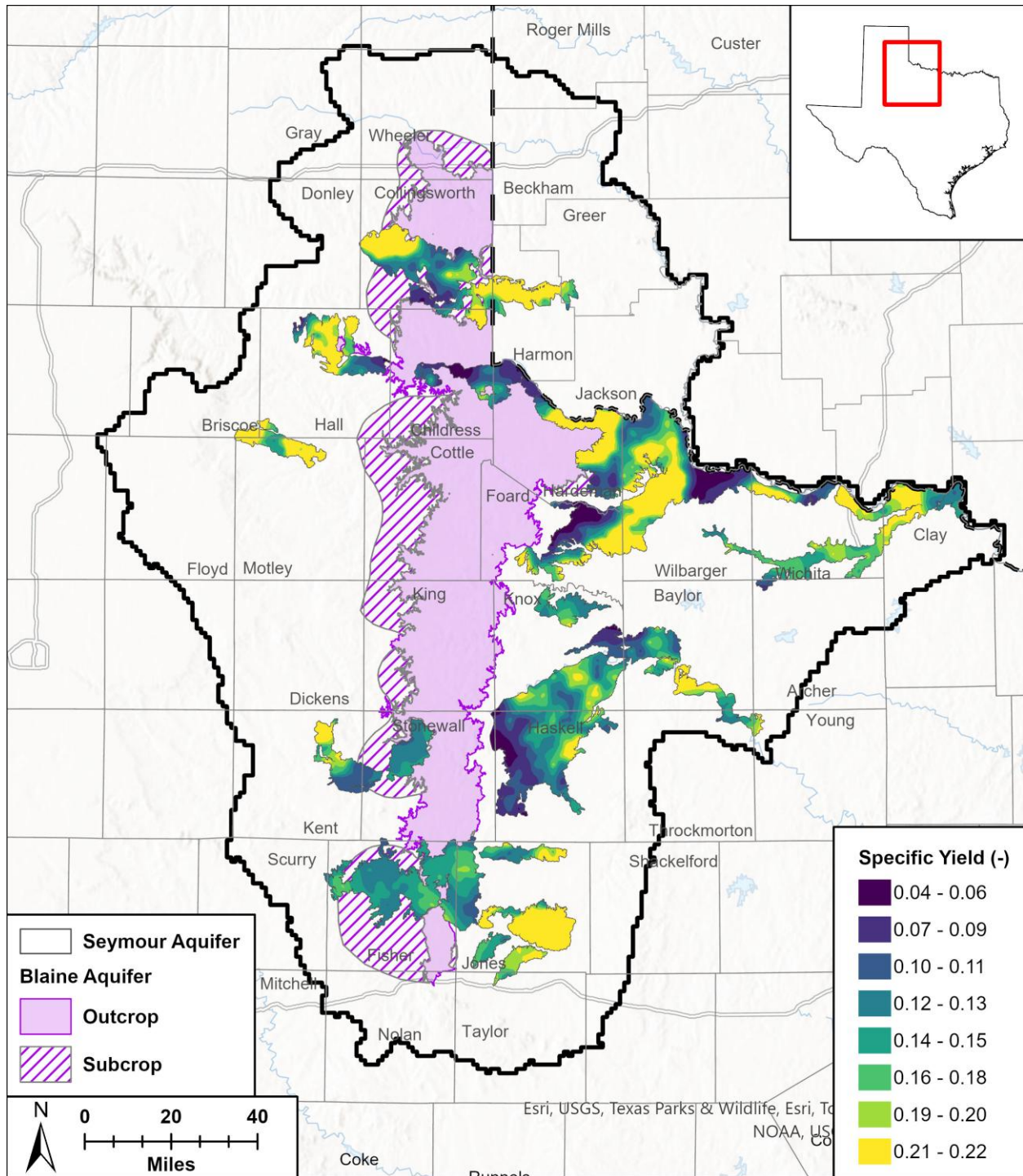


Figure 5.3-20. Calibrated specific yield for layer 1, the Seymour Aquifer.

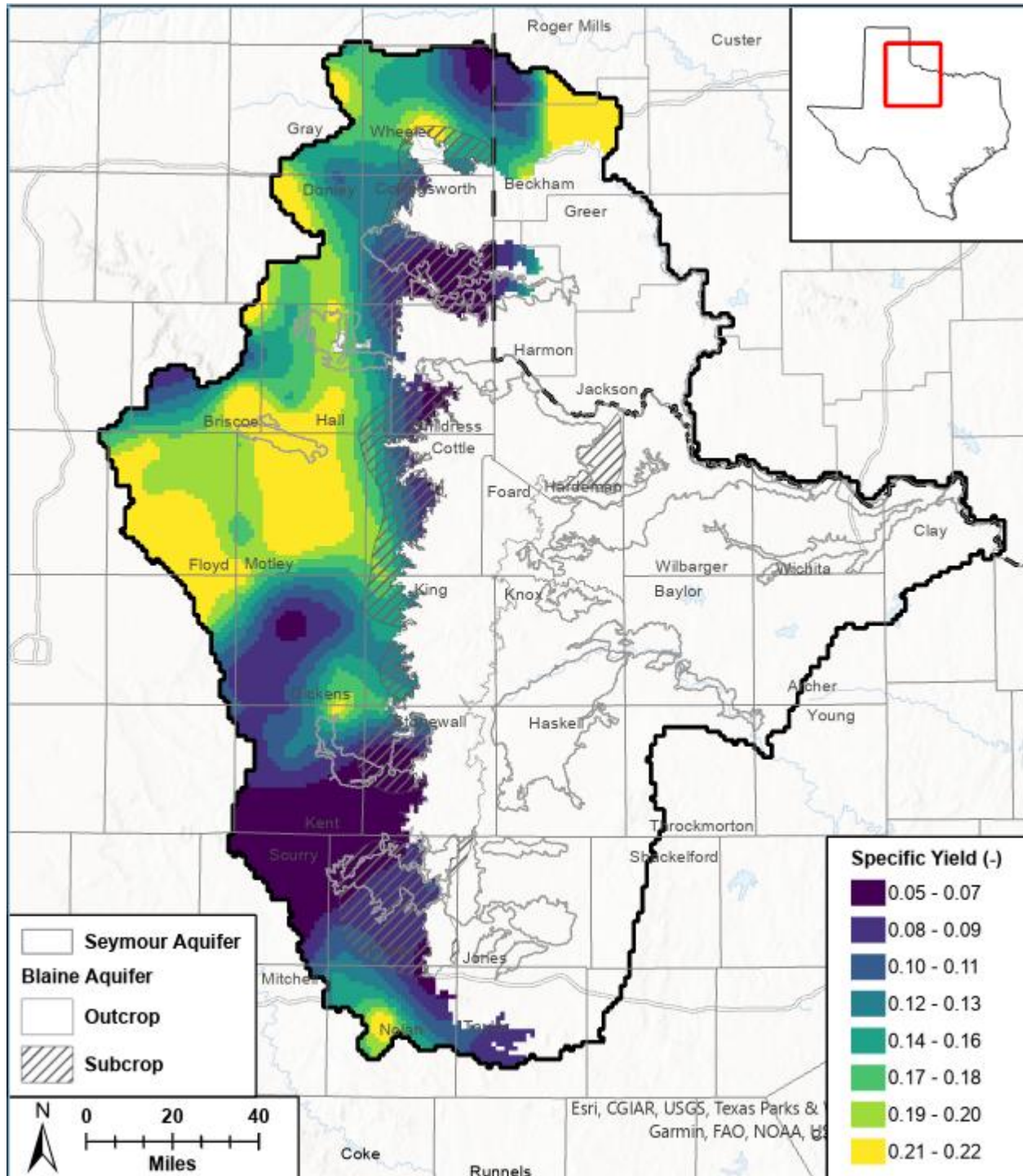


Figure 5.3-21. Calibrated specific yield for layer 2, the Whitehorse and Younger formation.

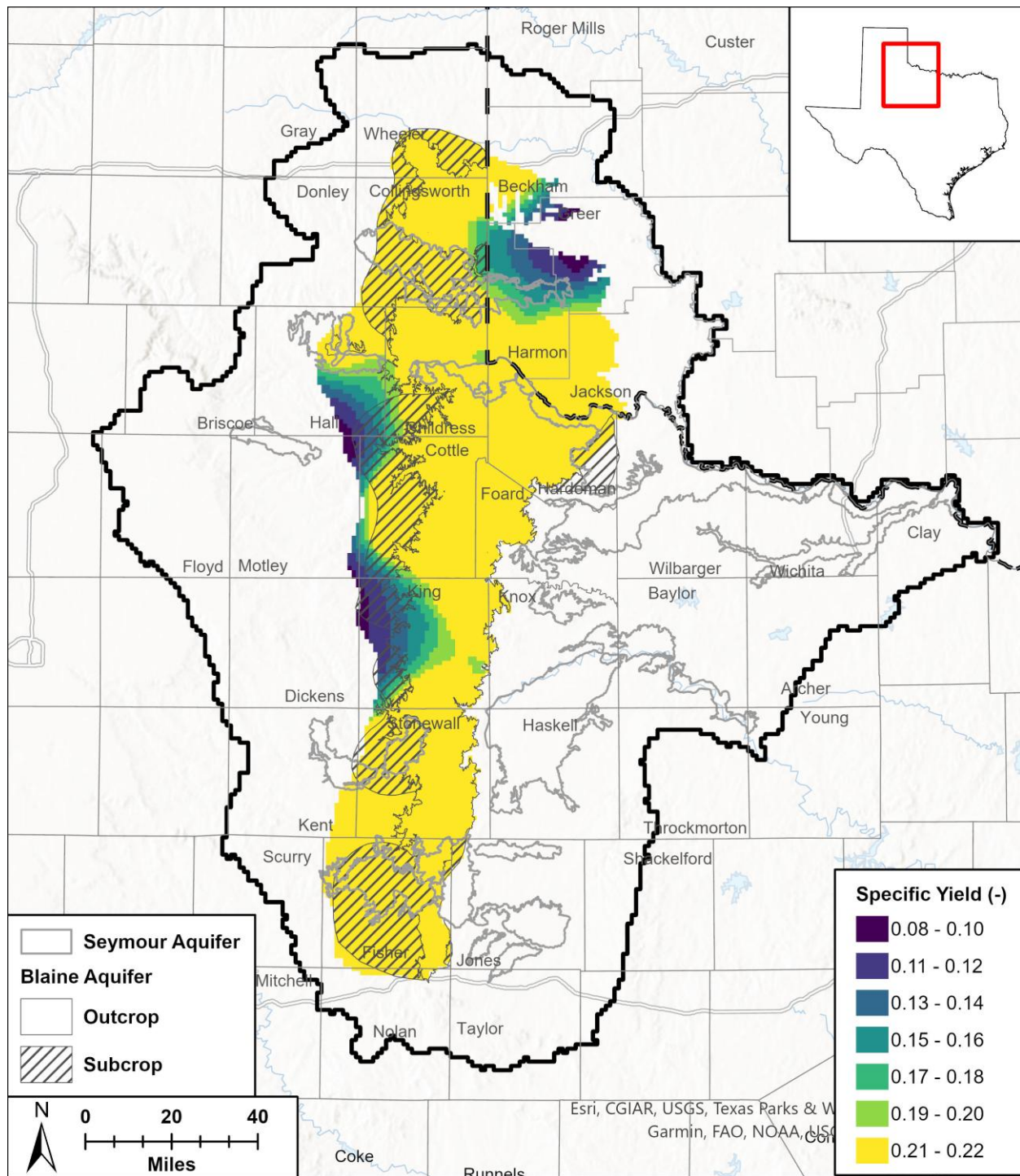


Figure 5.3-22. Calibrated specific yield for layer 3, the Blaine Aquifer.

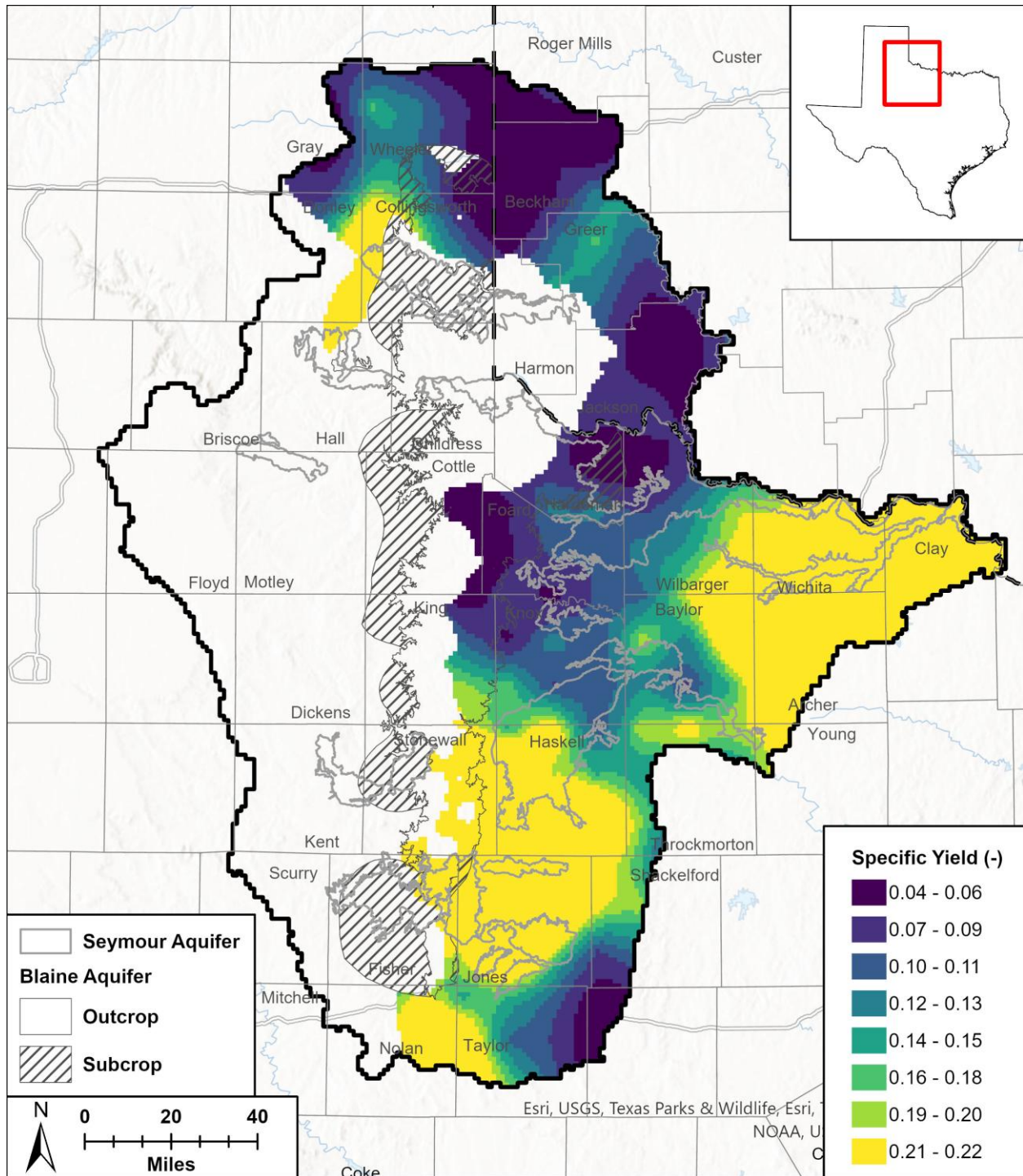


Figure 5.3-23. Calibrated specific yield for layer 4, the Flowerpot and Older formation.

Table 5-17. Calibrated Base Realization Specific Yield, Sy (-) by Layer. Layer 1 = Seymour pods, Layer 2 = Whitehorse and Younger, Layer 3 = Blaine, Layer 4 = Flowerpot and Older.

Layer	mean	median	minimum	maximum	1st Percentile	5th Percentile	25th Percentile	75th Percentile	95th Percentile	99th Percentile
1	0.15	0.15	0.04	0.22	0.05	0.07	0.11	0.19	0.22	0.22
2	0.13	0.13	0.05	0.22	0.05	0.05	0.09	0.18	0.22	0.22
3	0.21	0.22	0.08	0.22	0.10	0.13	0.22	0.22	0.22	0.22
4	0.14	0.14	0.04	0.22	0.05	0.05	0.08	0.22	0.22	0.22

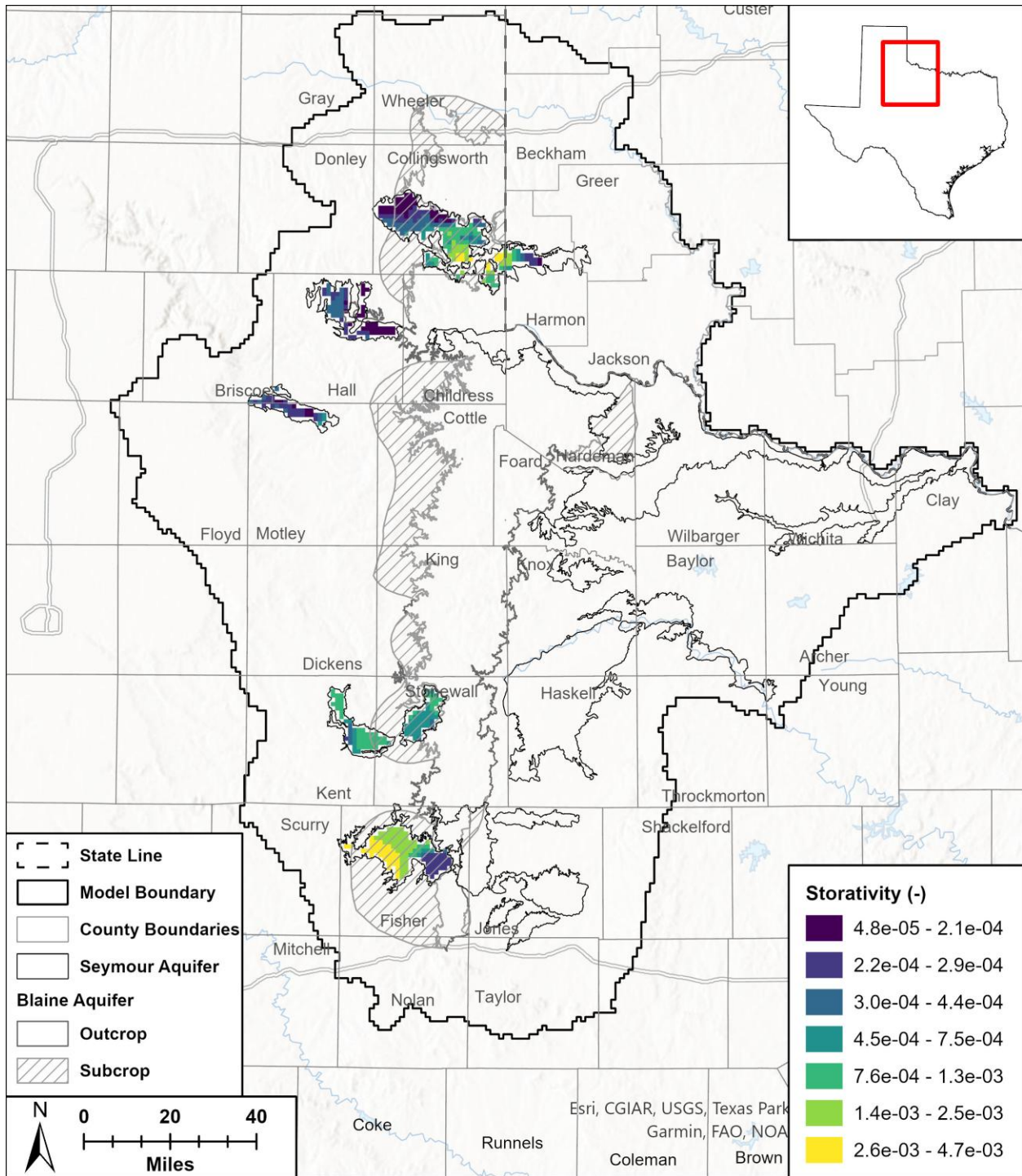


Figure 5.3-24. Calibrated storativity for layer 2, the Whitehorse and Younger Permian units.

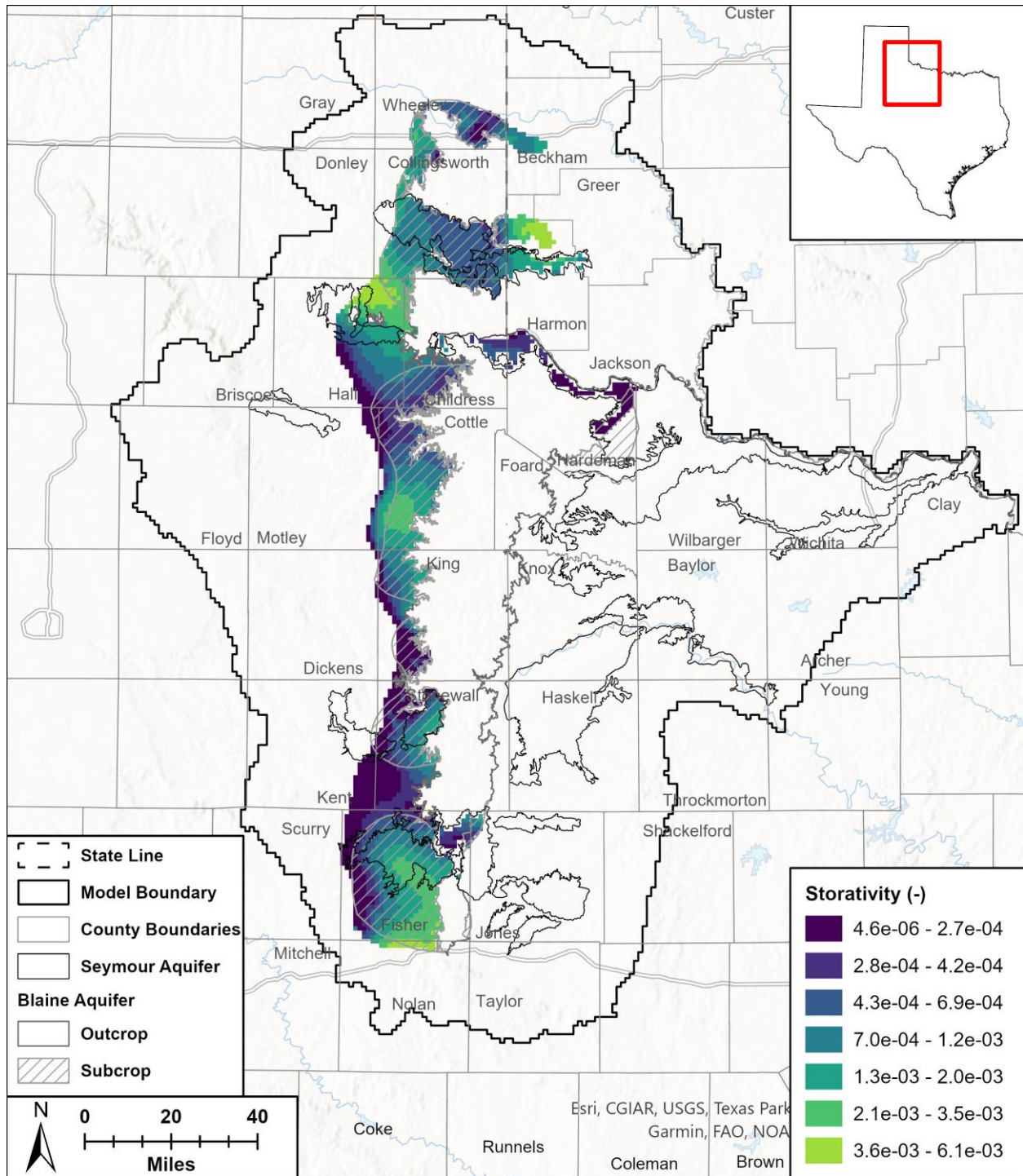


Figure 5.3-25. Calibrated storativity for layer 3, the Blaine Aquifer.

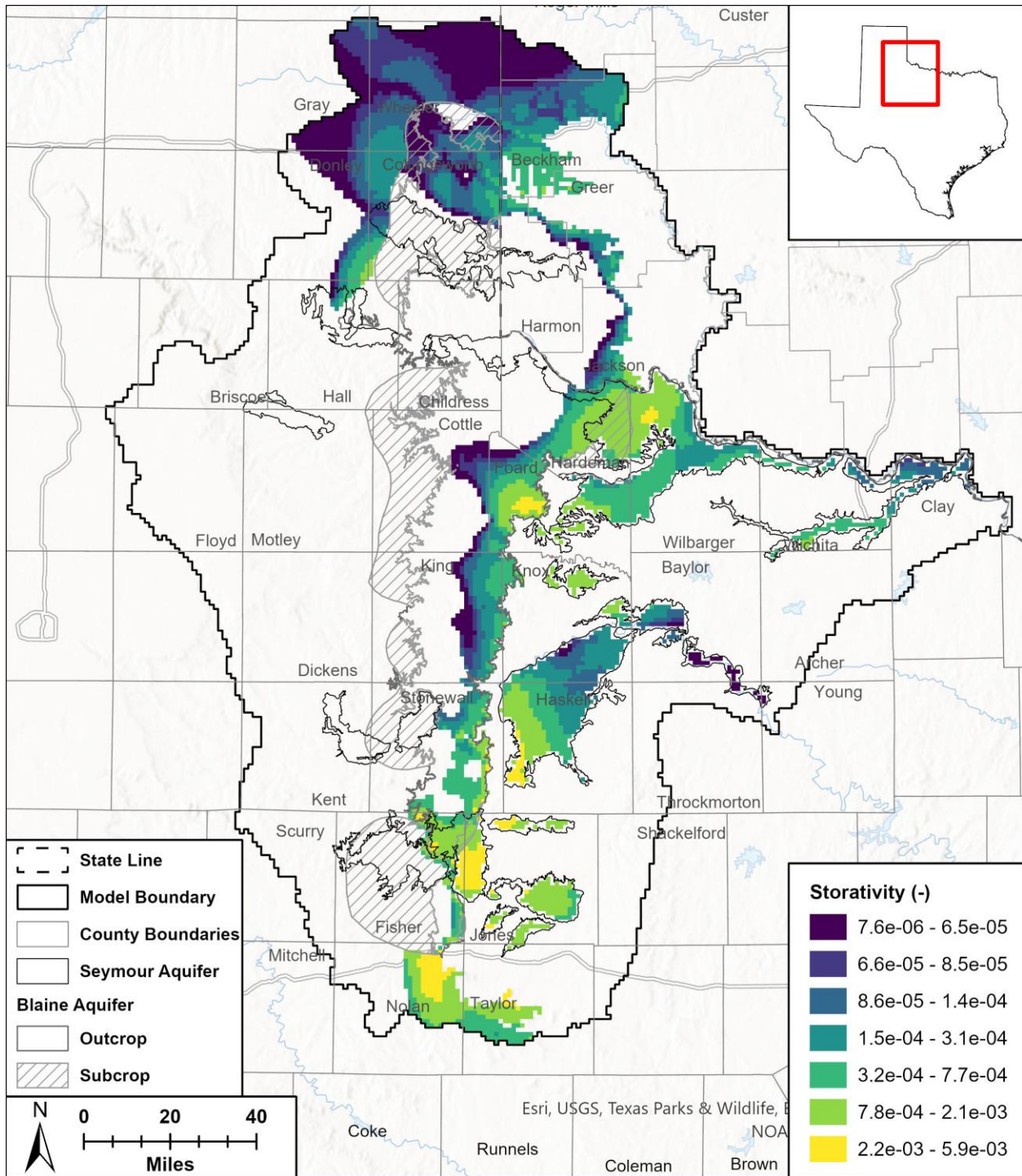


Figure 5.3-26. Calibrated storativity for layer 4, the Flowerpot and Older Permian units.

Table 5-18. Calibrated base realization storativity (unitless) by layer. Layer 2 = Whitehorse and Younger, Layer 3 = Blaine, Layer 4 = Flowerpot and Older.

Layer	mean	median	min	max	1st Percentile	5th Percentile	25th Percentile	75th Percentile	95th Percentile	99th Percentile
2	9.10E-04	5.47E-04	4.79E-05	4.68E-03	6.11E-05	9.77E-05	2.55E-04	1.18E-03	2.90E-03	3.75E-03
3	9.81E-04	6.73E-04	4.55E-06	6.06E-03	2.04E-05	4.53E-05	3.58E-04	1.29E-03	2.90E-03	4.55E-03
4	4.79E-04	2.03E-04	7.64E-06	5.91E-03	1.42E-05	2.82E-05	8.13E-05	5.97E-04	1.81E-03	3.04E-03

Recharge

Simulated groundwater levels in the calibrated model are highly sensitive to recharge estimates across the study area. Recharge and hydraulic conductivity are strongly correlated parameters; changes in one can be compensated by corresponding changes in the other while still producing similar simulated groundwater levels. Because of this correlation, recharge parameterization was designed to allow calibration flexibility while preserving conceptual recharge patterns and spatial distribution.

Steady-state recharge was parameterized using spatially distributed base recharge rates applied within the Seymour Aquifer (layer 1) at the pod scale, reflecting that each pod represents a distinct Seymour outcrop area with its own infiltration characteristics. Deeper units (layers 2–4) were parameterized using both a formation-scale constant multiplier and spatially distributed pilot point multipliers, allowing recharge to vary within each Permian unit while maintaining broad consistency with the conceptual formation-scale recharge pattern. Prior base recharge values ranged from approximately 0.2 to 2.0 inches per year across Seymour pods, with lower values assigned to the deeper hydrostratigraphic units; 0.2 inch per year in layers 2 and 4; and 0.38 inch per year in the Blaine Aquifer (layer 3). Adjustable parameters included a global steady-state damping factor controlling topography-based recharge scaling, pod-specific base recharge multipliers in layer 1, and both formation-scale and spatially distributed pilot point multipliers for layers 2–4. Calibration bounds generally allowed recharge to vary by plus or minus 50 percent, with added flexibility in selected pods where recharge uncertainty was greater. A separate treatment was applied along the lateral margins of the Seymour Aquifer pods, where the digitized aquifer boundary and the 10-meter digital elevation model are locally inconsistent, producing cells that dewatered during preliminary steady-state runs. Recharge in these cells was assigned using a supplemental routine that estimates the rate required to maintain saturation, and is therefore specified directly rather than through the multipliers described above.

Transient recharge was generated by scaling the calibrated steady-state recharge distribution using annual precipitation variability derived from PRISM datasets spanning 1960–2020. For each stress period, annual precipitation totals were converted to multipliers relative to the long-term 1961–1990 normal, and those multipliers were applied to the steady-state recharge field through a global damping factor. The damping factor was treated as an adjustable calibration parameter, allowing calibration to control the magnitude of climate-driven recharge variability applied across the model domain. Parameter information for defining the prior distributions of recharge is provided in Table 5-7.

Figure 5.3-27 presents the prior and posterior distributions of total annual recharge volumes aggregated across all layers during the historical simulation period, showing a consistent shift toward higher recharge volumes in the posterior. Figure 5.3-28 shows the average recharge rate time series for the prior and posterior ensembles during the historical period for the entire model domain. The posterior ensemble

tracks consistently above the prior throughout the entire 1959–2020 record, with year-to-year variability in both ensembles reflecting the same precipitation-driven pattern. Year-by-year recharge rate statistics for the posterior ensemble are provided in Table 5-19. The posterior ensemble-averaged recharge rate ranges from approximately 1.90 inches per year (in 2011, the driest year of the historical record) to approximately 2.25 inches per year (in 2015), with a period mean of approximately 2.07 inches per year (Table 5-19). Figure 5.3-29 shows average recharge rates by model layer for the base realization throughout the historical period. The Seymour Aquifer exhibits the highest recharge rates, fluctuating between approximately 2.1 and 2.5 inches per year and reflecting the year-to-year precipitation variability characteristic of the Seymour outcrop areas. The Whitehorse and Younger Permian and the Blaine Aquifer calibrate to nearly identical recharge rates throughout the historical period, both ranging between approximately 0.5 and 0.7 inches per year, while the Flowerpot and Older Permian remains the lowest at approximately 0.25 to 0.30 inches per year. This layer-by-layer pattern is consistent with the conceptual model in which the Seymour Aquifer receives the majority of recharge through its surficial alluvial deposits, while the deeper, lower permeability Permian units receive limited recharge through their respective outcrop areas.

The spatial distribution of calibrated steady-state recharge rates in the Seymour Aquifer is shown in Figure 5.3-30. Across the pod interiors, calibrated recharge ranges from approximately 0.02 to 5 inches per year. Lower rates (generally less than about 2 inches per year) are widespread across the smaller and southern pods, whereas the highest rates (locally exceeding 3 to 5 inches per year) are concentrated in the cores of the larger pods. This pattern is consistent with the conceptual understanding that diffuse recharge in the Seymour Aquifer occurs preferentially in topographically higher interstream areas (Ewing and others, 2004; Jones and others, 2012). The highest rates in the Seymour Aquifer occur locally along the lateral pod margins, where recharge was assigned to maintain saturation rather than derived from the pod-scale multipliers. Because the Seymour Aquifer is discretized at 1/8 mile, this inflow is expressed as a high rate over a very small area; aggregated to the 1-mile grid, total steady-state recharge does not exceed 22 inches per year (Figure 5.3-31). These rates represent seepage-face discharge and lateral inflow at the pinch-out rather than diffuse, precipitation-derived recharge. Because the margin cells are thin, low-lying, and outside the productive portions of the aquifer, estimates of modeled available groundwater and evaluation of desired future conditions are unaffected.

Calibrated steady-state recharge rates for the three Permian units are shown in Figure 5.3-32, Figure 5.3-33 and Figure 5.3-34 for layers 2, 3, and 4, respectively. The Whitehorse and Younger Permian calibrates to a relatively uniform field of approximately 0.5 to 1.0 inches per year across most of the layer's western extent, with localized hot spots reaching above 2 inches per year along the Blaine subcrop boundary. The Blaine Aquifer exhibits the most spatially variable Permian-layer recharge field, with a pronounced central hot spot approaching 5 inches per year and lower rates of approximately 0.01 to 0.5 inches per year toward the southern outcrop margin. The Flowerpot and Older Permian exhibits the narrowest range of the three

Permian units, spanning approximately 0.01 to 0.6 inches per year, with the highest values concentrated across the eastern portion of the layer's extent. Across all three Permian units, posterior recharge rates remain low relative to the Seymour, consistent with the reduced infiltration capacity of these deeper, lower permeability units.

Aside from the pod-margin cells described above, posterior recharge values remained within prescribed parameter bounds and within the conceptual range expected for the system. The impact of calibrated recharge volumes on overall water balances is further examined in Section 5.3.4, and recharge rate sensitivity is discussed in detail in Chapter 6.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

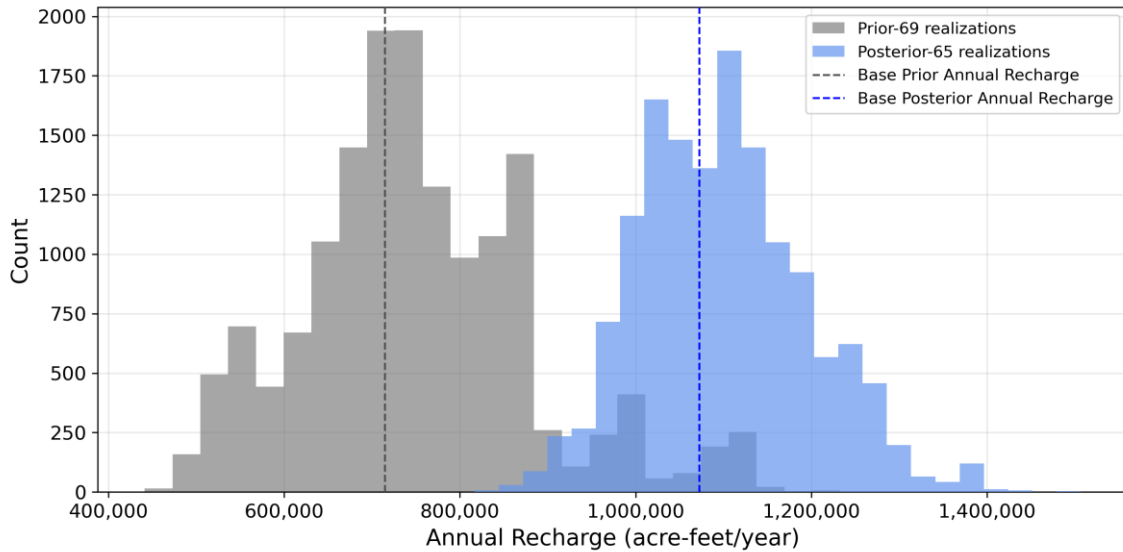


Figure 5.3-27. Prior (gray) and posterior (blue) distributions of total annual recharge volumes during historical simulation period. Base of prior (black dashed) and posterior (blue dashed) are displayed.

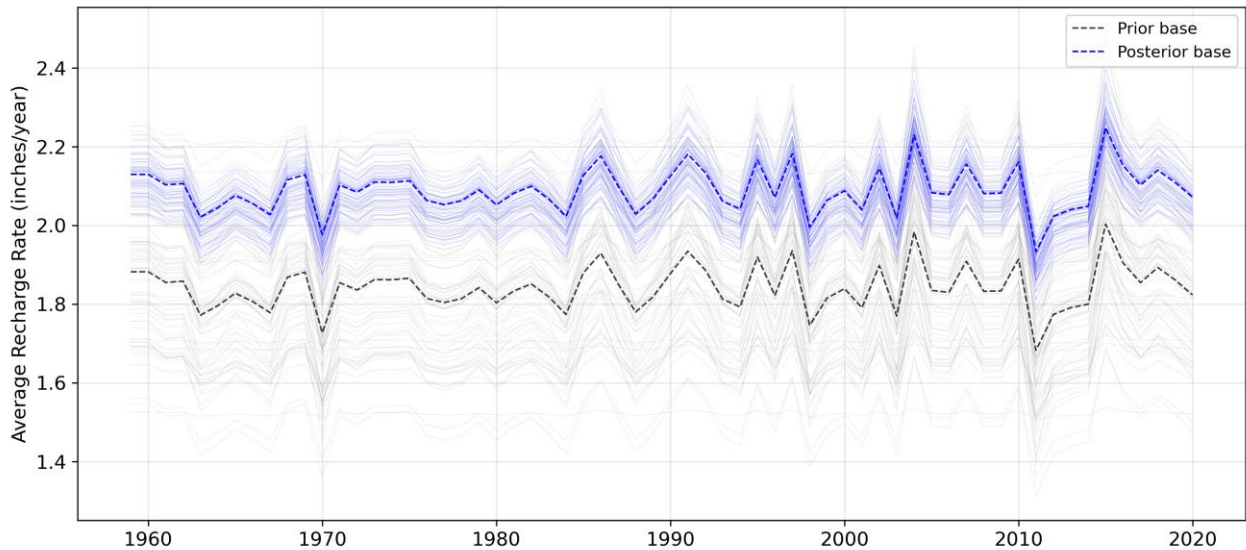
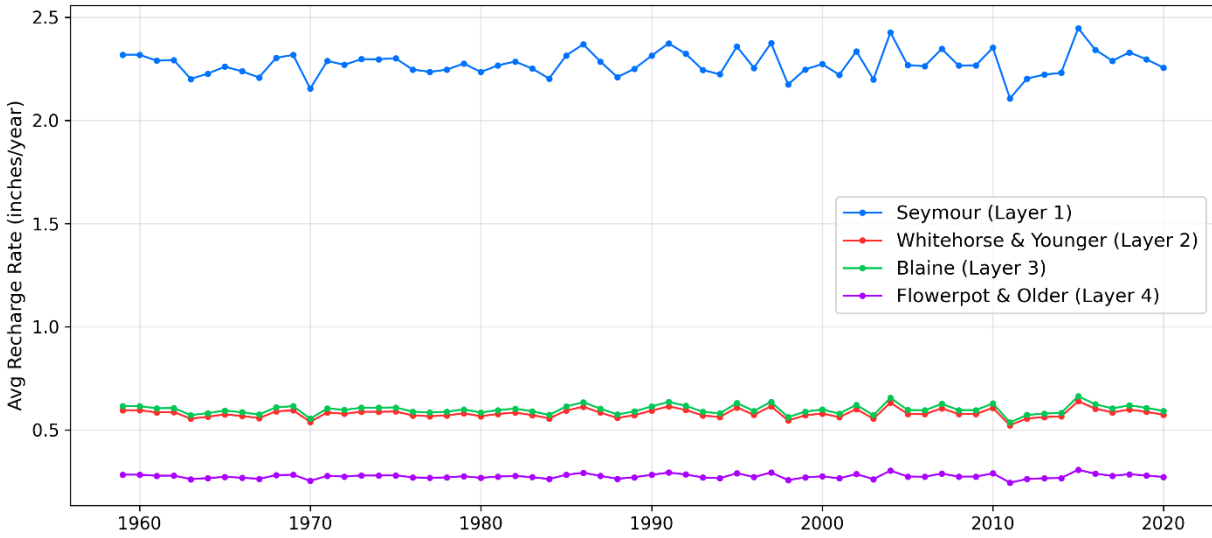


Figure 5.3-28. Prior (gray) and posterior (blue) distributions of average recharge rates during historical simulation period. Base of prior (black dashed) and posterior (blue dashed) are displayed.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers



Note: Avg = average

Figure 5.3-29. Average recharge rates (inches per year) by layer for base realization during historical simulation period.

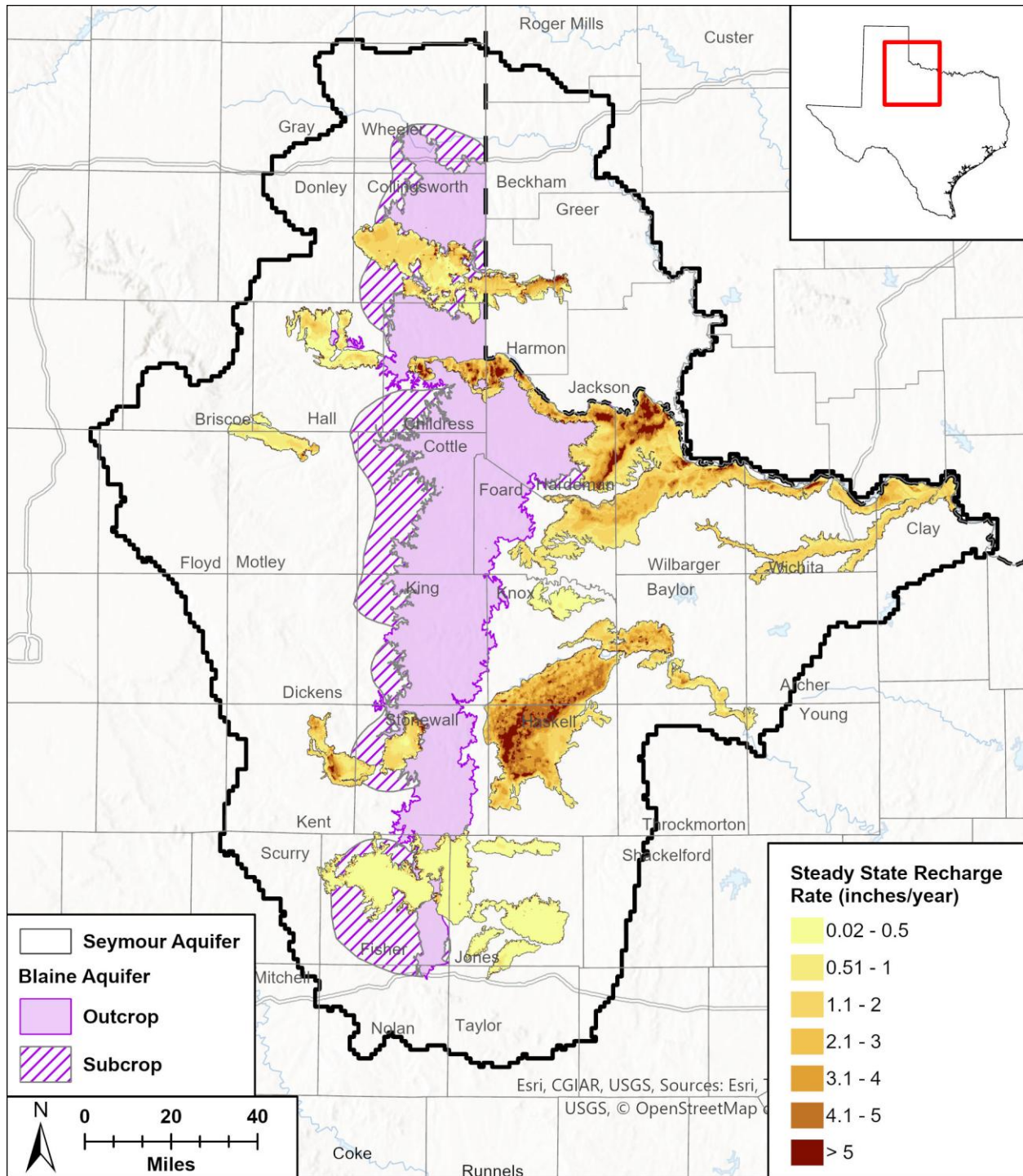


Figure 5.3-30. Calibrated steady-state recharge rate map (in inches per year) in layer 1, the Seymour Aquifer.

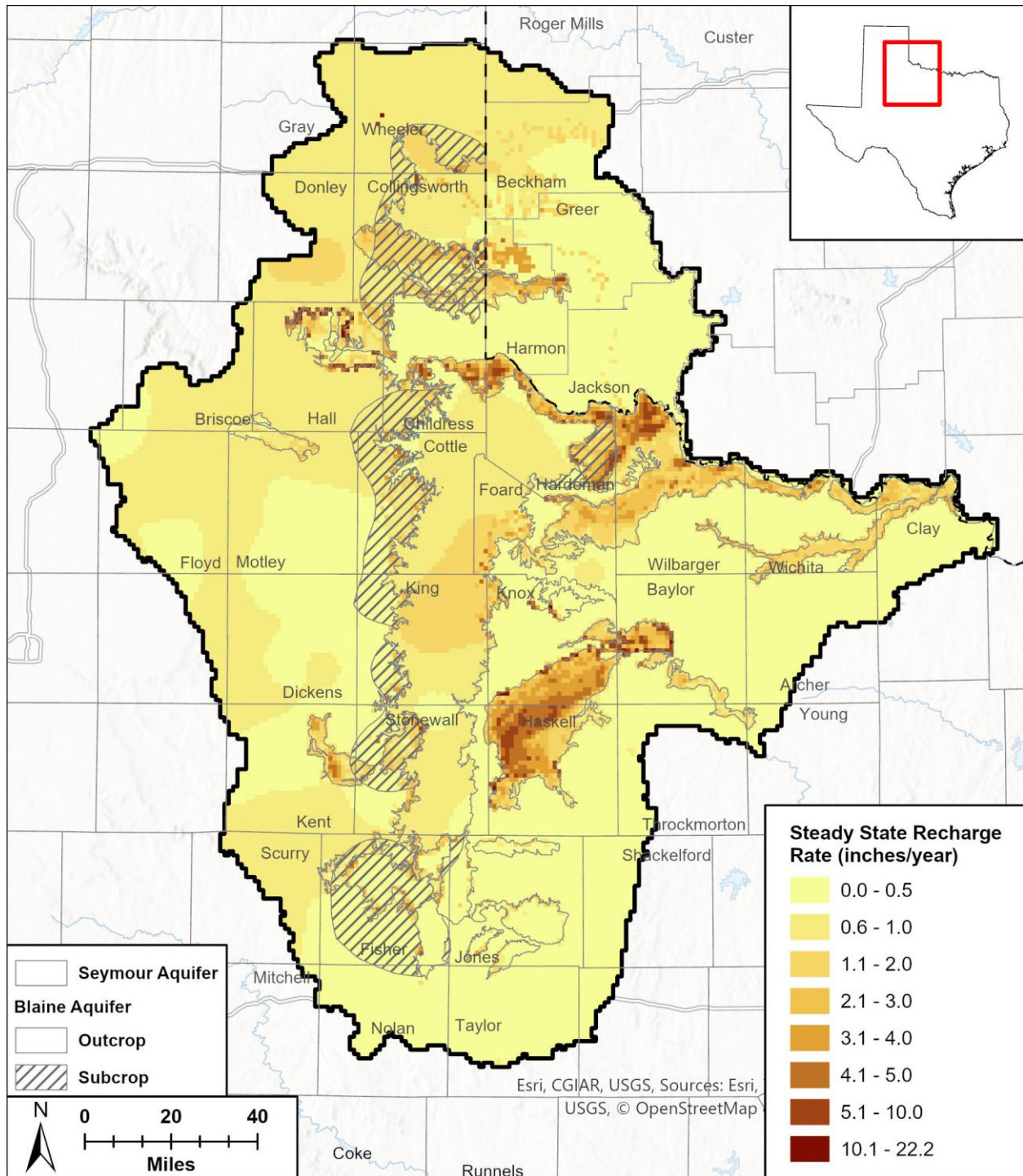


Figure 5.3-31. Total calibrated steady-state recharge rate (in inches per year) for all model layers, aggregated to the 1-mile model grid.

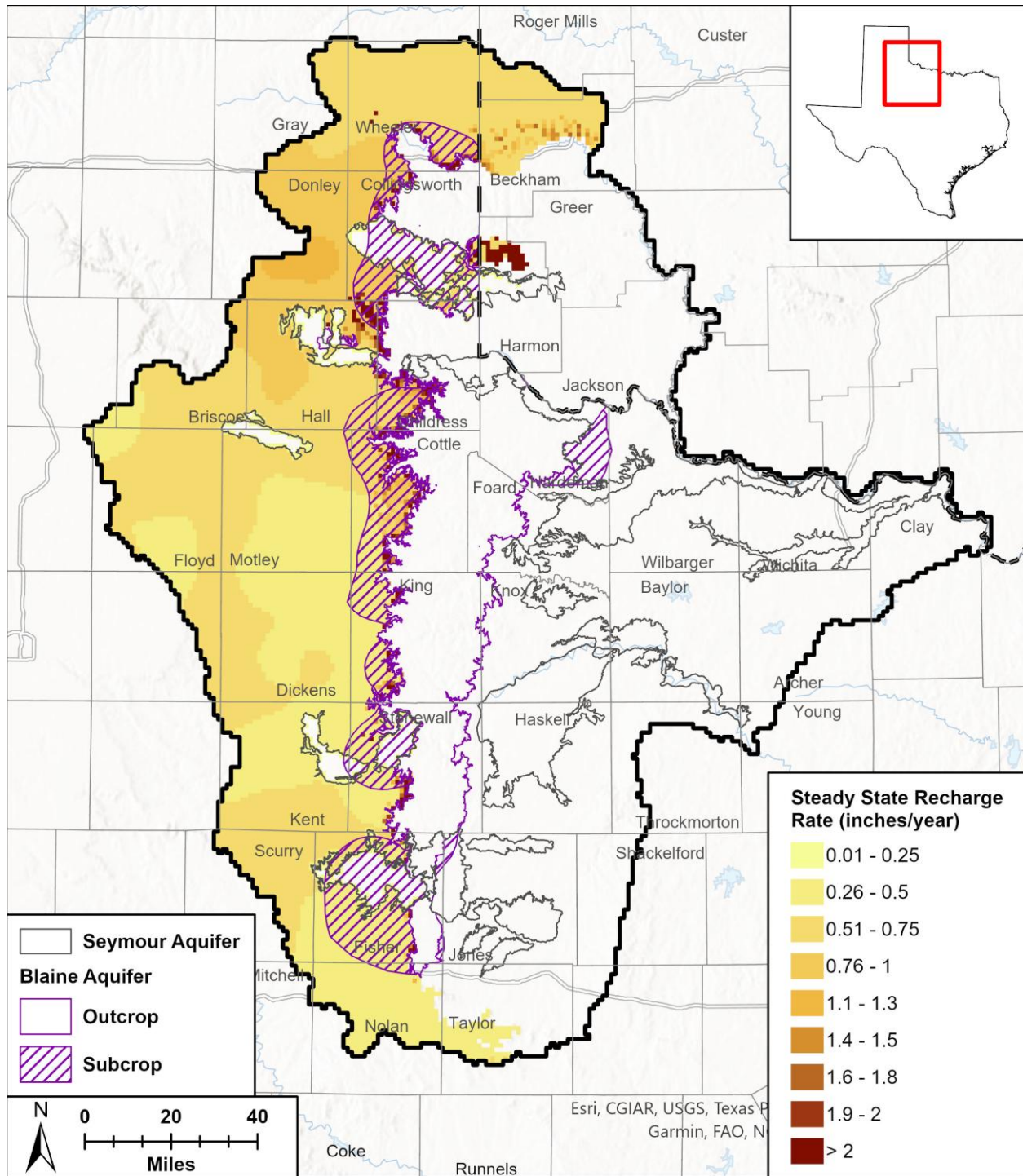


Figure 5.3-32. Calibrated steady-state recharge rate map (in inches per year) in layer 2, the Whitehorse and Younger.

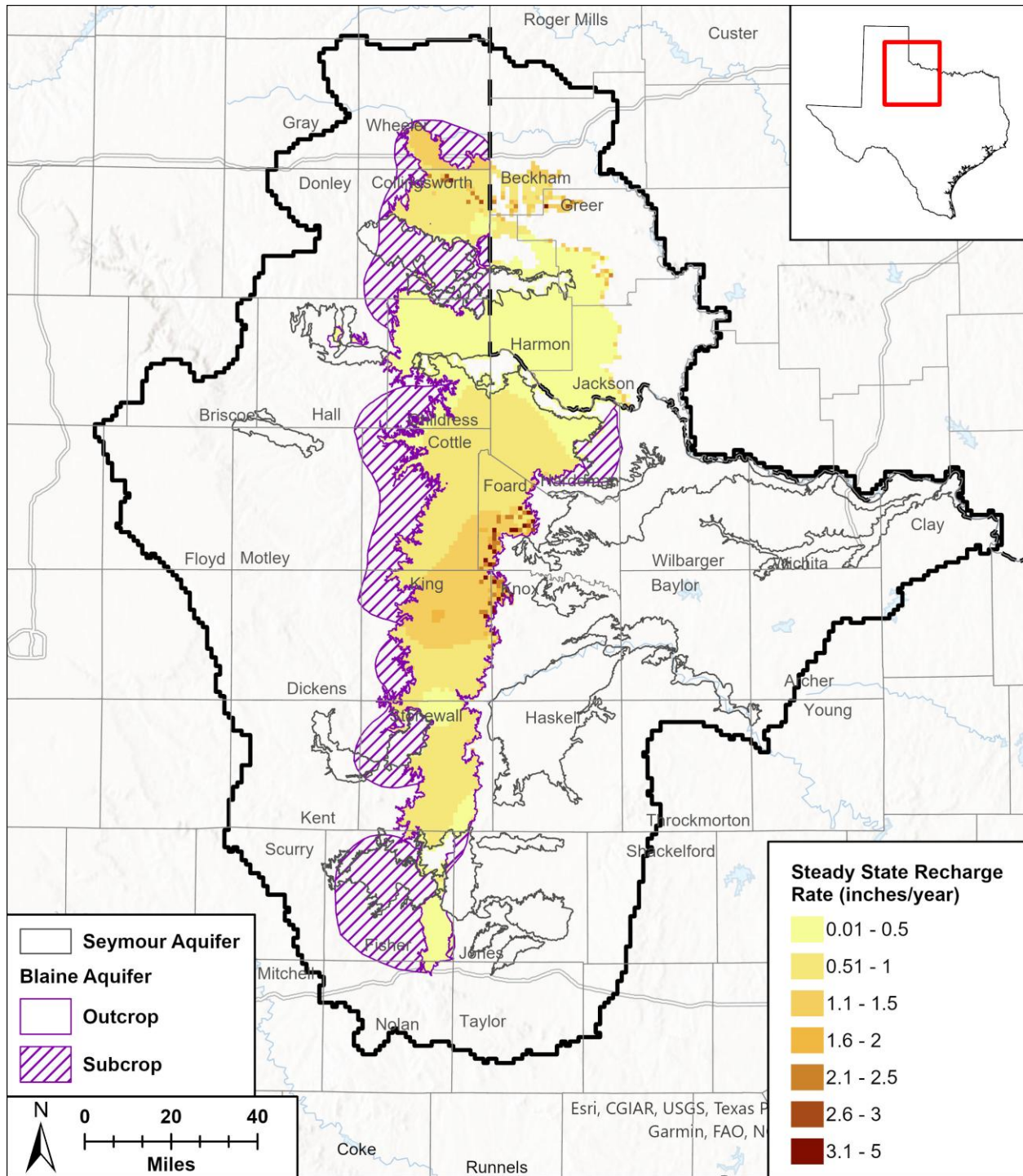


Figure 5.3-33. Calibrated steady-state recharge rate map (in inches per year) in layer 3, the Blaine Aquifer.

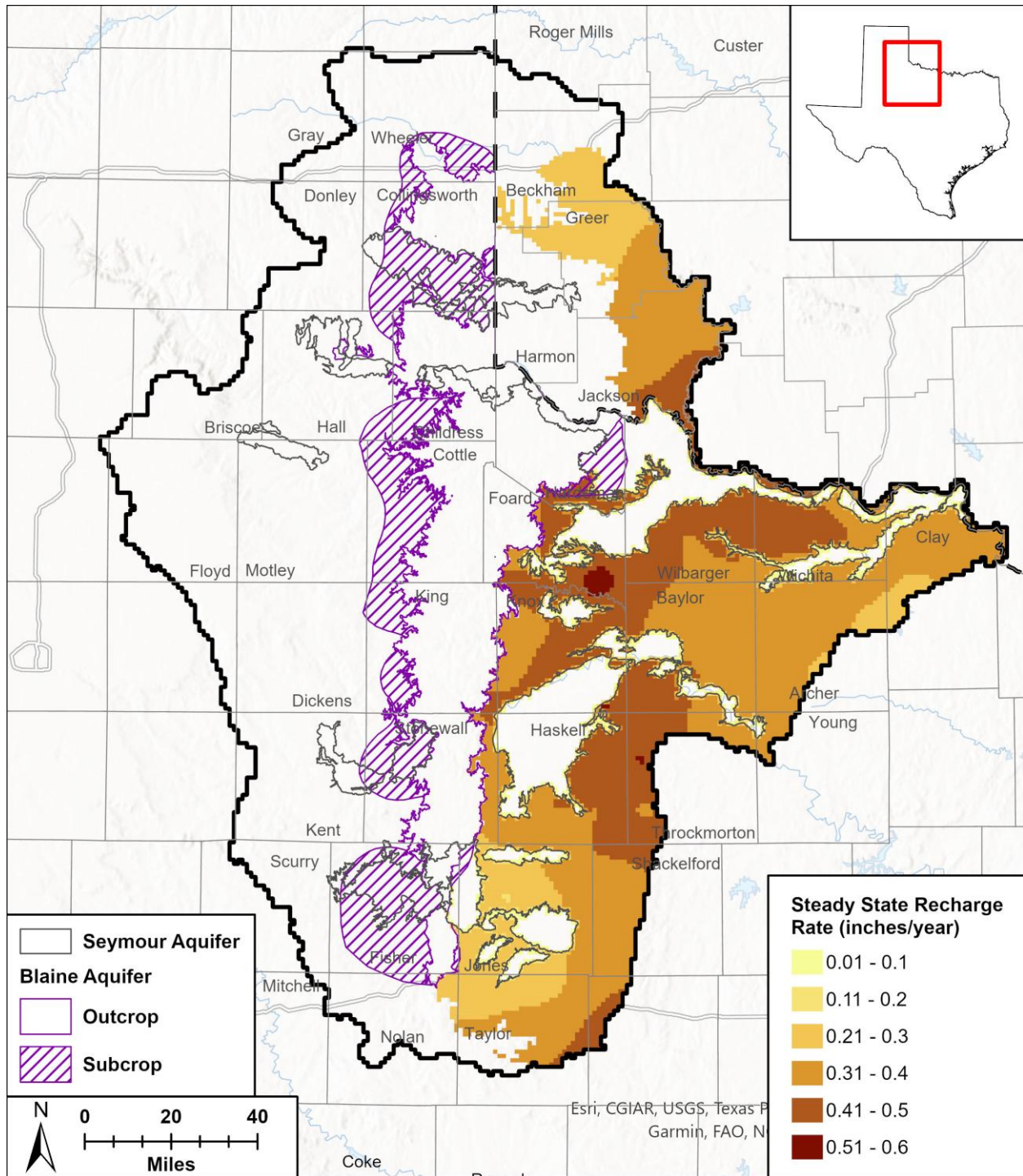


Figure 5.3-34. Calibrated steady-state recharge rate map (in inches per year) in layer 4, the Flowerpot and Older.

Table 5-19. Recharge rate (in inches per year) statistics for each year of the posterior ensemble. *SS = Steady-State (pre-development) conditions, which were assigned the 1960 precipitation multiplier.

Year	Average	Standard Deviation	Minimum	25th Percentile	Median	75th Percentile	Maximum
SS*	2.118	0.048	2.025	2.082	2.116	2.148	2.23
1960	2.118	0.048	2.025	2.082	2.116	2.148	2.23
1961	2.088	0.045	1.999	2.055	2.087	2.117	2.193
1962	2.091	0.046	2.002	2.058	2.09	2.12	2.197
1963	1.997	0.041	1.913	1.972	1.998	2.023	2.088
1964	2.024	0.042	1.942	1.997	2.029	2.053	2.113
1965	2.058	0.044	1.972	2.029	2.059	2.087	2.155
1966	2.035	0.043	1.952	2.007	2.04	2.064	2.126
1967	2.004	0.041	1.923	1.979	2.006	2.03	2.095
1968	2.102	0.046	2.012	2.068	2.101	2.132	2.21
1969	2.117	0.048	2.025	2.081	2.115	2.147	2.228
1970	1.948	0.04	1.848	1.921	1.949	1.976	2.043
1971	2.087	0.045	1.998	2.054	2.086	2.116	2.191
1972	2.067	0.044	1.981	2.037	2.067	2.096	2.166
1973	2.096	0.046	2.006	2.062	2.095	2.125	2.202
1974	2.095	0.046	2.006	2.062	2.094	2.125	2.202
1975	2.099	0.046	2.009	2.066	2.098	2.129	2.207
1976	2.044	0.043	1.96	2.015	2.047	2.073	2.137
1977	2.032	0.042	1.949	2.004	2.038	2.061	2.122
1978	2.043	0.043	1.959	2.014	2.047	2.072	2.136
1979	2.074	0.045	1.986	2.042	2.072	2.103	2.174
1980	2.031	0.042	1.949	2.004	2.037	2.06	2.121
1981	2.064	0.044	1.978	2.035	2.064	2.094	2.163
1982	2.084	0.045	1.995	2.051	2.083	2.113	2.187
1983	2.049	0.043	1.964	2.02	2.051	2.077	2.143
1984	1.999	0.041	1.916	1.974	2	2.025	2.09
1985	2.114	0.047	2.023	2.079	2.113	2.145	2.226
1986	2.17	0.052	2.066	2.134	2.167	2.205	2.295
1987	2.084	0.045	1.995	2.051	2.083	2.113	2.187
1988	2.006	0.041	1.925	1.98	2.008	2.032	2.096
1989	2.048	0.043	1.963	2.019	2.051	2.077	2.142
1990	2.113	0.047	2.021	2.077	2.111	2.143	2.223
1991	2.175	0.052	2.07	2.139	2.172	2.211	2.301
1992	2.122	0.048	2.03	2.086	2.121	2.153	2.236
1993	2.042	0.043	1.958	2.013	2.046	2.07	2.134
1994	2.02	0.042	1.938	1.993	2.025	2.048	2.109
1995	2.158	0.051	2.058	2.122	2.156	2.192	2.281
1996	2.052	0.043	1.967	2.023	2.054	2.081	2.147
1997	2.176	0.053	2.071	2.14	2.173	2.212	2.303
1998	1.969	0.041	1.876	1.944	1.971	1.996	2.062
1999	2.044	0.043	1.96	2.016	2.048	2.073	2.138
2000	2.071	0.044	1.984	2.04	2.07	2.1	2.171
2001	2.018	0.042	1.936	1.991	2.022	2.046	2.107

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Year	Average	Standard Deviation	Minimum	25th Percentile	Median	75th Percentile	Maximum
2002	2.135	0.049	2.041	2.097	2.132	2.165	2.251
2003	1.995	0.041	1.91	1.97	1.996	2.021	2.086
2004	2.229	0.058	2.107	2.189	2.229	2.268	2.369
2005	2.066	0.044	1.979	2.036	2.066	2.095	2.165
2006	2.061	0.044	1.975	2.031	2.061	2.09	2.158
2007	2.147	0.05	2.05	2.109	2.145	2.179	2.266
2008	2.063	0.044	1.977	2.034	2.064	2.093	2.162
2009	2.065	0.044	1.978	2.035	2.065	2.094	2.163
2010	2.153	0.05	2.055	2.115	2.15	2.186	2.274
2011	1.899	0.041	1.784	1.872	1.899	1.929	1.999
2012	1.999	0.041	1.916	1.974	2	2.025	2.09
2013	2.018	0.042	1.937	1.992	2.023	2.046	2.108
2014	2.028	0.042	1.945	2	2.034	2.057	2.117
2015	2.25	0.06	2.121	2.208	2.248	2.289	2.397
2016	2.142	0.05	2.047	2.105	2.14	2.174	2.261
2017	2.087	0.045	1.999	2.055	2.086	2.116	2.192
2018	2.13	0.049	2.036	2.092	2.127	2.16	2.245
2019	2.094	0.046	2.005	2.061	2.093	2.124	2.201
2020	2.053	0.043	1.968	2.024	2.055	2.082	2.149

Stream drain conductance

This section discusses stream drain conductance, which was treated as an adjustable parameter during calibration.

The stream drain package was included in the model to represent groundwater discharge to intermittent streams and lower-order stream reaches (Section 4.11), while perennial higher-order rivers are represented separately through the river package (Section 4.14 and following subsection). The drain cells act as head-dependent discharge boundaries that release water whenever simulated heads rise above the prescribed drain elevation, consistent with the conceptual expectation of predominantly gaining conditions where groundwater discharges to surface features.

Stream drain conductance was parameterized separately for each of the four model layers, with each layer assigned a formation-scale constant multiplier and spatially distributed pilot point multipliers. Calibration bounds on the multipliers allowed conductance to vary by a factor of five on the formation-scale constants and by up to a factor of ten on the pilot point multipliers, with ultimate bounds imposed to prevent physically unrealistic streambed hydraulic conductivity values. Parameter information for defining the prior distributions of stream drain conductance is provided in Table 5-6.

Prior and posterior distributions of total stream drain volumes are shown in Figure 5.3-35. The posterior distribution shifts toward higher discharge, with the posterior median increasing from approximately 490,000 acre-feet per year in the prior to approximately 750,000 acre-feet per year in the posterior. The posterior spread remains comparable to the prior spread, indicating that, while calibration consistently identified a higher overall discharge magnitude, year-to-year variability in the drain discharge remained broadly consistent across the ensemble. This upward shift reflects the combination of calibration adjustments to aquifer heads near stream drain cells and to stream drain conductance itself, both of which increased simulated groundwater discharge to the stream network in the posterior relative to the prior. Summary statistics for streambed drain hydraulic conductivity across all layers in the base realization are provided in Table 5-20.

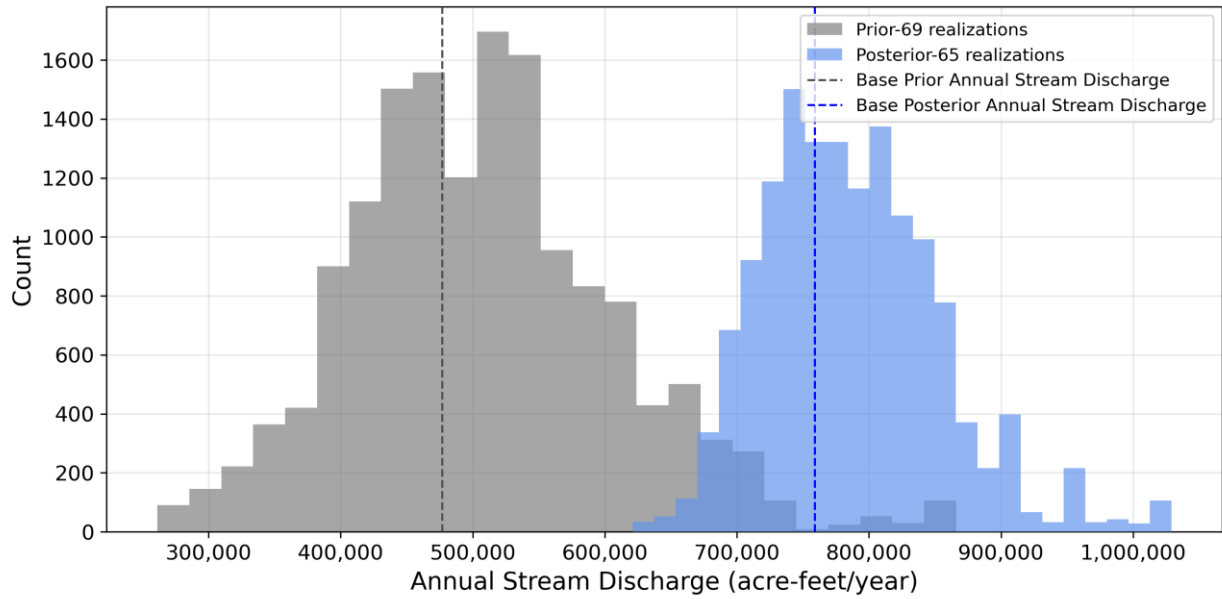


Figure 5.3-35. Prior (gray) and posterior (blue) distributions of total stream drain volumes during historical simulation period. Base of prior (black dashed) and posterior (blue dashed) are displayed.

Table 5-20. Streambed drain hydraulic conductivity (feet per day) for the calibrated base realization across all layers.

mean	median	minimum	maximum	1st Percentile	5th Percentile	25th Percentile	75th Percentile	95th Percentile	99th Percentile
2.5	1.4	0.1	23.4	0.1	0.2	0.6	3.2	8.3	18.1

River conductance

River conductance defines the hydraulic connection between the groundwater system and the higher-order stream network represented with the River Package. In contrast to drain cells, which function strictly as discharge boundaries, river cells simulate bidirectional exchange, allowing water either to enter or leave the groundwater system depending on local head gradients. River conductance therefore regulates surface water–groundwater interaction along perennial stream corridors and controls localized head distributions adjacent to river cells.

River conductance was parameterized separately for each of the four model layers that contain river cells, with each layer assigned to a formation-scale constant multiplier and spatially distributed pilot point multipliers. Calibration bounds on the multipliers allowed conductance to vary by a factor of five on the formation-scale constants and by up to a factor of ten on the pilot point multipliers, with ultimate bounds imposed to keep riverbed hydraulic conductivity values within hydrogeologically reasonable ranges. As with stream drain conductance, river conductance is rarely measured directly, so calibration relied on indirect system responses — primarily groundwater head gradients near river corridors and the overall water balance — to inform posterior adjustments. Parameter information for defining the prior distributions of river conductance is provided in Table 5-5.

Prior and posterior distributions of total annual river inflow and outflow are shown in Figure 5.3-36. The posterior median river inflow to the groundwater system (water entering the aquifer from losing reaches) increased from approximately 4,000 acre-feet per year in the prior to approximately 7,000 acre-feet per year in the posterior, indicating calibration-driven enhancement of losing-reach behavior. The posterior median river outflow (water leaving the aquifer to gaining reaches) increased from approximately 255,000 acre-feet per year in the prior to approximately 355,000 acre-feet per year in the posterior, indicating stronger gaining-stream behavior overall. The magnitude of river outflow is approximately one to two orders of magnitude greater than river inflow throughout the ensemble, consistent with the conceptual model of a predominantly gaining river system. Both posterior distributions are modestly narrower than their prior counterparts, reflecting reduced uncertainty in river exchange fluxes following calibration. Summary statistics for riverbed hydraulic conductivity across all layers in the base realization are provided in Table 5-21.

Texas Water Development Board Contract Number 2448302843
 Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

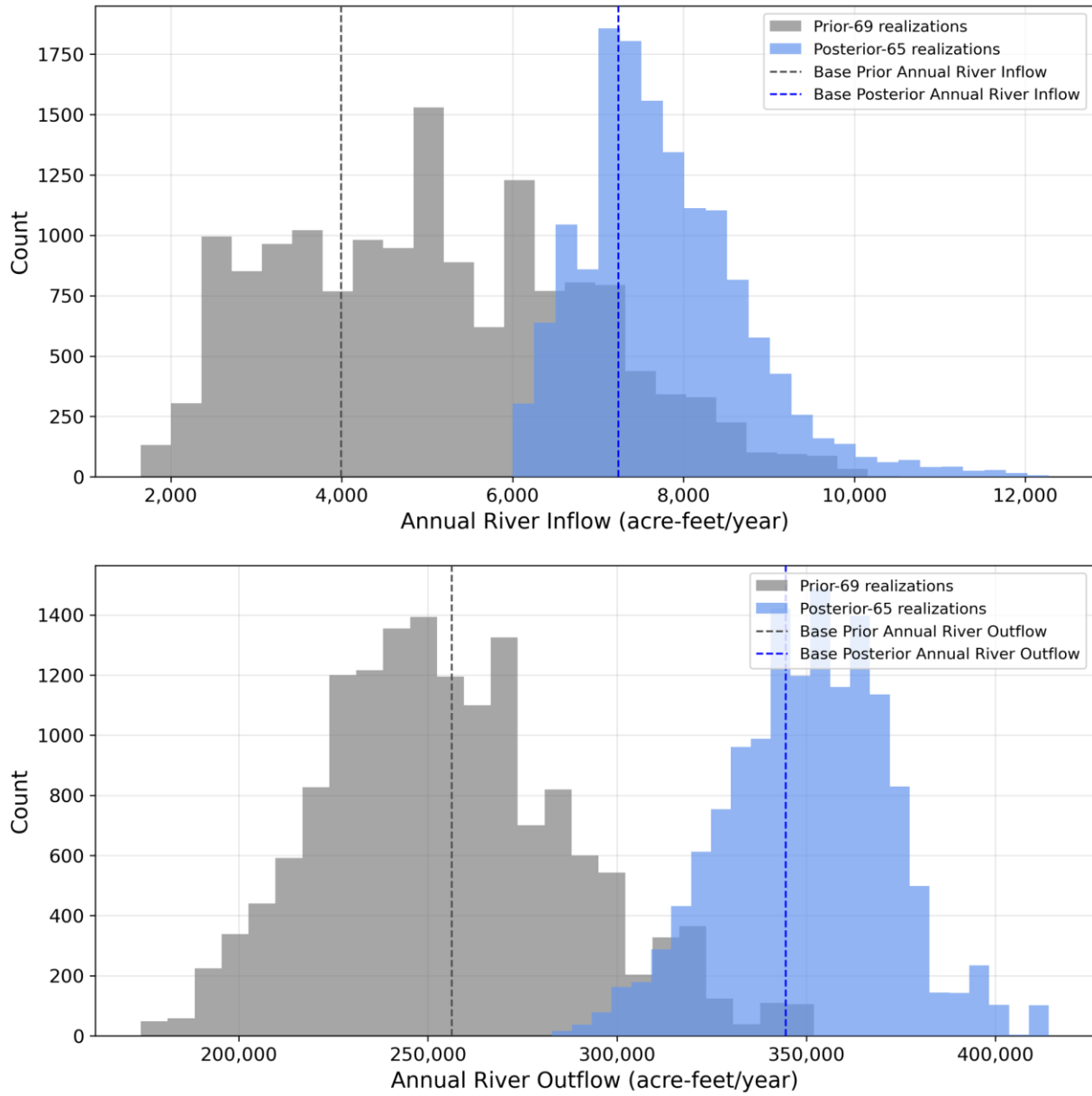


Figure 5.3-36. Prior (gray) and posterior (blue) river inflow (top panel) and river discharge (bottom panel) volumes in acre-feet per year.

Table 5-21. Calibrated base realization riverbed hydraulic conductivity (feet per day) across all model layers.

mean	median	min	max	1st Percentile	5th Percentile	25th Percentile	75th Percentile	95th Percentile	99th Percentile
4.4	2.7	0.1	23.4	0.4	0.6	1.2	5.8	14.1	21.5

Pumping

Groundwater pumping was parameterized as annual uncertain multipliers applied to the historical pumping datasets described in Chapter 3 and implemented through the Well Packages described in Chapter 4. Each multiplier was applied as a constant for a single stress period (one year) and adjusted temporally using a temporal covariance structure to preserve reasonable year-to-year correlation in calibrated pumping. The temporal correlation length implemented was 15 years to reduce the occurrence of unrealistically large fluctuations in pumping multipliers from year to year. Initial multiplier values were generally set to 1.0, representing the base pumping estimates, and bounds were assigned by use type and time period to reflect differences in data confidence. Parameter information for the prior distributions of pumping multipliers is provided in Table 5-8.

Irrigation pumping represents the majority of groundwater withdrawals in the model area and was parameterized with greater spatial resolution than other use types. Irrigation multipliers were subdivided by Seymour pod within layer 1 and applied as a single category for the Blaine Aquifer (layer 3), allowing calibration to refine withdrawals in individual Seymour outcrop areas where irrigation demand and aquifer response are most strongly connected. Other pumping categories, including domestic (separately for the Seymour and Blaine aquifers), municipal, manufacturing, mining, livestock, metered, and Oklahoma withdrawals, were parameterized with a single multiplier per category per stress period applied across the relevant well locations within the model domain.

Temporal uncertainty was incorporated into the multiplier design. For most pumping categories, multipliers for the 1960 to 1975 period were allowed to vary between 0.5 and 1.4, reflecting the comparatively limited survey record in the early decades of the simulation, while multipliers for the 1976 to 2020 period were constrained more tightly between 0.75 and 1.25, reflecting the availability of consistent survey data in the later period. Several pumping categories received special treatment reflecting specific data considerations: irrigation in Pod 3 was assigned asymmetric bounds with the lower bound fixed at 1.0 for both time periods, allowing calibration to increase but not decrease the prior pumping estimate; irrigation in pods 6 and 10 was assigned constant bounds of 0.5 to 1.5 across the full simulation period; irrigation in Pod 9 was assigned four distinct temporal periods (1960 to 1969, 1970 to 1975, 1976 to 2000, and 2001 to 2020), with initial values and bounds adjusted to reflect the unique historical development sequence in that portion of the aquifer; and metered pumping, which is available only for the 2004 to 2020 period, was assigned narrow bounds of 0.85 to 1.2, reflecting the high confidence associated with metered data.

Prior and posterior time series of parameterized pumping by use type are shown in Figure 5.3-37 through Figure 5.3-42. Posterior pumping rates remain within the prior ensemble bounds across all use types and time periods, consistent with the calibration framework in which pumping multipliers were constrained by parameter bounds reflecting the estimated range of uncertainty in the historical pumping record.

Across the Seymour pod irrigation categories, Pod 7 in the Haskell-Knox-Baylor area is the principal irrigation pumping region and shows the most visible calibration response, with the posterior tracking below the prior base across most of the historical record and crossing above the prior in the final decade. Most other Seymour pods calibrate within the prior bounds, with adjustments generally toward the lower portion of the bounds and a few pods (Pods 3, 5, and 15) calibrating modestly above the prior base. Pods 6, 8, 9, 10, and 12 contribute negligible pumping volumes regardless of prior or posterior values. Blaine irrigation calibrates toward the lower portion of the prior bounds across most of the post-1976 record.

Among the non-irrigation pumping categories, the largest calibration adjustments are concentrated in the pre-1976 period where the prior bounds were widest. Domestic and municipal pumping calibrate above the prior base in the 1960–1976 period and closer to or below the prior thereafter. Mining and manufacturing pumping calibrate modestly above the prior base, with the largest adjustments concentrated around the 1976 and post-2007 spikes. Livestock and Oklahoma pumping calibrate below the prior base across most of the historical record. Metered pumping, available in the later portion of the historical record, calibrates above the prior.

The pumping parameterization framework allowed greater adjustment flexibility for pre-1975 estimates and for pods where the historical record is least complete, while preserving tighter constraints on more recent and better-documented datasets such as the metered records. The concentration of posterior adjustments in the 1970s is consistent with this design, reflecting the greater uncertainty in pumping estimates during that period rather than a calibration-driven departure from well-documented recent pumping. The broader impact of calibrated pumping on overall water budgets is further examined in Section 5.3.4.

Texas Water Development Board Contract Number 2448302843
 Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

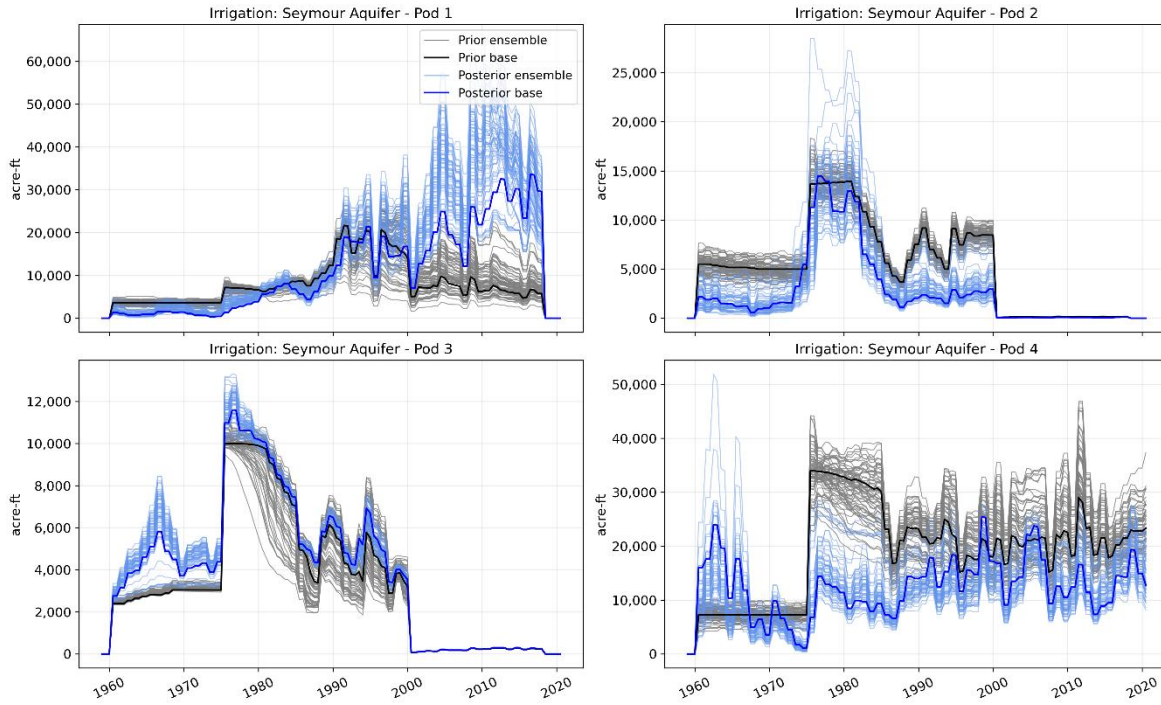


Figure 5.3-37. Pumping use types parameterized during calibration (in acre-feet): Irrigation Pods 1 through 4.

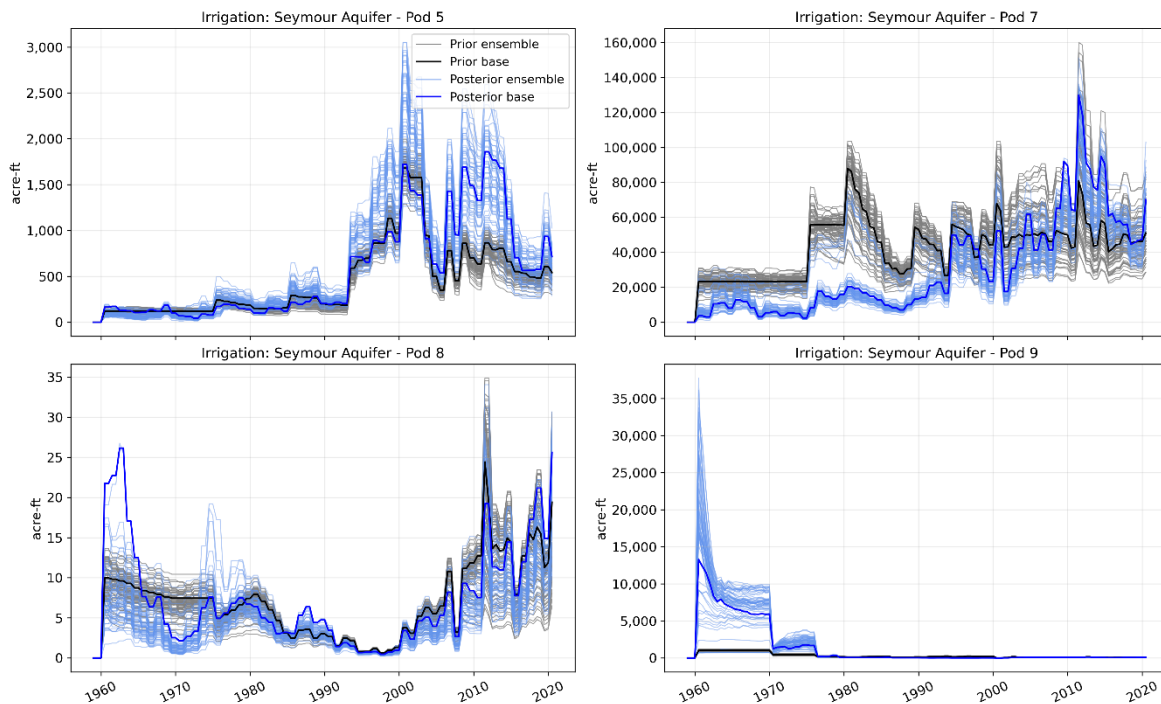


Figure 5.3-38. Pumping use types parameterized during calibration (in acre-feet): Irrigation Pods 5 through 9.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

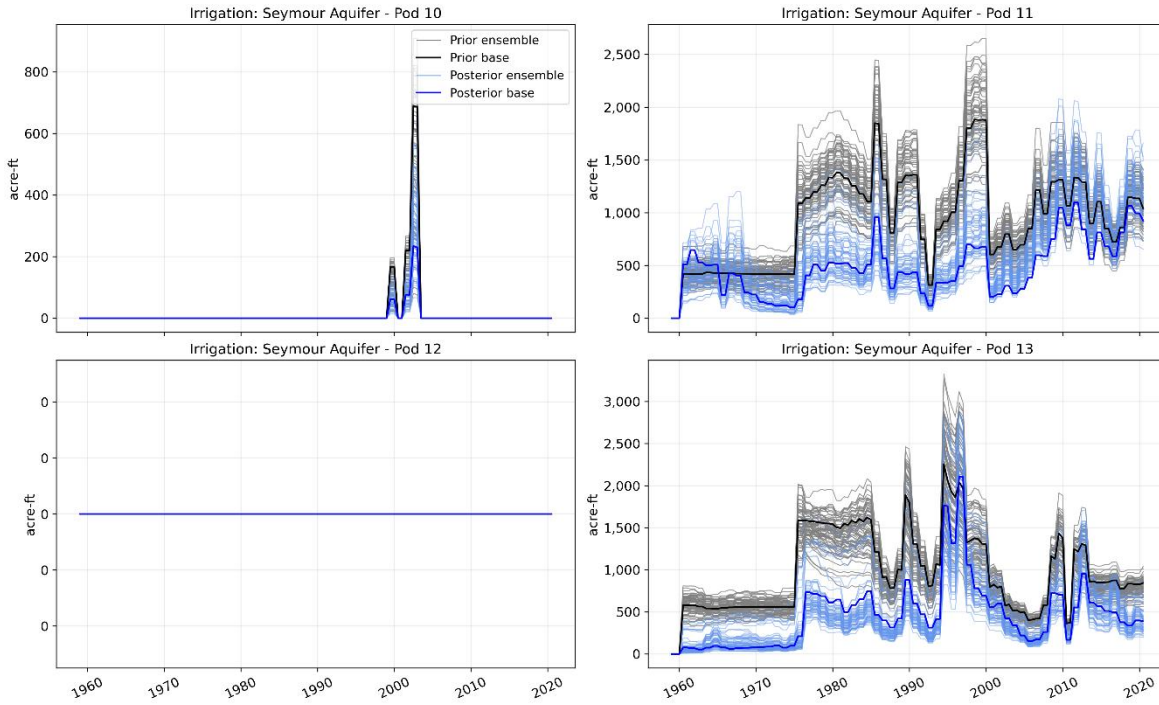


Figure 5.3-39. Pumping use types parameterized during calibration (in acre-feet): Irrigation Pods 10 through 13.

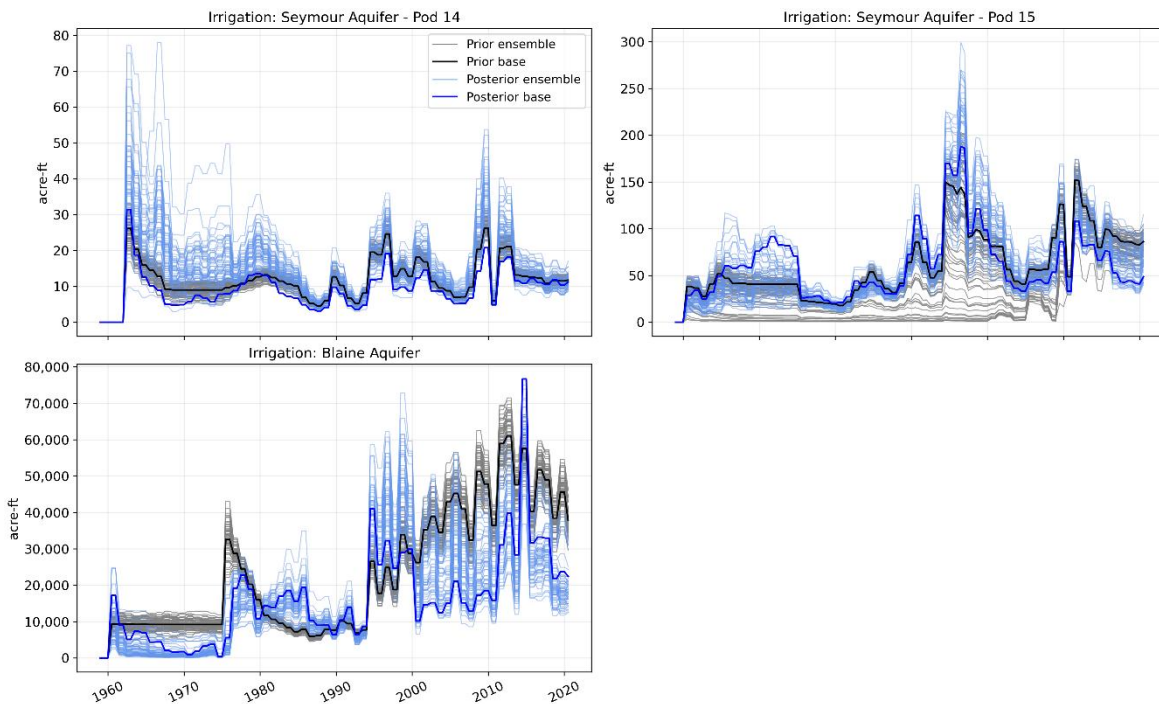


Figure 5.3-40. Pumping use types parameterized during calibration (in acre-feet): Irrigation Pods 14 and 15 and the Blaine Aquifer.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

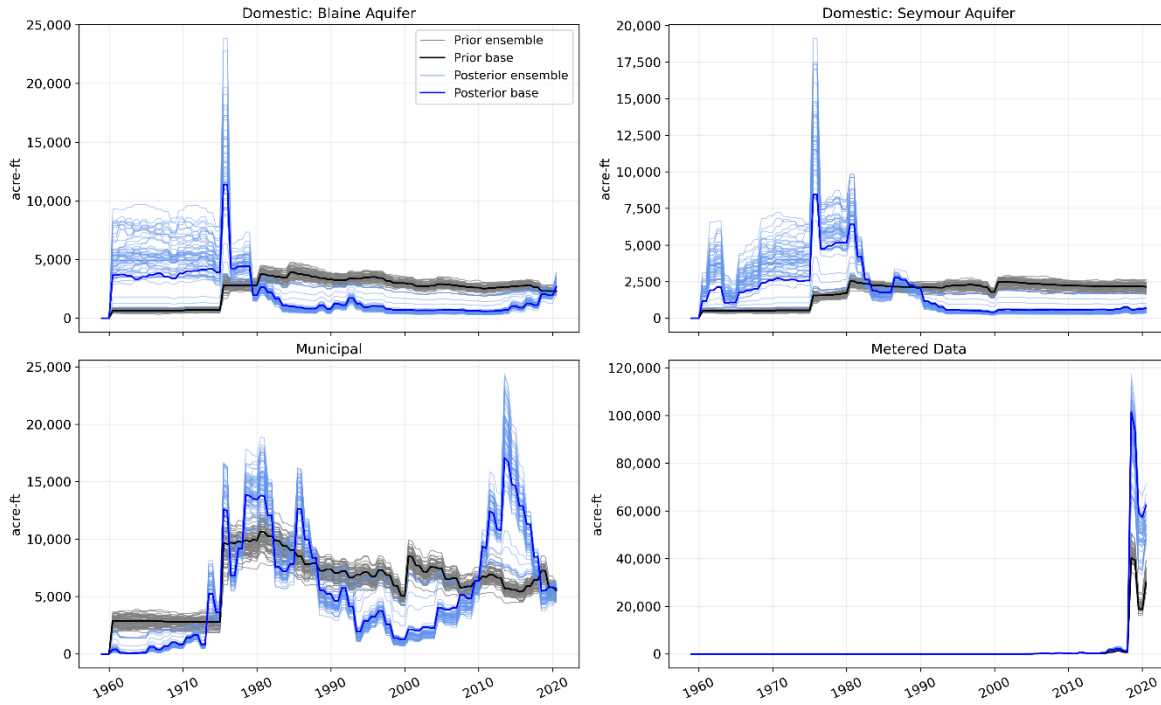


Figure 5.3-41. Pumping use types parameterized during calibration (in acre-feet): Domestic, Municipal and Metered Data.

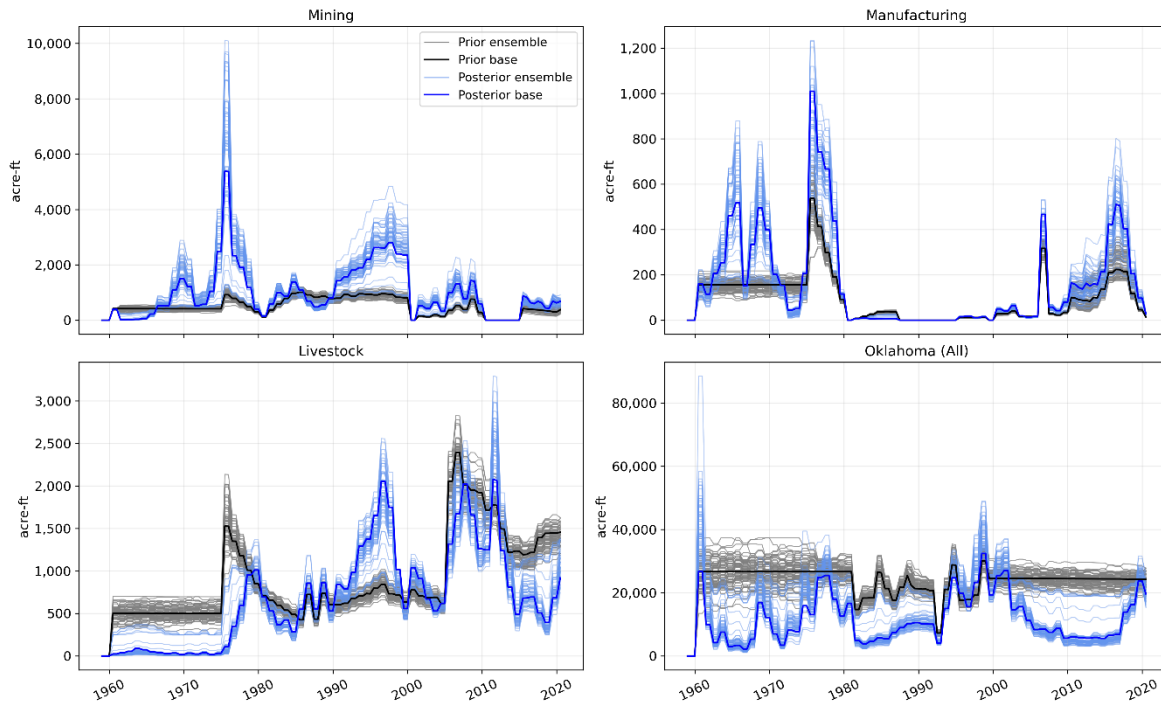


Figure 5.3-42. Pumping use types parameterized during calibration (in acre-feet): mining, manufacturing, livestock, and Oklahoma.

5.3.2 Hydraulic head calibration

Model calibration for simulating hydraulic heads is typically assessed using residuals, which represent the difference between observed and simulated hydraulic heads (Anderson and Woessner, 1992). Residuals are defined in Equation 5-2:

$$r = h_o - h_s \quad (\text{Equation 5-2})$$

where r is the residual at the observation location, h_o is the observed hydraulic head, and h_s is the simulated hydraulic head. A positive residual indicates that the model underpredicts the observed water level elevation, while a negative residual indicates that the model overpredicts the observed water level elevation.

To quantify model fit, root mean square error is commonly used as shown in Equation 5-3:

$$\text{Root Mean Squared Error} = \sqrt{\frac{1}{n} \sum_{t=1}^n (h_o - h_s)_t^2} \quad (\text{Equation 5-3})$$

where n is the number of observations and t is the time; root mean square error provides an overall measure of model error but does not indicate spatial biases in residuals. To address this limitation, mean error (Equation 5-4) and mean absolute error (Equation 5-5) are also considered:

$$\text{Mean Error} = \frac{1}{n} \sum_{t=1}^n (h_o - h_s)_t \quad (\text{Equation 5-4})$$

$$\text{Mean Absolute Error} = \frac{1}{n} \sum_{t=1}^n |h_o - h_s|_t \quad (\text{Equation 5-5})$$

Mean error identifies whether the model systematically overpredicts or underpredicts hydraulic heads, while mean absolute error quantifies overall error magnitude, ensuring that over- and underpredictions do not cancel out. A traditional calibration criterion for groundwater availability models requires that root mean square error be less than or equal to 10 percent of the observed hydraulic head range within the simulated hydrogeologic unit. The calibration statistics for the model simulation are summarized in Table 5-22 by aquifer and by Seymour pod.

At the aquifer scale, the calibration is well within the 10 percent criterion. Normalized root mean square error is 0.7 percent for the Seymour Aquifer (all pods combined), 3.2 percent for the Blaine Aquifer, and 1.4 percent at the global model scale. Aquifer-wide mean residuals are small: 0.01 foot for the Seymour Aquifer, 0.08 foot for the Blaine Aquifer, and 0.04 foot at the global scale, indicating no meaningful systematic bias at the aquifer or model scale. Mean absolute error is 7.7 feet for the Seymour Aquifer and 24.5 feet for the Blaine Aquifer.

At the pod scale, the calibration statistics reflect the uneven distribution of observations across the Seymour Aquifer. The well-observed pods (Pod 4 with 3,272 observations and Pod 7 with 3,141 observations) achieve the best calibration performance, with normalized root mean square error values of 1.3 and 2.0 percent,

respectively, and mean residuals less than 0.25 feet. Pods 1 and 13, with several hundred observations each, achieve normalized root mean square error values of 3.3 and 3.9 percent, respectively. Pod 1 shows a positive mean residual of 5.5 feet, indicating a modest tendency to simulate heads lower than observed. Pod 3 shows a negative mean residual of -7.5 feet, indicating that simulated heads in Pod 3 are higher than observed on average. Data-poor pods (Pods 6, 8, 9, 10, 11, 12, 14, and 15) show normalized root mean square error values ranging from approximately 5 to 12 percent, with the exception of Pod 9 (24 percent). The normalized errors in these pods are inflated by the small ranges in measured head in their observation networks. Calibration results in the data-poor pods should be interpreted with greater caution than those for the well-observed pods, as noted in Section 5.3.1, Hydraulic conductivity and anisotropy.

Pod-level residual distributions for the base realization are shown in Figure 5.3-43 through Figure 5.3-57 for the 15 Seymour pods and in Figure 5.3-58 for the Blaine Aquifer. Each figure presents a 1:1 plot of observed versus simulated heads and a histogram of residuals, with the top ten wells contributing observations in each pod indicated. Residual distributions are approximately symmetric about zero for most Seymour pods and for the Blaine Aquifer, with the exception of Pod 3 noted above. For the well-observed pods, the 1:1 plots show close clustering of simulated and observed values along the unit-slope line across the full range of observed heads, with no visible trend suggesting bias.

The spatial distribution of average groundwater level residuals for the base realization for the steady-state period is shown in Figure 5.3-59 for the Seymour Aquifer and Figure 5.3-60 for the Blaine Aquifer. In the Seymour Aquifer (Figure 5.3-59), residuals are spatially intermingled across the pod network, with positive and negative residuals distributed throughout the individual pods and without a systematic spatial bias. In the Blaine Aquifer (Figure 5.3-60), observations are concentrated in the northern portion of the aquifer where the historical monitoring record is most extensive, with a mixture of positive and negative residuals in that area and relatively sparse observation coverage farther south. Larger residual magnitudes are present in the northern Blaine, reflecting both the greater range of observed heads and the higher density of observations in that area.

The spatial distribution of transient high-frequency residuals for the base realization is shown in Figure 5.3-61 for the Seymour Aquifer and Figure 5.3-62 for the Blaine Aquifer. The Seymour transient residuals (Figure 5.3-61) show a narrower residual range than the steady-state residuals, with most residuals falling within approximately 15 feet of zero, though a cluster of larger positive residuals is present in Pod 1, and a few larger negative residuals are scattered across Pods 3 and 4. The overall spatial pattern shows no systematic regional bias across the pod network. The Blaine transient residuals (Figure 5.3-62) follow a similar pattern to the steady-state Blaine residuals, with observations concentrated in the northern portion of the aquifer and a mixture of positive and negative residuals that does not suggest a strong systematic spatial bias. For all four residual maps, the base realization from the posterior ensemble is shown. The base realization represents the central tendency of the

posterior distribution and serves as the recommended parameter realization for deterministic simulations of the Seymour and Blaine groundwater availability model.

Average simulated versus average observed groundwater level contours for the base realization for the Seymour Aquifer are shown in Figure 5.3-63, with simulated contours (blue) and observed contours (orange) plotted together at a 50-foot interval. Average simulated water levels were calculated for each model cell as the arithmetic mean of simulated heads across the calibration period. Average observed water levels were calculated for each well as the mean of all water level measurements used as calibration targets over the same period. The two contour sets track each other closely across the full extent of the Seymour pods, indicating that the calibrated model captures the regional head distribution and hydraulic gradients throughout the aquifer. A corresponding contour comparison for the Blaine Aquifer is shown in Figure 5.3-64, where simulated contours are compared against interpolated observed contours from the Brackish Resources Aquifer Characterization Study (Finch and others, 2016). The simulated and interpolated observed contours for the Blaine show close agreement across the outcrop and subcrop areas, supporting the calibrated model's representation of regional Blaine flow.

The simulated change in hydraulic head for the base realization is shown at two reference points: between pre-development and the beginning of the transient period (1980), shown in Figure 5.3-65 for the Seymour Aquifer and Figure 5.3-66 for the Blaine Aquifer; and between pre-development and the end of the transient period (2020), shown in Figure 5.3-67 for the Seymour Aquifer and Figure 5.3-68 for the Blaine Aquifer. The year 1980 was chosen as the start of the transient period for these figures because that is when the simulation has had sufficient time to adequately transition between the idealized pre-development steady-state initial condition and the state of the aquifer in 1980 when conditions were better known across the model domain as the transient water level observations demonstrate.

In the Seymour Aquifer, declines exceeding 40 feet had developed by 1980 in the most heavily pumped areas, concentrated in Pod 7 and with additional declines in parts of Pods 1 and 4. By 2020, the largest cumulative declines (approximately 30 to 105 feet) are concentrated in Pod 7 and Pod 1, consistent with the concentration of historical irrigation pumping in those pods, and moderate declines (approximately 5 to 30 feet) are simulated across the remaining Seymour pods, including Pod 4. In the Blaine Aquifer, declines of approximately 15 to 47 feet had developed by 1980 in the northern outcrop, with smaller changes elsewhere. By 2020, the largest cumulative declines (approximately 50 to 110 feet) are concentrated in the northern portion of the aquifer where Blaine irrigation pumping has been most intensive, with moderate declines across the central Blaine and minimal declines in the southern extent.

Whereas the residual maps and 1:1 plots presented above evaluate overall model bias and goodness-of-fit at the aquifer and pod scales, hydrographs of observed and simulated groundwater levels at individual wells provide insight into how well the posterior ensemble reproduces observed temporal trends at specific locations. To highlight the calibration response at the most informative monitoring locations,

hydrographs for select wells with high-frequency calibration targets are presented in Figure 5.3-69 through Figure 5.3-81; the complete set of hydrographs for all high-frequency monitoring wells (those with more than five measurements and a record length of at least five years, as described in Section 5.2.1) is provided in Appendix D.

Figure 5.3-69 through Figure 5.3-81 show the well locations within the aquifer alongside a hydrograph panel for each well. The panels display the base realization of the posterior ensemble (dark blue line), the full range of posterior realizations (light blue lines), the prior ensemble (gray lines), the model bottom (dashed line), and observed water levels as weighted calibration targets (red dots) or unweighted observations (black dots). Unweighted observations are measurements with reported water levels below the model bottom. Since the model cannot simulate heads below the aquifer base, they were excluded from calibration but retained on the hydrographs to show where the framework limits reproduction of the observed record. Simulated water levels extend through the predictive period to 2080. The key evaluation criterion is whether the range of simulated groundwater elevations encompasses the observed values, indicating that the posterior ensemble captures the observed variability at that location.

A major source of uncertainty in groundwater availability models is the historical record of pumping rates. In the Seymour and Blaine groundwater availability model, pumping data are uncertain particularly in the pre-1980 period, which makes it difficult to determine whether calibration mismatches result from natural aquifer property variability, poorly constrained historical withdrawals, or a combination of these factors. The posterior ensemble approach helps mitigate this uncertainty by capturing a range of plausible groundwater conditions that are all consistent with the calibration observations, providing confidence that the model reflects regional-scale dynamics even where individual well-level mismatches remain. Despite these uncertainties, the posterior ensemble approach ensures that the calibrated model provides a robust representation of regional groundwater conditions over the historical calibration period. Limitations and their implications for model reliability are further discussed in Chapter 7.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

Table 5-22. Calibration statistics for hydraulic heads. % = percent, MAE = mean absolute error, RMSE = root mean squared error.

Aquifer	Pod	Count	Average Residual (feet)	Median Residual (feet)	RMSE (feet)	MAE (feet)	Measured Range (feet)	Normalized MAE (%)	Normalized RMSE (%)
Seymour	1	567	5.54	6.23	14.56	11.67	438.33	2.66	3.32
Seymour	2	151	-5.63	-1.35	20.41	11.48	443.11	2.59	4.61
Seymour	3	255	-7.46	-10.81	29.7	23.42	427	5.48	6.96
Seymour	4	3,272	0.09	-0.19	9.44	7.07	730.62	0.97	1.29
Seymour	5	202	-2.69	-0.48	10.3	6.32	205.26	3.08	5.02
Seymour	6	110	2.14	2.81	9.2	7.06	127.93	5.52	7.19
Seymour	7	3,141	0.22	0.15	8.12	6.27	402.2	1.56	2.02
Seymour	8	14	2.81	3.34	7.76	6.36	168.3	3.78	4.61
Seymour	9	81	4.37	1.85	11.56	8.11	47.6	17.04	24.28
Seymour	10	5	-0.52	-1.87	2.24	2.19	26.09	8.39	8.59
Seymour	11	32	6.07	0.93	14.98	9.37	139.85	6.7	10.71
Seymour	12	34	5.94	3.29	10.22	7.46	141.15	5.29	7.24
Seymour	13	731	-2.27	-2.88	9.8	7.73	254	3.04	3.86
Seymour	14	20	-1.04	1.83	7.99	6.74	69.1	9.75	11.57
Seymour	15	38	-2.11	-1.97	8.76	7.23	135.75	5.32	6.45
Seymour	All Pods	8,653	0.01	-0.06	10.94	7.7	1566.26	0.49	0.7
Blaine	-	4,670	0.08	2.84	33.63	24.48	1059.3	2.31	3.17
Global	-	13,323	0.04	0.37	21.77	13.58	1566.26	0.87	1.39

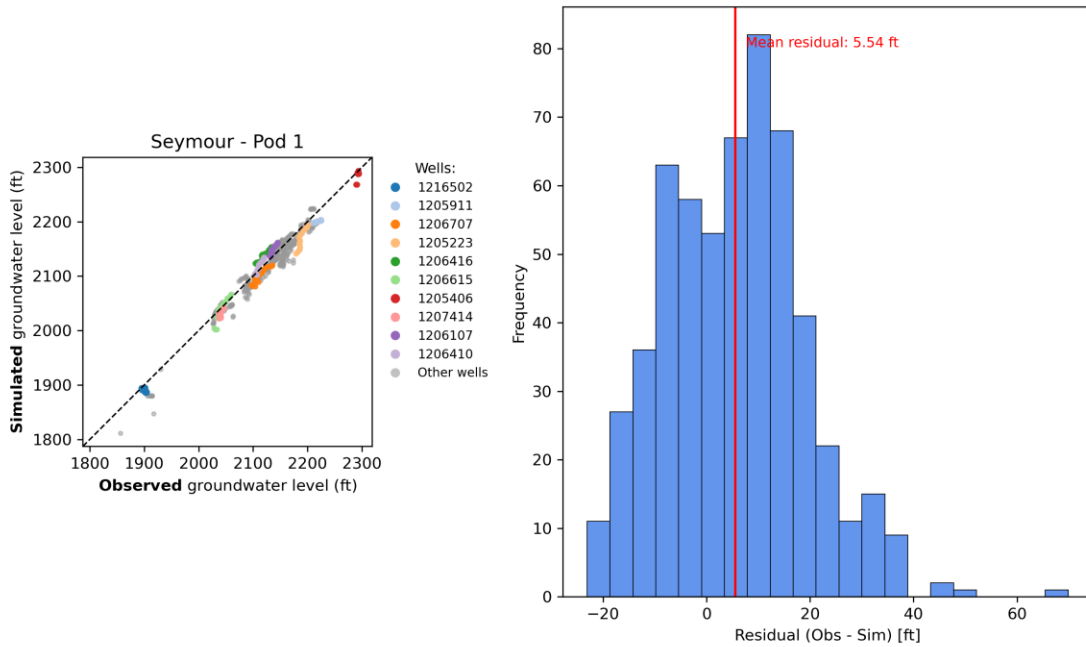


Figure 5.3-43. Average groundwater level residuals (in feet) for each observation well location in Pod 1 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

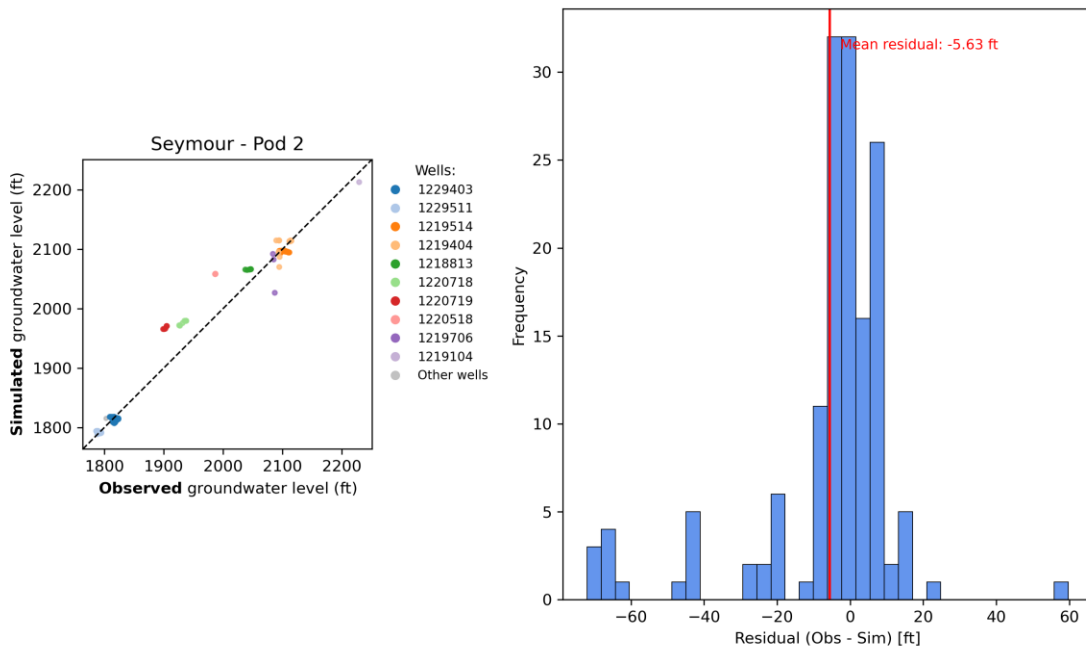


Figure 5.3-44. Average groundwater level residuals (in feet) for each observation well location in Pod 2 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

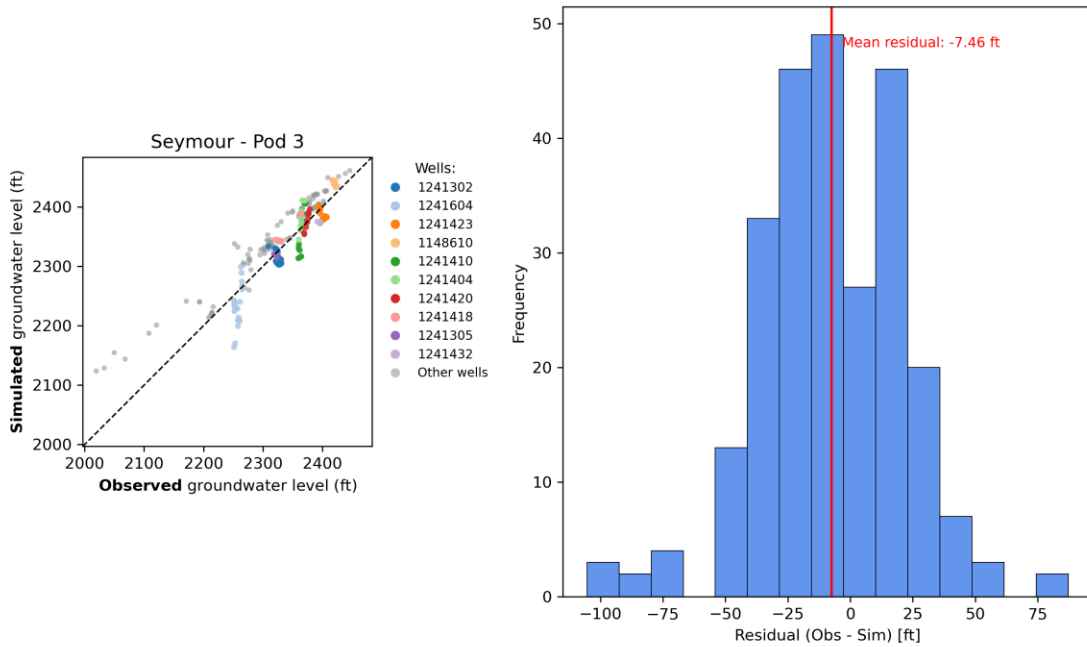


Figure 5.3-45. Average groundwater level residuals (in feet) for each observation well location in Pod 3 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

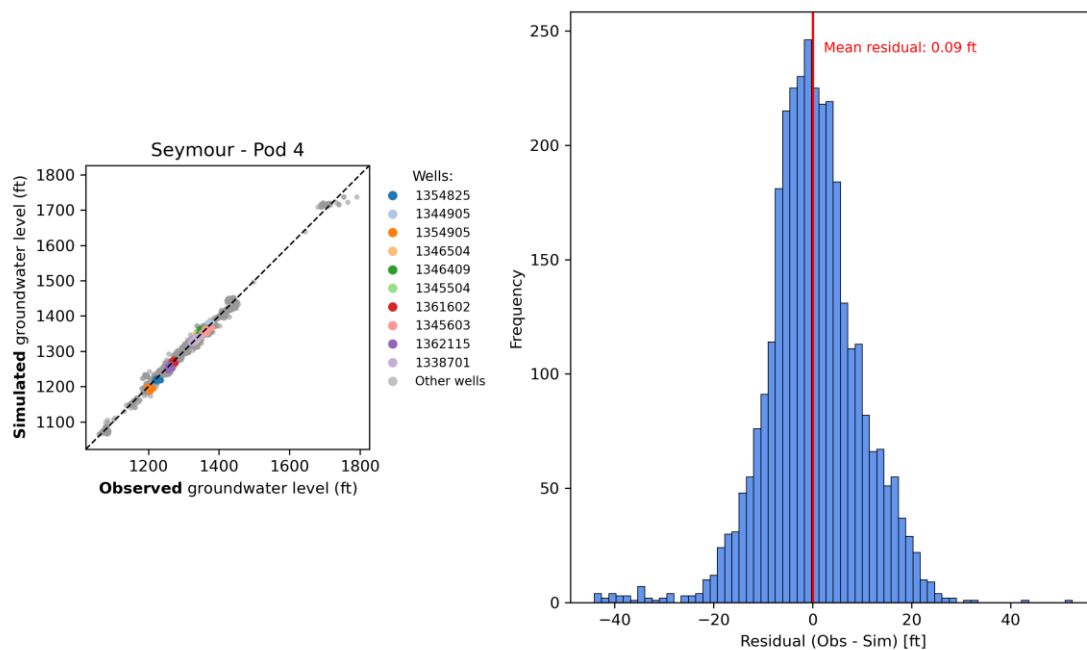


Figure 5.3-46. Average groundwater level residuals (in feet) for each observation well location in Pod 4 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

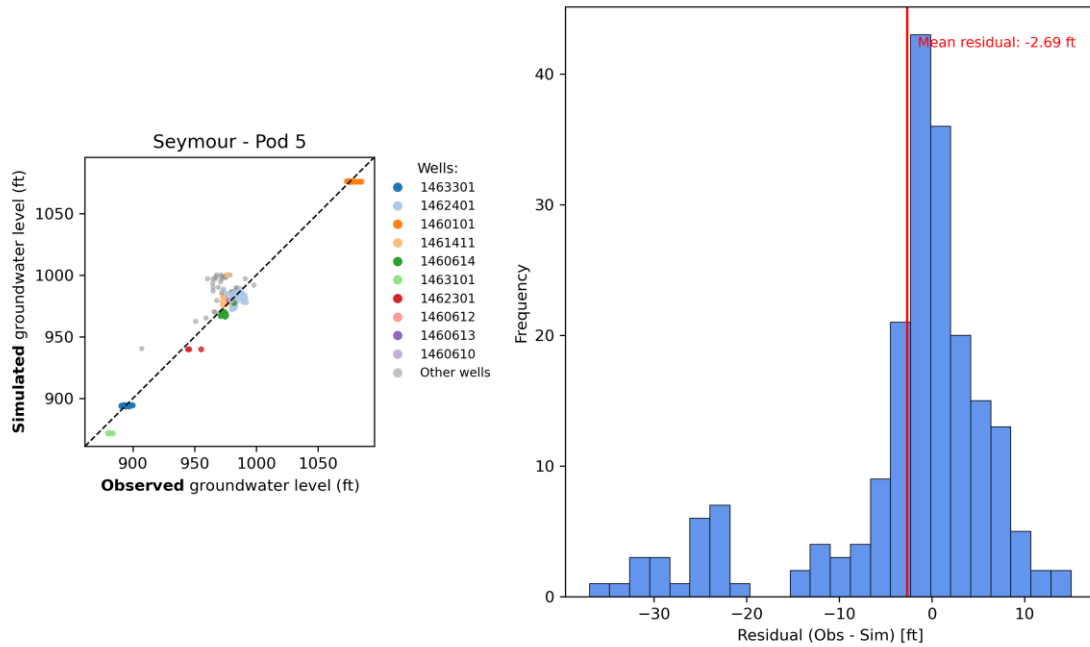


Figure 5.3-47. Average groundwater level residuals (in feet) for each observation well location in Pod 5 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

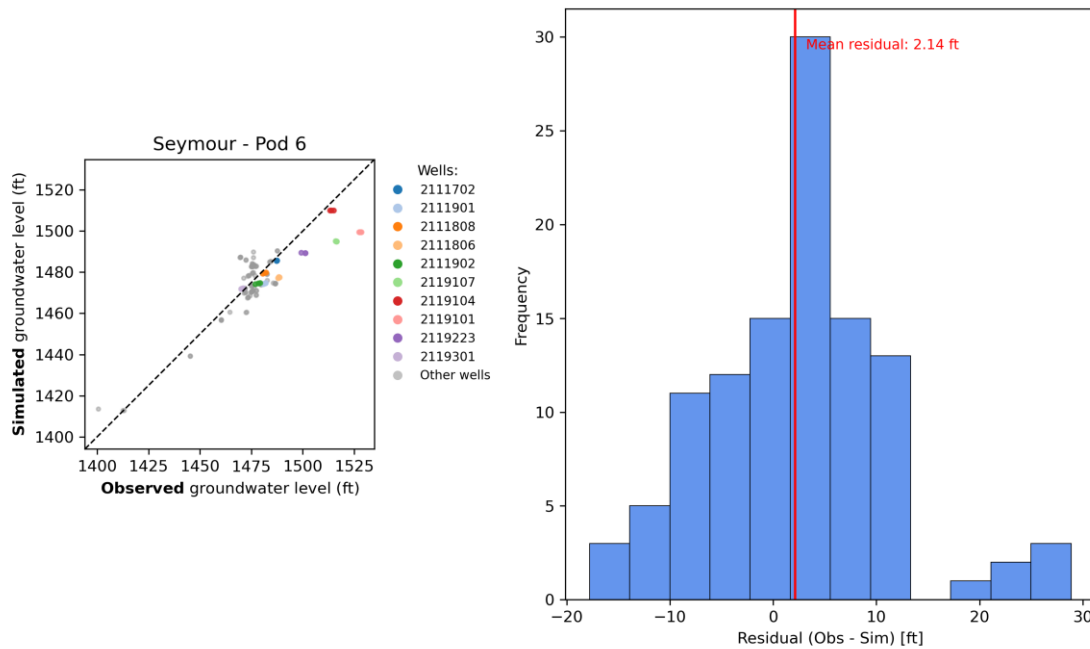


Figure 5.3-48. Average groundwater level residuals (in feet) for each observation well location in Pod 6 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

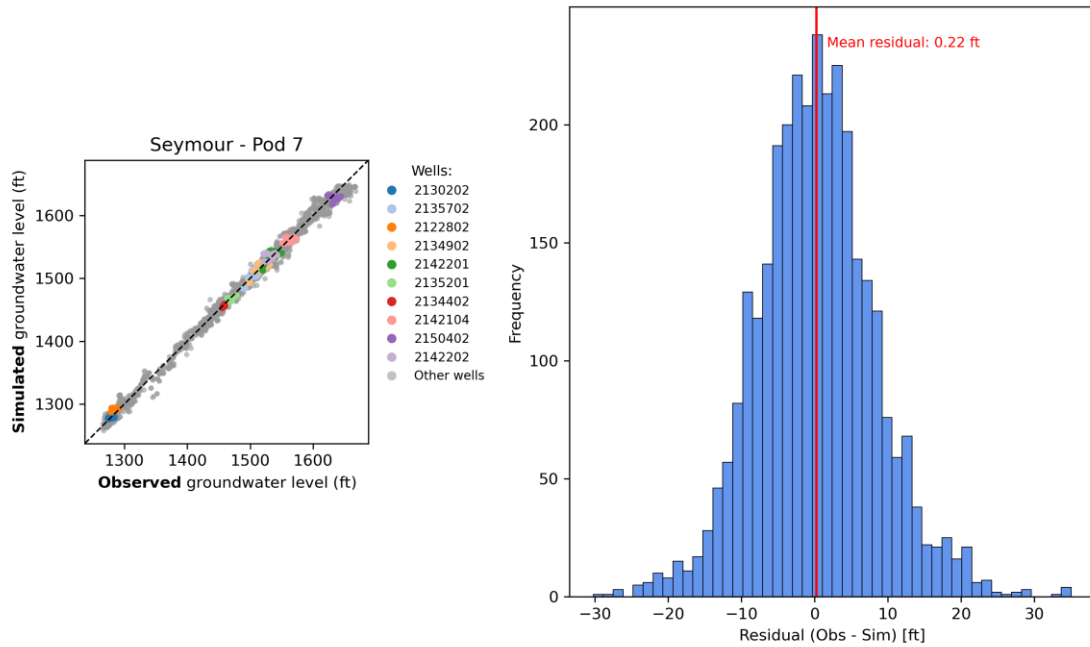


Figure 5.3-49. Average groundwater level residuals (in feet) for each observation well location in Pod 7 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

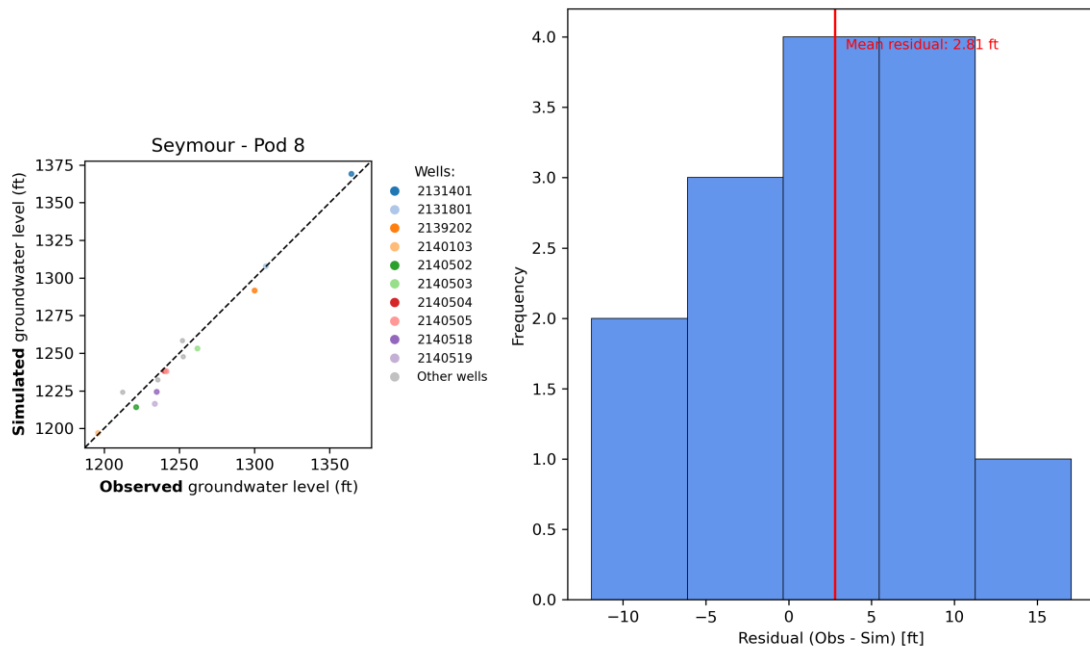


Figure 5.3-50. Average groundwater level residuals (in feet) for each observation well location in Pod 8 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

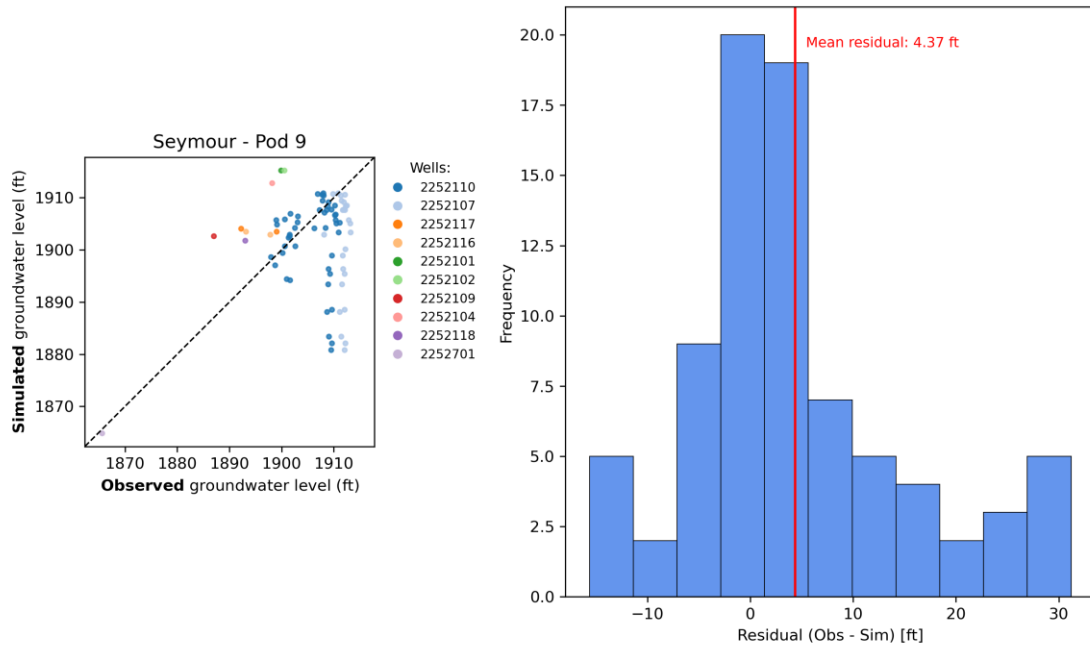


Figure 5.3-51. Average groundwater level residuals (in feet) for each observation well location in Pod 9 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

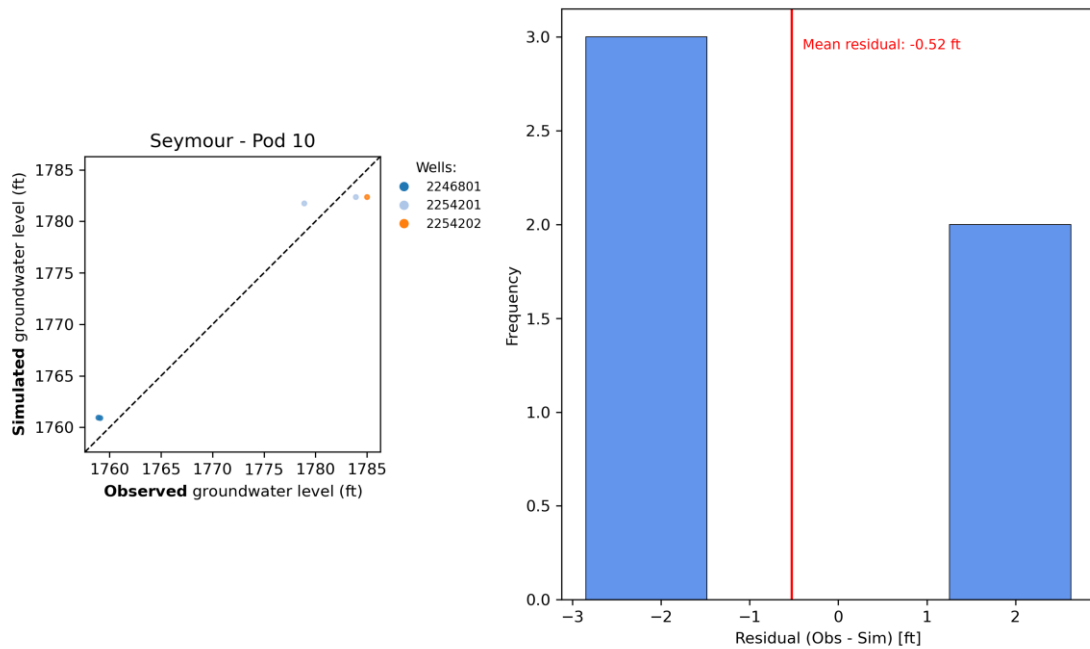


Figure 5.3-52. Average groundwater level residuals (in feet) for each observation well location in Pod 10 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

Texas Water Development Board Contract Number 2448302843
 Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

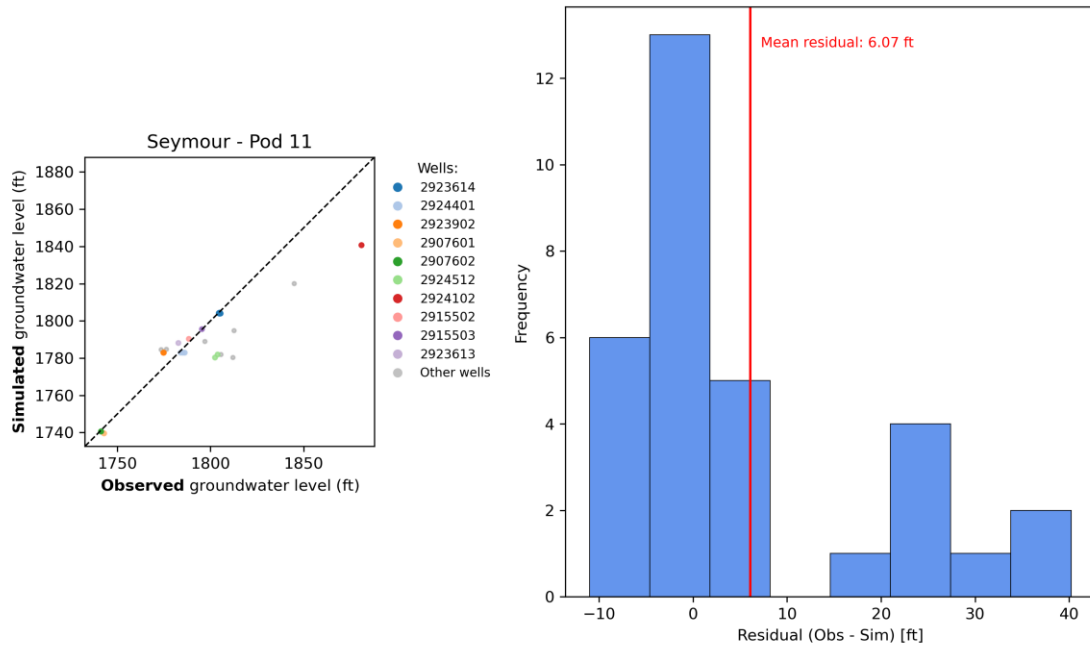


Figure 5.3-53. Average groundwater level residuals (in feet) for each observation well location in Pod 11 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

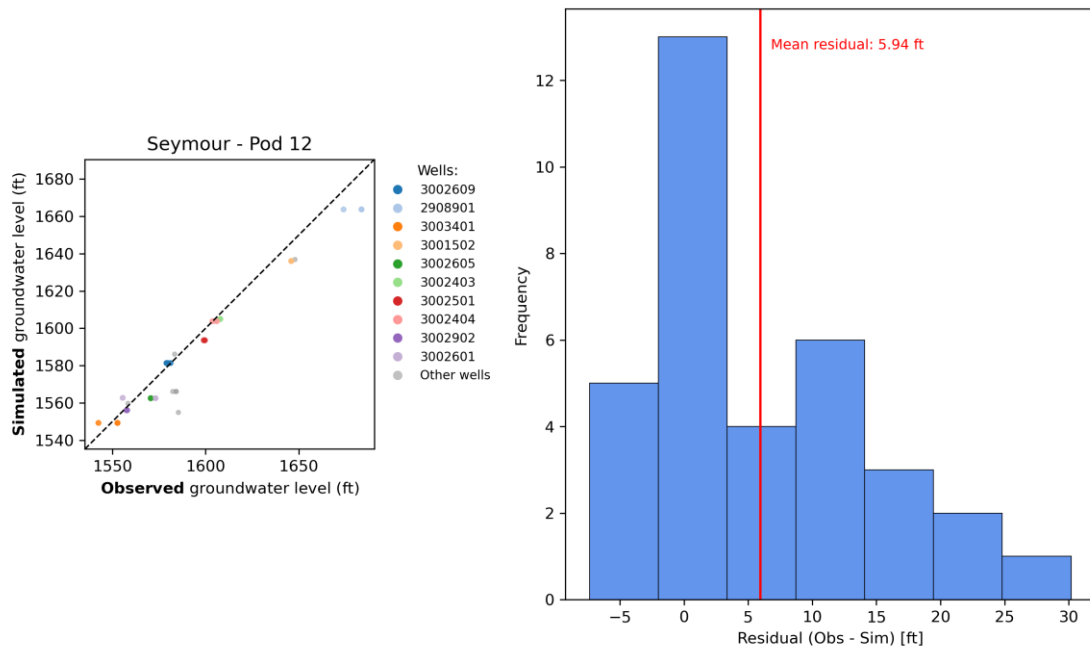


Figure 5.3-54. Average groundwater level residuals (in feet) for each observation well location in Pod 12 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

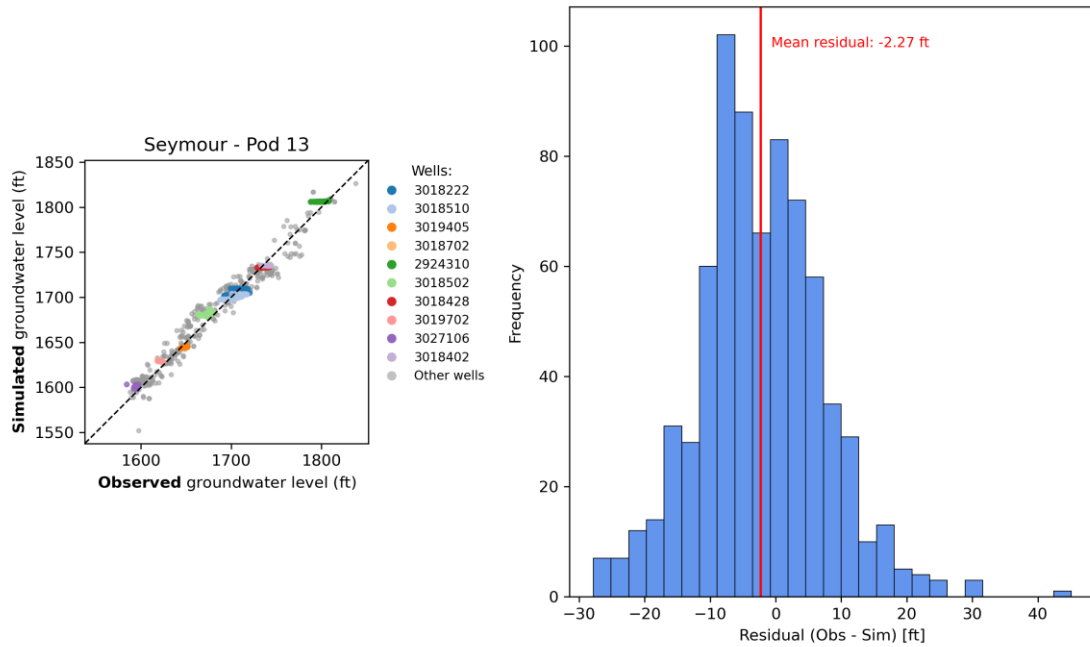


Figure 5.3-55. Average groundwater level residuals (in feet) for each observation well location in Pod 13 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

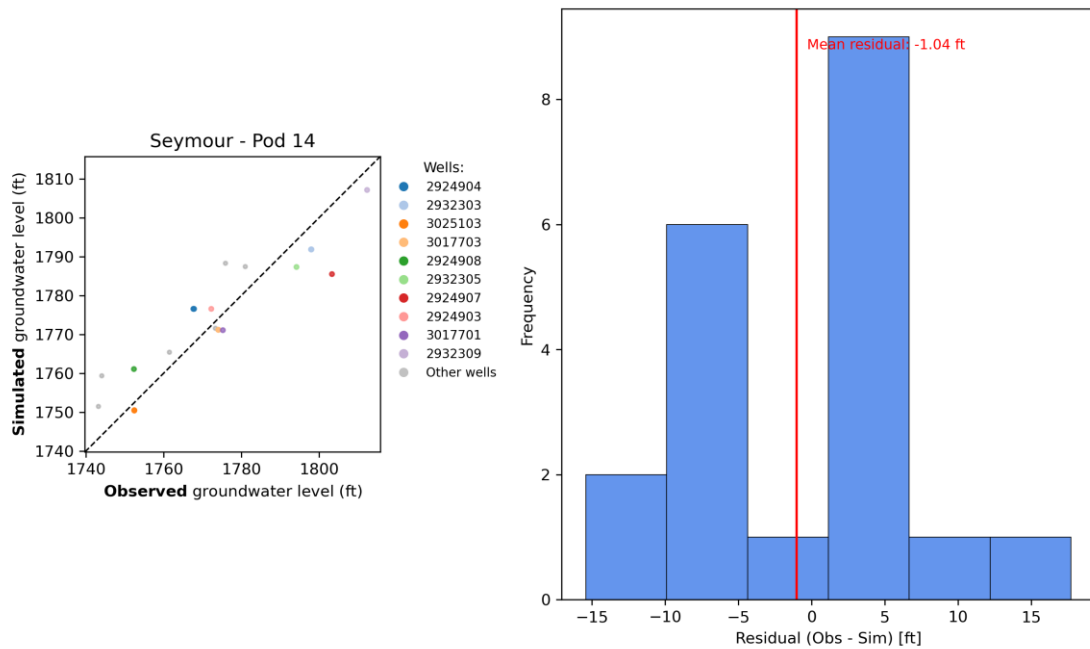


Figure 5.3-56. Average groundwater level residuals (in feet) for each observation well location in Pod 14 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

Texas Water Development Board Contract Number 2448302843
 Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

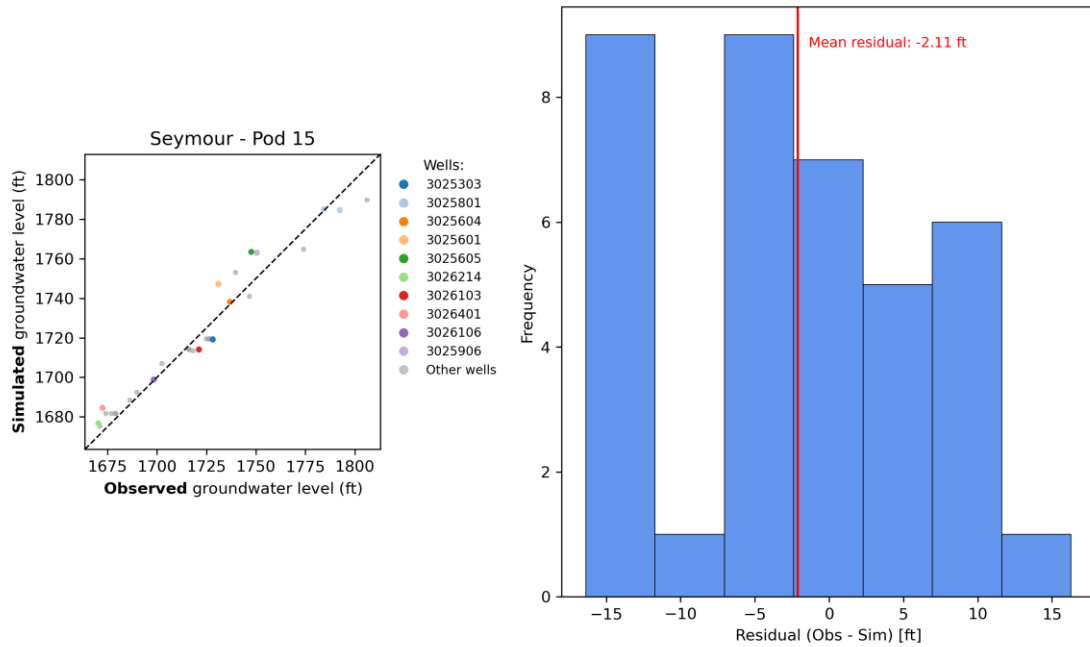


Figure 5.3-57. Average groundwater level residuals (in feet) for each observation well location in Pod 15 in Seymour Aquifer. (ft = feet, obs = observed, sim = simulated).

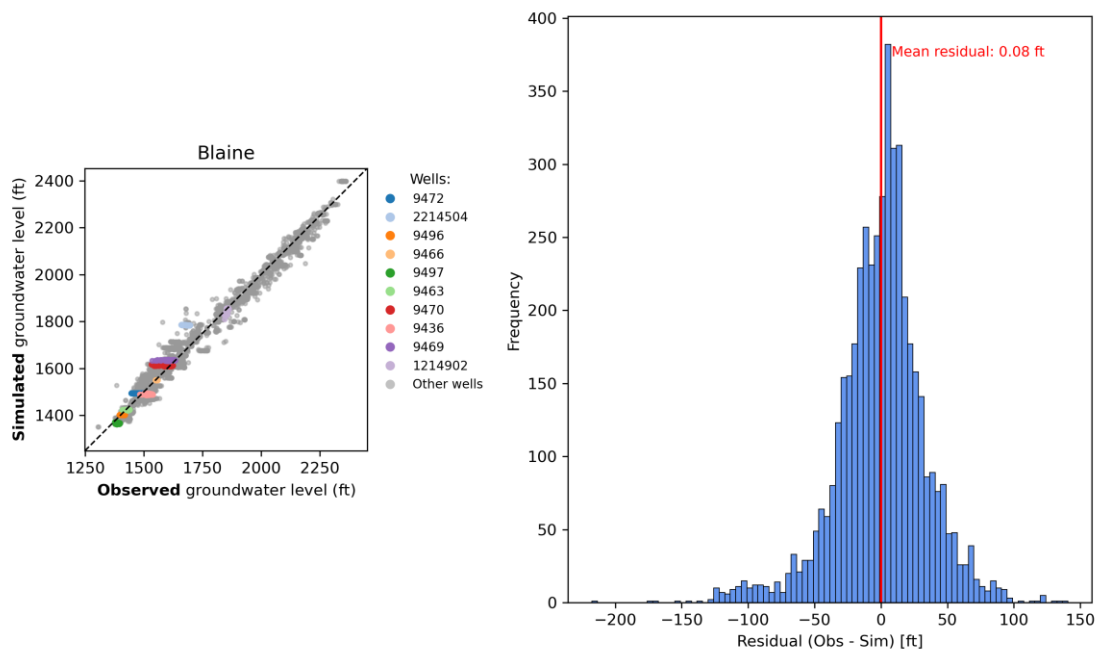


Figure 5.3-58. Average groundwater level residuals (in feet) for each observation well location in Blaine Aquifer. (ft = feet, obs = observed, sim = simulated).

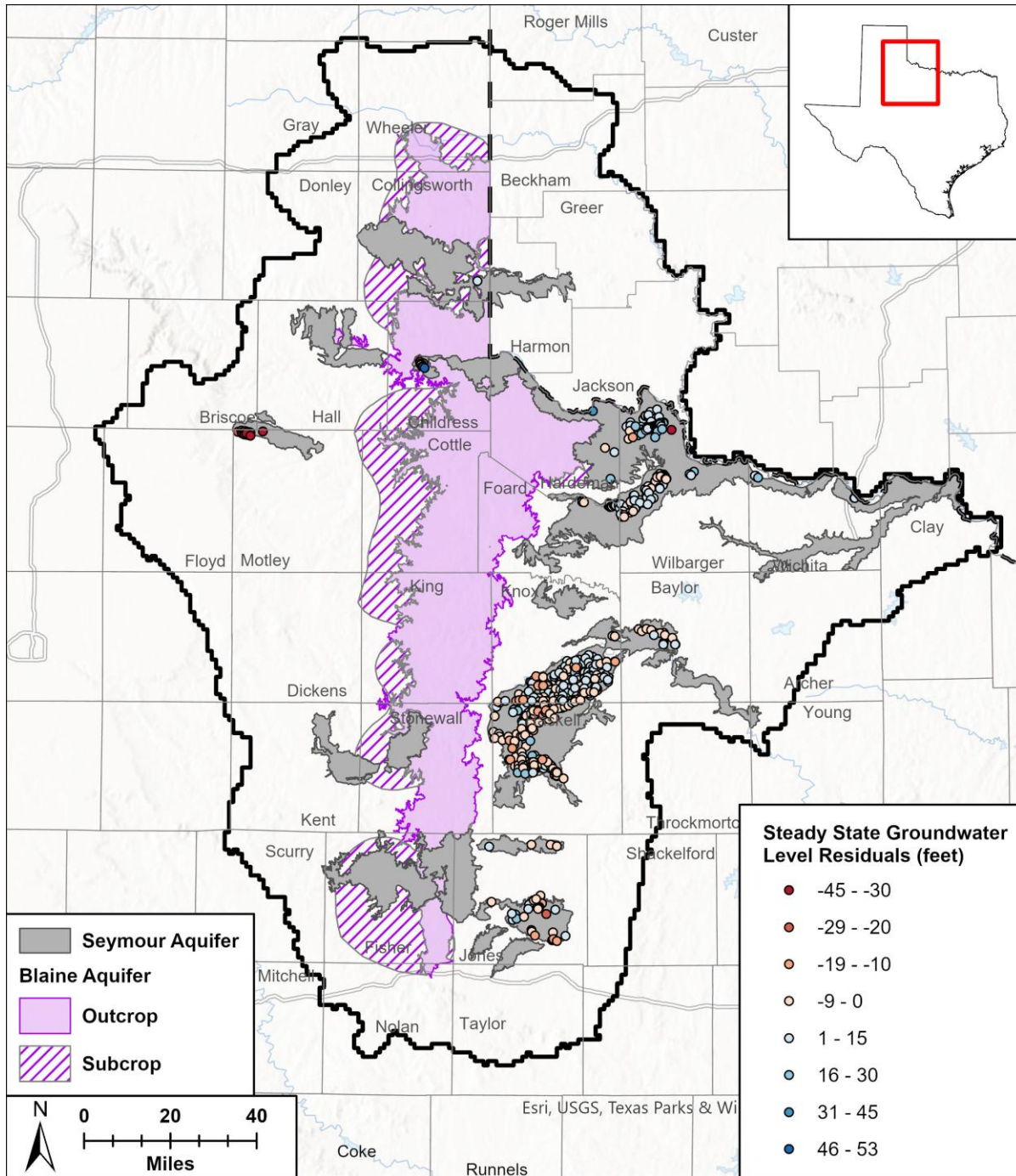


Figure 5.3-59. Steady-state groundwater level residuals (observed minus simulated, in feet) in the Seymour Aquifer.

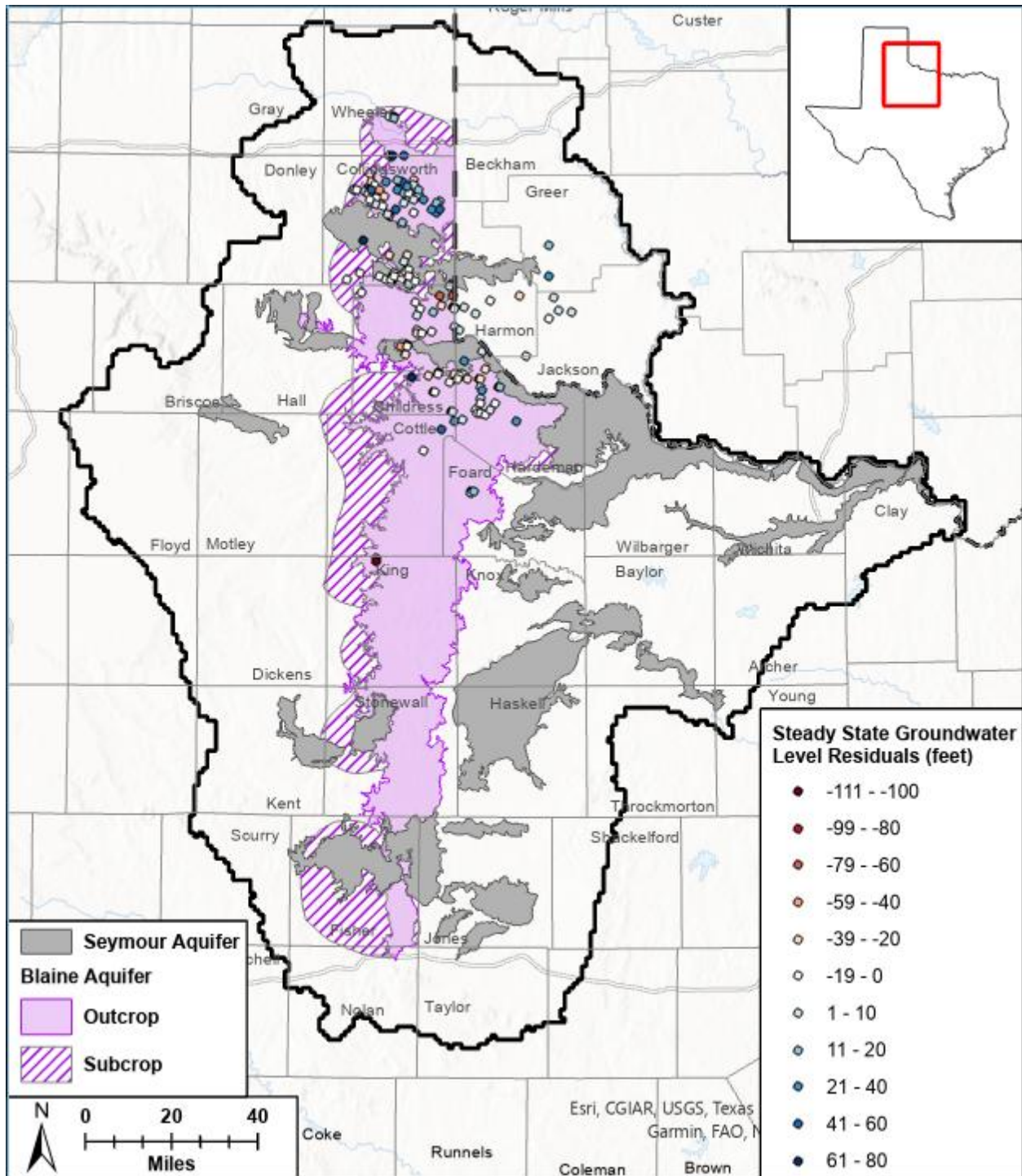


Figure 5.3-60. Steady-state groundwater level residuals (observed minus simulated, in feet) in the Blaine Aquifer.

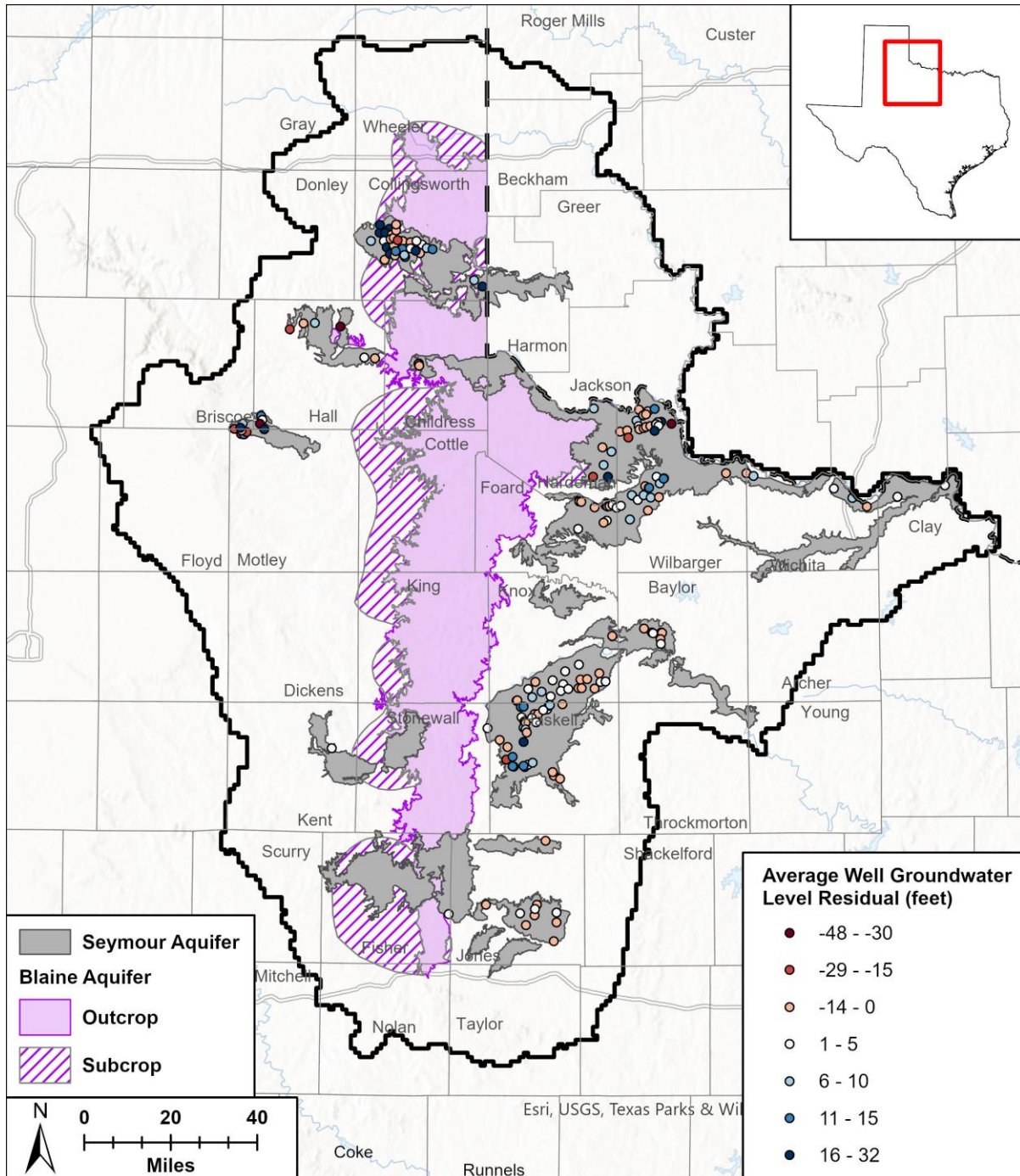


Figure 5.3-61. Transient high-frequency groundwater level residuals (observed minus simulated, in feet) in the Seymour Aquifer.

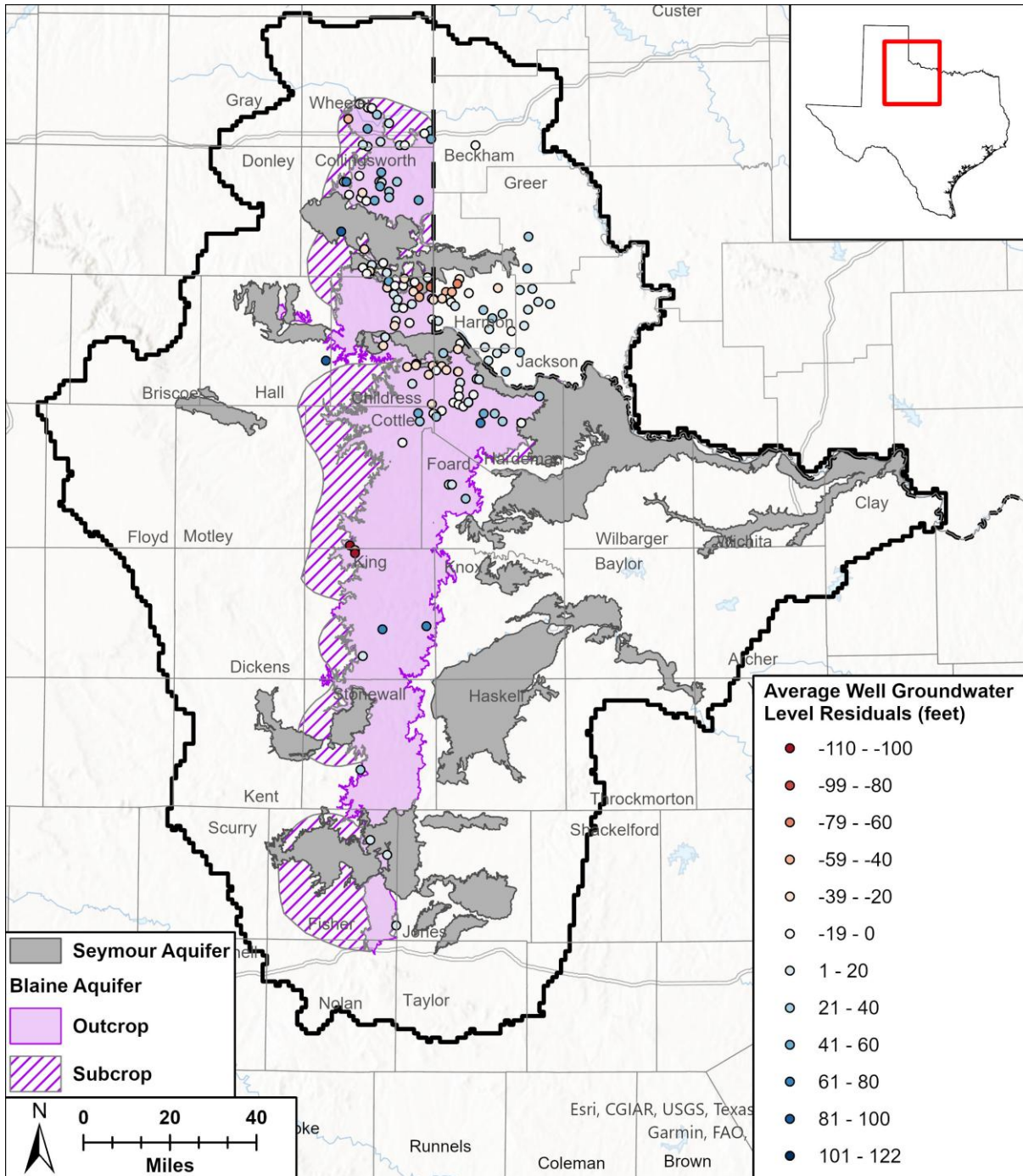


Figure 5.3-62. Transient high-frequency groundwater level residuals (observed minus simulated, in feet) in the Blaine Aquifer.

Texas Water Development Board Contract Number 2448302843
 Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

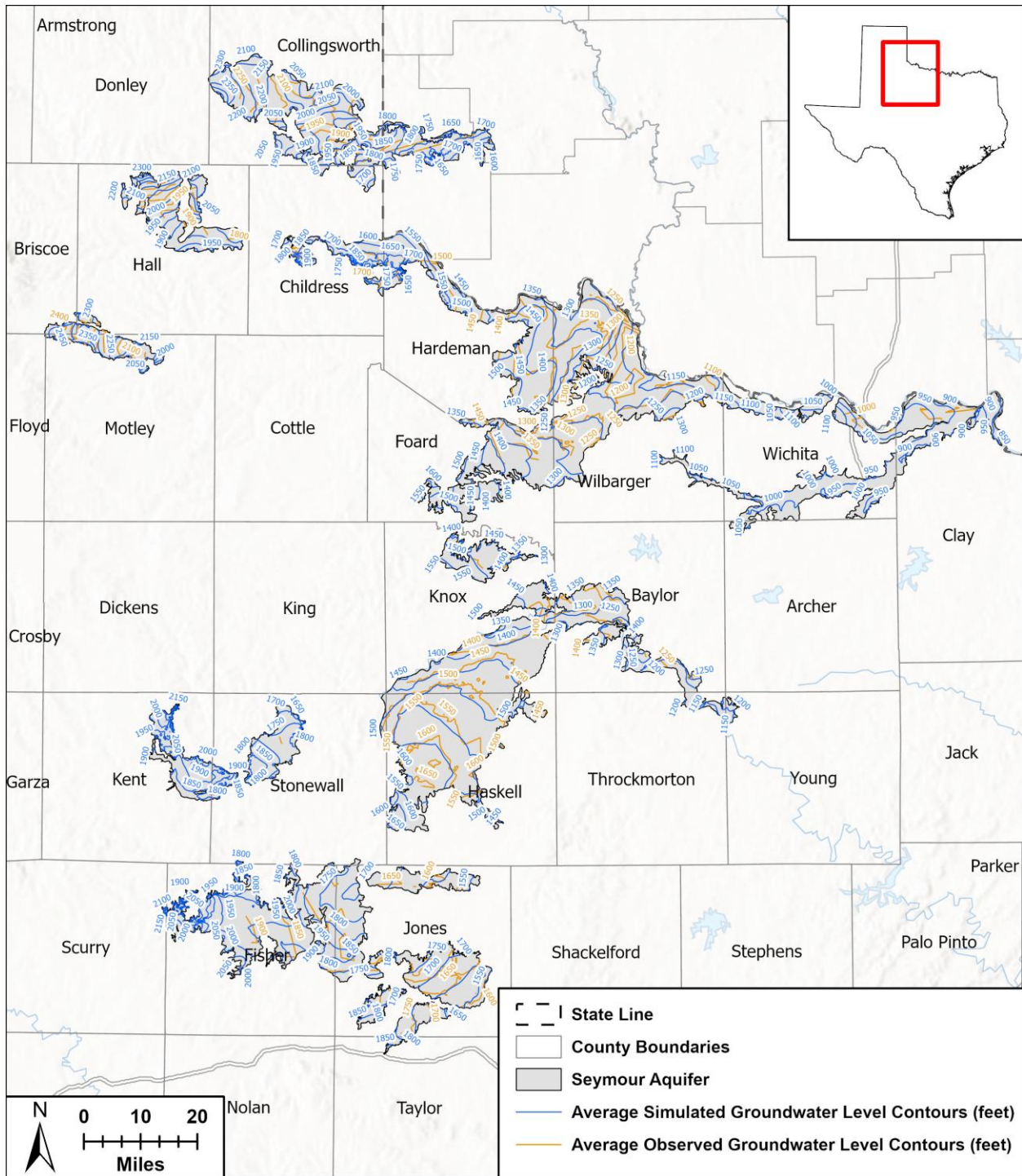


Figure 5.3-63. Average simulated and average observed groundwater elevation contours for the Seymour Aquifer. Contour interval is 50 feet. Averages are temporal means over the calibration period.

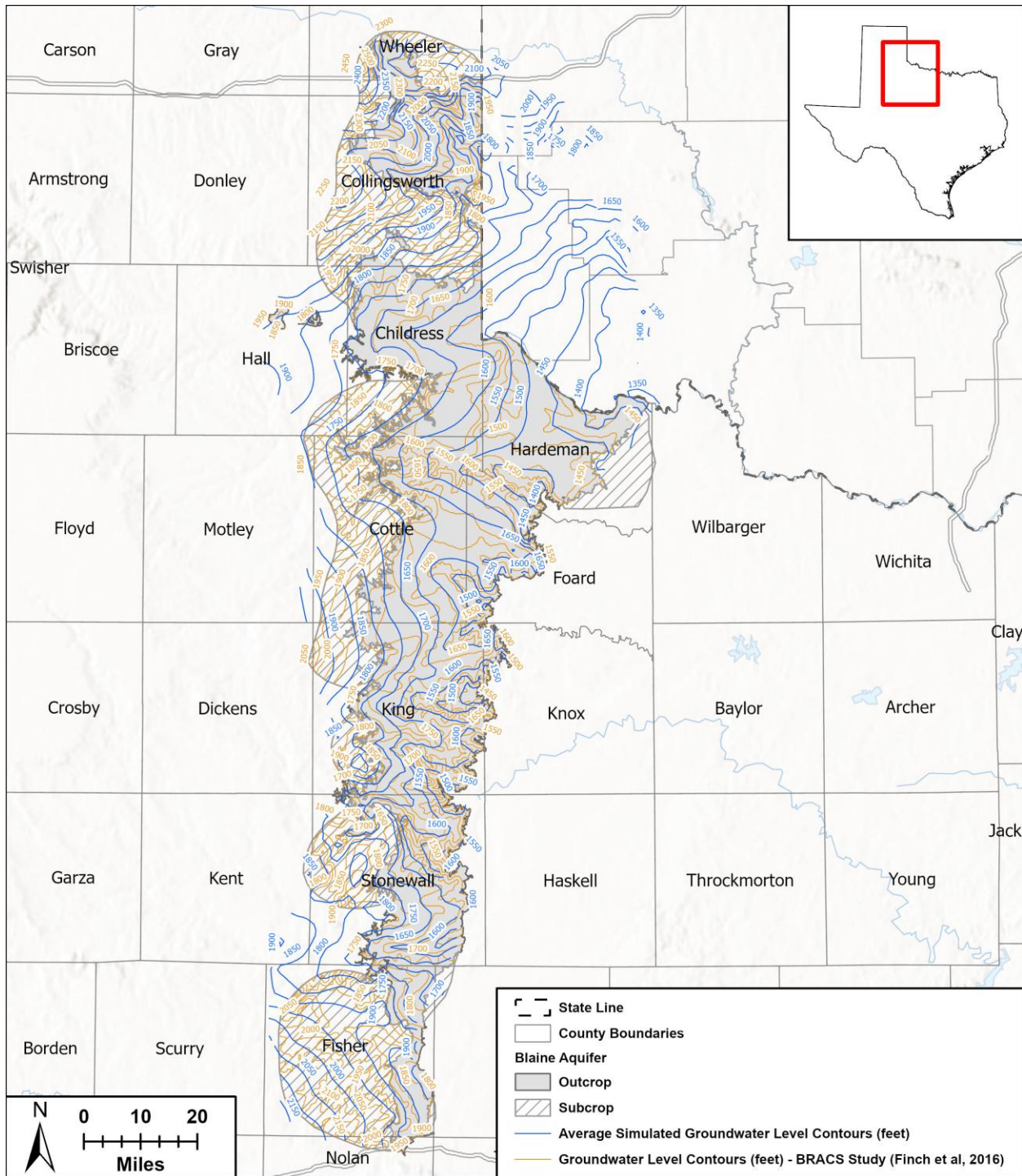


Figure 5.3-64. Average simulated groundwater elevation contours compared to interpolated observed groundwater elevation contours from the Brackish Resources Aquifer Characterization Study (Finch and others, 2016) for Blaine Aquifer. Contour interval is 50 feet. Simulated averages are temporal means over the calibration period.

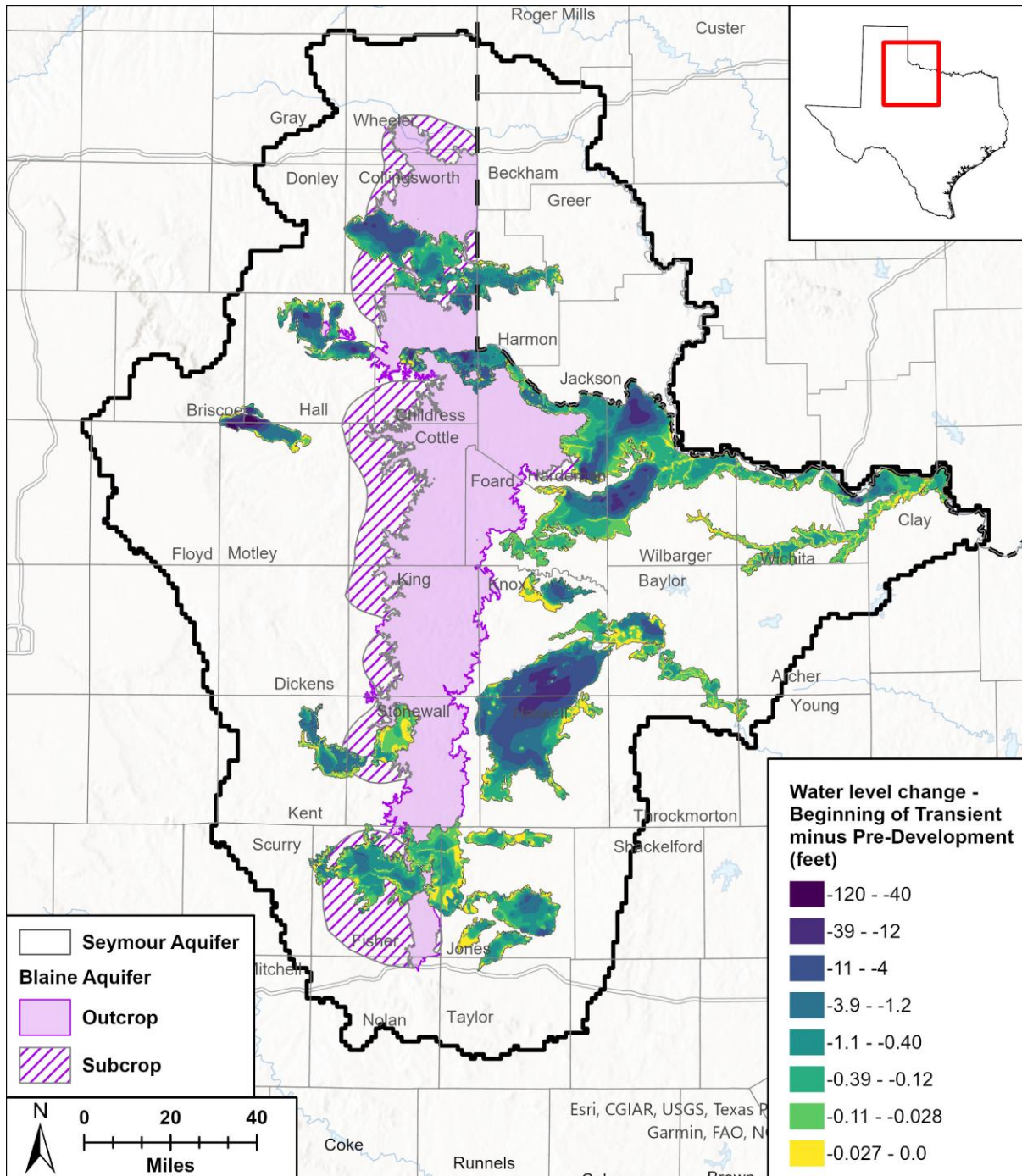


Figure 5.3-65. Change in simulated water level between pre-development and the start of the transient period (in feet) in the Seymour Aquifer.

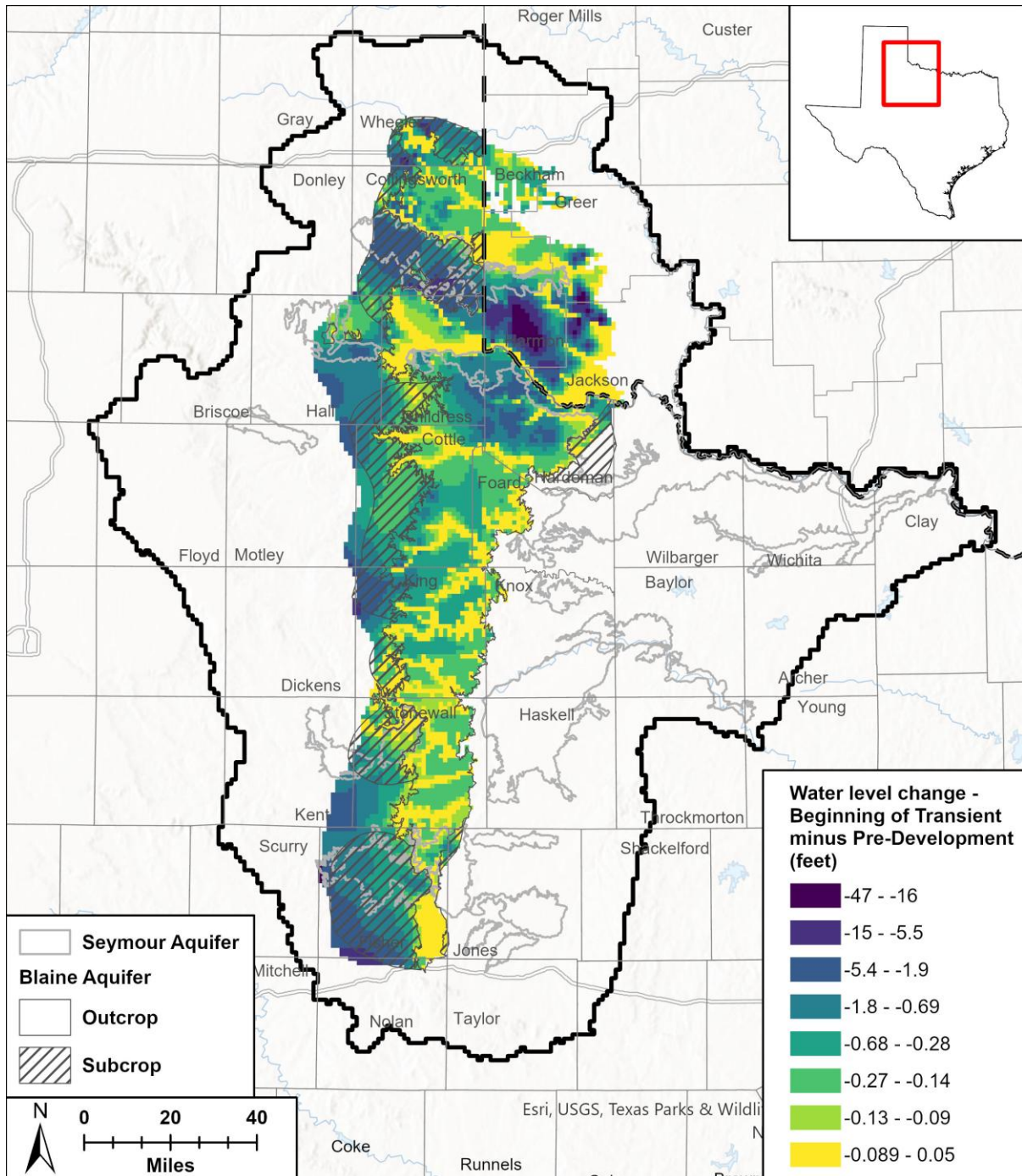


Figure 5.3-66. Change in simulated water level between pre-development and the start of the transient period (in feet) in the Blaine Aquifer.

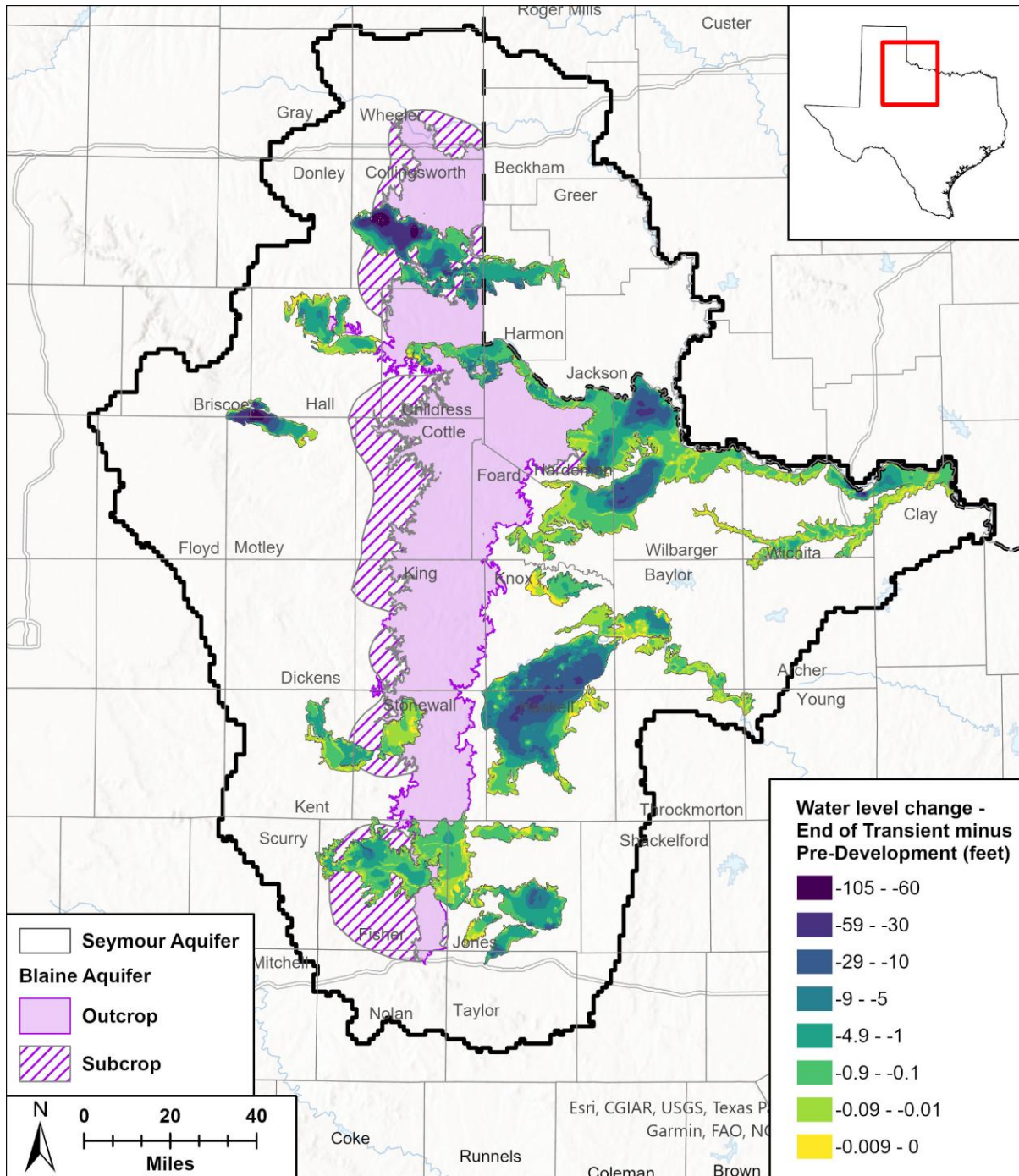


Figure 5.3-67. Change in simulated water level between pre-development and the end of the transient period (in feet) in the Seymour Aquifer.

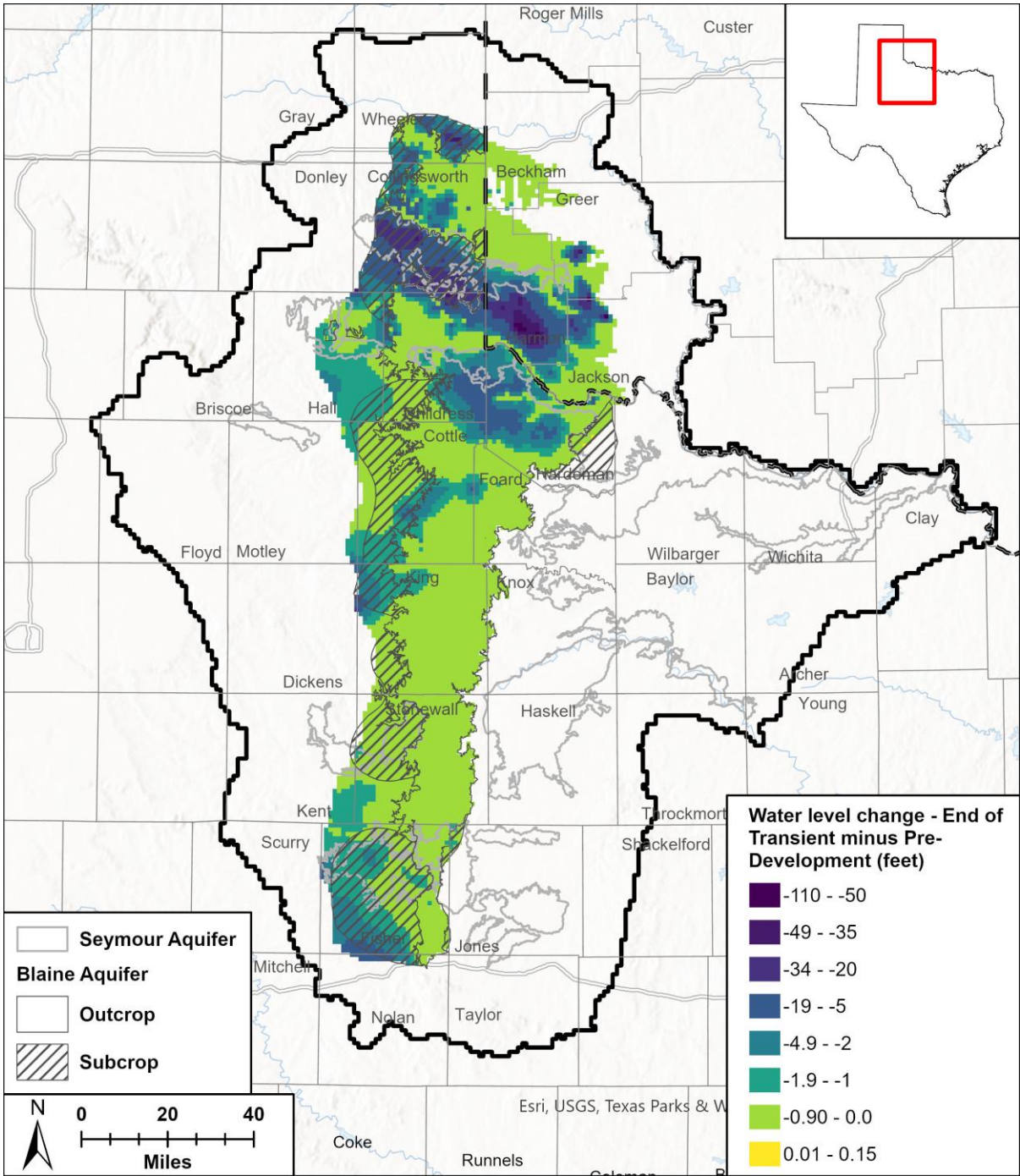


Figure 5.3-68. Change in simulated water level between pre-development and the end of the transient period (in feet) in the Blaine Aquifer.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

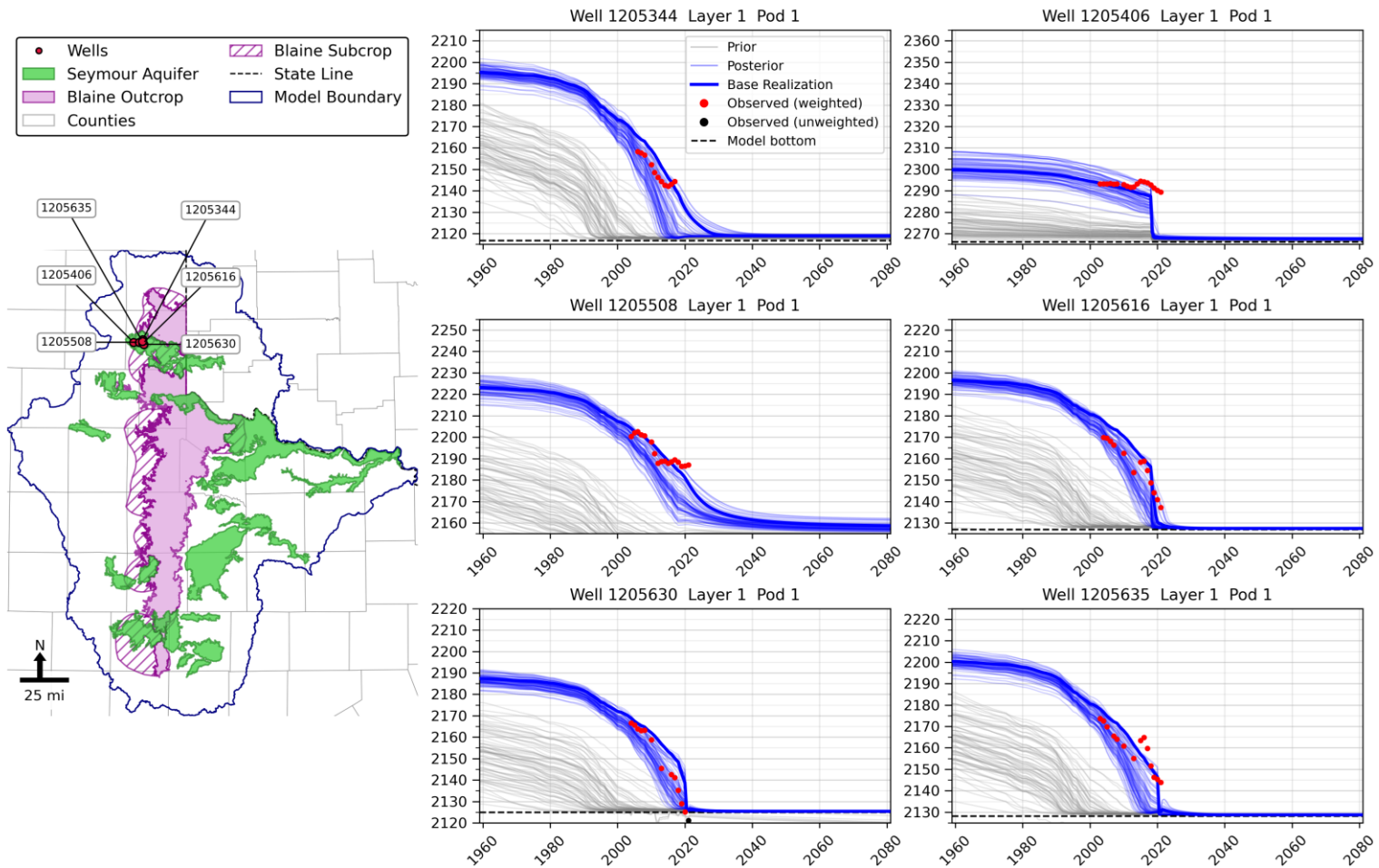


Figure 5.3-69. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 1.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

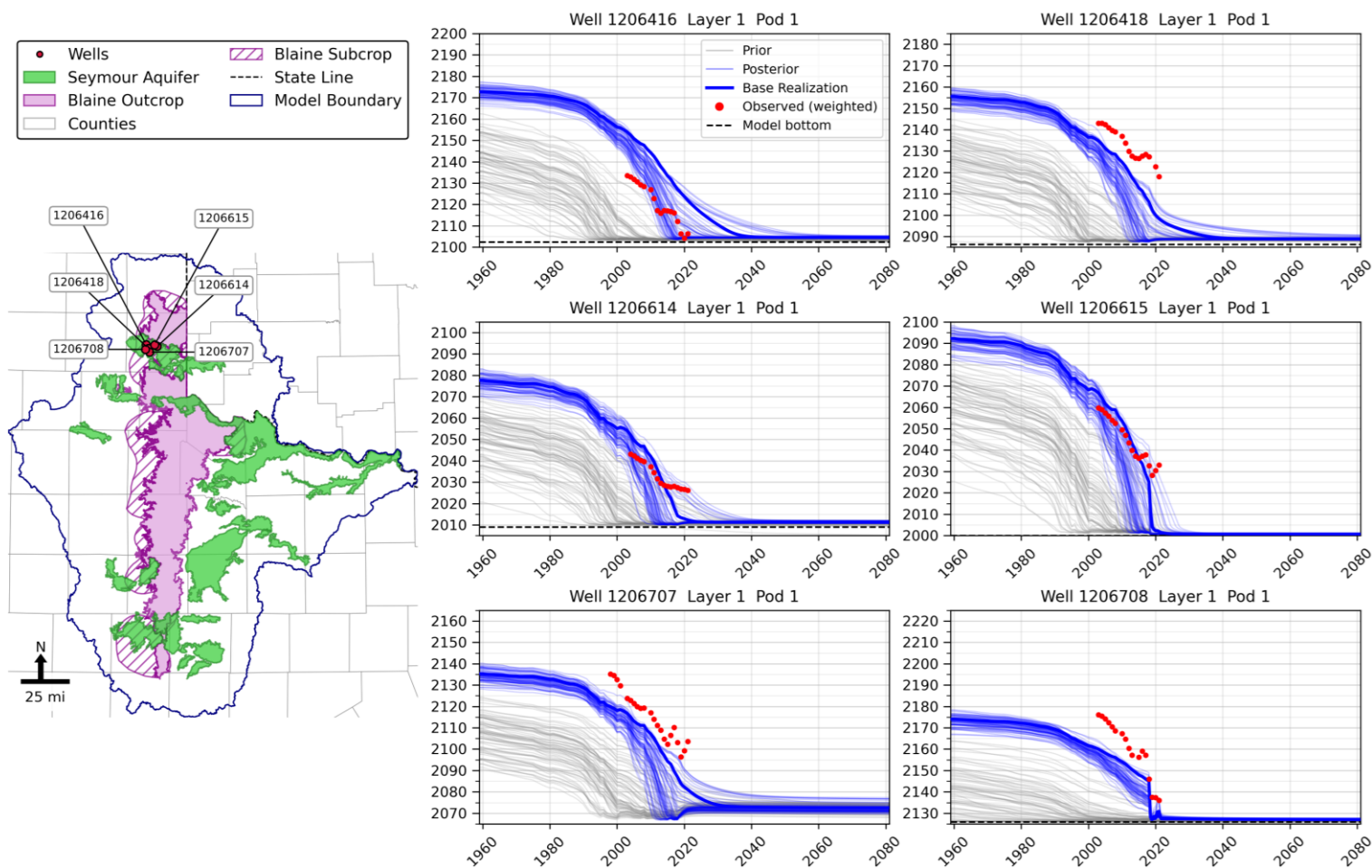


Figure 5.3-70. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 1 (Continued).

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

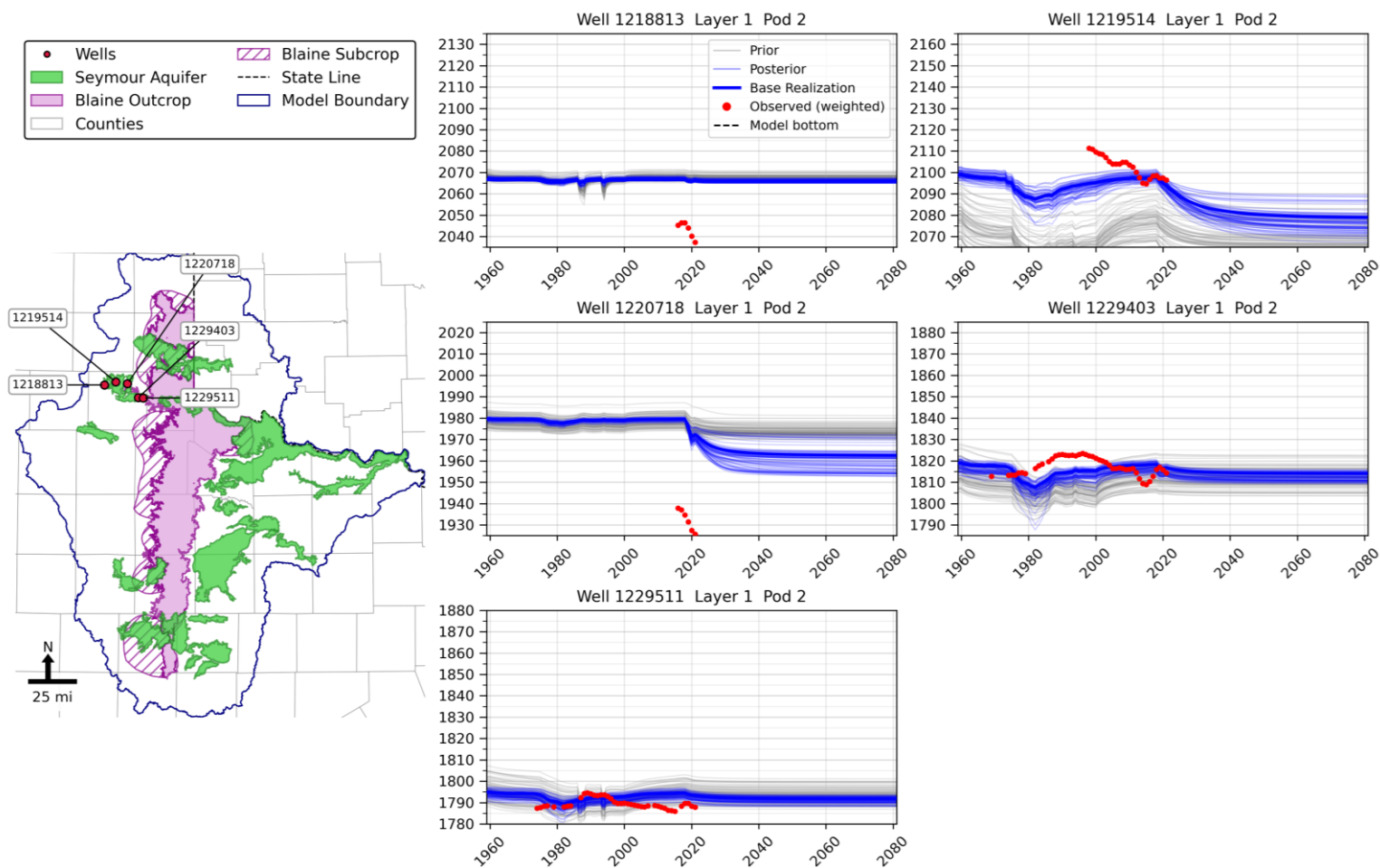


Figure 5.3-71. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 2.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

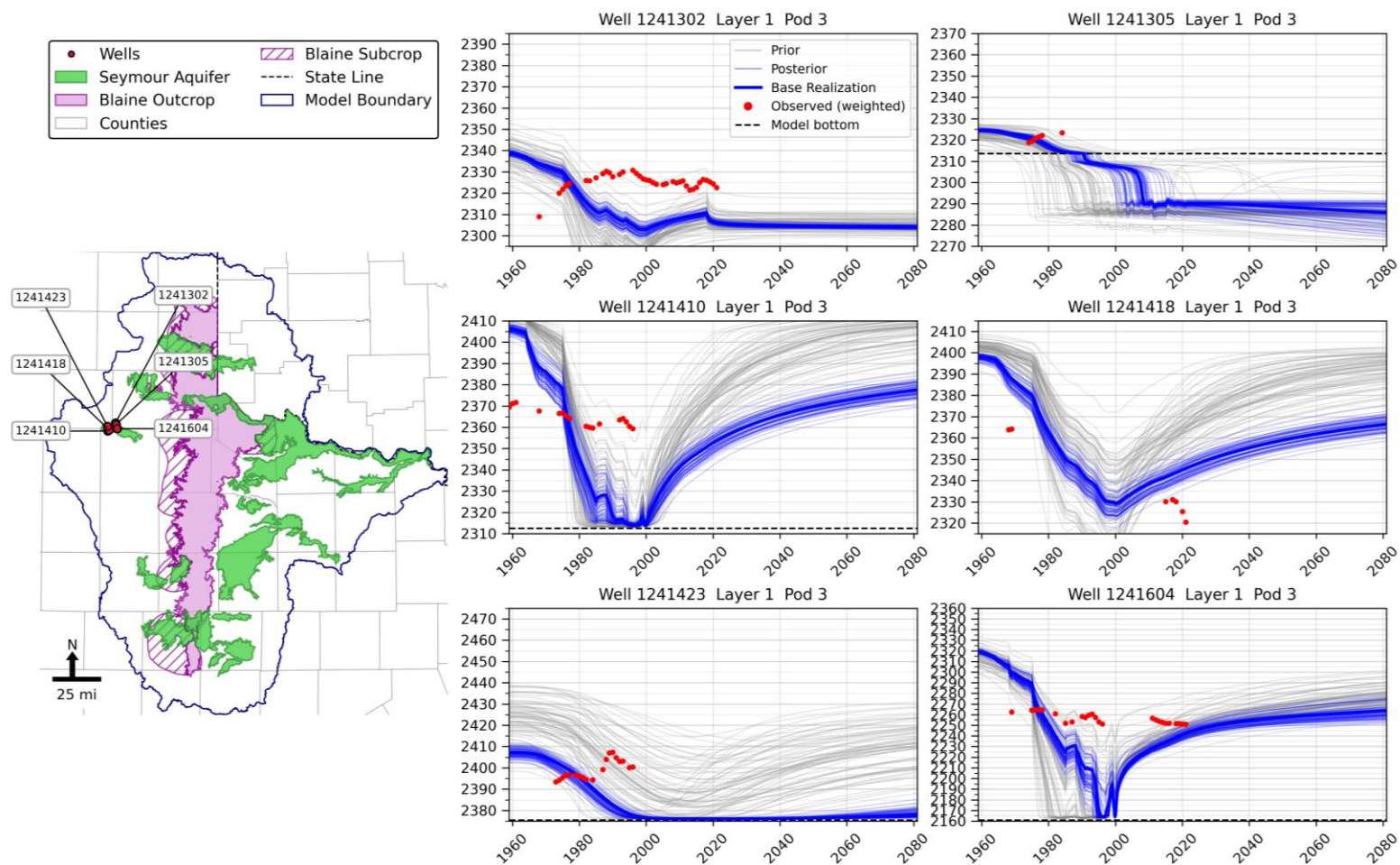


Figure 5.3-72. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 3.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

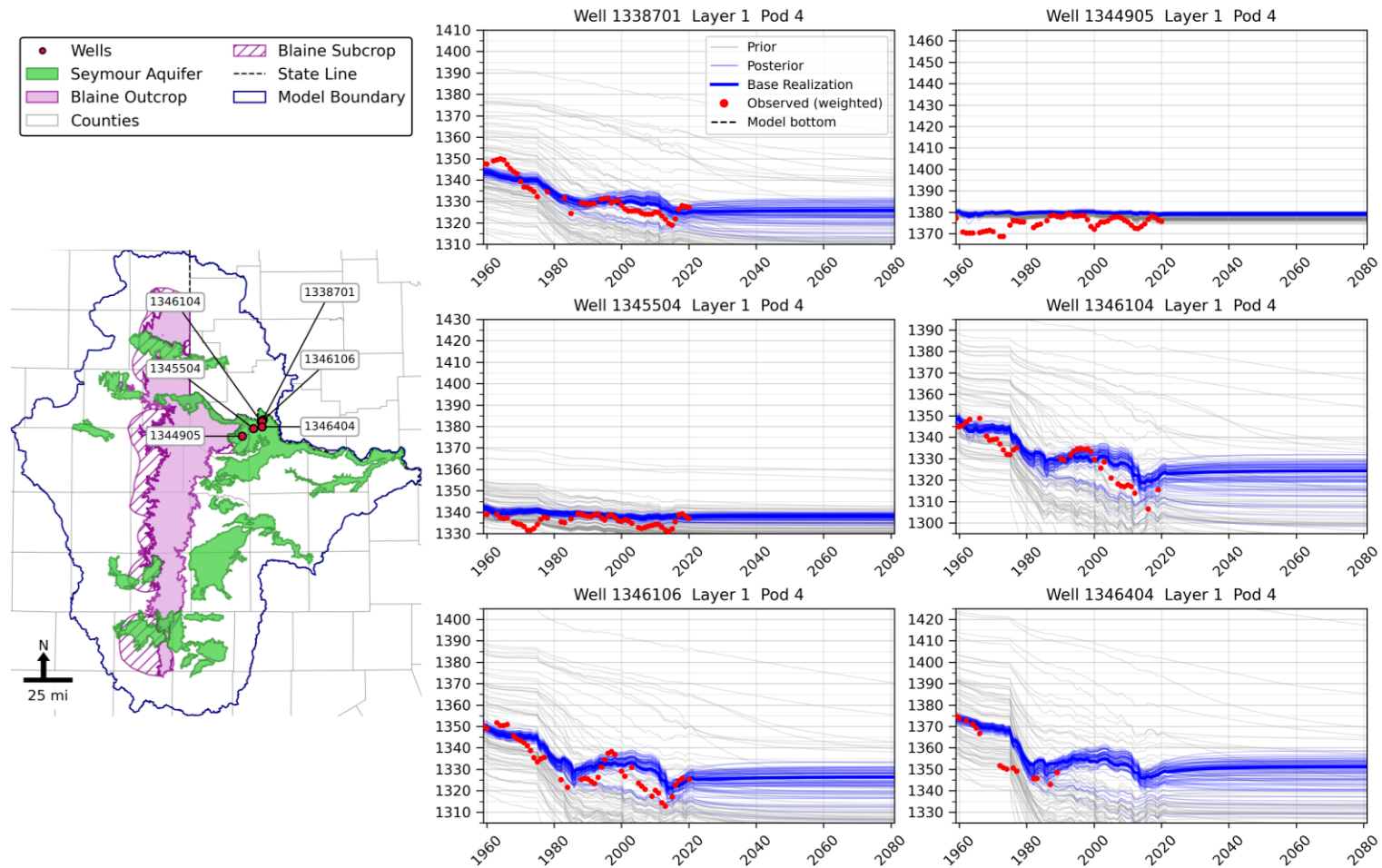


Figure 5.3-73. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 4.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

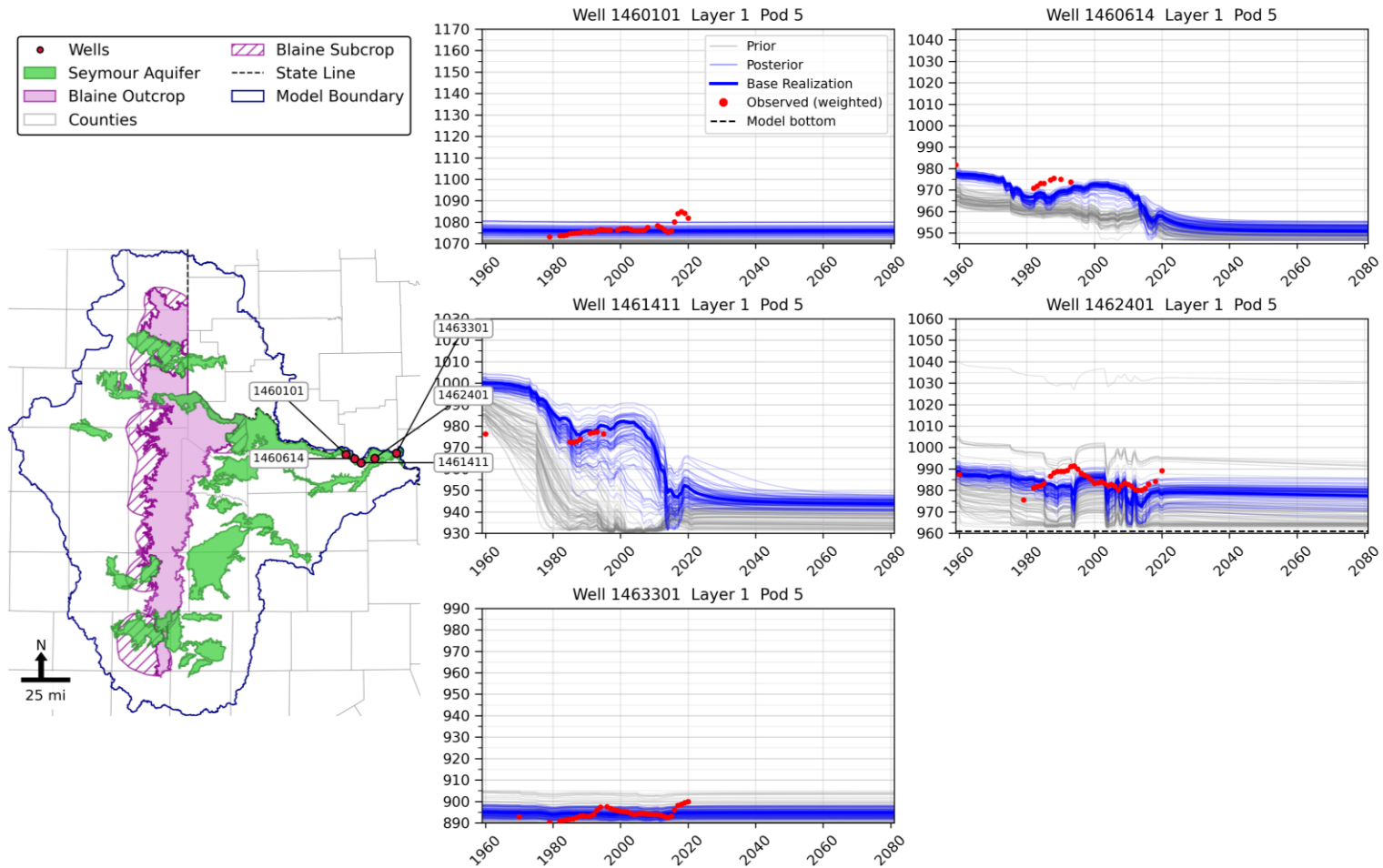


Figure 5.3-74. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 5.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

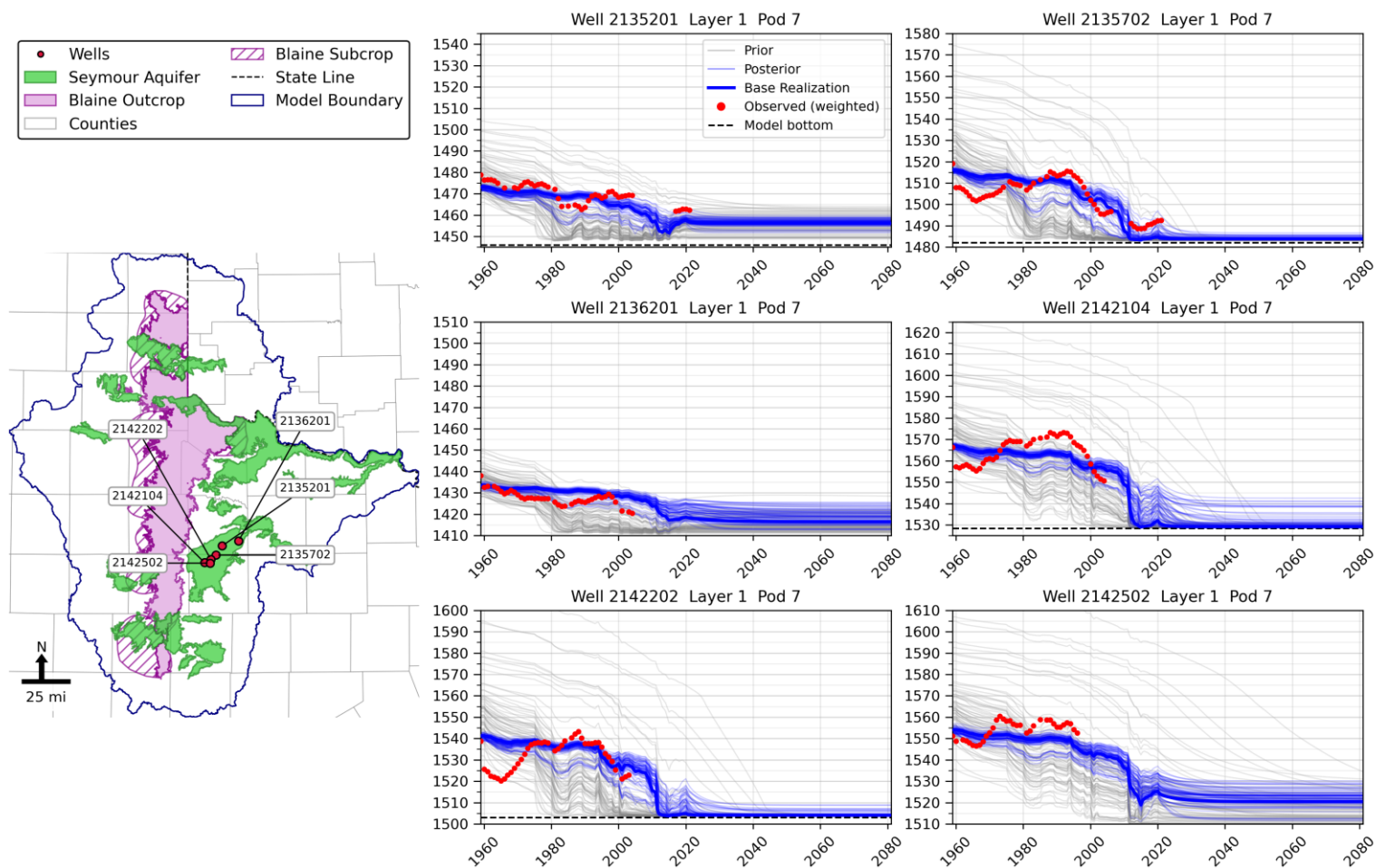


Figure 5.3-75. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 7.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

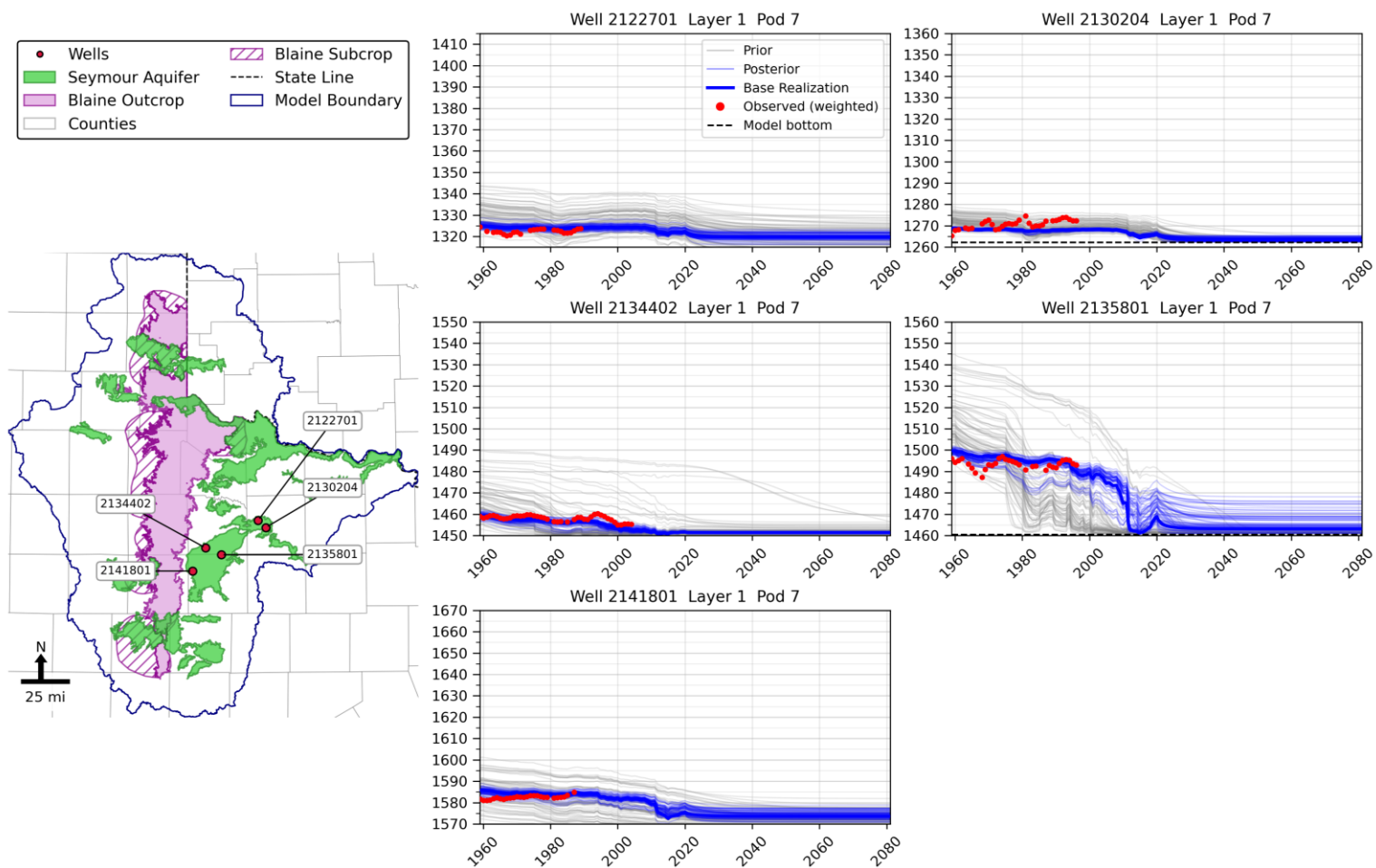


Figure 5.3-76. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 7 (Continued).

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

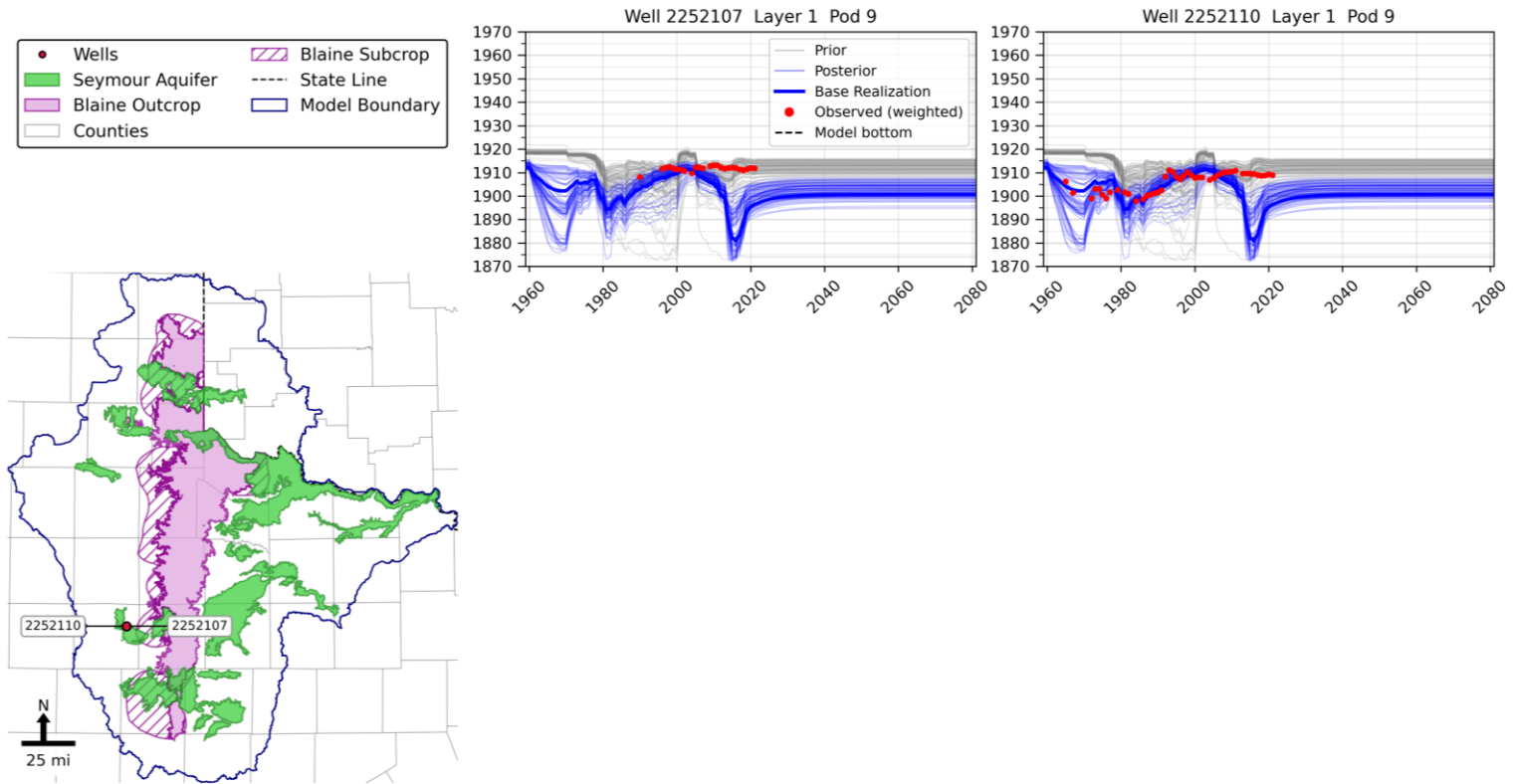


Figure 5.3-77. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 9.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

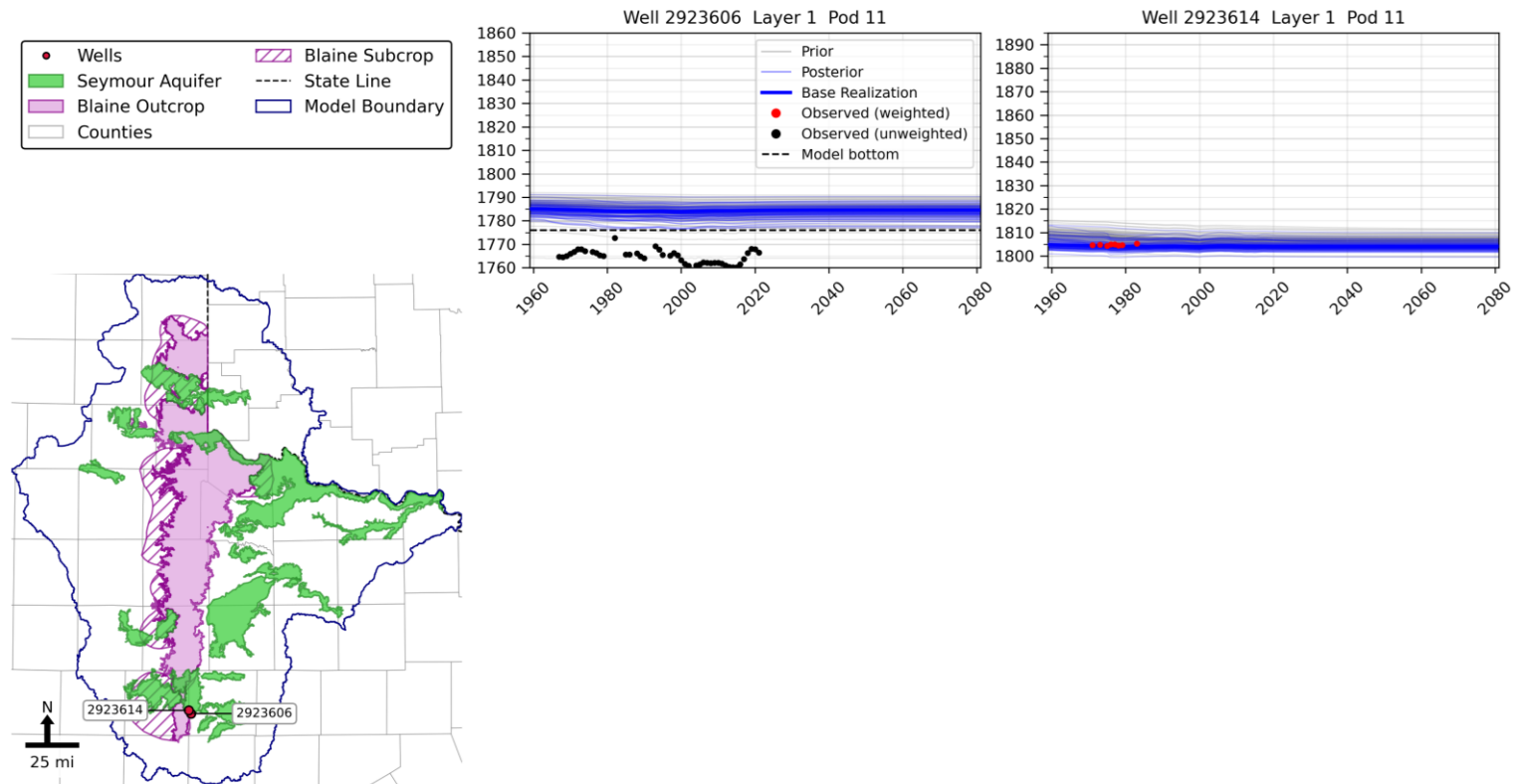


Figure 5.3-78. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 11.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

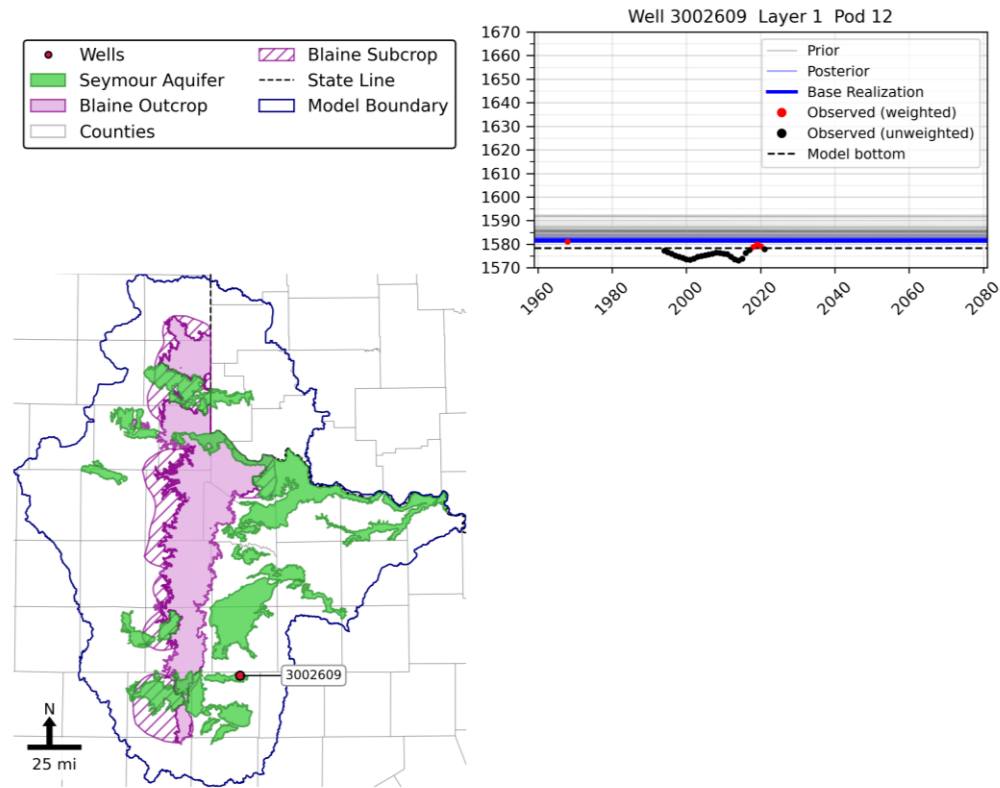


Figure 5.3-79. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 12.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

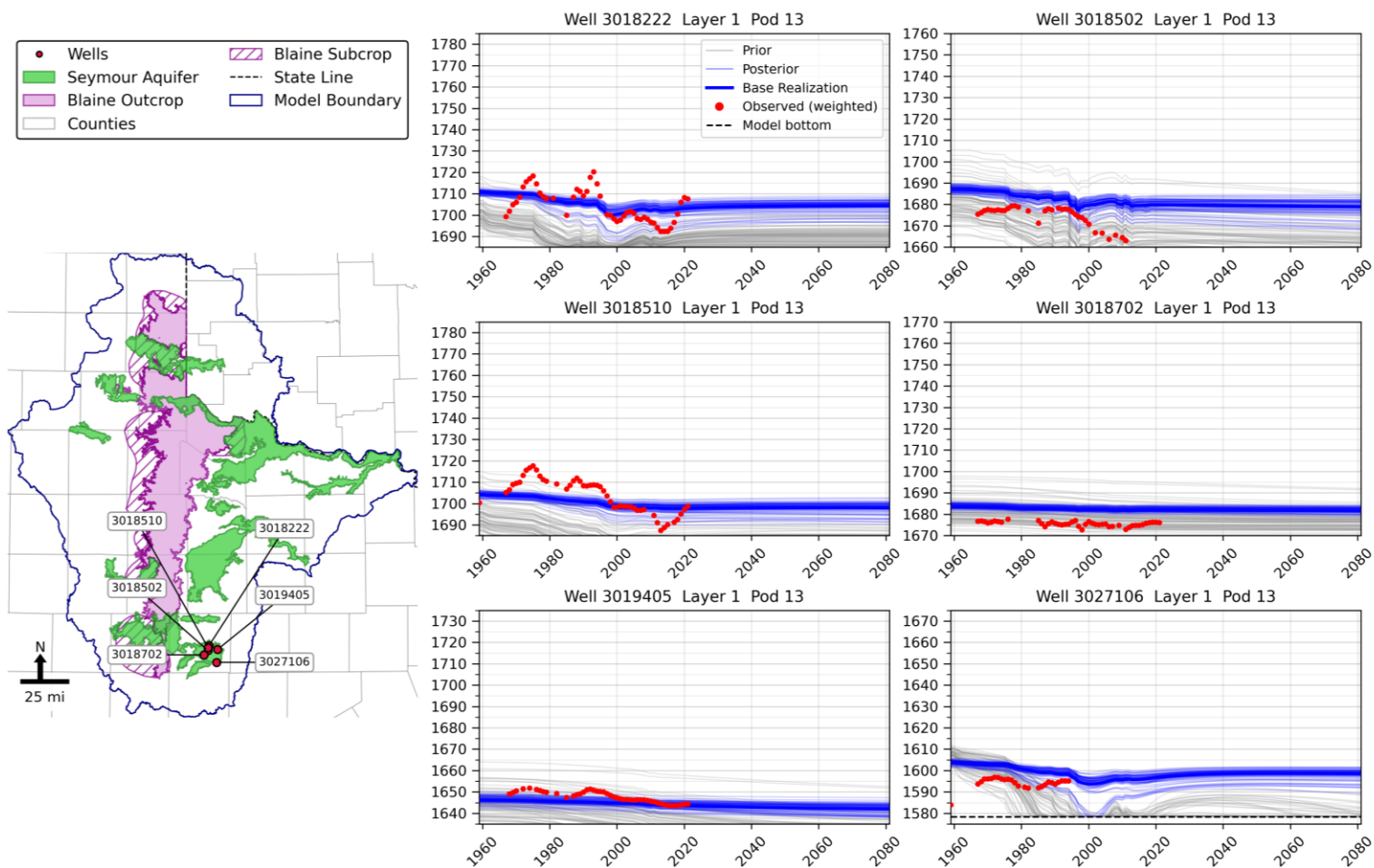


Figure 5.3-80. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Pod 13.

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Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

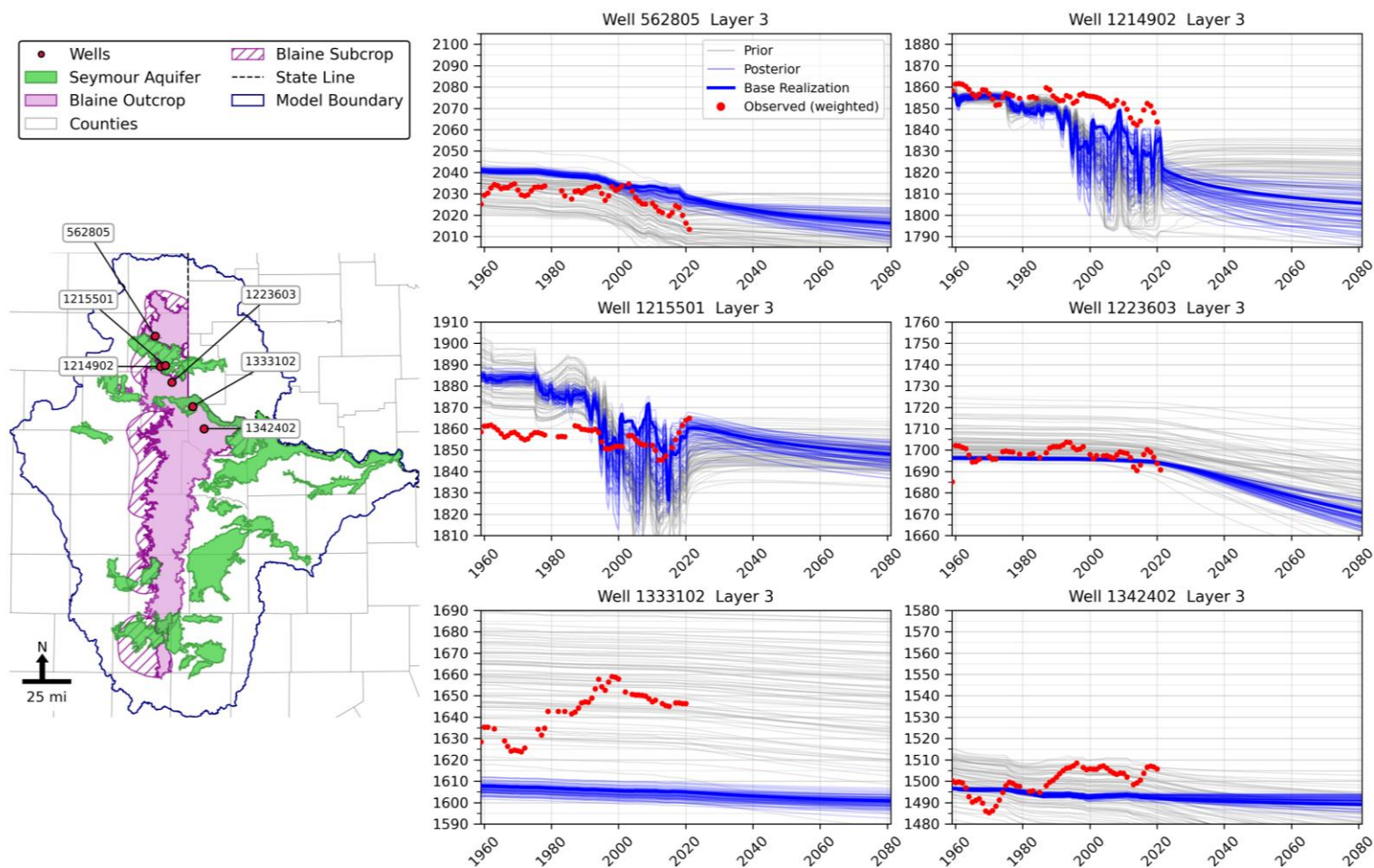


Figure 5.3-81. Observed (red dots) and simulated (blue lines) groundwater levels (in feet above mean sea level [y axis]) for Blaine Aquifer.

5.3.3 Spring head calibration

Spring head elevations were included as calibration targets. The spring head target dataset was compiled from multiple sources, including Brune (1975), Brune (1981), and TWDB and United States Geological Survey spring records. All spring elevations simulated with the model, including those used for explicit calibration targets, were cut-in 15 feet from surface elevation to accommodate limitations with the coarser spatial discretization of the model cells relative to the smaller spatial footprint of springs and seeps. Spring drain elevations were not adjusted during the automated calibration process.

A one-to-one plot of simulated versus observed spring head elevations for the base realization is shown in Figure 5.3-82. The plot includes the spring head targets used in calibration as well as additional observed spring head elevations from the same source databases that were not implemented as explicit calibration observation targets. These additional values were excluded from the calibration target set because their temporal information was either missing or of questionable reliability, but they are shown here as an independent check on simulated heads at spring locations outside of the explicit calibration targets. Across the full range of observed spring head elevations (approximately 850 to 3,100 feet above mean sea level), simulated values cluster closely along the 1:1 line. The normalized root mean square error is 2.83 percent, well within the 10 percent calibration criterion and consistent with the quality of match achieved for the transient hydraulic head calibration described in Section 5.3.2.

The spatial distribution of spring head residuals (observed minus simulated) for the base realization is shown in Figure 5.3-83. Residuals are predominantly positive, indicating that the model tends to simulate spring head elevations lower than observed; negative residuals are rare and small in magnitude (no more than approximately 6 feet). The majority of spring locations show positive residuals within approximately 50 feet of zero, with larger positive residuals (greater than 100 feet) occurring at a small number of isolated locations scattered across the model domain rather than concentrated in any one region. No systematic spatial bias is apparent in the spatial distribution, and the calibrated base posterior realization model reproduces the regional pattern of spring head elevations across the full range of topographic settings represented in the observation record.

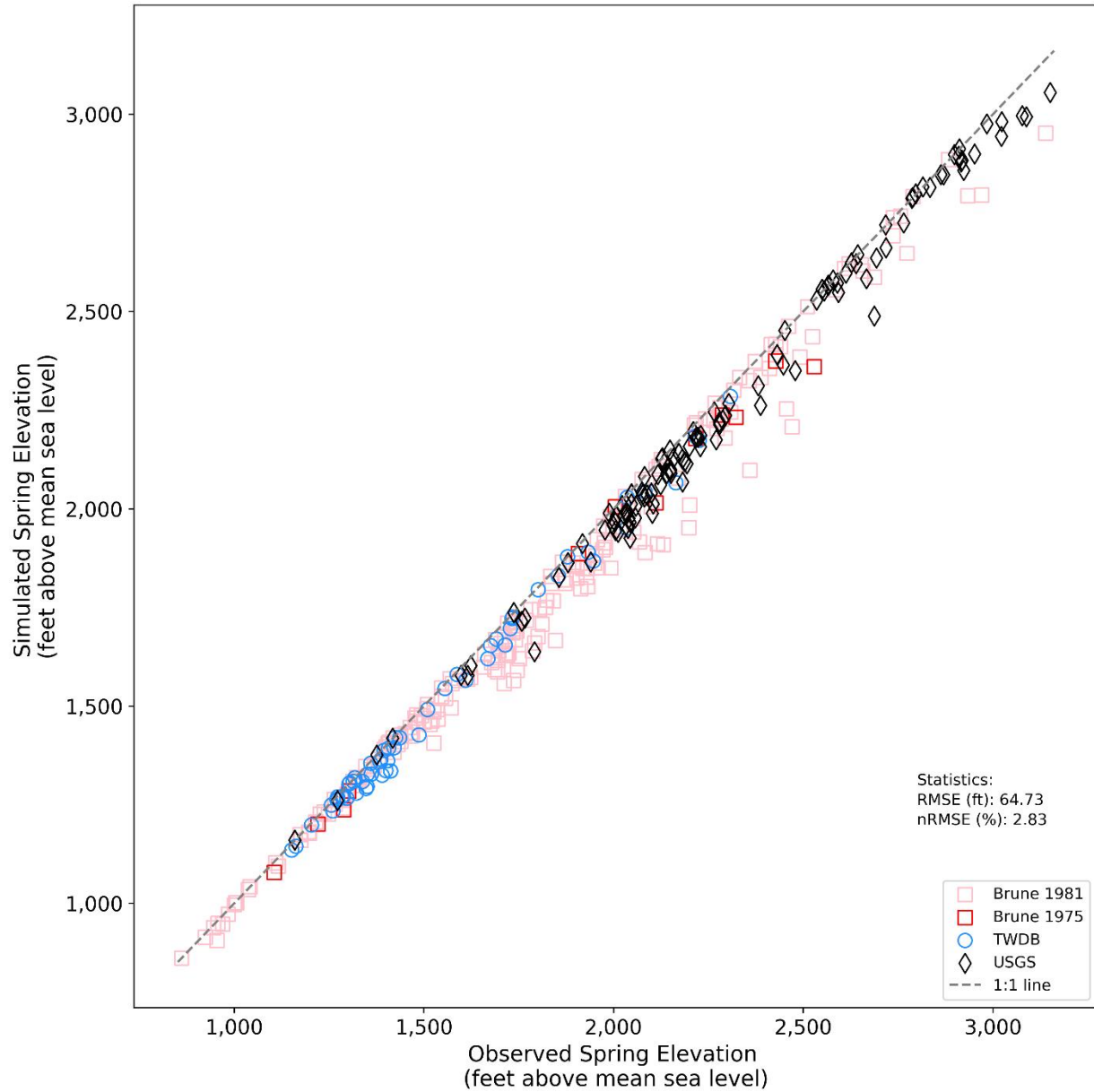


Figure 5.3-82. Simulated spring head elevation versus observed spring head elevation in feet above mean sea level. (% = percent, ft = feet, USGS = United States Geological Survey).

Texas Water Development Board Contract Number 2448302843
 Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

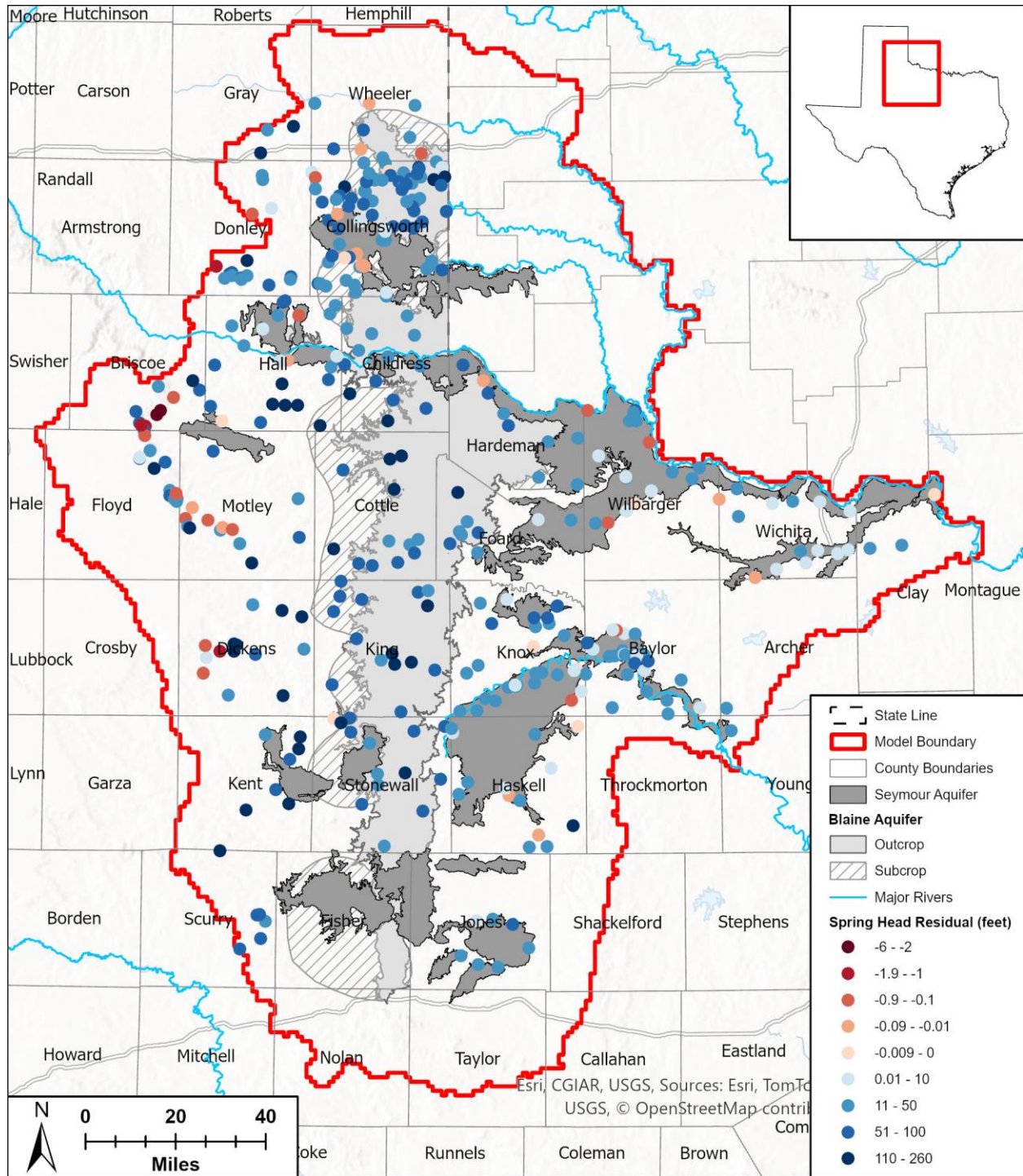


Figure 5.3-83. Spring head residuals (in feet) for each observation (observed minus simulated).

5.3.4 Water budgets

The simulated water balance from the base posterior realization is described in this section, focusing on the inflows and outflows of the Seymour and Blaine aquifers. Steady-state water budgets are presented first, followed by the transient water budget over the historical calibration period and the predictive period through 2080. Additional water budget information for individual counties and Groundwater Conservation Districts within the model boundary is provided in Appendix E and F, respectively. Each county or district was defined as a single ZONEBUDGET zone spanning all four model layers, so the budgets represent all layers combined and include storage change. The inter-county and inter-district flow terms represent lateral exchange with adjacent counties or districts.

Steady-state water budgets

Steady-state water budgets for the Seymour and Blaine aquifers for the base realization are summarized in Table 5-23 and Table 5-25, respectively. For completeness, budgets for the two Permian units that separate and underlie them are provided in Table 5-24 (Whitehorse and younger units) and Table 5-26 (Flowerpot and older units).

For the Seymour Aquifer (Table 5-23), recharge is the dominant inflow, contributing approximately 428,000 acre-feet per year. Additional inflow from rivers along losing reaches provides approximately 5,000 acre-feet per year, and cross-formational inflow from the three underlying Permian layers totals approximately 9,000 acre-feet per year. Outflow from the Seymour is partitioned among river discharge along gaining reaches (approximately 143,000 acre-feet per year), cross-formational outflow to the underlying Permian layers (approximately 112,000 acre-feet per year), stream drains (approximately 101,000 acre-feet per year), and spring drains (approximately 87,000 acre-feet per year). Total simulated inflow and outflow are each approximately 442,000 acre-feet per year, with the steady-state budget closing within the conventional groundwater availability model mass-balance tolerance.

For the Blaine Aquifer (Table 5-25), recharge contributes approximately 150,000 acre-feet per year, and cross-formational inflow from the other three model layers totals approximately 154,000 acre-feet per year, making cross-formational exchange a comparable component to recharge in the Blaine Aquifer budget — and a much larger component than in the Seymour Aquifer budget. Outflow from the Blaine Aquifer is dominated by stream drains (approximately 159,000 acre-feet per year) and river discharge along gaining reaches (approximately 107,000 acre-feet per year), with additional cross-formational outflow of approximately 40,000 acre-feet per year. The Blaine Aquifer steady-state budget is also well-balanced, with total inflow and outflow each approximately 305,000 acre-feet per year.

The Whitehorse and Younger Permian unit (Table 5-24) carries the largest total flux of any layer (approximately 726,000 acre-feet per year), reflecting both recharge on their outcrop (approximately 345,000 acre-feet per year) and lateral boundary exchange with the Ogallala and Edwards-Trinity (Plateau) aquifers, which is simulated through

general-head boundary cells in this layer (approximately 308,000 acre-feet per year in, 138,000 acre-feet per year out); discharge is predominantly to stream drains. The Flowerpot and Older Permian unit (Table 5-26) has a smaller budget (approximately 214,000 acre-feet per year), with recharge of approximately 150,000 acre-feet per year discharging mainly to stream drains and gaining river reaches. Together with the Seymour and Blaine budgets, the cross-formational terms of the four layers sum to zero, closing the model-wide steady-state budget.

Cross-formational exchange between each aquifer and the other three model layers is summarized in Table 5-27 (Seymour) and Table 5-28 (Blaine). The Seymour Aquifer is a net source of groundwater to the underlying Permian layers under steady-state conditions, cross-formational outflow (approximately 112,000 acre-feet per year) exceeding cross-formational inflow (approximately 9,000 acre-feet per year) by more than an order of magnitude, consistent with the regional conceptual model of downward cross-formational flow from the unconfined Seymour into the underlying Permian section (Ewing and others, 2004). The Blaine Aquifer is a net receiver of cross-formational inflow, with total inflow of approximately 154,000 acre-feet per year exceeding total outflow of approximately 40,000 acre-feet per year by a factor of approximately four. The Whitehorse and Younger Permian is the single largest source of cross-formational inflow to the Blaine, contributing approximately 97,000 acre-feet per year.

Table 5-23. Water budget of the Seymour Aquifer for the calibrated steady-state stress period. Values are in acre-feet per year.

Flux	Inflows	Outflows
Recharge	427,826	-
River	5,089	142,533
Stream Drains	-	100,894
Spring Drains	-	86,553
Other Layers	9,041	111,975
Total	441,956	441,956
Percent Difference	0.00E+00	2.50E-10

Table 5-24. Water budget of the Whitehorse and Younger Permian Unit for the calibrated steady-state stress period. Values are in acre-feet per year.

Flux	Inflows	Outflows
Recharge	344,969	-
River	682	59,501
Lateral boundary flow (GHB)	307,775	137,958
Stream Drains	-	381,346
Spring Drains	-	27,539
Other Layers	72,430	119,512
Total	725,857	725,857
Percent Difference	0.00E+00	2.82E-12

Table 5-25. Water budget of the Blaine Aquifer for the calibrated steady-state stress period. Values are in acre-feet per year.

Flux	Inflows	Outflows
Recharge	149,935	-
River	880	107,028
Stream Drains	-	158,500
Spring Drains	-	8
Other Layers	154,257	39,537
Total	305,072	305,072
Percent Difference	0.00E+00	-1.89E-11

Table 5-26. Water budget of the Flowerpot and Older Permian Unit for the calibrated steady-state stress period. Values are in acre-feet per year.

Flux	Inflows	Outflows
Recharge	149,697	-
River	189	49,177
Stream Drains	-	135,870
Spring Drains	-	133
Other Layers	64,127	28,832
Total	214,013	214,013
Percent Difference	0.00E+00	4.65E-12

Table 5-27. Groundwater flow into and out of the Seymour Aquifer from other model layers for the steady-state stress period. Values are in acre-feet per year.

Layer	Name	Inflows	Outflows
2	Whitehorse and Younger	2,413	45,191
3	Blaine	3,397	44,659
4	Flowerpot and Older	3,232	22,124
Total		9,041	111,975

Table 5-28. Groundwater flow into and out of the Blaine Aquifer from other model layers for the steady-state stress period. Values are in acre-feet per year.

Layer	Name	Inflows	Outflows
1	Seymour	44,659	3,397
2	Whitehorse and Younger	97,310	13,927
4	Flowerpot and Older	12,288	22,213
Total		154,257	39,537

Transient water budgets

The transient water budget evolution over the historical calibration period (1960 to 2020) and the predictive simulation period (2021 to 2080) is shown in Figure 5.3-84 through Figure 5.3-91. For the entire model area (Figure 5.3-84), recharge is the dominant inflow at approximately 1 million acre-feet per year, followed by general-head boundary inflow. Outflows are dominated by stream discharge, and followed by river discharge along gaining reaches, general-head boundary outflow, and pumping. Net storage change (negative values indicate declining storage) is consistently negative, averaging approximately -250,000 acre-feet per year over the historical period and diminishing to approximately -43,000 acre-feet per year over the predictive period as the system approaches a new equilibrium.

The transient water budgets for the Seymour and Blaine aquifers are shown in Figure 5.3-85 and Figure 5.3-86. In the Seymour Aquifer, recharge dominates inflow, and outflow is partitioned among cross-formational outflow to the Permian layers, pumping, stream discharge, river discharge, and springs and seeps. Pumping rises from approximately 40,000 acre-feet per year in 1960 to a peak near 170,000 acre-feet per year in the early 2010s. Seymour net storage change oscillates near zero, with losses coinciding with high pumping years. In the Blaine Aquifer, cross-formational inflow equals or exceeds recharge in most years, and outflow is dominated by stream and river discharge. Blaine net storage change is negative in nearly all years, averaging approximately -25,000 acre-feet per year through both periods.

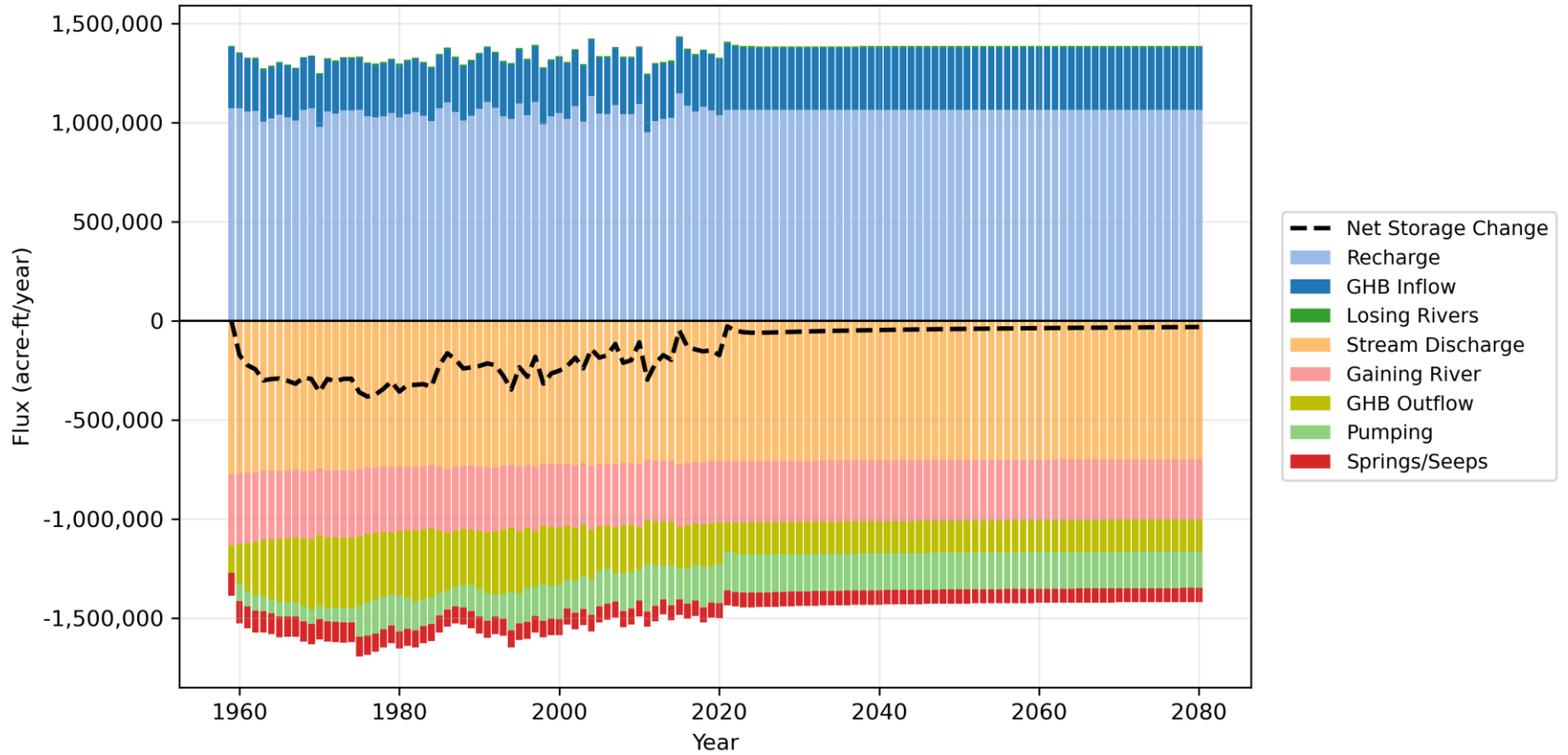
The relative magnitudes of inflow and outflow components in 2020 are shown in Figure 5.3-87 and Figure 5.3-88. Inflow in 2020 is approximately 68 percent recharge, 19 percent general-head boundary inflow, and 12 percent release from storage.

Outflow is approximately 47 percent stream seepage, 20 percent river discharge, 14 percent general-head boundary outflow, 13 percent pumping, and 5 percent springs and seeps.

Pumping by use type over the full simulation period is shown in Figure 5.3-89. Irrigation pumping is the dominant use type, varying between approximately 40,000 and 210,000 acre-feet per year during the historical period and stabilizing near 100,000 acre-feet per year during the predictive period. Oklahoma withdrawals are variable across the historical record, generally ranging between approximately 5,000 and 30,000 acre-feet per year, and stabilize near 15,000 acre-feet per year through the predictive period. Metered pumping is predominantly made up of irrigation pumping with minor municipal pumping and enters the simulation as a distinct dataset in the late portion of the historical record (beginning in 2004), contributing approximately 95,000 acre-feet per year in 2019–2020 and stabilizing near 50,000 acre-feet per year through the predictive period. All remaining use types each contribute less than 20,000 acre-feet per year throughout the simulation.

Cross-formational exchange between each aquifer and the other model layers over the simulation period is shown in Figure 5.3-90 (Seymour) and Figure 5.3-91 (Blaine). Both aquifers maintain stable cross-formational flow patterns throughout the historical and predictive periods, with the Seymour continuing to function as a net source to the underlying Permian layers and the Blaine continuing to function as a net receiver, consistent with the steady-state water budget. Inflow to the Seymour from the Whitehorse and Younger Permian shows a modest increase between 1980 and 2000 in Figure 5.3-90. In the Blaine budget (Figure 5.3-91), cross-formational inflow from the Whitehorse and Younger Permian is the dominant cross-formational component, ranging from approximately 97,000 to 105,000 acre-feet per year, with a slight increasing trend over the simulation.

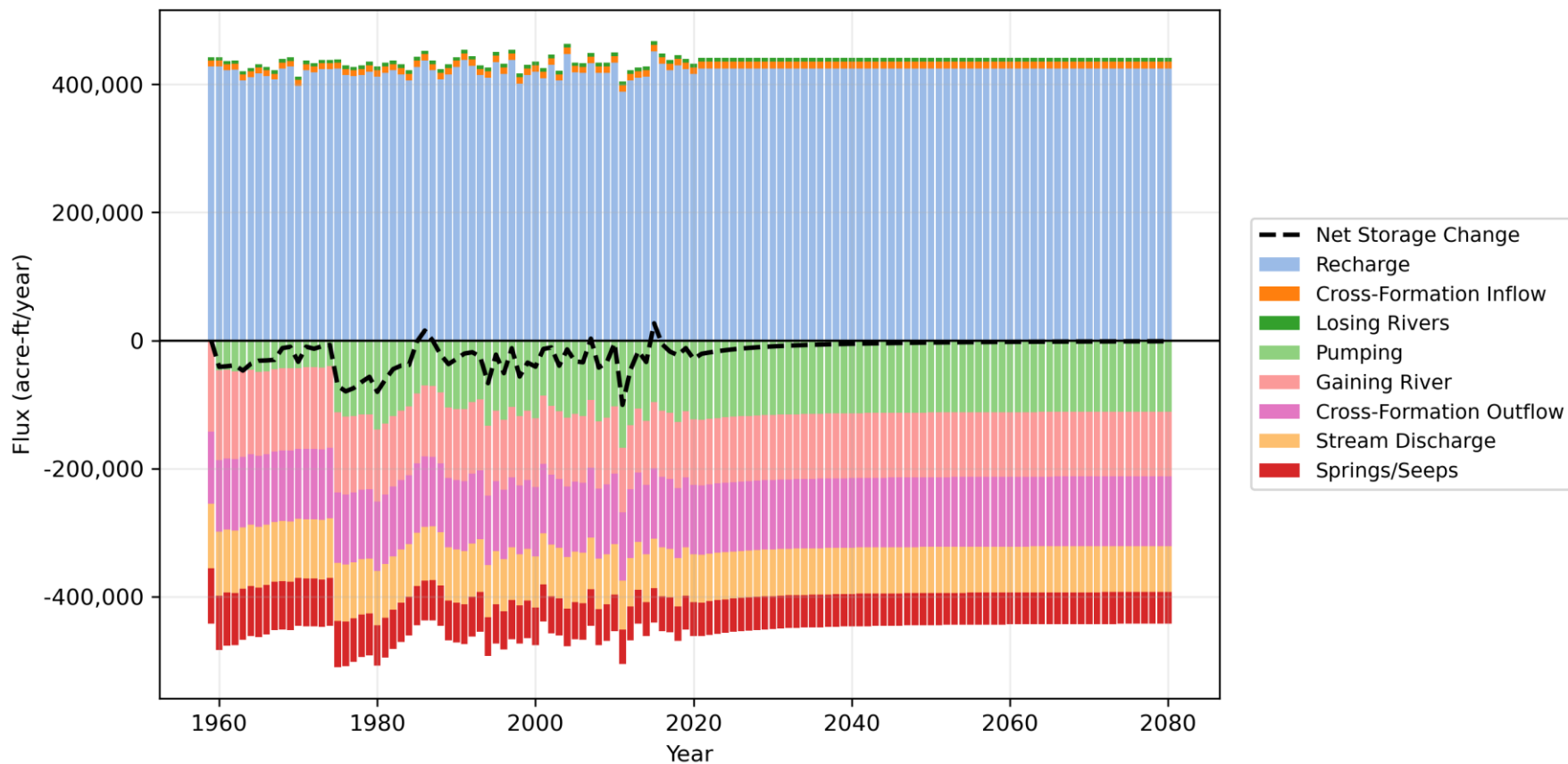
Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers



Note: GHB = general head boundary

Figure 5.3-84. Natural inflow and outflow mechanisms of the entire model area. Values are in acre-feet per year. Net storage change is reported as change in stored water (negative = declining storage)

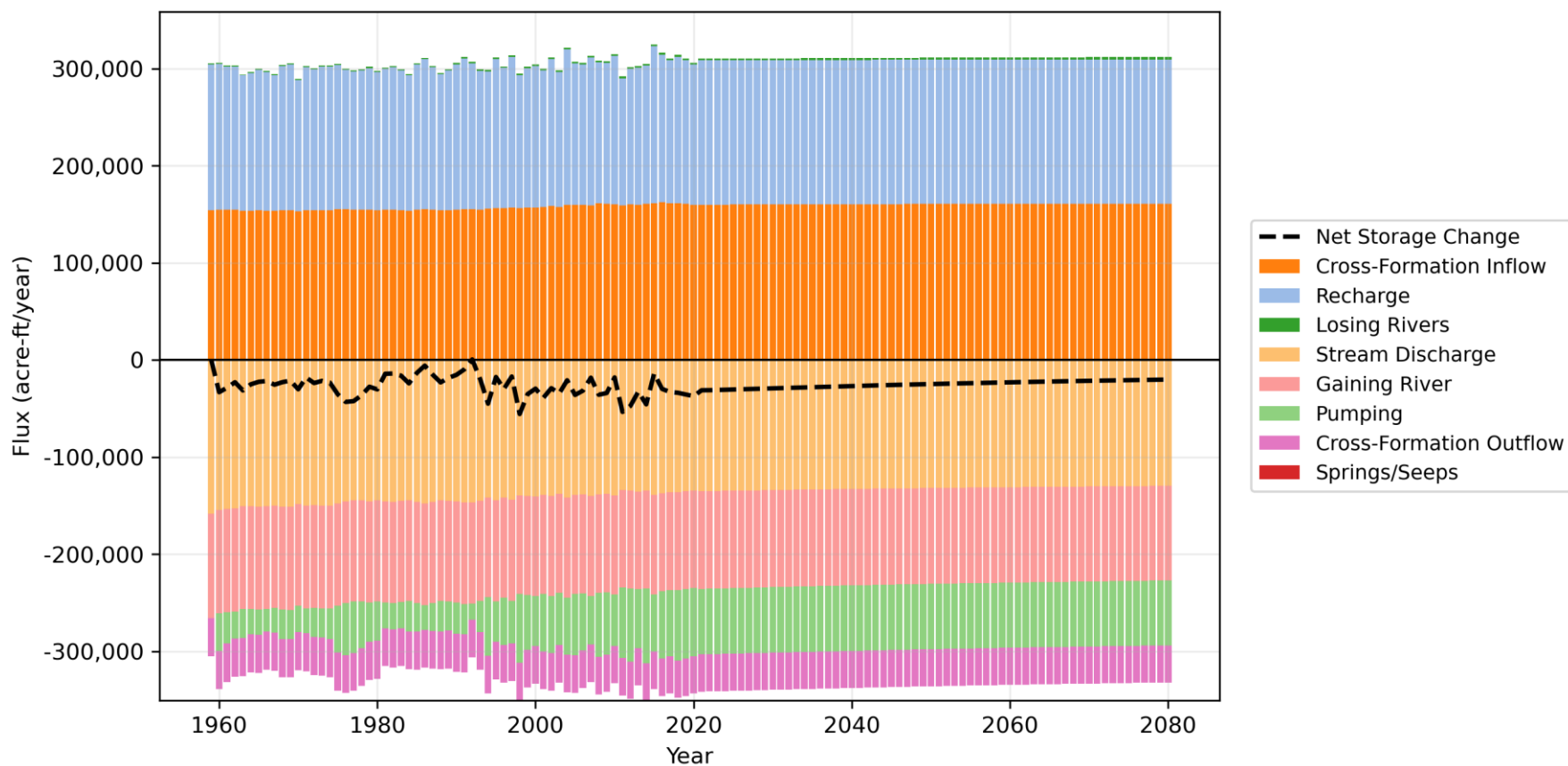
Texas Water Development Board Contract Number 2448302843
 Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers



Note: GHB = general head boundary

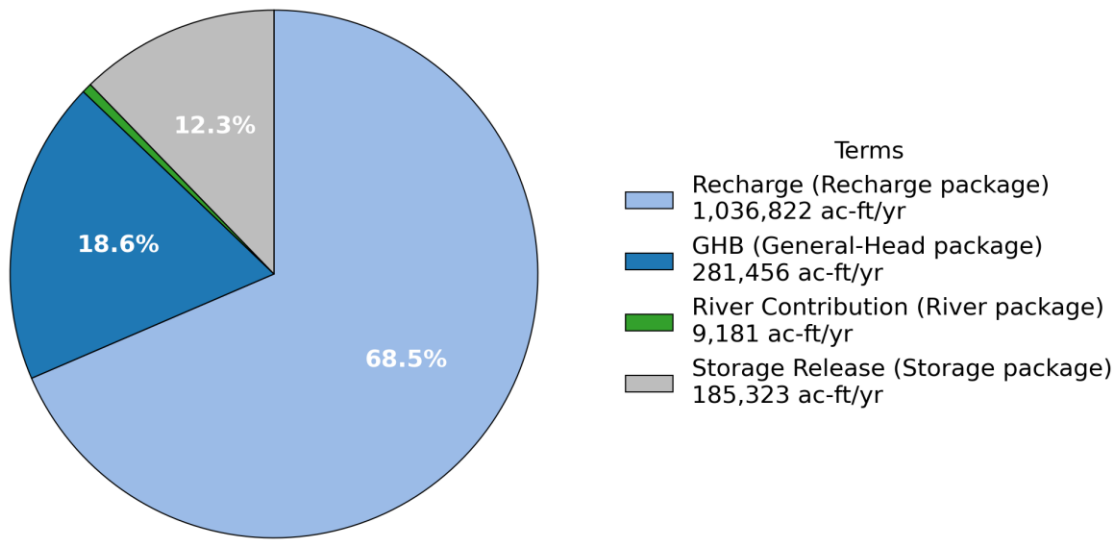
Figure 5.3-85. Natural inflow and outflow mechanisms of the Seymour Aquifer. Values are in acre-feet per year. Net storage change is reported as change in stored water (negative = declining storage)

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers



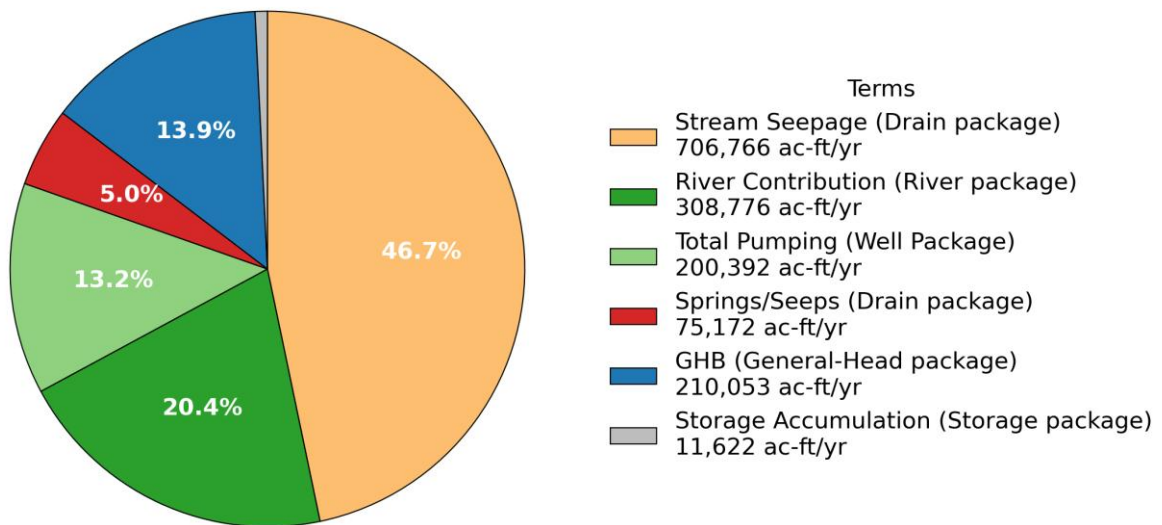
Note: GHB = general head boundary

Figure 5.3-86. Natural inflow and outflow mechanisms of the Blaine Aquifer. Values are in acre-feet per year. Net storage change is reported as change in stored water (negative = declining storage)



Note: % = percent, ac-ft/year = acre-feet per year, GHB = general head boundary.

Figure 5.3-87. Inflows over the entire model area in 2020.



Note: % = percent, ac-ft/year = acre-feet per year, GHB = general head boundary.

Figure 5.3-88. Outflows over the entire model area in 2020.

Texas Water Development Board Contract Number 2448302843
 Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

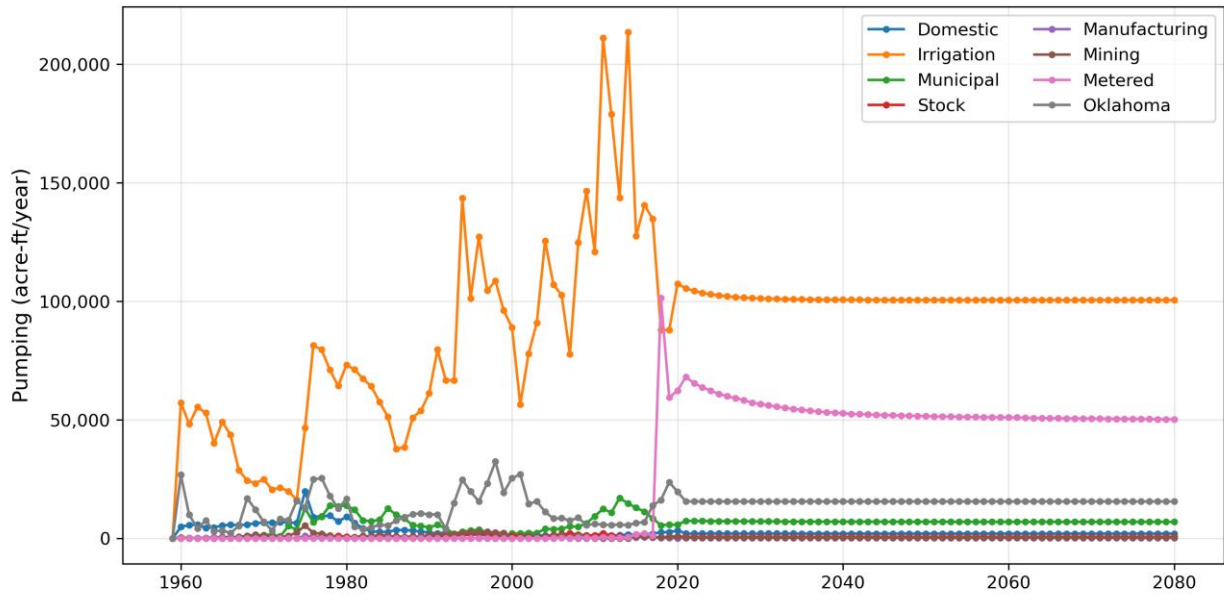


Figure 5.3-89. Domestic and non-domestic pumping within the model domain. Values are in acre-feet per year.

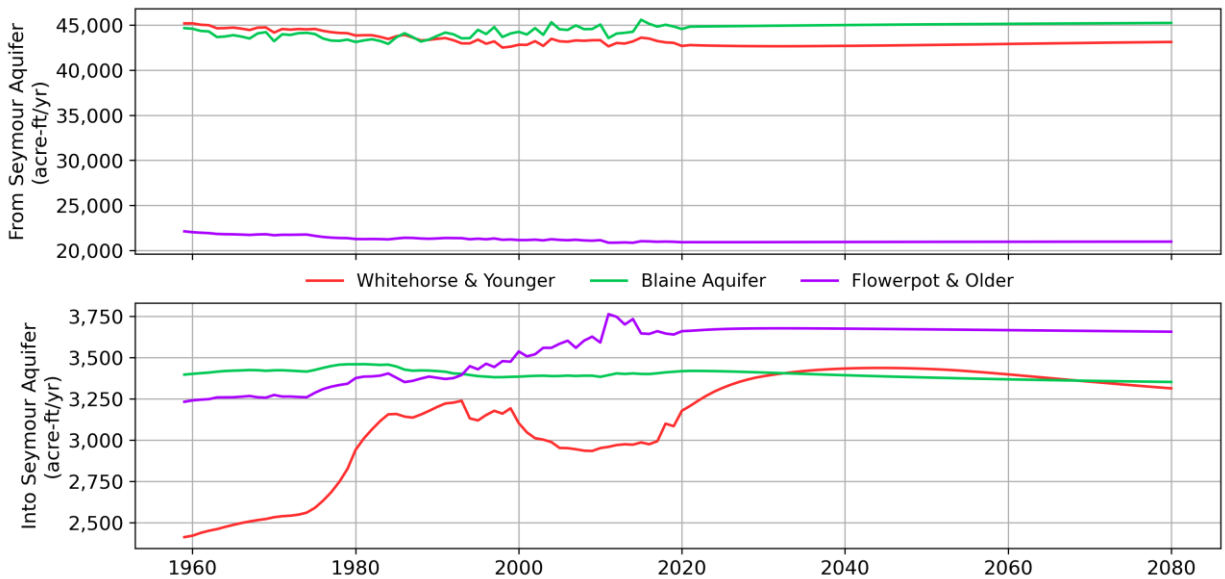


Figure 5.3-90. Groundwater flow into the Seymour Aquifer and out of the Seymour Aquifer from intersecting aquifers. Values are in acre-feet per year.

Texas Water Development Board Contract Number 2448302843
Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers

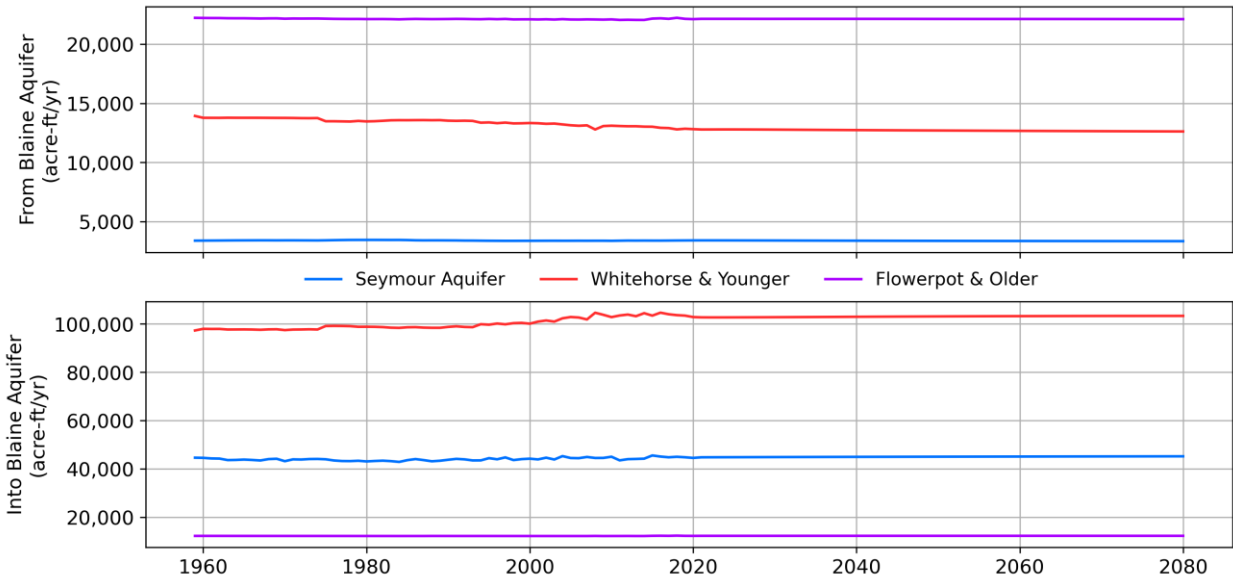


Figure 5.3-91. Groundwater flow into the Blaine Aquifer and out of the Blaine Aquifer from intersecting aquifers. Values are in acre-feet per year.

6 Sensitivity analysis

A global sensitivity analysis was conducted on the calibrated parameter set to assess the influence of parameters on model results and specific observation groups. Unlike local sensitivity analysis, which evaluates sensitivity at or very near a single point in parameter space and does not account for the nonlinear behavior of the Seymour and Blaine groundwater availability model, global sensitivity analysis computes statistics that recognize a parameter's sensitivity as being influenced not only by its own value but also by the values of other parameters (Saltelli and others, 2008).

The Method of Morris (Morris, 1991; Saltelli and others, 2008) was used to estimate the mean and standard deviation of parameter sensitivity to individual observation groups, providing a computationally efficient approach for models with long run times and numerous parameters of interest. This analysis helps identify non-influential parameters, those that exhibit linear behavior, and those that are nonlinear or interact with other parameters. Such insights are valuable for decision support when using the model to simulate future conditions or assess the likelihood of undesired outcomes.

6.1 Sensitivity analysis procedure

The Method of Morris, often referred to as a one-at-a-time approach, evaluates sensitivity by altering each parameter individually along composite trajectories across plausible parameter space (Morris, 1991). This method estimates the mean parameter sensitivity by evaluating its impact at multiple points across the defined parameter space. By following a structured sampling strategy, the model is run multiple times, varying parameter values within their defined distributions to obtain resulting model outputs. The variation in these outputs is used to estimate each parameter's mean and standard deviation sensitivity to selected observation groups.

The mean and standard deviation of the sensitivity distribution represent the influence a parameter has on the selected output and the variability of this influence. The standard deviation serves as a measure of a parameter's nonlinearity or a measure of how the parameter interacts with other parameters (Saltelli and others, 2008).

The Method of Morris was performed using parameter groupings to reduce the dimensionality of the sensitivity analysis while preserving interpretability. Before running the analysis, pilot point parameters were fixed so that only the formation-scale constant multipliers remained adjustable. Parameters were then grouped by shared physical role and model layer and assigned a group name (e.g., horizontal hydraulic conductivity in layer 3 was assigned to the parameter group named kh_L3, all pumping category multipliers across all stress periods and all use types were assigned to a single pumping group), and the tie-by-group option was enabled in PESTPP-SEN so that parameters sharing a group move together during trajectory steps. For the Seymour Aquifer (layer 1), this grouping additionally aggregates the 15 pod-specific parameter subgroups for each physical property (horizontal hydraulic conductivity, vertical hydraulic conductivity, specific yield, and recharge base multipliers) into a single layer-scale group. The resulting grouping reduces the thousands of individual adjustable parameters to 29 grouped sensitivity factors, listed

in Table 6-1. Observation groups were similarly aggregated into four groups for sensitivity analysis: steady-state heads in the Seymour Aquifer (observation group named ss-hds-L1), steady-state heads in the Blaine Aquifer (observation group named ss-hds-L3), transient heads in the Seymour Aquifer (observation group named tr-hds-L1), and transient heads in the Blaine Aquifer (observation group named tr-hds-L3). The transient head groups combine all pod-level and frequency-level subgroups that were used for weighting during calibration into a single aquifer-wide observation group.

The analysis was conducted using 10 Morris trajectories, which provides a robust estimate of sensitivity metrics for the number of grouped factors examined. The total number of model evaluations was 300. The recharge_damp parameter group (the global damping multipliers applied uniformly to all recharge across the model domain) is excluded from the sensitivity figures presented in Section 6.2 because it acts as a global scaling factor and does not provide insight into which parameters dominate sensitivity within individual aquifers. The grouping approach allows for a balance between computational efficiency and statistical robustness, while focusing the interpretation on key hydrogeologic processes rather than on individual parameters.

Table 6-1. Parameter groups adjusted for sensitivity analysis.

Parameter Group	Description	Layer(s)
recharge_L1 through recharge_L4	Steady-state recharge base multipliers; layer 1 aggregates 15 pod-specific Seymour bases	L1, L2, L3, L4
recharge_damp	Global recharge damping multipliers (steady-state and transient) applied uniformly across all layers	L1, L2, L3, L4
kh_L1 through kh_L4	Horizontal hydraulic conductivity multipliers; layer 1 aggregates the 15 pod-specific Seymour hydraulic conductivity (Kh) groups	L1, L2, L3, L4
kv_L1 through kv_L4	Vertical hydraulic conductivity multipliers; layer 1 aggregates the 15 pod-specific Seymour vertical hydraulic conductivity (Kv) groups	L1, L2, L3, L4
sy_L1 through sy_L4	Specific yield multipliers; layer 1 aggregates the 15 pod-specific Seymour specific yield (Sy) groups	L1, L2, L3, L4
s_L2 through s_L4	Storativity multipliers for each Permian layer; not parameterized for the Seymour Aquifer	L2, L3, L4
rivcond_L1 through rivcond_L4	River conductance multipliers	L1, L2, L3, L4
strdrncond_L1 through strdrncond_L4	Stream drain conductance multipliers	L1, L2, L3, L4
pumping	Combined municipal, irrigation, domestic, and other pumping	L1 and L3

6.2 Sensitivity analysis results

The Method of Morris sensitivity analysis was executed using PESTPP-SEN. Sensitivity outputs include the mean sensitivity, absolute mean sensitivity, and standard deviation of sensitivity for each parameter group relative to each observation group.

Results are summarized using two complementary plot types: bar plots of normalized absolute mean sensitivity and standard deviation of sensitivity, and scatter plots of normalized standard deviation of sensitivity versus normalized absolute mean sensitivity. Both metrics are normalized by the maximum value within each observation group, allowing comparison of relative importance and nonlinearity among parameter groups. Bar plots highlight the top five most sensitive parameter groups influencing each steady-state observation group and the top ten most sensitive parameter groups influencing each transient observation group, with high absolute mean sensitivity indicating strong influence and low standard deviation of sensitivity, suggesting linear behavior across the parameter space.

The scatter plots follow the conceptual interpretation shown in Figure 6.2-1. Parameter groups that fall above the one-to-one line (standard deviation of sensitivity/absolute mean sensitivity greater than 1) exhibit non-monotonic effects, indicating that the simulated response does not consistently increase or decrease as the parameter value changes. Parameter groups in the upper-right region have both high absolute mean sensitivity and high standard deviation of sensitivity, indicating strong influence coupled with strong interaction or nonlinearity. Parameter groups below the one-to-one line are influential but behave more linearly, with responses that are largely independent of other parameters. Parameter groups clustered near the origin have both low absolute mean sensitivity and low standard deviation of sensitivity, indicating limited influence on the selected observation group.

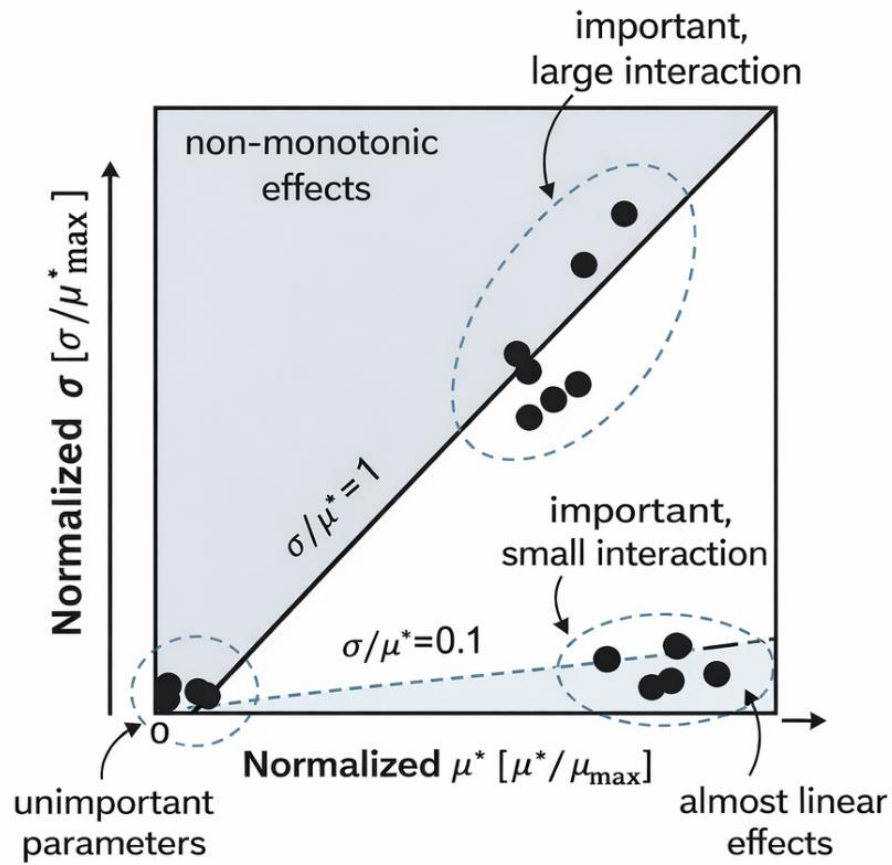


Figure 6.2-1. Conceptual interpretation of Morris parameter sensitivity. μ^* = absolute mean sensitivity. σ = standard deviation of sensitivity.

6.2.1 Steady-state sensitivities

Parameter sensitivity for steady-state head observations is shown in Figure 6.2-2 for the Seymour Aquifer (parameter group ss-hds-L1) and Figure 6.2-3 for the Blaine Aquifer (parameter group ss-hds-L3).

In the Seymour Aquifer (Figure 6.2-2), the most sensitive parameter group is recharge_L1, with normalized absolute mean sensitivity approximately 0.6 and normalized standard deviation of sensitivity approximately 1.0, plotting well above the 1:1 line in the non-linear or interacting region of the absolute mean sensitivity-standard deviation of sensitivity space. Horizontal hydraulic conductivity in layer 1 (parameter group kh_L1) is the second most sensitive parameter group, with absolute mean sensitivity approximately 0.45 and standard deviation of sensitivity approximately 0.72, also plotting above the 1:1 line. The remaining three parameter groups in the top five (kh_L4, strdrncond_L1, and kv_L2) cluster near the origin and show comparatively low sensitivity relative to recharge_L1 and kh_L1. As expected, pumping and storage parameter groups are not influential under steady-state conditions, because pumping is not active during steady-state and storage does not contribute to equilibrium head responses.

In the Blaine Aquifer (Figure 6.2-3), the most sensitive parameter group is kh_L3, with normalized absolute mean sensitivity approximately 0.85 and standard deviation of sensitivity approximately 1.0, plotting near the upper-right corner and indicating both strong influence and substantial parameter interaction. Recharge in layer 3 (parameter group recharge_L3) is the second most sensitive parameter group, with absolute mean sensitivity approximately 0.7 and standard deviation of sensitivity approximately 0.8, plotting close to the 1:1 line. The remaining three parameter groups in the top five (kh_L4, kv_L3, and kv_L2) cluster in the lower-left region, indicating comparatively low sensitivity. Steady-state heads in the Blaine are therefore primarily controlled by horizontal hydraulic conductivity and recharge in layer 3, with secondary contributions from vertical conductivity in adjacent layers.

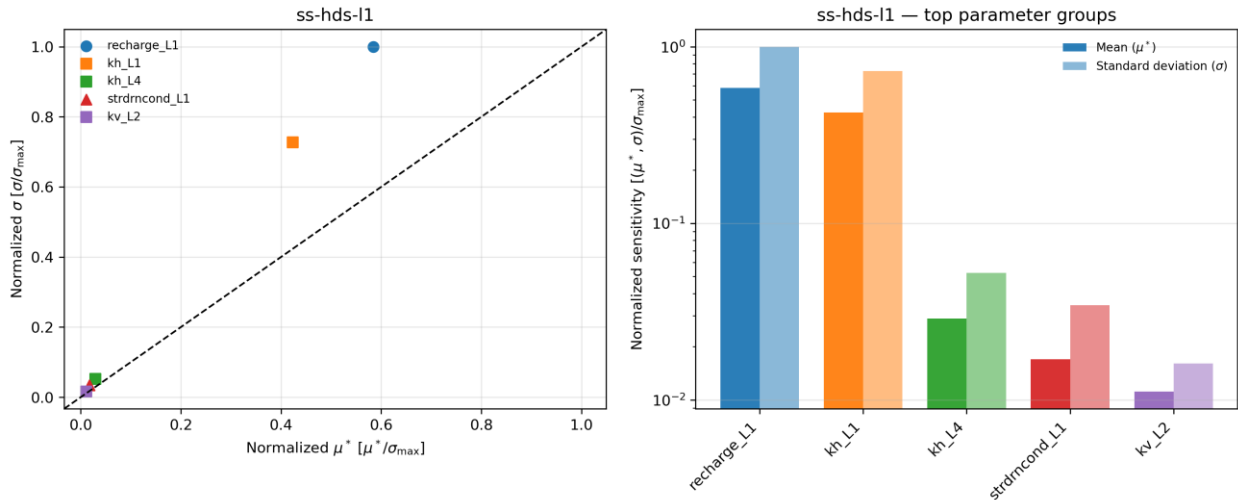


Figure 6.2-2. Parameter sensitivity for the steady-state groundwater levels in the Seymour Aquifer. (Kh = horizontal hydraulic conductivity. Kv = vertical hydraulic conductivity. Strdrncond = stream drain conductances. μ = mean. σ = standard deviation.)

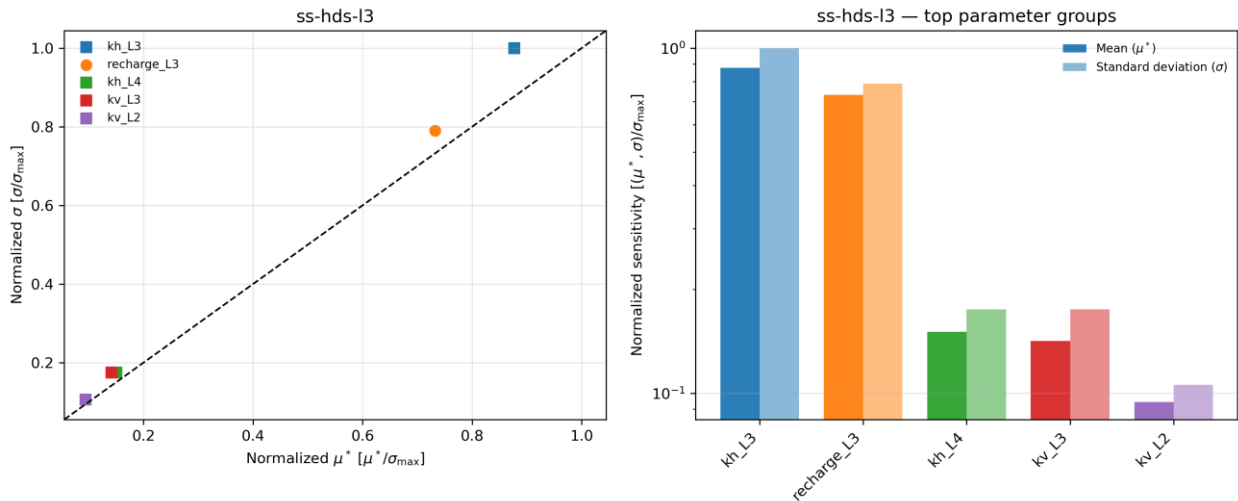


Figure 6.2-3. Parameter sensitivity for the steady-state groundwater levels in the Blaine Aquifer. (Kh = horizontal hydraulic conductivity. Kv = vertical hydraulic conductivity μ = mean. σ = standard deviation.)

6.2.2 Transient sensitivities

Parameter sensitivity for transient head observations is shown in Figure 6.2-4 for the Seymour Aquifer (parameter group tr-hds-L1) and Figure 6.2-5 for the Blaine Aquifer (parameter group tr-hds-L3). The bar plots in each figure highlight the top ten most sensitive parameter groups for each observation group. The transient head observation groups combine all pod-level subgroups and frequency-based weighting subgroups that were used during calibration into a single aquifer-wide observation group, allowing the sensitivity analysis to focus on aquifer-scale drivers of transient head variability.

In the Seymour Aquifer (Figure 6.2-4), recharge_L1 remains the most sensitive parameter group under transient conditions (absolute mean sensitivity approximately 0.65, standard deviation of sensitivity approximately 1.0), followed by kh_L1 (approximately 0.40 and 0.57, respectively). Both plot above the 1:1 line, indicating non-linear or interacting behavior. The pumping parameter group appears third in the top ten (absolute mean sensitivity approximately 0.27, standard deviation of sensitivity approximately 0.32), with absolute mean sensitivity comparable to its standard deviation of sensitivity, in contrast to the top two parameter groups, indicating a more linear and less interactive influence on Seymour transient heads. The remaining parameter groups in the top ten (recharge_L2, strdrncond_L3, strdrncond_L4, recharge_L4, s_L4, kh_L2, and strdrncond_L2) each exhibit sensitivities similar to pumping.

In the Blaine Aquifer (Figure 6.2-5), the parameter groups with the highest standard deviation of sensitivity — recharge_L4, rivcond_L1, and strdrncond_L4, each with standard deviation of sensitivity approximately 1.0 — plot well above the 1:1 line, indicating strongly non-linear or interacting behavior. Specific yield in layer 3 (sy_L3) and stream drain conductance in layer 3 (strdrncond_L3) also plot well above the 1:1 line, with standard deviation of sensitivity approximately 0.88. Pumping appears third in the top ten by absolute mean sensitivity (approximately 0.48, standard deviation of sensitivity approximately 0.78). The remaining parameter groups in the top ten (recharge_L2, recharge_L3, kh_L3, and sy_L2) reflect contributions from adjacent-layer recharge, layer 3 recharge and hydraulic conductivity, and additional storage parameters to Blaine transient head variability.

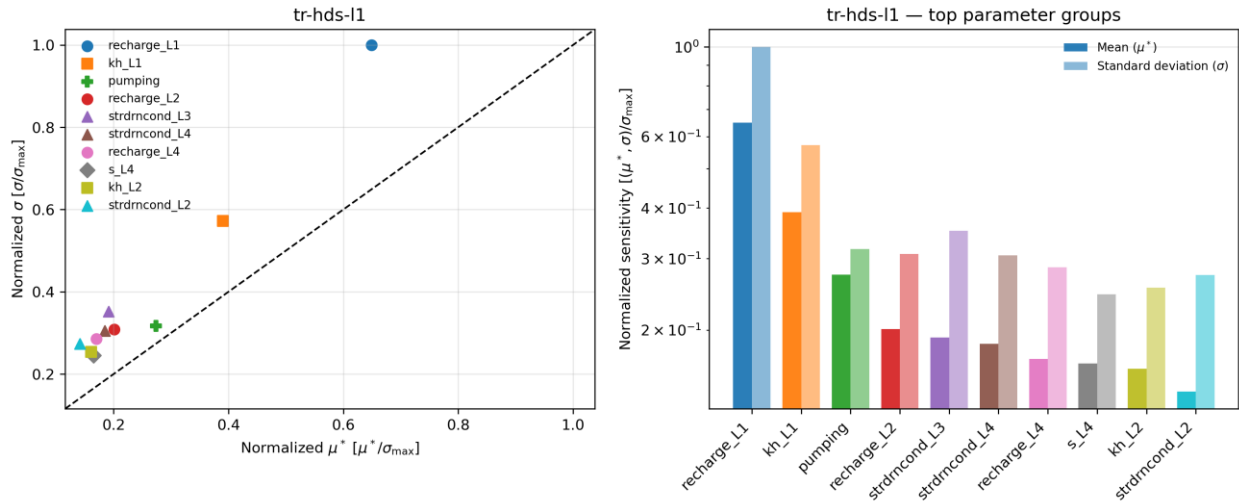


Figure 6.2-4. Parameter sensitivity for the transient heads in the Seymour Aquifer. (Kh = horizontal hydraulic conductivity. μ = mean. σ = standard deviation.)

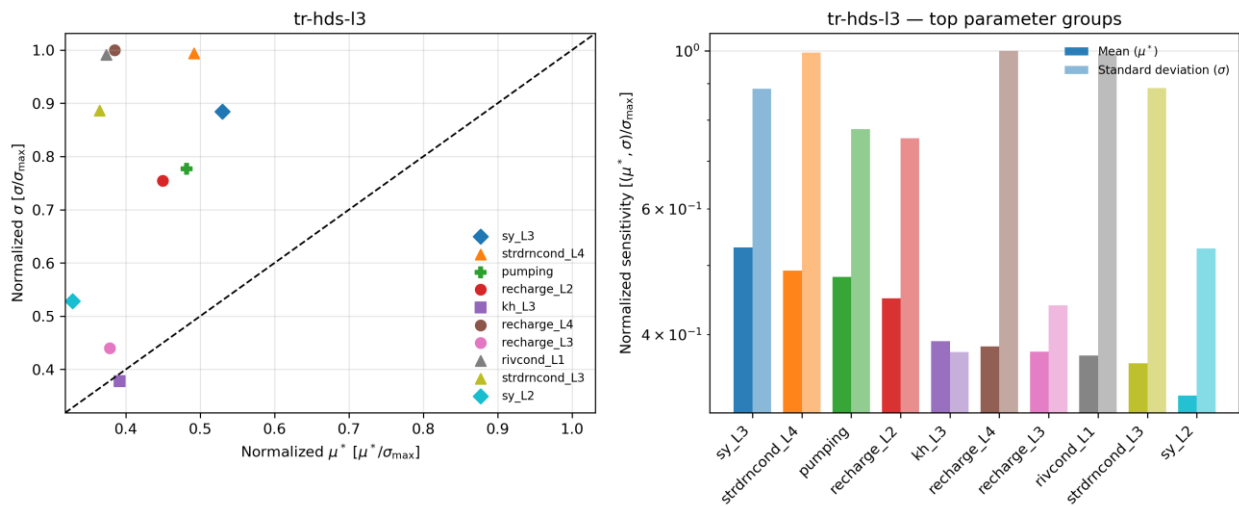


Figure 6.2-5. Parameter sensitivity for the transient heads in the Blaine Aquifer. (Sy = specific yield. Kh = horizontal hydraulic conductivity. s = storativity. μ = mean. σ = standard deviation.)

7 Model limitations

Every groundwater model is a simplified representation of a complex natural system (Anderson and Woessner, 1992), and the development of a regional-scale model necessarily introduces assumptions and simplifications. The Seymour and Blaine aquifers Groundwater Availability Model is intended to support regional-scale water planning, management decisions, and evaluation of long-term groundwater availability. This section describes the principal limitations of the model that users should consider when interpreting results.

7.1 Intended use and spatial scale

The Seymour and Blaine aquifers Groundwater Availability Model is a regional-scale model designed for evaluating regional groundwater availability, responses to changes in pumping and recharge, and boundary conditions for more detailed local models. It is constructed using a regional-scale grid with over 250,000 active cells representing a large geographic area. Despite improvements in discretization in the Seymour pods compared to the 2004 groundwater availability model, each model cell still represents averaged hydrogeologic conditions over a spatial scale that may mask important local variability. For example, highly conductive terrace deposits may occur adjacent to lower-conductivity materials typical of the Seymour Aquifer, but these contrasts are averaged within individual cells.

As a result, the model is not intended for site-specific applications such as predicting drawdown at individual wells, evaluating localized impacts of pumping, or assessing conditions at a finer scale than the model grid supports. Applications requiring higher spatial resolution or site-specific accuracy should be supported by refined local-scale models developed using additional local data. The level of spatial averaging is nonetheless appropriate for the model's intended purpose of simulating regional-scale groundwater processes, including flow patterns, recharge distribution, and system response to management scenarios. At this scale, the loss of small-scale variability does not significantly affect the model's ability to inform regional decision-making.

The model domain includes four layers, with layer 1 (Seymour) and layer 3 (Blaine) representing the major and minor aquifers that are the primary focus of the groundwater availability analysis. Layers 2 (Whitehorse and Younger Permian) and 4 (Flowerpot and Older Permian) are included to support cross-formational flow but are not intended to support groundwater management calculations such as modeled available groundwater or total estimated recoverable storage. Simulated results in these layers should be interpreted only as context for the Seymour and Blaine aquifers.

7.2 Hydraulic properties

Hydraulic properties (horizontal hydraulic conductivity, vertical hydraulic conductivity, specific yield, and storativity) are among the largest sources of uncertainty in the model. Direct field measurements of these properties are spatially limited and unevenly distributed across the model domain. Coverage is particularly limited in the

Permian units (Layers 2, 3, and 4), where few aquifer tests are available, and within the Seymour Aquifer, where coverage is biased toward more productive pods such as Pod 7 (Haskell, Knox, and Baylor counties) and Pod 4 (Wilbarger County).

To address these data gaps, hydraulic properties were parameterized using pilot points and formation- or pod-scale constant multipliers (Section 5.3.1, Hydraulic conductivity and anisotropy). While this approach supports calibration flexibility, it inherently smooths local heterogeneity. Several Seymour pods (Pods 6, 8, 9, 10, 11, 12, 14, and 15) support fewer than 200 observations each, and the posterior parameter distributions for these pods show minimal narrowing relative to the prior. Calibrated hydraulic property values for these data-poor pods should therefore be interpreted with greater uncertainty than those for the well-observed pods.

7.3 Recharge

Recharge is the dominant inflow component for both the Seymour and Blaine aquifers (Section 5.3.4) and is a key driver of simulated behavior. Recharge estimates used in this model are informed by literature values, previous groundwater availability models (Ewing and others, 2004; Jigmond and others, 2014), and PRISM precipitation data (Section 3.5), which are derived from indirect methods and point-scale measurements. Estimates of recharge as a percentage of precipitation vary substantially across published sources, ranging from less than 0.2 inch per year in some Seymour pods to more than 4 inches per year in others (Table 3-2).

Recharge in the model is applied at the spatial scale of the pilot point network and pod-scale (layer 1) or formation-scale (layers 2, 3, and 4) multipliers. Focused recharge was only applied at the edges of the Seymour pods.

Temporal variability of recharge over the historical simulation period is driven entirely by the PRISM-based annual precipitation signal passed through a single global damping factor (Section 5.3.1, Recharge). Year-to-year variability in recharge captured by the model therefore reflects spatial-average precipitation variability rather than pod-specific or layer-specific temporal patterns. Seasonal recharge variability is not represented because the model uses annual stress periods.

7.4 Historical pumping

Historical pumping is the primary anthropogenic stress on the system and, outside of metered data available after 2004, is highly uncertain. Water use survey data are available from the TWDB for 1974 and 1980 through 2020, while pumping for 1960 through 1974 and the 1974 to 1980 interval required extrapolation and assumptions (Section 3.4). The calibration framework reflects these data-confidence differences by allowing wider multiplier bounds (0.5 to 1.4) for the 1960 to 1975 period and tighter bounds (0.75 to 1.25) for the 1976 to 2020 period, but the underlying pre-1980 pumping volumes remain a significant source of uncertainty (Section 5.3.1, Pumping).

Vertical allocation of pumping to specific aquifer layers was determined using rule-based assumptions from total well depth rather than screened interval records, which

are not consistently available. Wells less than 250 feet deep were assigned pumping at approximately 80 percent of total well depth, and wells deeper than 250 feet were assigned pumping at approximately 50 feet above the well bottom (Section 4.10). This rule-based approach can misclassify pumping between layers, particularly in areas of multi-aquifer use, where wells may screen multiple aquifers.

Pod-specific pumping uncertainty is evident in the calibrated results. For Pod 3, the pumping bounds were set with the lower bound fixed at 1.0 to allow calibration to increase pumping above the prior base but not below it. Despite this freedom, Pod 3 shows the largest systematic head bias in the Seymour Aquifer, with a mean residual of -18 feet (Section 5.3.2), suggesting that the prior pumping estimate for Pod 3 was too low and the upper bound of 1.25 to 1.4 was insufficient to match observed drawdown. Although the pumping framework provides a defensible basis for calibration, improved pumping data at the well level, particularly for pods and time periods with sparse historical records, would significantly enhance accuracy and reduce reliance on assumptions.

7.5 Surface water–groundwater interaction

Surface water-groundwater interactions are represented using river and stream drain boundary conditions. These boundary conditions rely on conductance parameters (Sections 5.3.1, Stream drain conductance and 5.3.1, River conductance) that are rarely measured directly and are therefore constrained only indirectly through head calibration. Simulated stream-aquifer exchange fluxes are not directly constrained by observed streamflow data. Posterior stream drain discharge increased significantly relative to the prior base, reflecting calibration adjustments driven entirely by the head observations. Simulated stream-aquifer exchange magnitudes should therefore be interpreted with appropriate caution, particularly at individual stream reaches where localized conditions may differ from the regional pattern.

Spring and seeps drain conductance was held fixed during calibration and was not adjusted as a calibration parameter. Simulated spring head elevations were calibrated against observed records from Brune (1975; 1981), TWDB, and United States Geological Survey (Section 5.3.3), but simulated spring flows are not direct calibration outputs and should be interpreted from the perspective of calibrated heads at the spring cells rather than as independently validated quantities.

Evapotranspiration is not explicitly represented in the model (Section 4.15). The hydrologic processes typically represented by a dedicated evapotranspiration package are absorbed implicitly into the calibrated river and drain conductance and recharge parameters. This simplification reduces computational cost but means that water losses attributable to evapotranspiration cannot be separately quantified from stream and river discharge in the model water budget.

7.6 Observation data and calibration

The calibration relied heavily on weighted observations of hydraulic head observations, both steady-state and transient (Section 5.2). Observation coverage is

uneven across the model domain. In the Seymour Aquifer, more than 6,400 of the approximately 8,650 head observations come from Pods 4 and 7 alone, which are the most productive and most intensively monitored pods. The remaining 13 pods together contribute fewer than 2,300 head observations, with some pods supporting fewer than 50 observations. In the Blaine Aquifer, the approximately 4,670 head observations are concentrated in the northern portion of the aquifer (Wheeler, Collingsworth, Childress, and Hardeman counties in Texas), with comparatively sparse coverage across the central and southern Blaine.

This uneven observation coverage limits calibration confidence in areas with few observations. The pilot-point-based parameterization allows calibration to produce plausible values in data-poor areas, but these values are weakly constrained and should be interpreted as consistent with regional trends rather than as locally validated.

The calibration used the PESTPP Iterative Ensemble Smoother with 70 prior realizations reduced to 66 posterior realizations across three iterations (Chapter 5). The ensemble approach characterizes parameter uncertainty and supports probabilistic interpretation of model predictions but does not eliminate non-uniqueness. Multiple parameter combinations may produce similarly acceptable fits to the calibration data, so calibrated parameter values for any individual realization should not be interpreted as unique.

AUTOFLOW reduction targets were implemented as inequality constraints to limit calibration from matching heads through unrealistic reduction of irrigation withdrawals (Section 5.2.2, AUTOFLOW reduction-based targets). These constraints were applied to irrigation pumping in the principal Seymour pods (1, 3, 4, 7, 11, and 13). The relative weight assigned to the AUTOFLOW constraints reflects a balance between limiting excessive reduction and preserving objective-function contribution from the weighted hydraulic head targets, which represent direct field measurements. As a result, some AUTOFLOW reduction still occurs in these pods during simulations, though to a lesser extent than would occur without the constraints. In other pods and for non-irrigation use types, the AUTOFLOW constraint does not apply, and simulated AUTOFLOW reductions may occur where the simulated aquifer could not sustain the prescribed withdrawal.

7.7 Conceptual simplifications

Several conceptual simplifications are worth noting. First, faults that may affect regional structure of the Permian units (Section 2.7) are not explicitly represented in the model. Fault-related flow barriers or conduits are therefore not explicitly simulated. Second, the saline and brine groundwater at depth below the fresh groundwater flow system is represented as a boundary rather than as an active model component; density-dependent flow between fresh and saline zones is not simulated.

7.8 Predictive simulation

The predictive period (2021 through 2080) was simulated as a 60-year continuation of the historical simulation using averaged conditions from the last five historical years (2016 through 2020) as the input. This approach assumes that recent calibrated conditions (pumping, recharge, and boundary conditions) persist into the future and does not incorporate climate change projections, anticipated population or land-use changes, or specific planning-period pumping scenarios. The predictive period serves as a quality-assurance baseline showing that simulated trends remain consistent with historical behavior under average conditions. It does not represent a forecast of specific future conditions, and users evaluating future scenarios should apply the model with scenario-specific inputs rather than relying on the default predictive continuation.

8 Summary and conclusions

The development of the groundwater availability model for the Seymour and Blaine aquifers represents a significant step in improving the understanding of groundwater flow and availability within the aquifers. By including updates to the conceptual model, refining the representation of the hydrostratigraphy of the aquifers and surrounding formations, adding significant refinement to the numerical model grid, and utilizing an advanced calibration approach, the model provides a more accurate and functional tool for regional water resource management than existing models.

This numerical model not only captures the large-scale dynamics of groundwater movement but also accounts for key uncertainties. The calibration process, driven by the PESTPP Iterative Ensemble Smoother ensemble-based optimization framework, ensures that the model remains both faithful to observed water levels and consistent with conceptual hydrogeologic constraints. The probabilistic output can be used to evaluate predictive uncertainty in water management decisions. In addition, the sensitivity analysis provides insight into model behavior, particularly the influence of model parameters on key observations. While the model effectively balances empirical accuracy and conceptual integrity, certain limitations—such as the scarcity of deep aquifer data and localized baseflow discrepancies—underscore the need for ongoing refinement and future data collection efforts.

These improvements make the Seymour and Blaine aquifers groundwater availability model a valuable and dynamic tool for long-term groundwater planning and management, providing insights that can guide water planning in the region.

8.1 Updates to conceptual model

The foundation of this numerical groundwater model is the conceptual model reported in the Groundwater Availability Model for the Seymour Aquifer (Ewing and others, 2004). During development of this numerical model, INTERA updated the conceptual model of the aquifers in several critical areas to improve its representation in a numerical framework. The model domain was extended beyond the official Texas Water Development Board boundaries for the Seymour and Blaine aquifers to capture hydrologic boundaries better within the geologic formations in hydraulic communication with the Seymour and Blaine aquifers.

To account for the interaction between the Seymour Aquifer and the discharge to streams within the underlying formations as well as the interaction between the Blaine Aquifer and the other Permian formations underlying and overlying it, four hydrostratigraphic layers were considered in the model. Layer 1 represents the Seymour Aquifer in its entirety. The Whitehorse and younger Permian units comprise model Layer 2. Layer 3 represents the Blaine Aquifer in its entirety and as an independent model layer. This is a significant update to the original model (Ewing and others, 2004), in which the Blaine Aquifer was lumped with other Permian units. The Flowerpot Shale and older Permian units comprise Layer 4. Structural interpretations and water quality data from Finch and others (2016) were used to define the top and base of the Blaine Aquifer. Elsewhere, the base of the Permian units represents the

shallow groundwater flow system, below which the water quality is observed to degrade. This addition provides a more realistic representation of groundwater availability while also ensuring consistency with observed water quality patterns.

Historical groundwater use estimates were also refined. Updated domestic and agricultural pumping estimates were developed using high-resolution census and water use data, enabling a more detailed spatial and temporal representation of groundwater withdrawals. Groundwater pumping was categorized by use type—including domestic, irrigation, municipal, mining, and livestock—allowing for differentiated uncertainty representation in calibration. For instance, domestic pumping, estimated using census-based population distributions and per capita water use, is relatively well-constrained. In contrast, irrigation withdrawals, which depend on factors such as climate variability and crop selection, include greater uncertainty. In addition, metered pumping data provided by Rolling Plains Groundwater Conservation District, Mesquite Groundwater Conservation District, and Panhandle Groundwater Conservation District were incorporated. By explicitly accounting for these differences, the model better captures the relative reliability of various pumping estimates and improves the robustness of the calibration process.

8.2 Numerical model development and calibration

The groundwater model was implemented using MODFLOW 6, the latest version of the widely used groundwater modeling software, which provides enhanced flexibility and modularity compared to previous versions. The Seymour and Blaine aquifers groundwater availability model integrates key MODFLOW 6 packages to represent critical hydrologic processes. The General Head Boundary package simulates groundwater inflows and outflows along model boundaries, ensuring proper exchange with adjacent aquifers, primarily the Ogallala and Edwards-Trinity aquifers. The River package captures river-aquifer interactions, allowing for dynamic baseflow contributions and streamflow depletion effects. The Recharge package applies the refined recharge estimates, improving the representation of groundwater replenishment across the study area. Additionally, the Drain package accounts for groundwater discharge to minor streams and springs, helping to simulate baseflow dynamics and surface water-groundwater interactions more accurately. The Well package was used to simulate pumping within the aquifers. The Unstructured Discretization package was used to allow significant refinement (1/8-mile by 1/8-mile) for the isolated pods of the Seymour Aquifer while maintaining a coarser refinement (1-mile by 1-mile) for the Blaine Aquifer and other Permian-age formations.

The calibration of the Seymour and Blaine aquifers groundwater availability model was performed using the PESTPP Iterative Ensemble Smoother routine, an advanced parameter estimation method that improves upon traditional calibration techniques by efficiently managing uncertainty while ensuring consistency with both observed data and conceptual model constraints. Unlike traditional manual or gradient-based calibration approaches, which often require significant trial and error and may struggle with non-uniqueness in parameter estimation, PESTPP Iterative Ensemble Smoother employs an ensemble-based optimization framework. This approach allows for

simultaneous adjustments across multiple parameters while maintaining physically realistic relationships between them, ultimately leading to a more robust and stable calibration.

A key challenge in calibrating the Seymour and Blaine aquifers model is the inherent tradeoff between fitting observed groundwater levels and maintaining fidelity to the conceptual model. The aquifers contain both higher-permeability deposits, which respond more dynamically to recharge and pumping, and low-permeability formations that exhibit more subdued groundwater movement. The exact locations of these heterogeneities are poorly constrained by data, however.

To address this, the PESTPP Iterative Ensemble Smoother routine enables a hybrid calibration approach, where adjustments to key parameters—such as hydraulic conductivity, storage properties, and streambed conductance—are constrained by conceptual model expectations while also optimizing the fit to observed groundwater levels. The ensemble-based approach allows the calibration to incorporate both measurement data and prior hydrogeologic knowledge, ensuring that the final parameter set is not only statistically optimized but also physically meaningful. Additionally, the PESTPP Iterative Ensemble Smoother framework inherently quantifies uncertainty in parameter estimates, providing a probabilistic evaluation of model reliability.

Through this process, the calibrated model effectively balances empirical accuracy with conceptual integrity, ensuring a realistic representation of groundwater conditions for both historical evaluation and future water management applications. The final calibration achieved a strong agreement with observed hydraulic heads, with most residuals falling within an acceptable range. While some localized discrepancies persist, particularly in areas with limited groundwater monitoring, these deviations are largely attributable to data sparsity rather than systemic model bias.

Uncertainty in hydrogeologic properties is inherent in regional groundwater models. The calibration process significantly reduced the range of uncertainty in the posterior distributions of hydrogeologic properties compared to the prior distribution. This indicates that, despite data limitations, the calibration successfully refined these parameters, constraining them to a range that supports a well-conditioned model fit while maintaining conceptual consistency.

8.3 Sensitivity analysis

The sensitivity analysis provided valuable insights into how key model parameters influence simulated groundwater levels and overall model performance. By using the Method of Morris (Morris, 1991) within a global sensitivity framework, we were able to identify which parameters exert the strongest control on model outputs, which behave in a predictable linear manner, and which demonstrate nonlinear or interacting effects.

For the Seymour Aquifer, recharge and horizontal hydraulic conductivity are the two most sensitive parameters for both the steady-state and transient models, with pumping also being sensitive in the transient model. For the Blaine Aquifer, hydraulic

conductivity and recharge are the two most sensitive parameters in the steady-state model while specific yield and pumping are sensitive in the transient model. Inflow from recharge in the Whitehorse and younger formations and outflow governed by the stream conductance in the Flowerpot and older formations, along with the hydraulic conductivity of the Blaine Aquifer, are also sensitive model parameters in the transient model for the Blaine Aquifer.

Parameter influence on specific observation groups was also evaluated as part of the sensitivity analysis. For steady-state conditions, recharge and primary aquifer hydraulic conductivities were the primary drivers of water level equilibrium. An imbalance between these factors can lead to either dry or flooded conditions within the Seymour Aquifer, which is relatively thin compared to even the refined 1/8-mile by 1/8-mile lateral grid size.

Nonlinearity interactions among key parameters were identified as part of the sensitivity analysis. This information is important when using the model for future management decisions, ensuring a clear understanding of how parameters influence both the simulated results and each other.

In conclusion, this sensitivity analysis enhances our understanding of how different hydrogeologic parameters influence model behavior and provides a basis for refining future simulations. Future work should focus on improving parameter constraints through additional field data collection, refining stream-aquifer interactions, and exploring alternative approaches for representing deeper hydrogeologic layers.

9 Future improvements

As with all regional groundwater models, the Seymour and Blaine aquifers groundwater availability model should be treated as a living tool—one that evolves and improves as new data are collected and our understanding of the aquifer system advances. This model offers a robust framework for regional-scale planning and long-term water budget evaluations. As population growth and groundwater demands increase across the region, future refinements will be essential to enhance both the predictive accuracy and the applicability of the model to more localized water management decisions.

9.1 Additional supporting data

Several types of data could be collected to better support future enhancement of the Seymour and Blaine aquifers groundwater availability model. These include additional water-level monitoring in Seymour pods and areas of the Blaine Aquifer with sparse measurements, recharge studies, surface-water/groundwater studies, and addition of stream gages. Because of the character of the Seymour Aquifer (e.g., small pods, thin saturated thicknesses over many areas, and a water-table aquifer intersected by streams), all parameters related to recharge to the aquifer, flow within the aquifer, and discharge from the aquifer impact the accuracy to simulate processes occurring in the aquifer.

Additional water-level monitoring in Seymour pods in Hall, Motley, Childress, Wichita, Foard, Knox (pod 6 and the northern portion of pod 7), Kent, Stonewall, Fisher, and Jones (pods 11 and 12) counties, and the southern half of the Blaine Aquifer, would be valuable. Although pumping from these portions of the aquifers is small, it is still advantageous to monitor water levels in those areas to improve aquifer understanding. It is also important to increase water-level monitoring in areas with future development potential even if they are not currently extensively developed. If monitoring begins prior to increased development, the model can be calibrated against the pre-development response to improve model predictive capability in those regions.

Recharge is the primary method by which water enters the Seymour and Blaine aquifers. Because the Seymour is a shallow water-table aquifer, long-term stability of the aquifer requires a balance between inflow from recharge and decreased discharge and outflow through pumping. Improving the understanding of recharge into the aquifers will greatly enhance future models and their ability to predict future aquifer conditions accurately based on projected pumping estimates. Studies should be continued into the nature of recharge in the Seymour and Blaine aquifers.

Because streams represent a source of aquifer discharge, data on stream/aquifer interaction is valuable to understanding groundwater within the Seymour and Blaine aquifers. Knowledge of surface water-groundwater interaction requires good coverage of stream gages in both the Seymour Aquifer and the Permian units underlying and surrounding it. The model's ability to represent actual aquifer conditions will be greatly enhanced with aquifer-specific data regarding surface water-groundwater interaction.

In addition, it would be beneficial if publicly available surface water models were developed for the Seymour and Blaine aquifers region. These would provide better estimates of the hydrography of the aquifers and could be coupled with MODFLOW in future model improvements.

Currently, horizontal hydraulic conductivity data are limited for the Seymour and Blaine aquifers and very limited for the other Permian sediments. Any additional hydraulic conductivity and storativity estimates interpreted from aquifer tests will further help parameterize the Seymour and Blaine aquifers and the Permian sediments for future improvement to this model.

Large portions of the Seymour Aquifer have a thin saturated thickness. Therefore, accurate location of the elevation of the aquifer base is important. Previous studies in some areas of the aquifer provided good data on the Seymour base. These areas include portions of Pod 7 in Haskell and Knox counties (R.W. Harden & Associates, 1978), portions of Pod 7 in Baylor County (Preston, 1978), portions of Pod 4 in Wilbarger County (Price, 1979), and portions of Pods 12, 13, 14, and 15 in Jones County (Price, 1978). In the remainder of the aquifer, however, coverage of data for determining the structure of the Seymour Aquifer is limited. With additional data, the ability of the model to represent the geometry of the aquifer would be improved.

The study by Finch and others (2016) adds significantly to the representation of the freshwater-brackish water interface for the Blaine Aquifer system, which includes the Whitehorse Formation. Additional water quality data elsewhere across the model domain would further constrain the understanding of base of the shallow flow system used to define the lower model boundary in the other Permian units.

Pumping is a major avenue of discharge for both the Seymour and Blaine aquifers. Attempts were made to distribute pumping to known wells based on use type and county-aquifer locations. Metered pumping removes ambiguity in the assignment of pumping location as well as volumes and improves the accuracy of the model. Additional metering of pumping would greatly benefit future models of the Seymour and Blaine aquifers.

9.2 Future model implementation improvements

Beyond data acquisition, implementation improvements to the model could improve simulation accuracy and functionality. A single model was used to represent the entire Seymour Aquifer even though it consists of isolated pods that are not hydraulically connected. In addition, the hydraulic condition of the aquifer varies from pod to pod. Some pods are heavily pumped for irrigation purposes while others are lightly pumped. While a single model of the Seymour allows estimation of consistent boundary conditions and hydraulic properties at a regional scale, smaller inset models employing boundary conditions from this regional model could be used for computationally efficient model runs at the pod scale.

Although the model includes river and drain packages to simulate streams, future versions could benefit from site-specific refinement of conductance values and

streambed characteristics, particularly in major streams and regions where current results suggest strong sensitivity and potential nonlinearity.

Lastly, the predictive simulations are based on an average of the current climatic conditions (recharge and streams) and pumping in the aquifers. Including future climate scenarios may improve the predictive capacity of the model.

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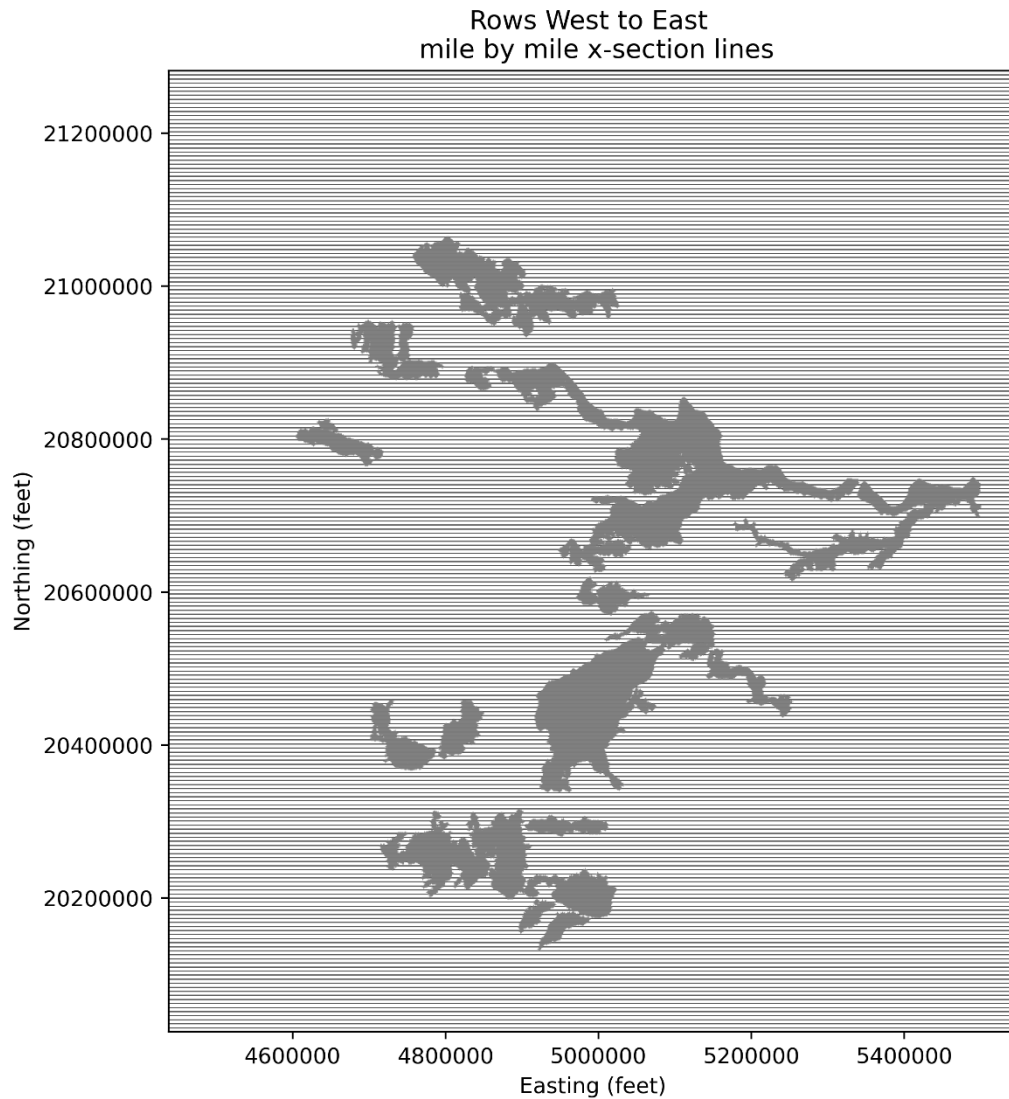
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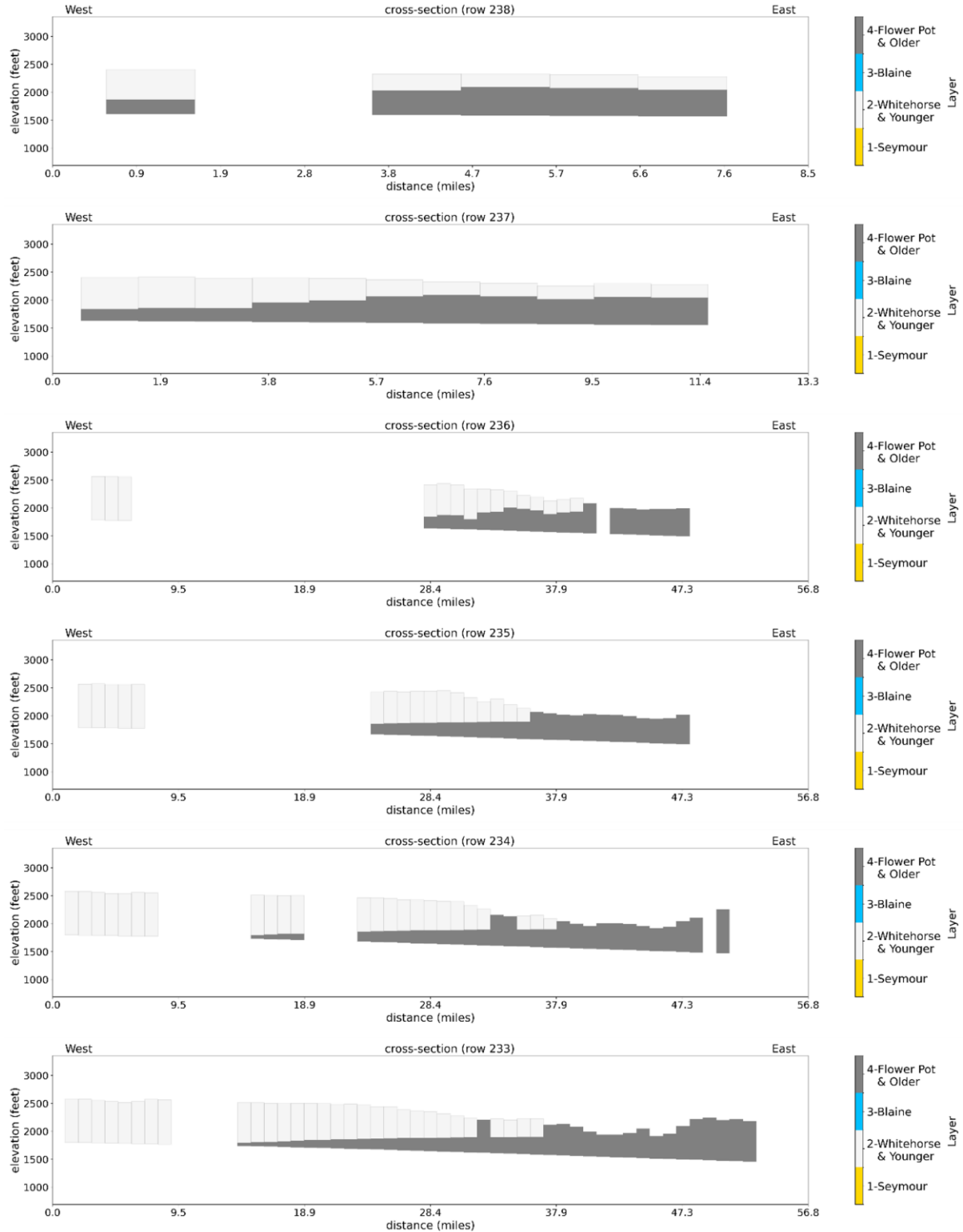
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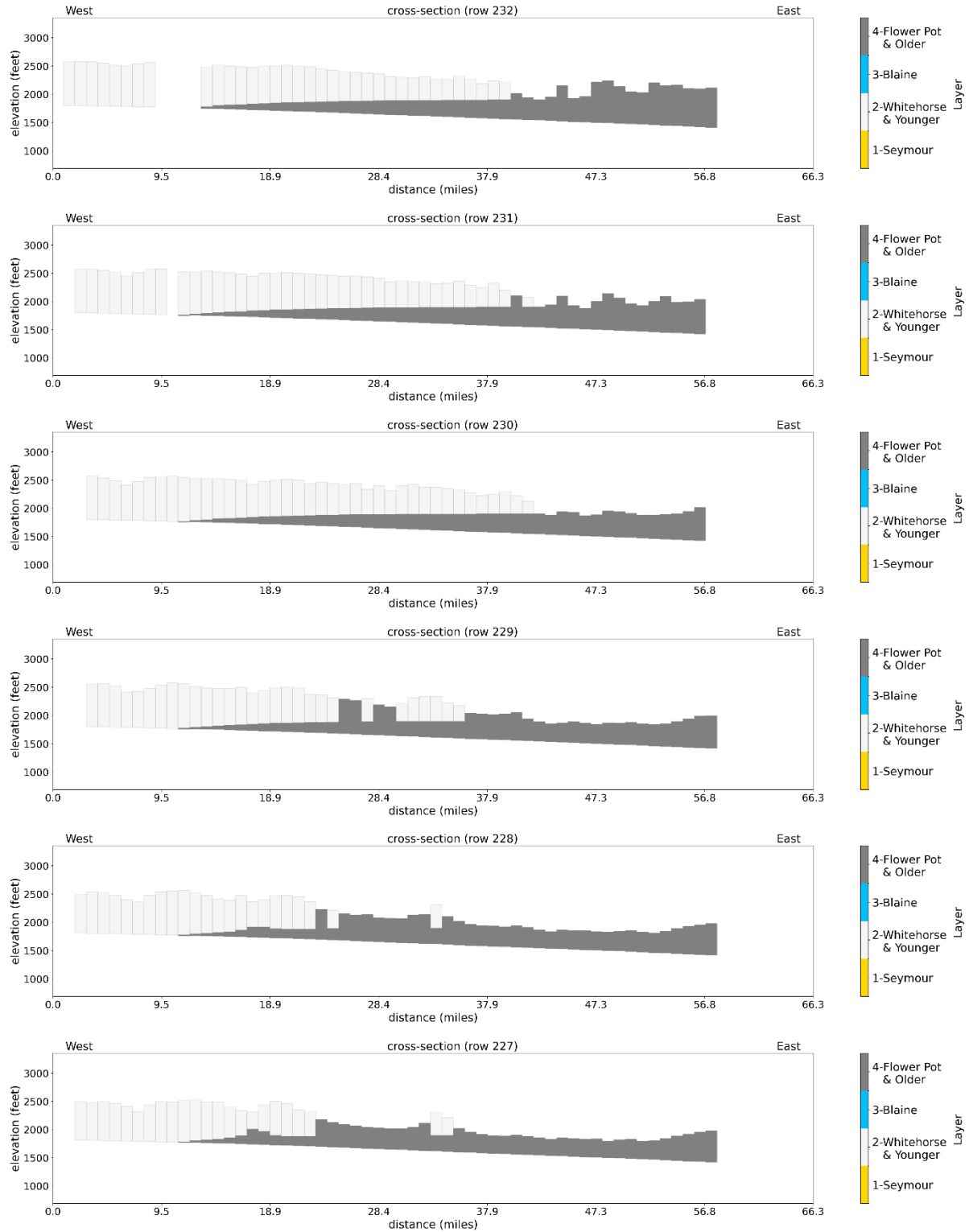
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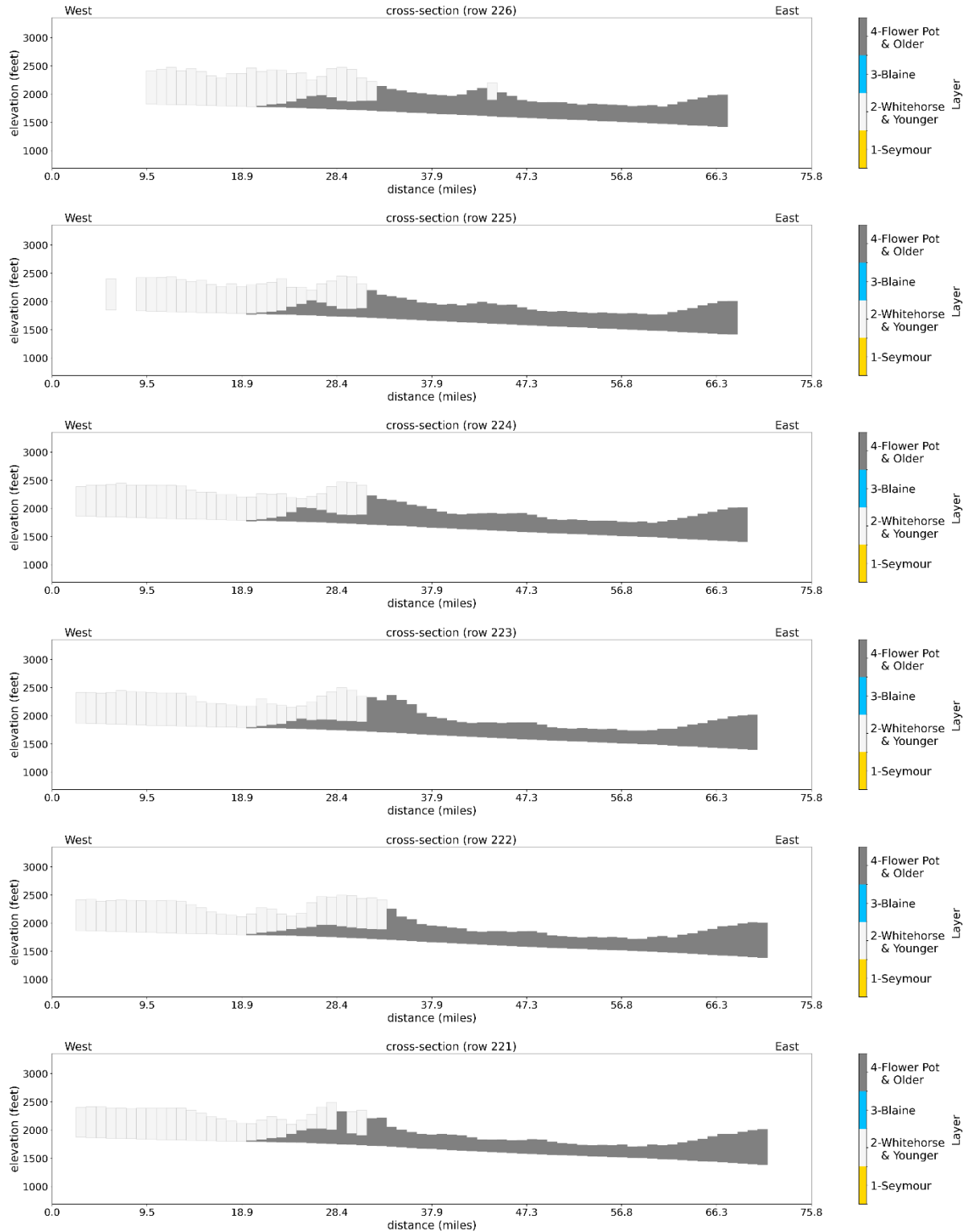
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Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers



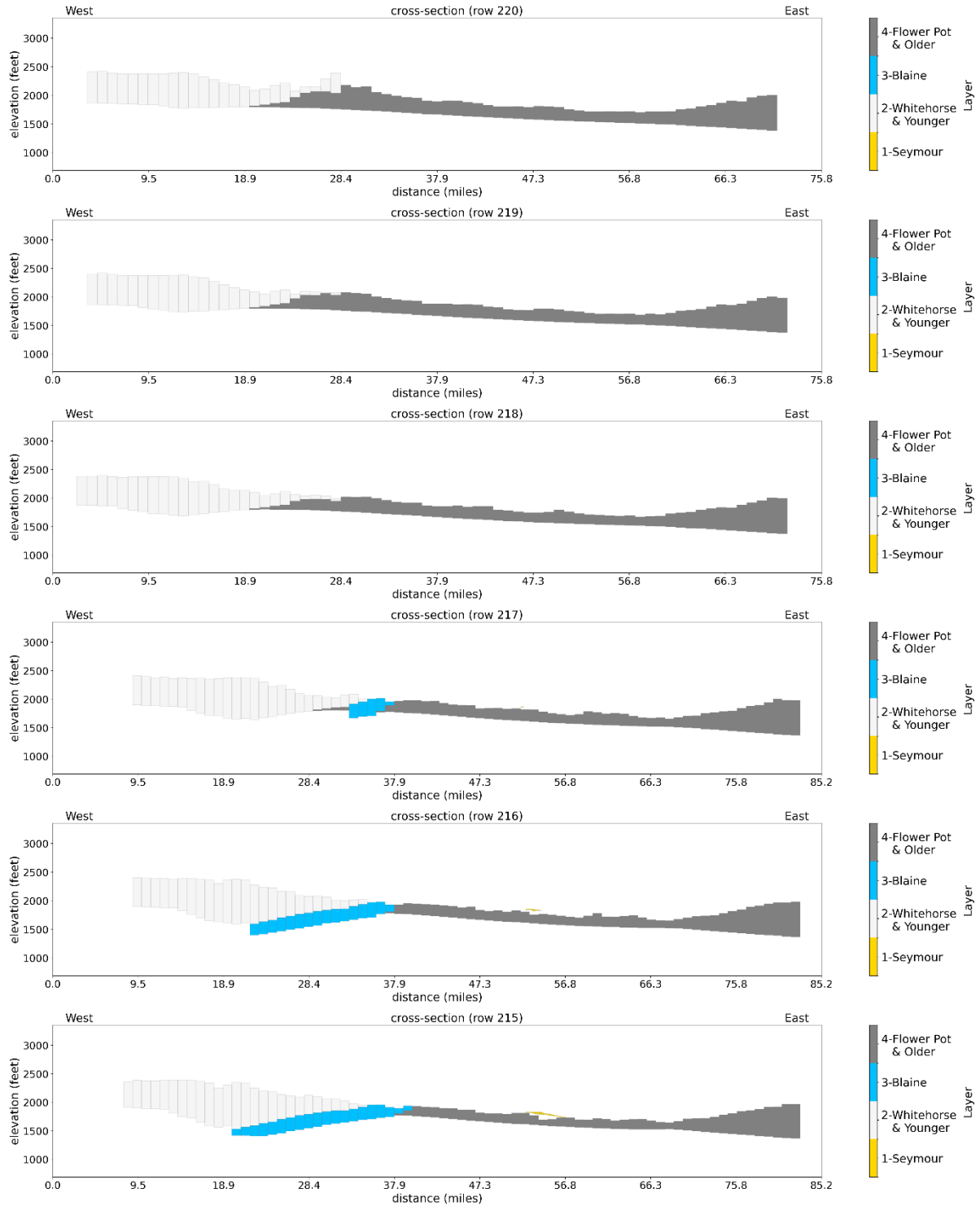
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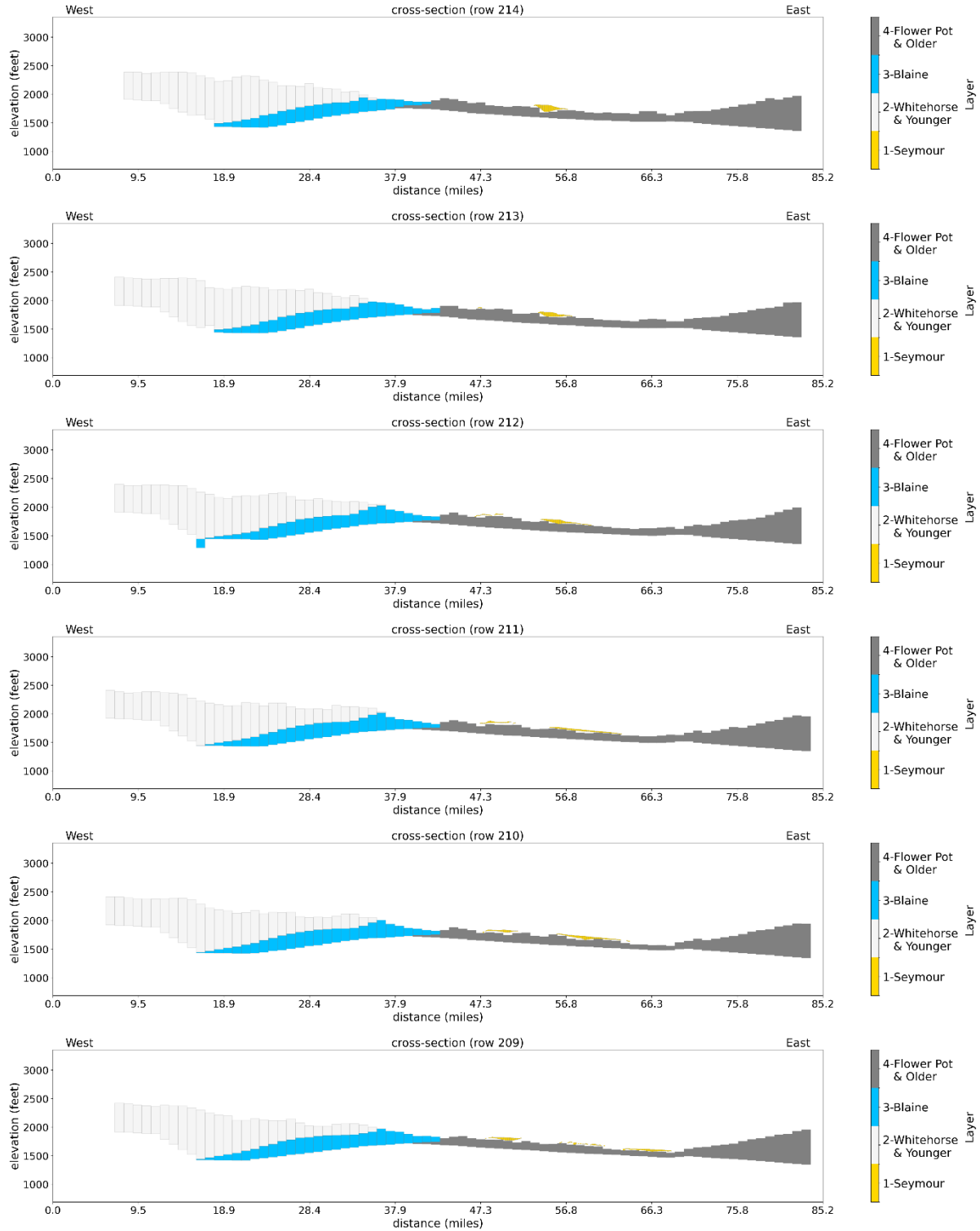
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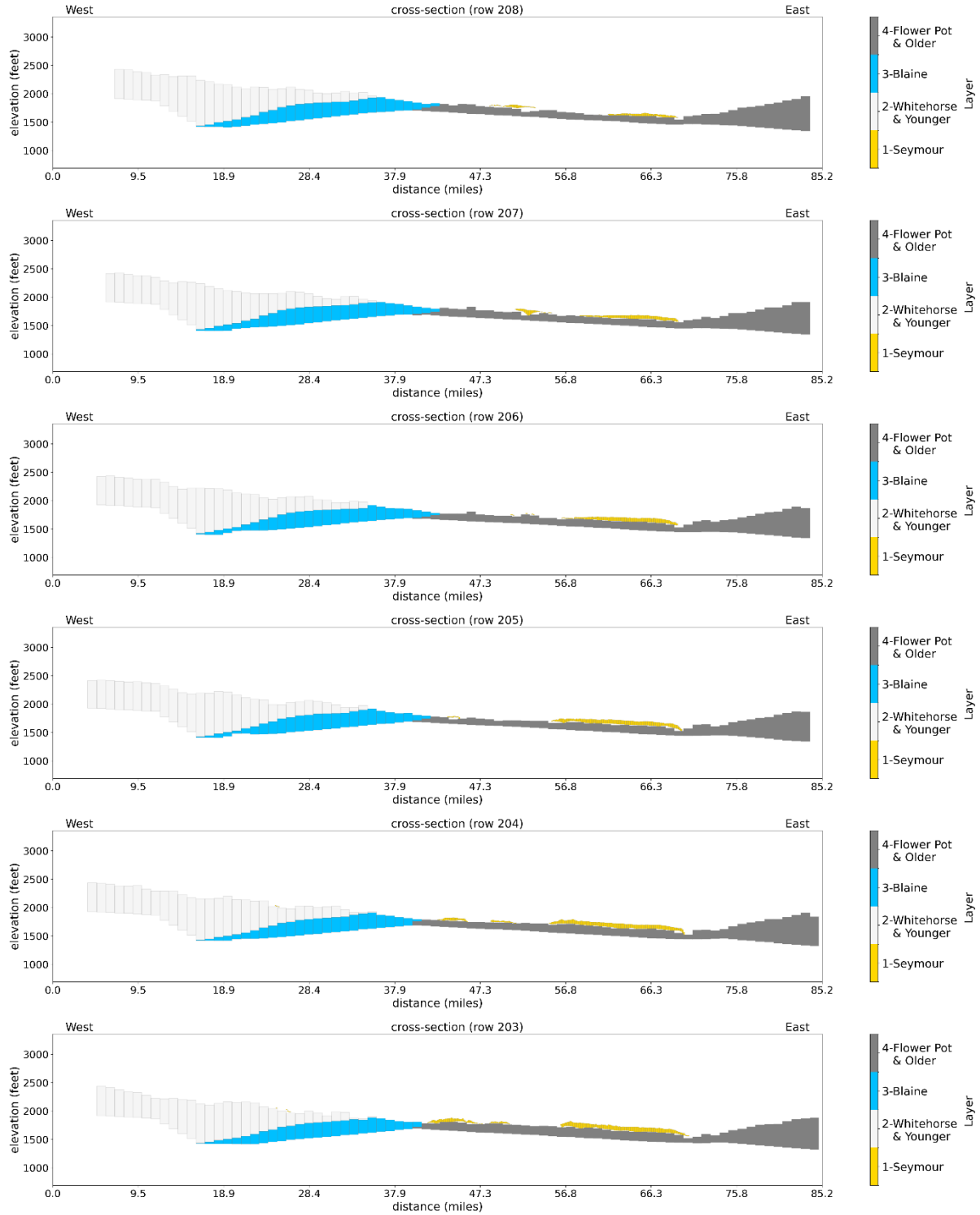
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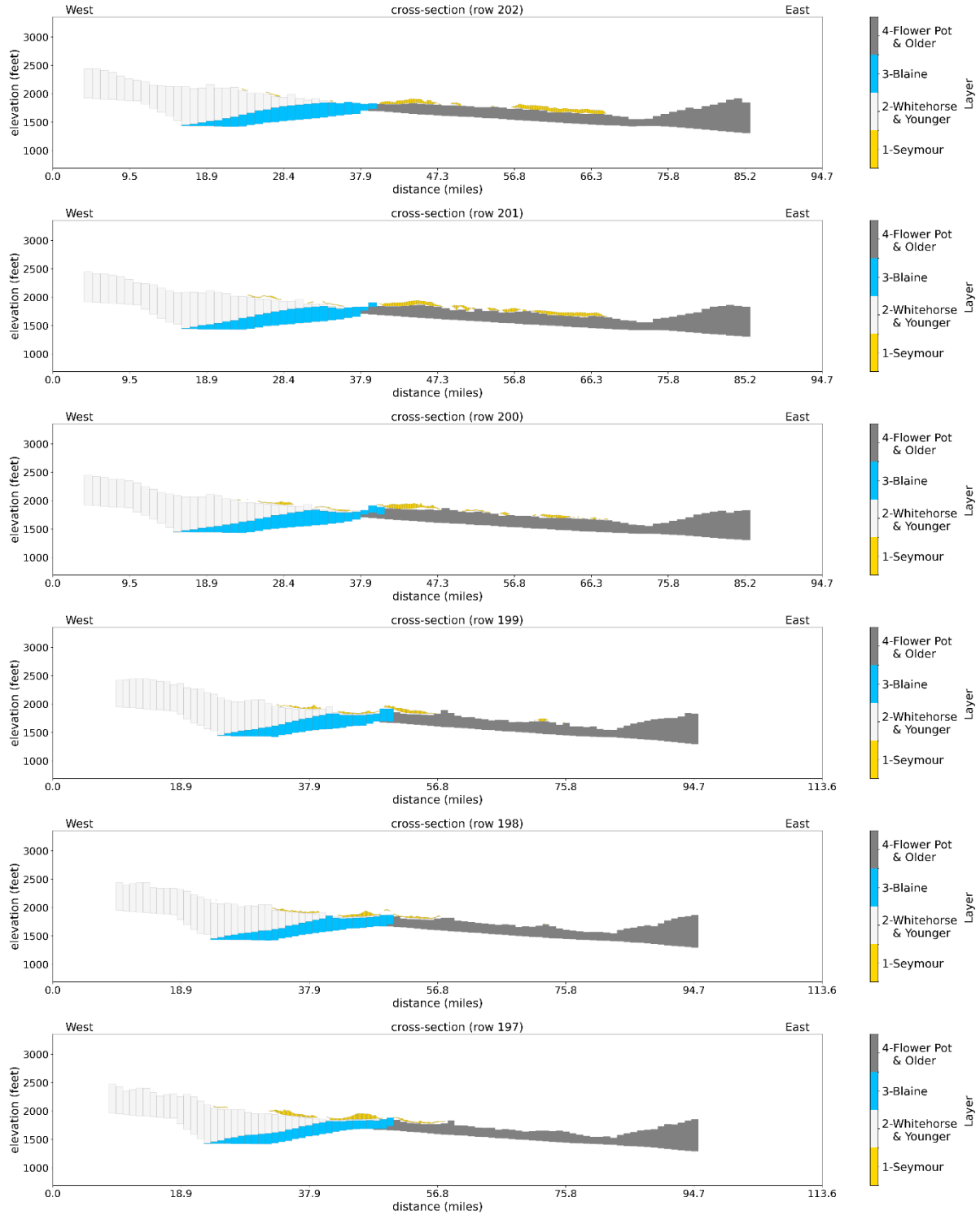
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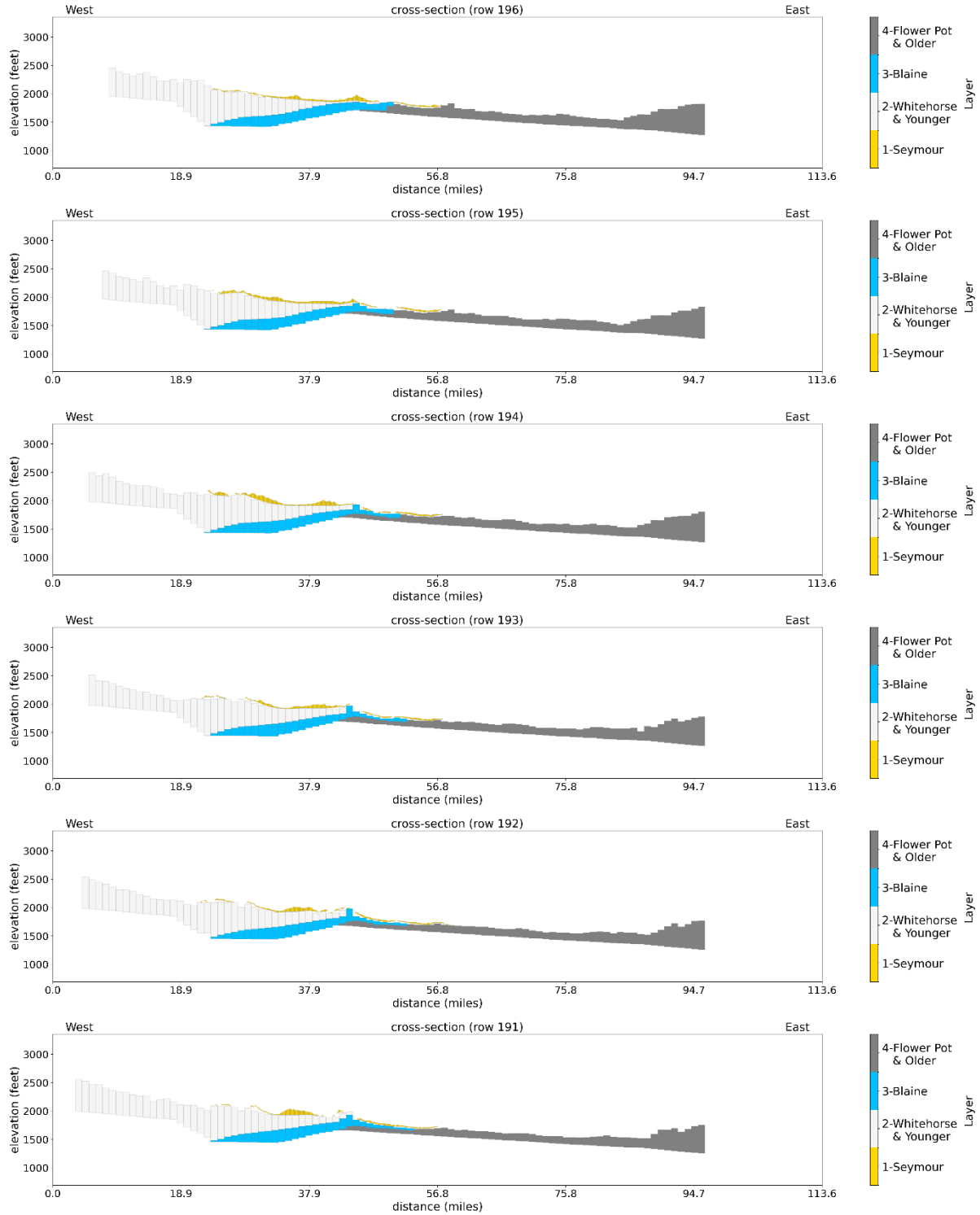
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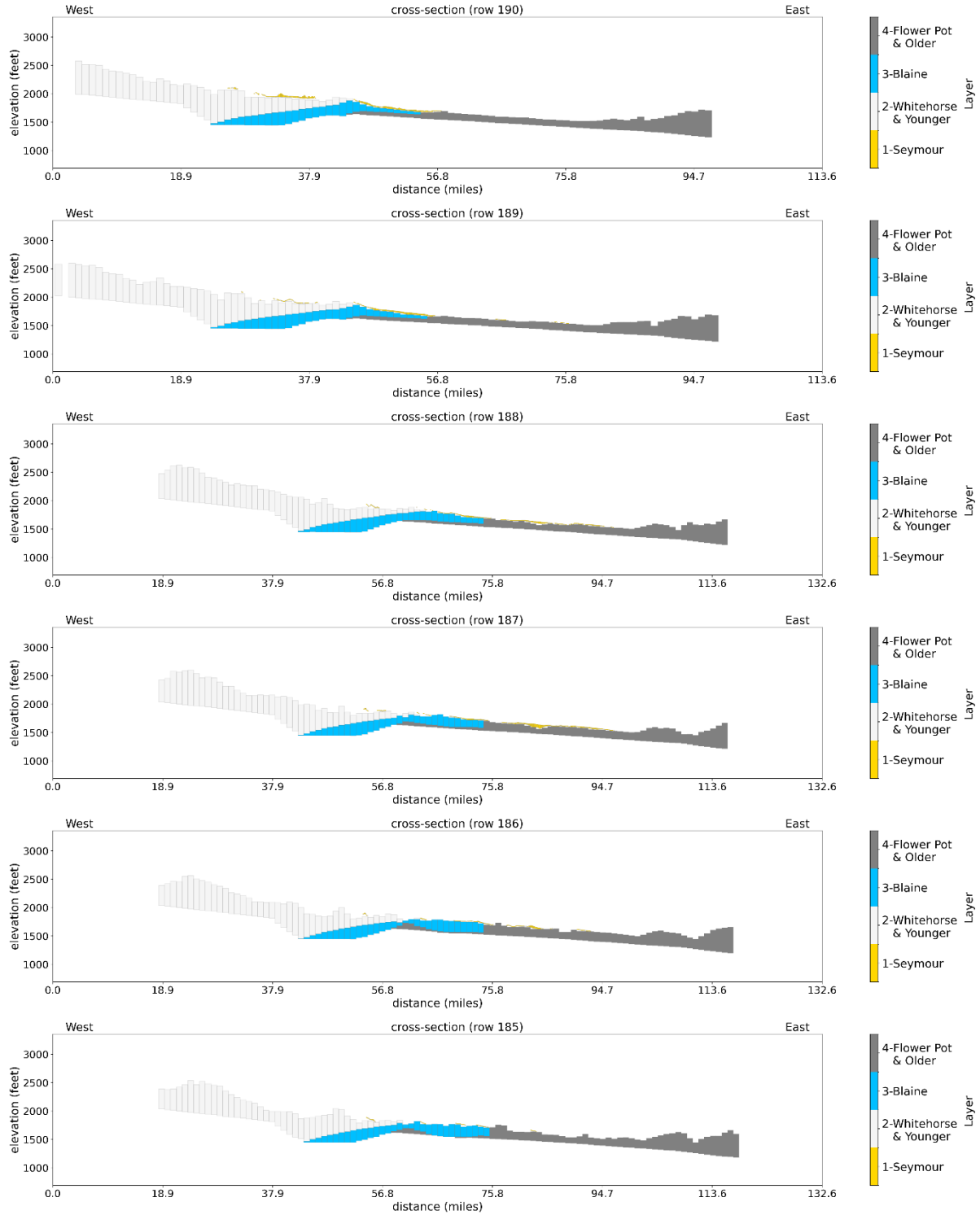
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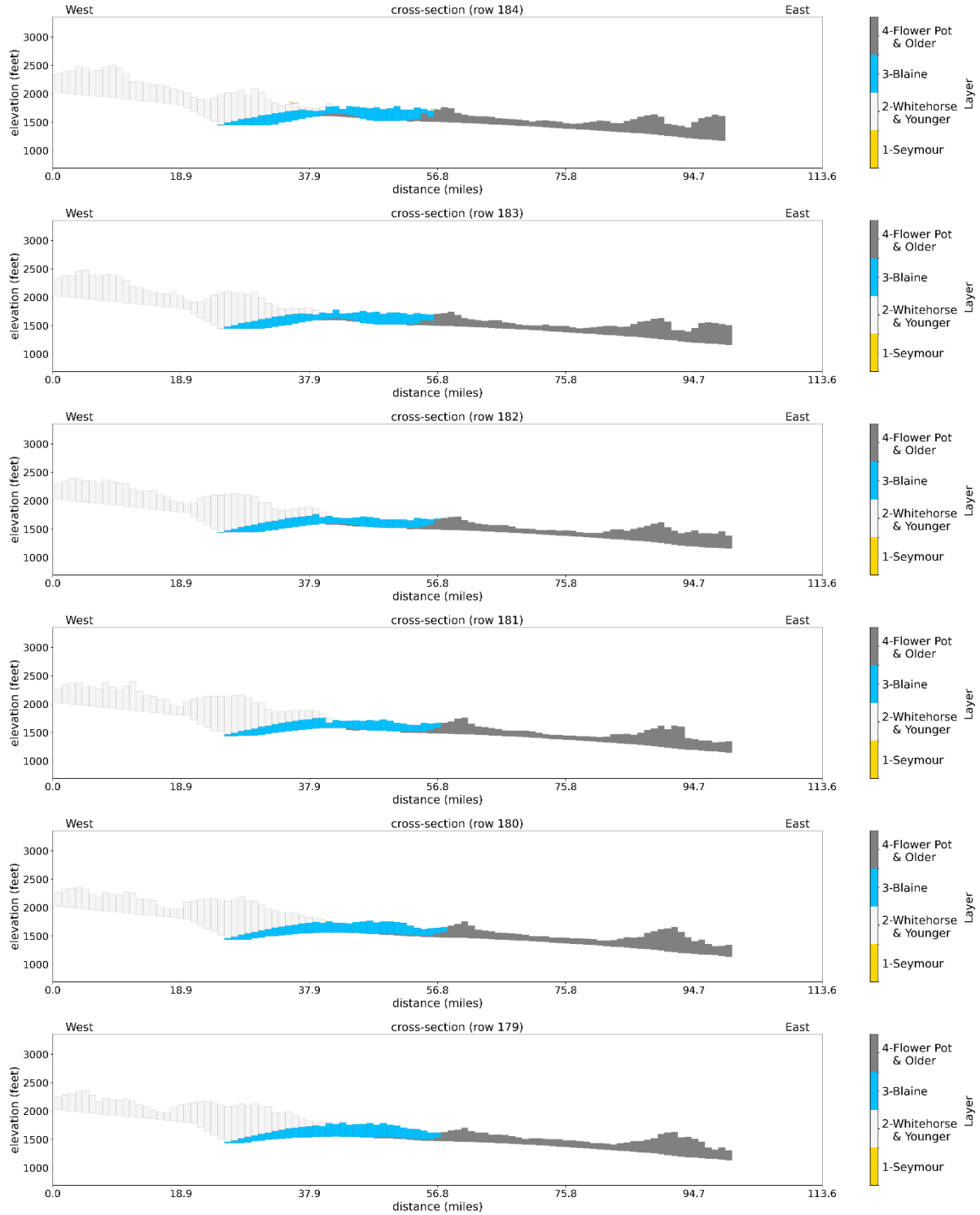
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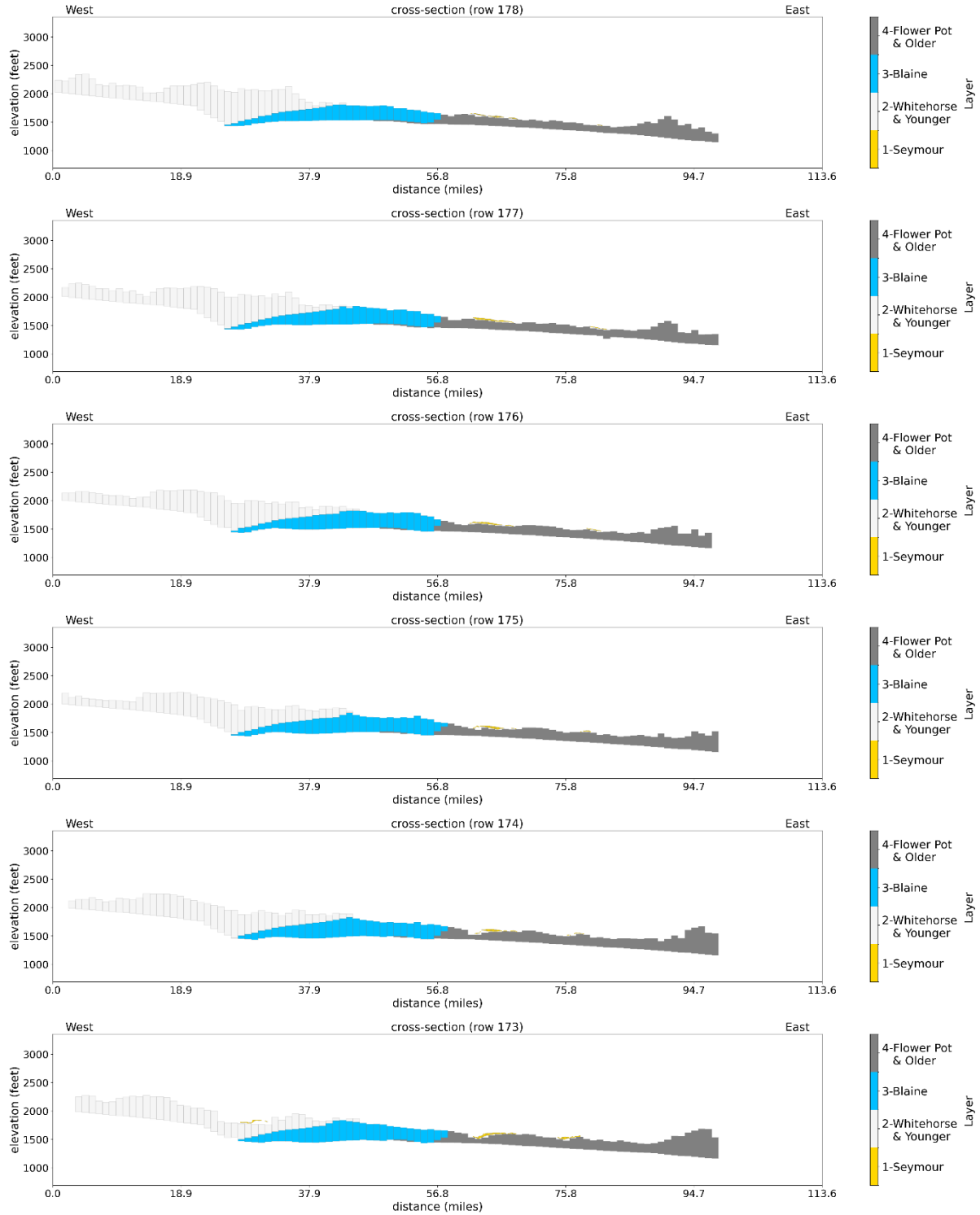
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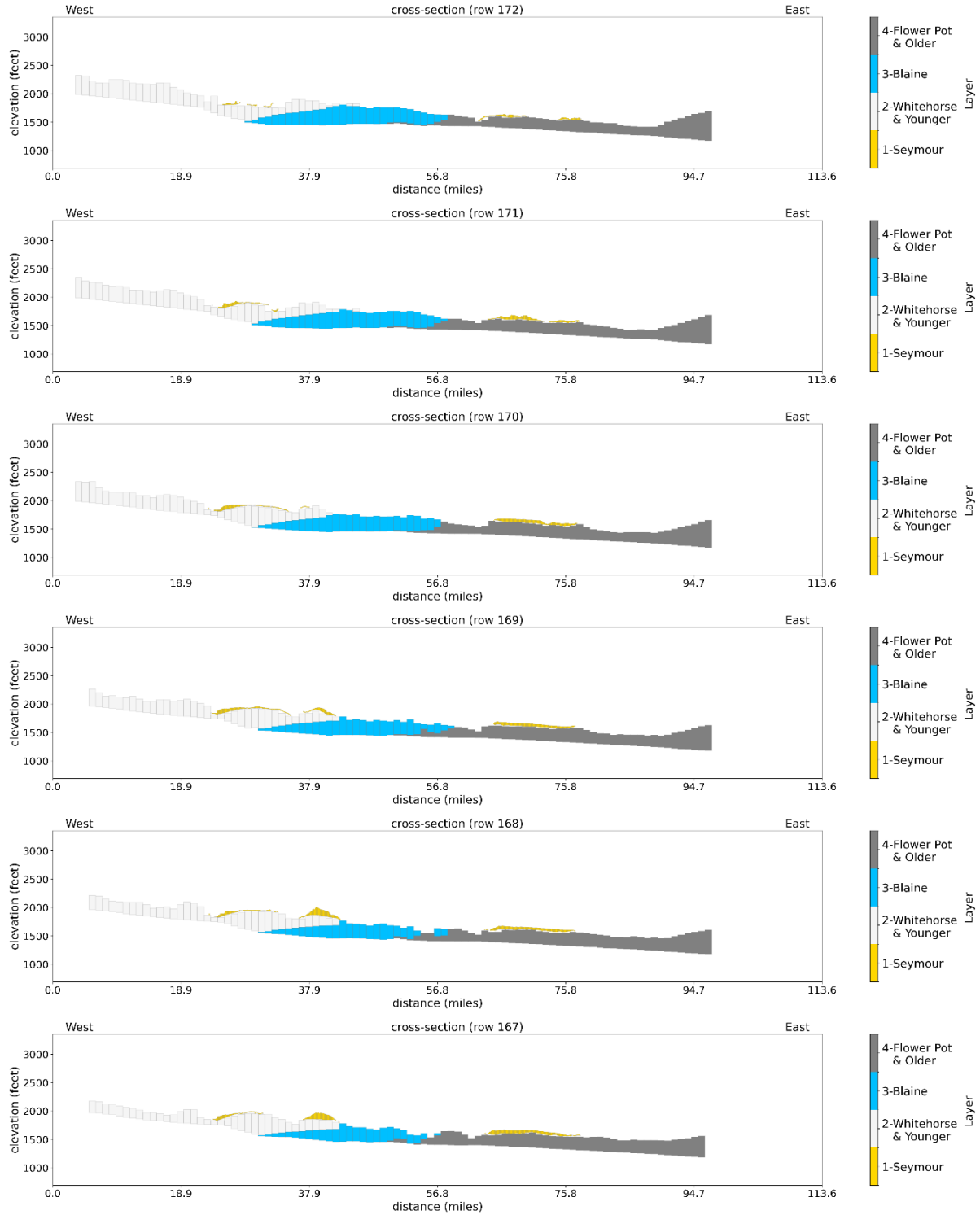
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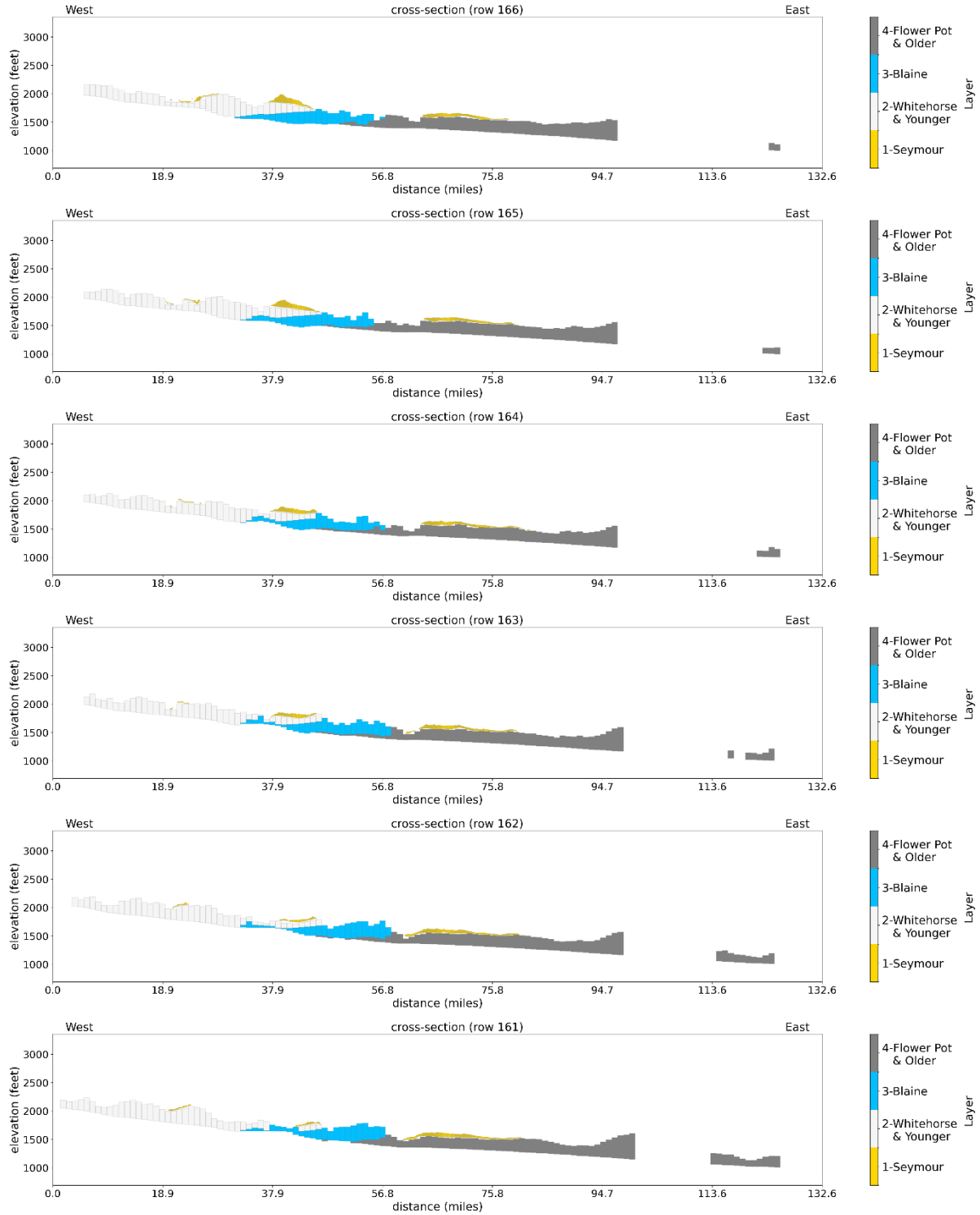
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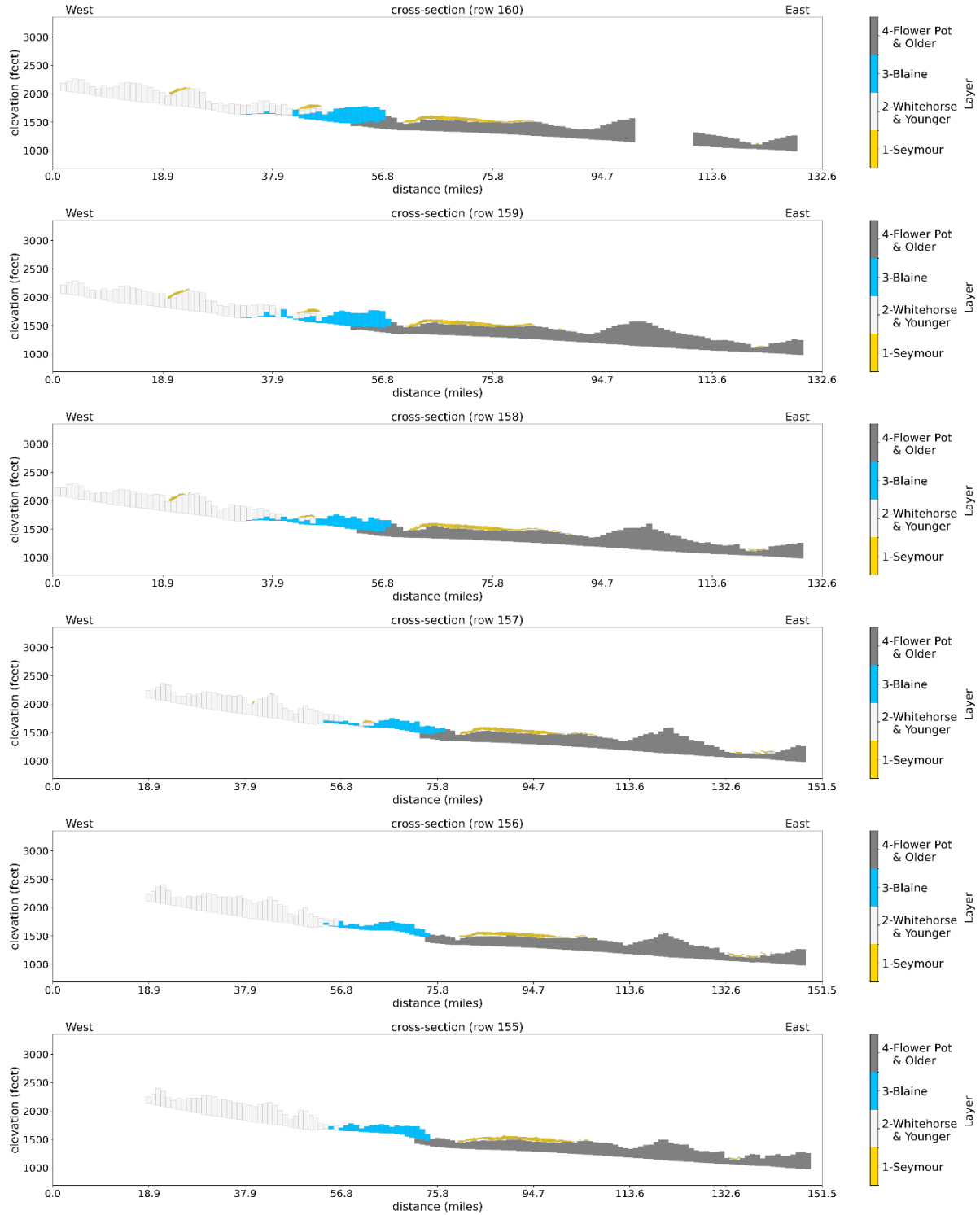
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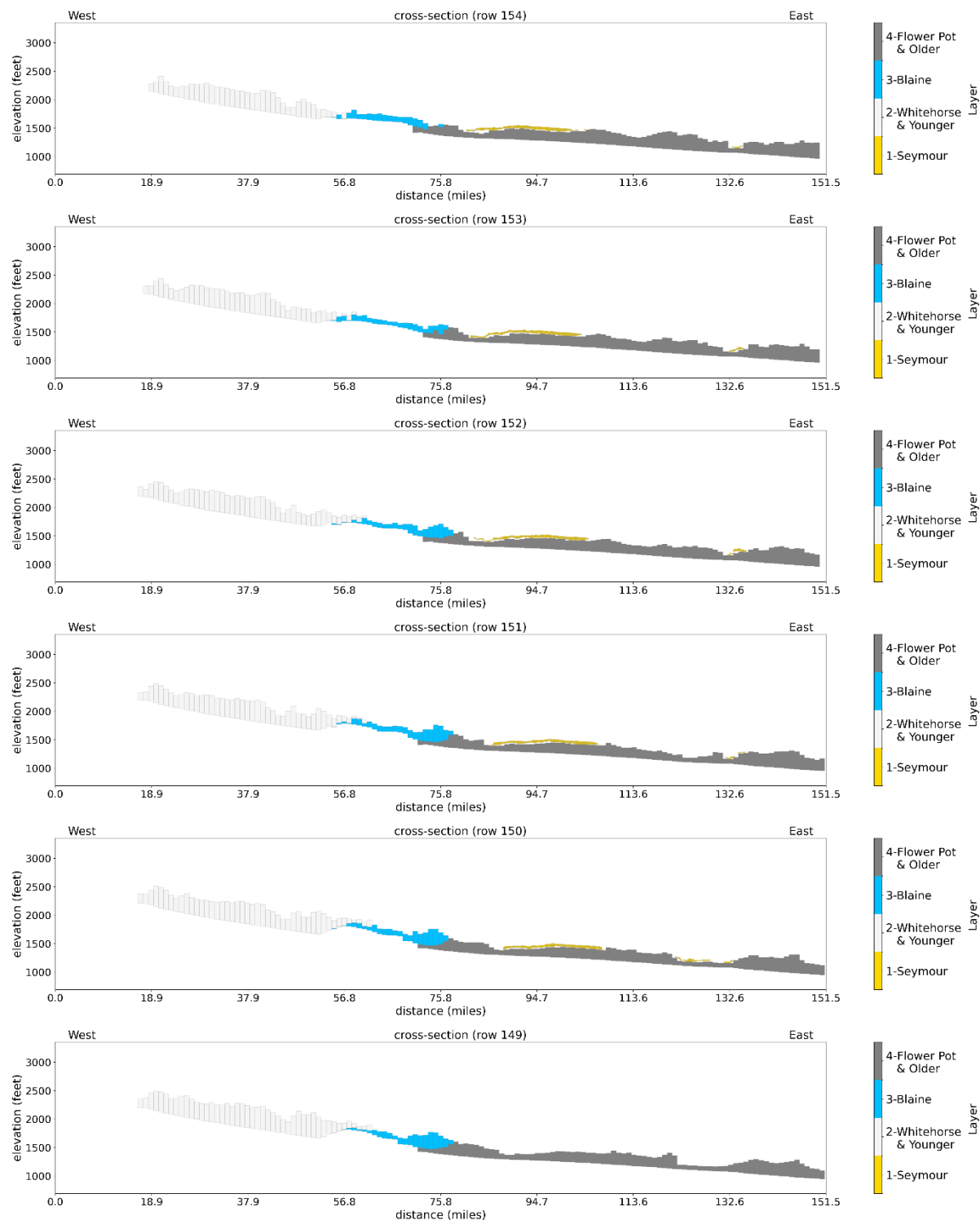
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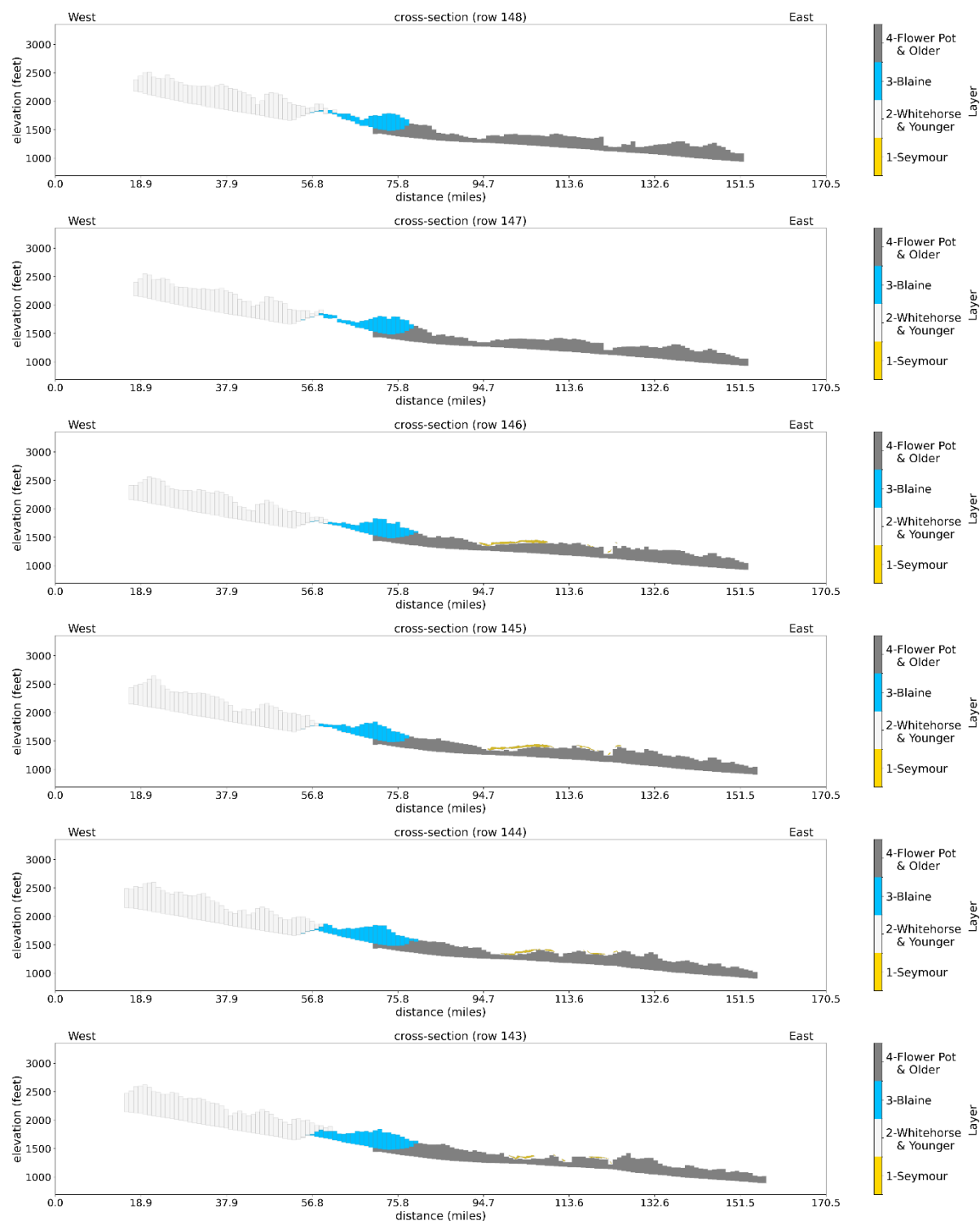
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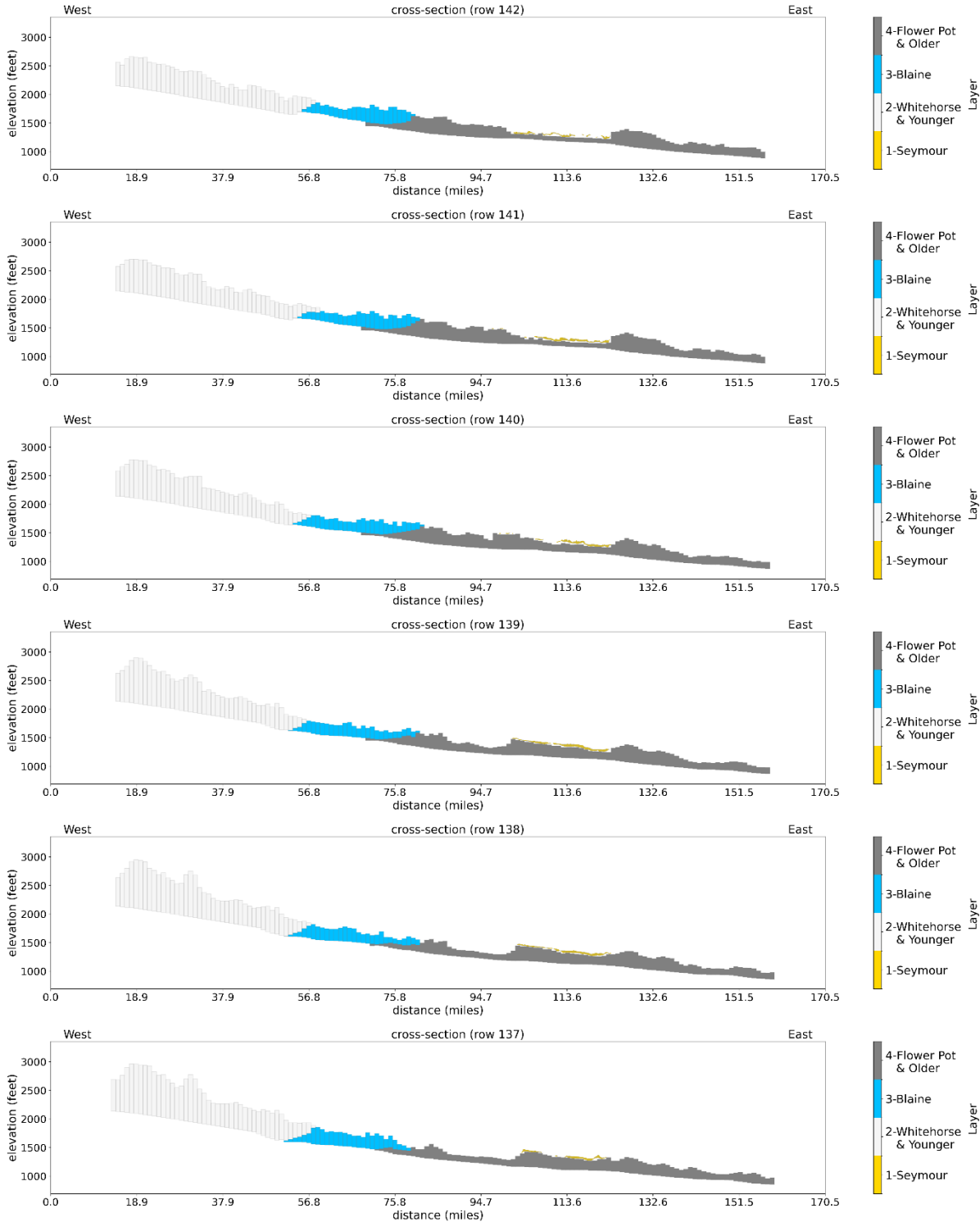
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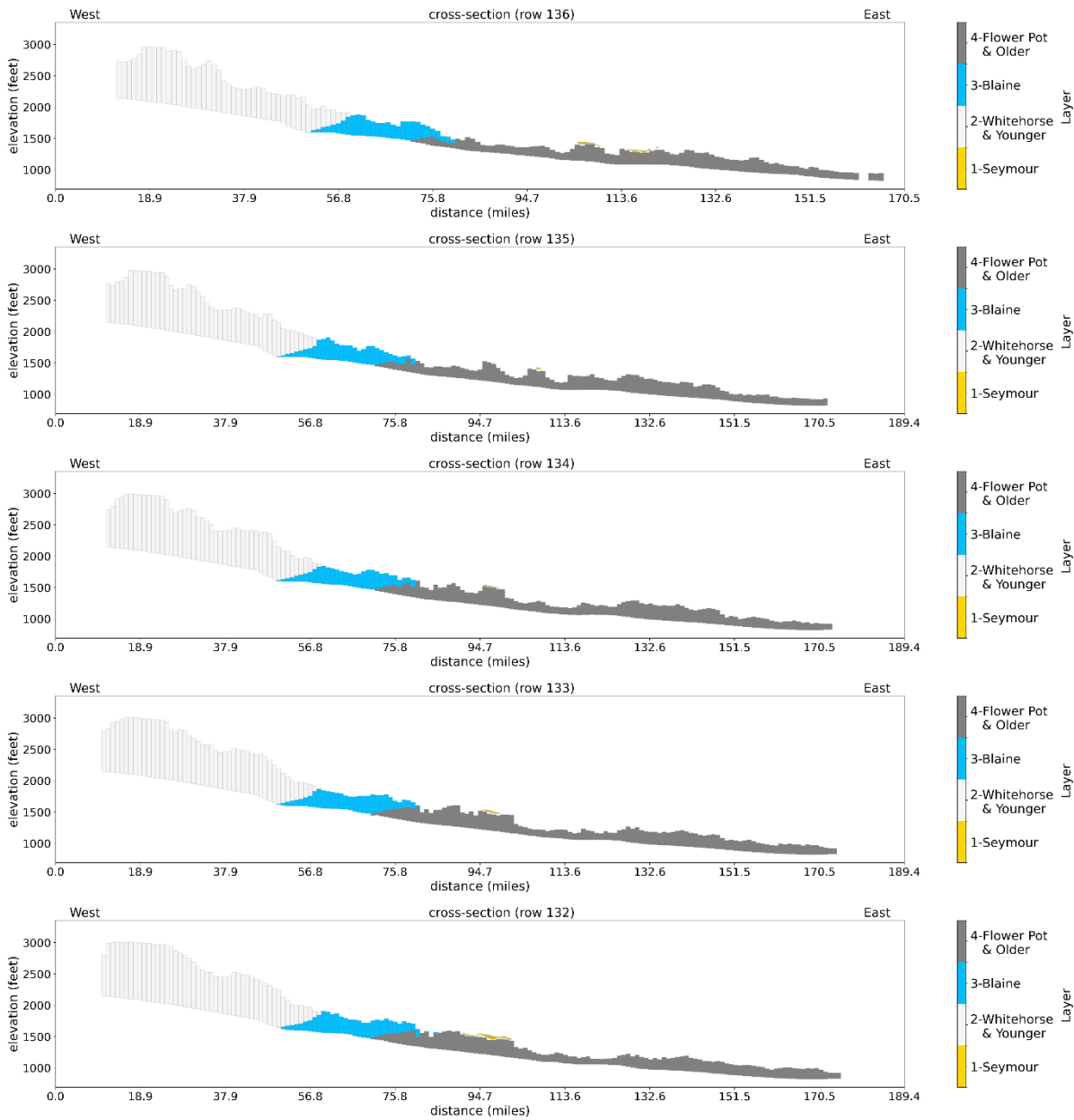
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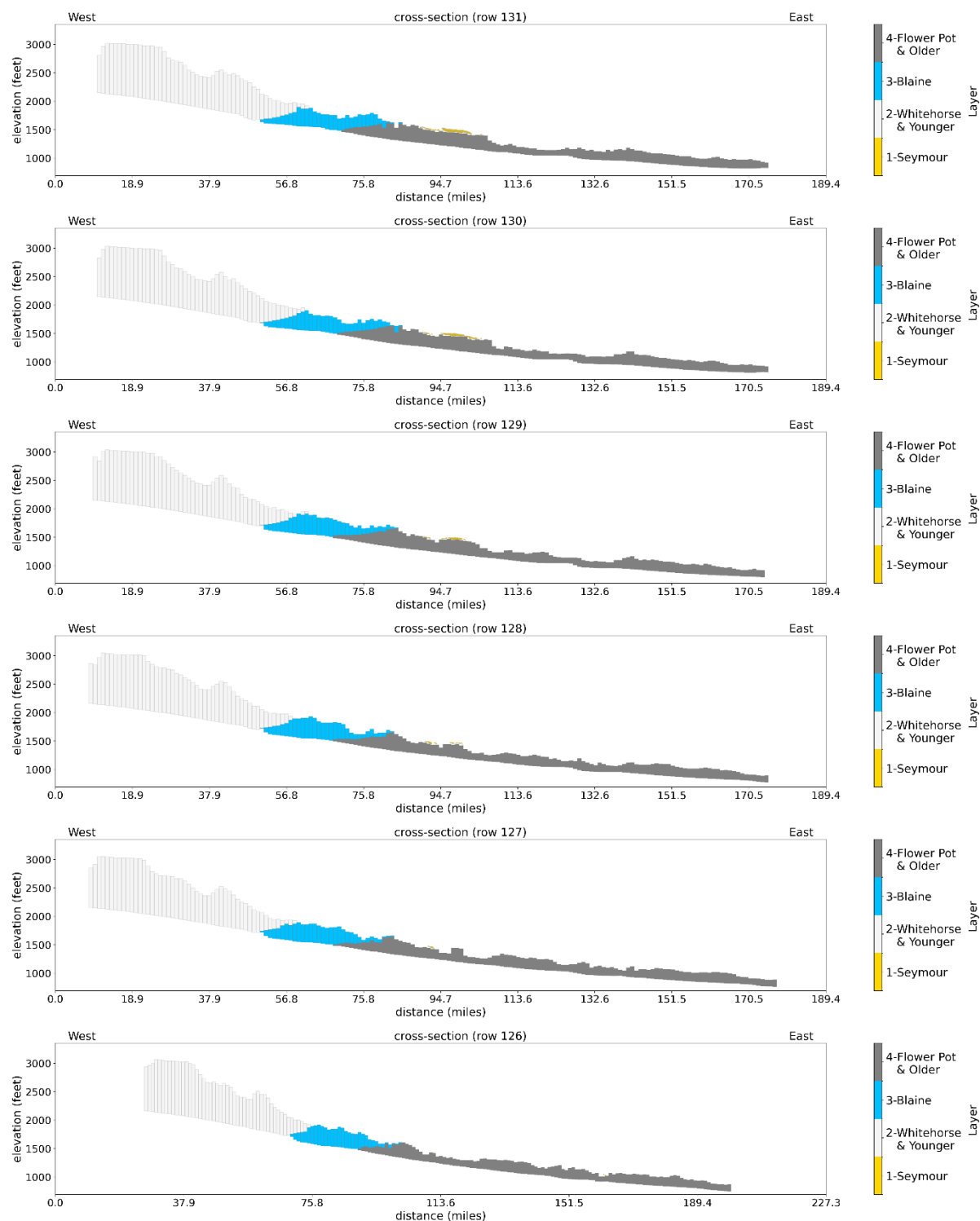
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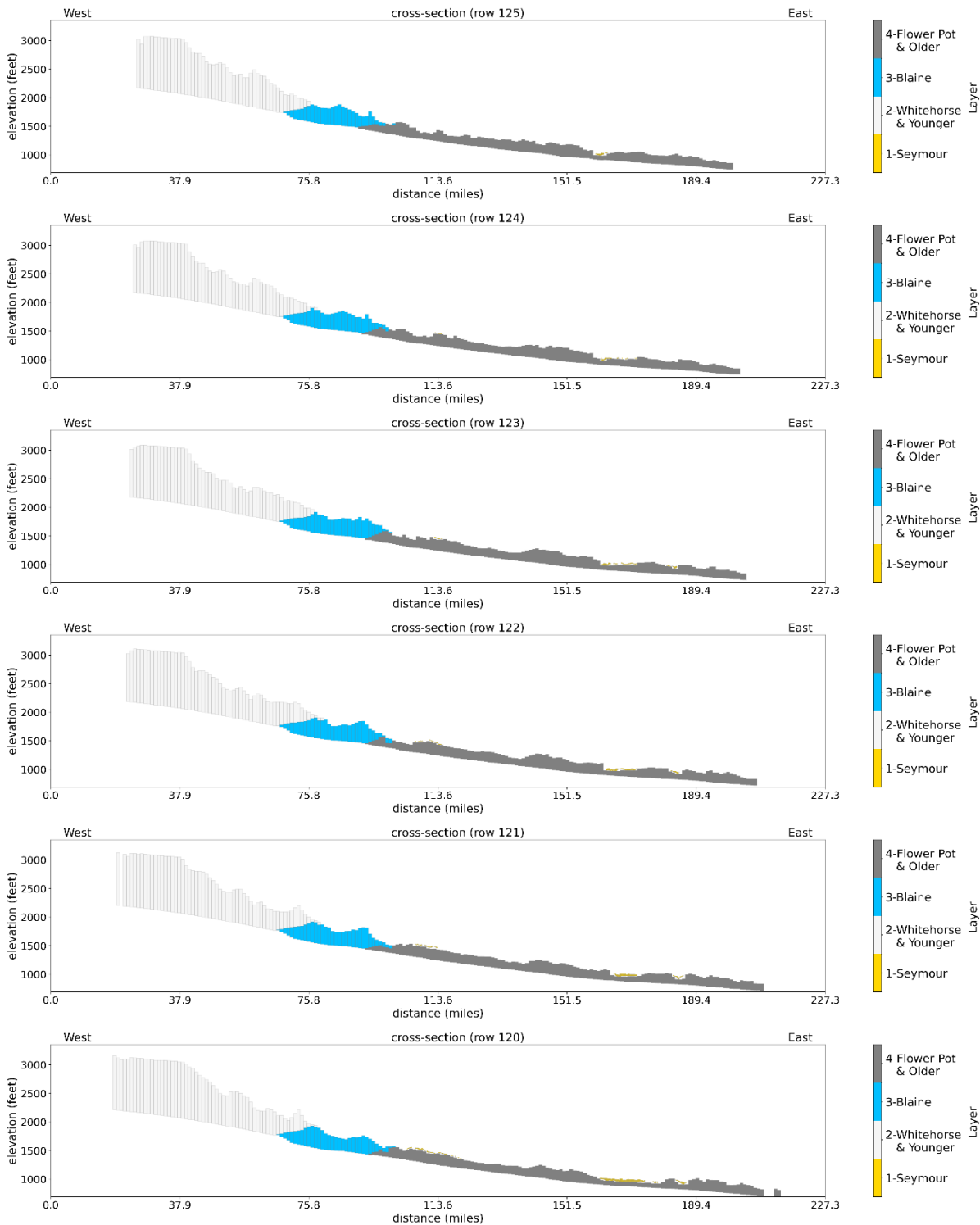
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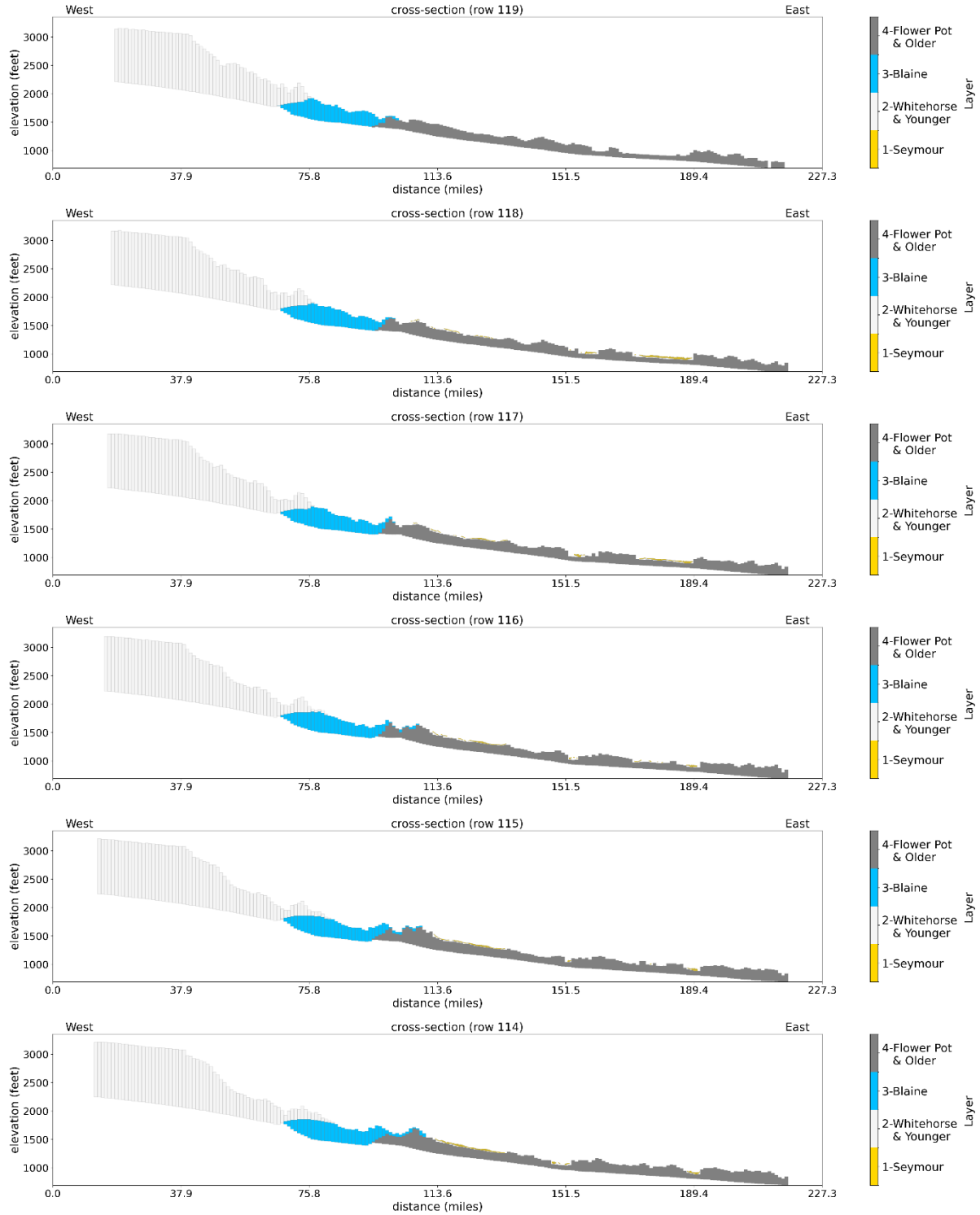
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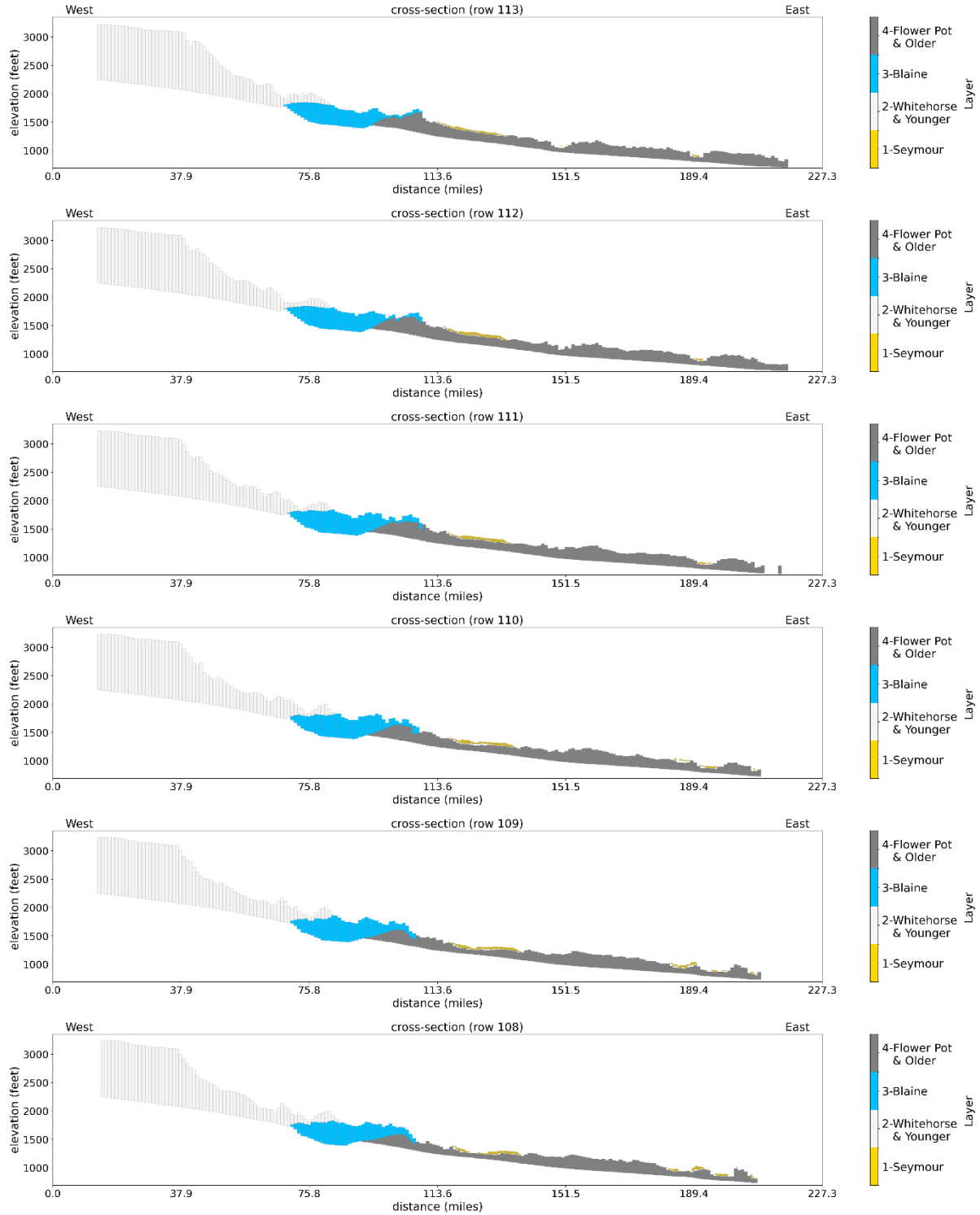
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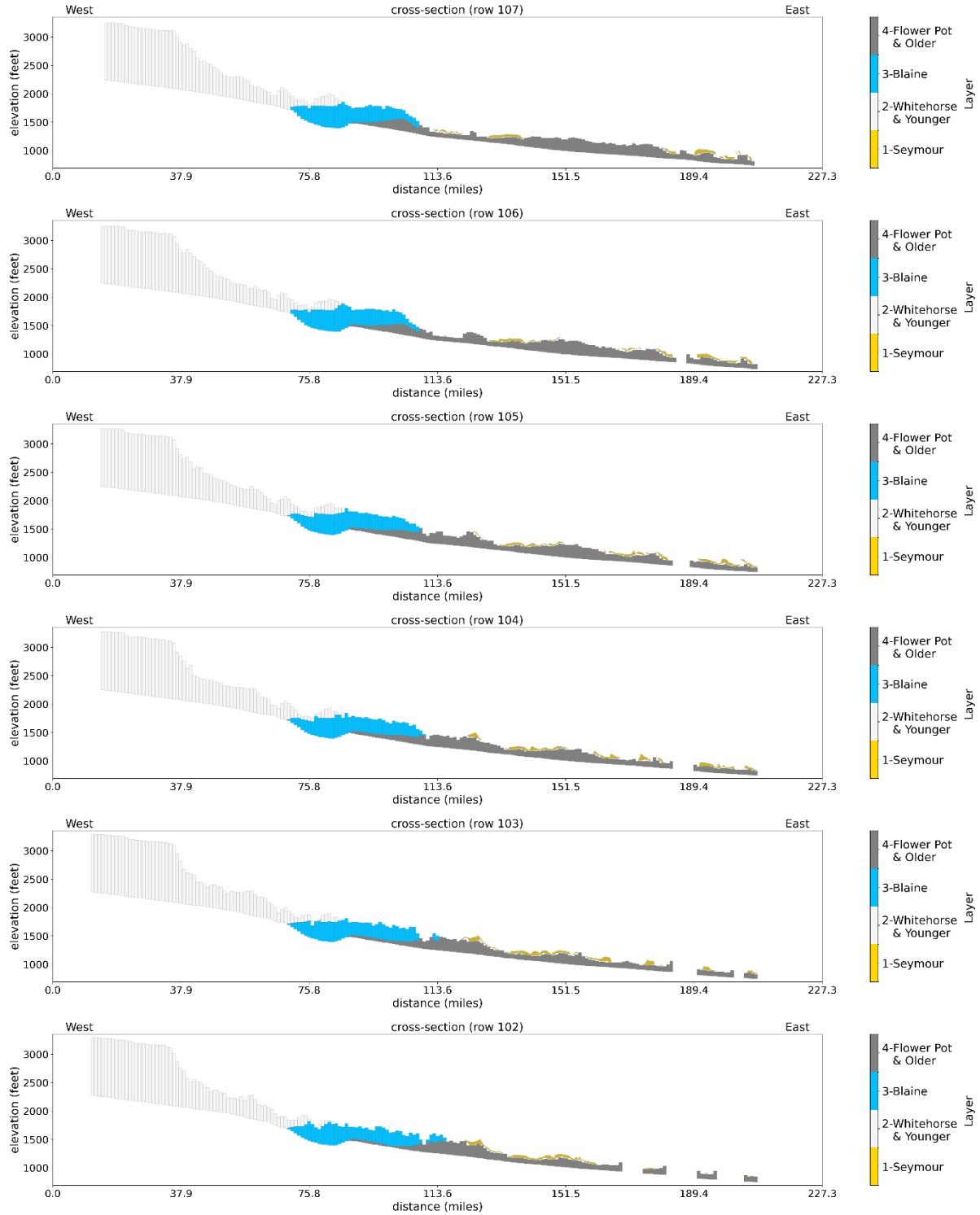
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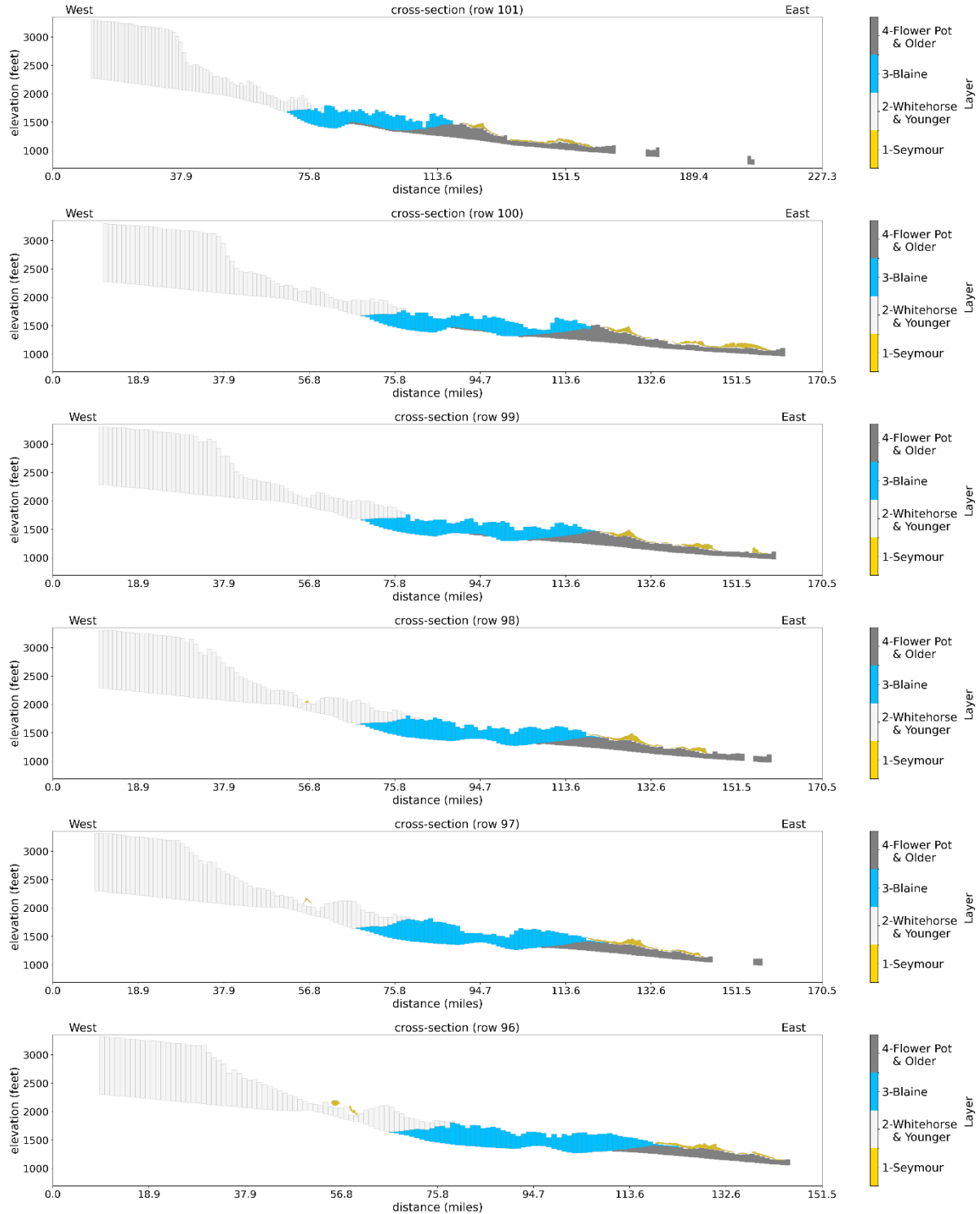
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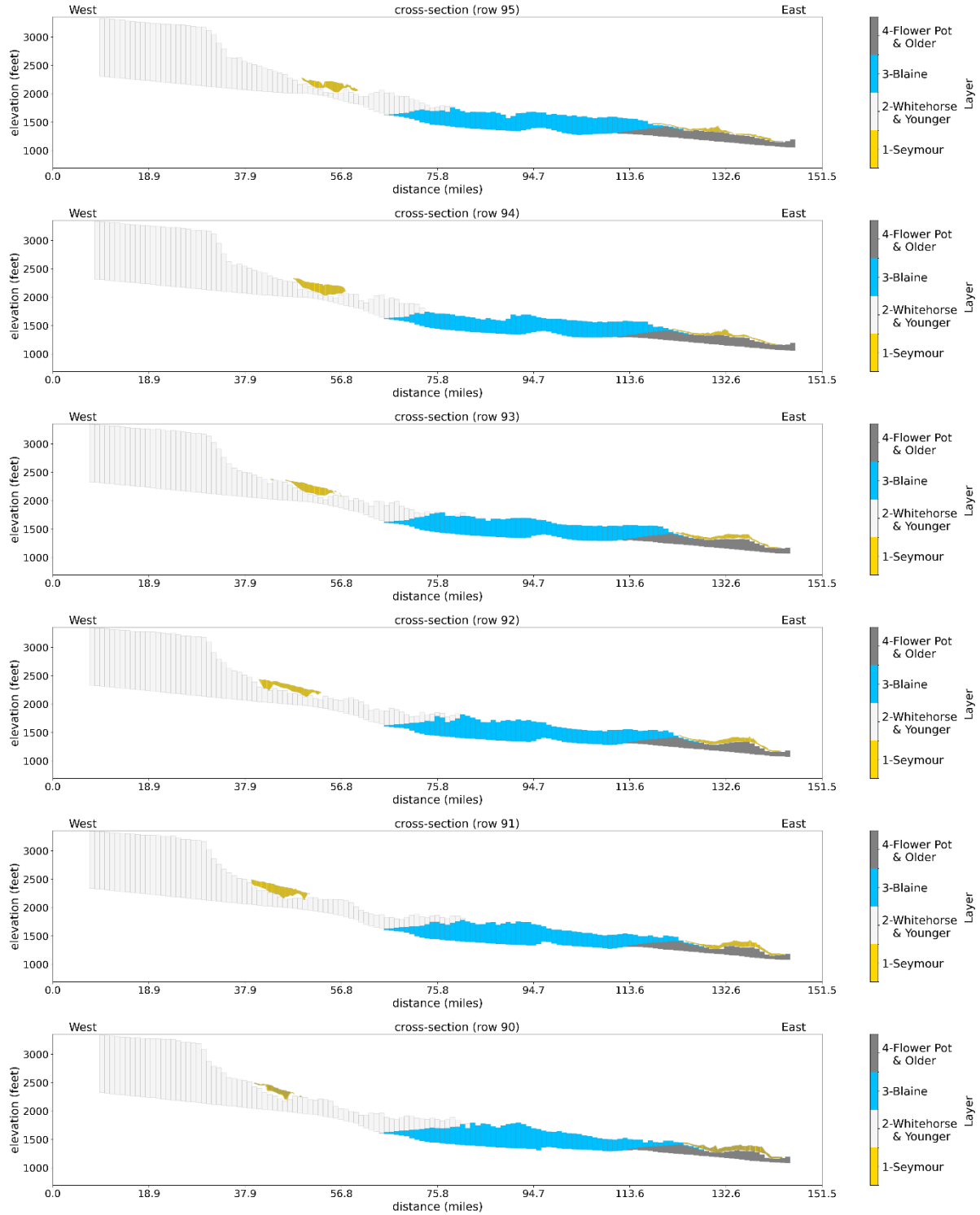
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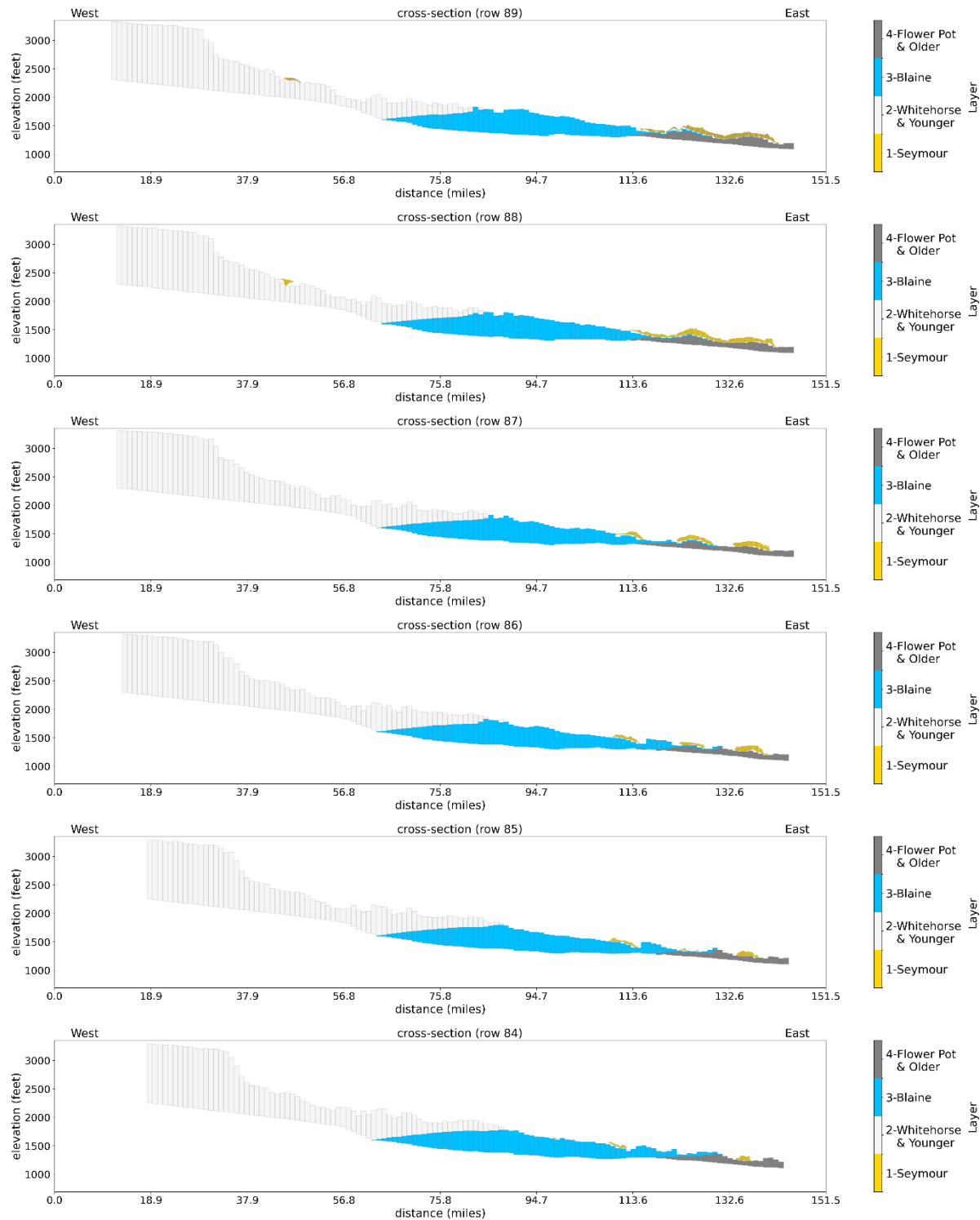
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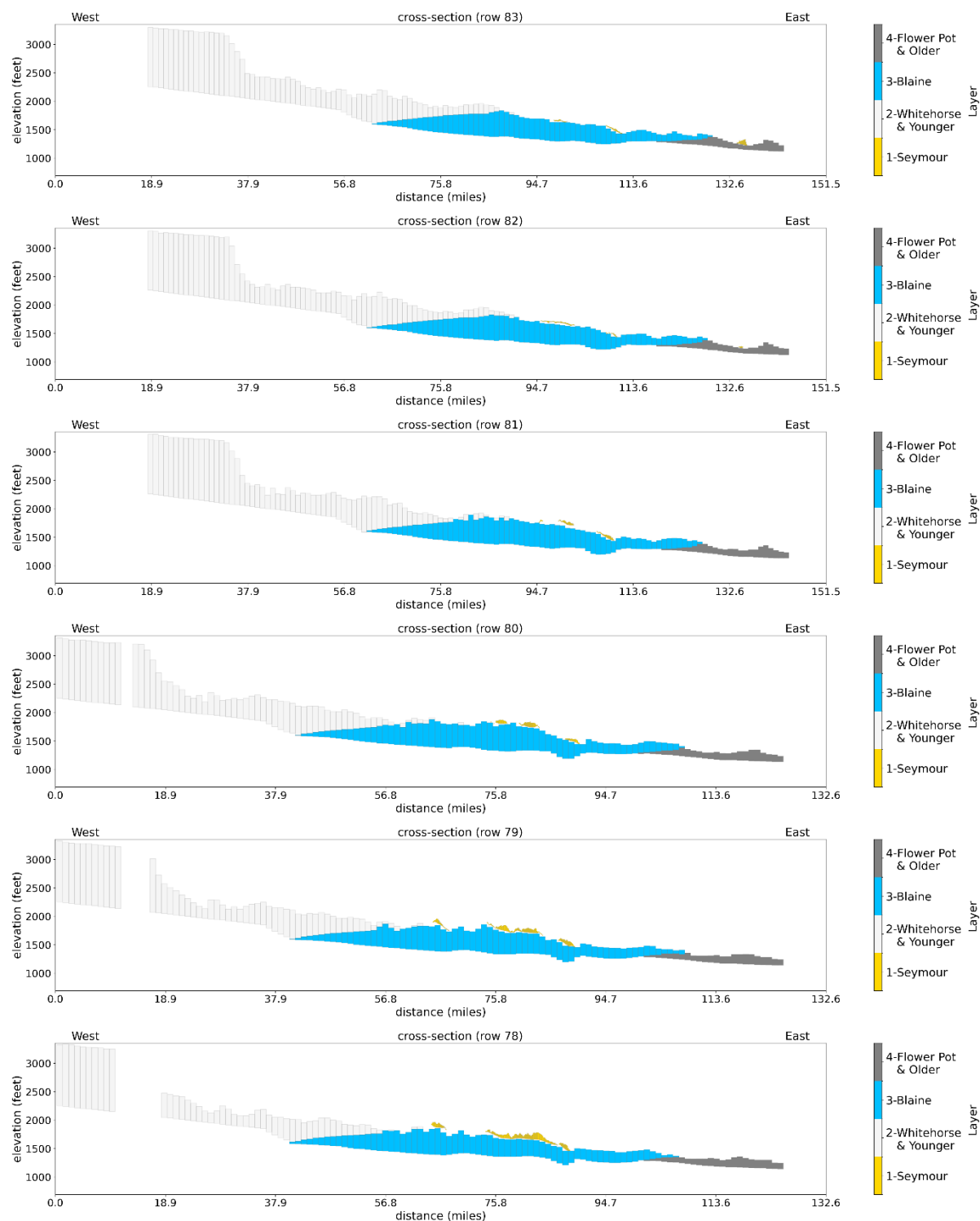
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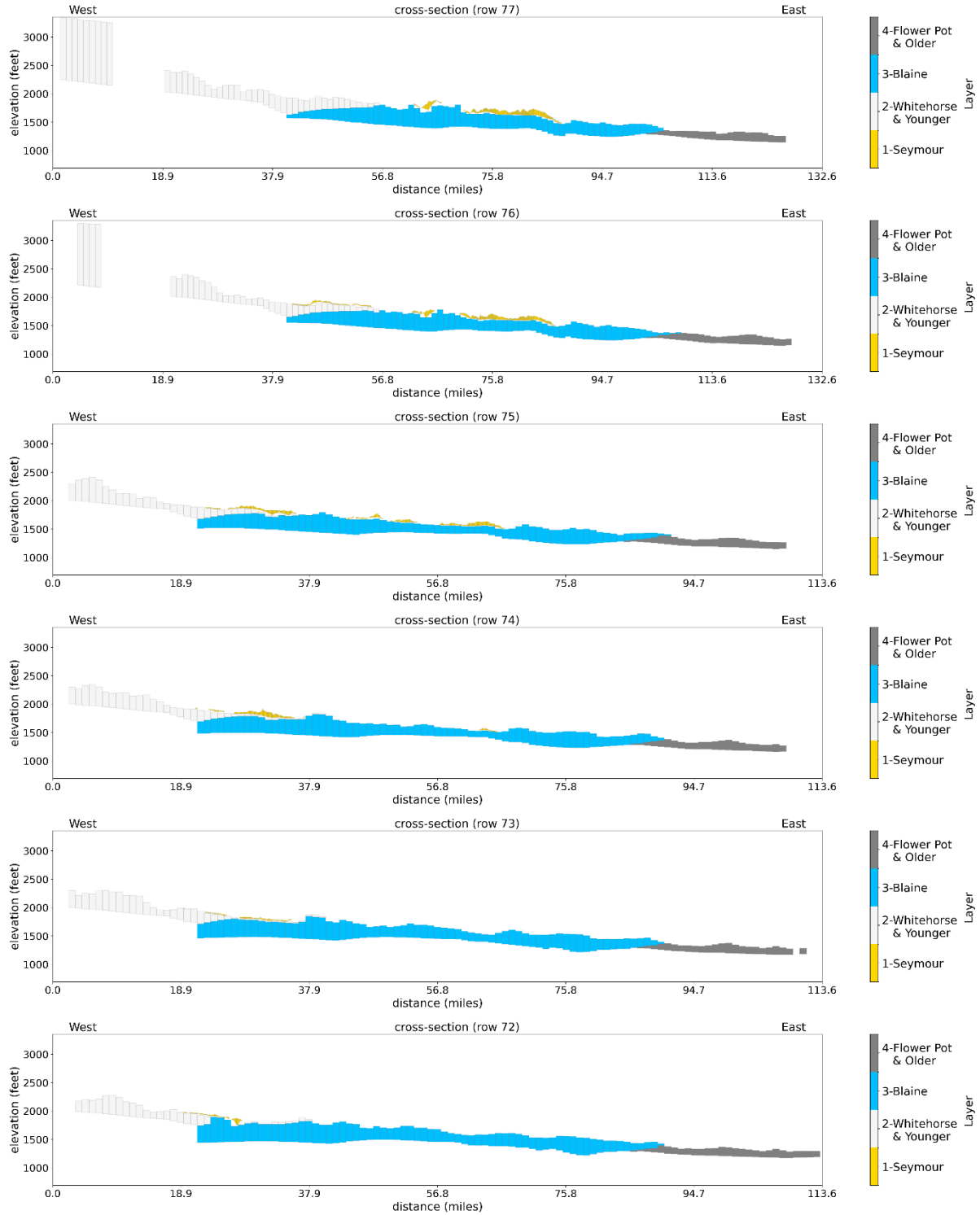
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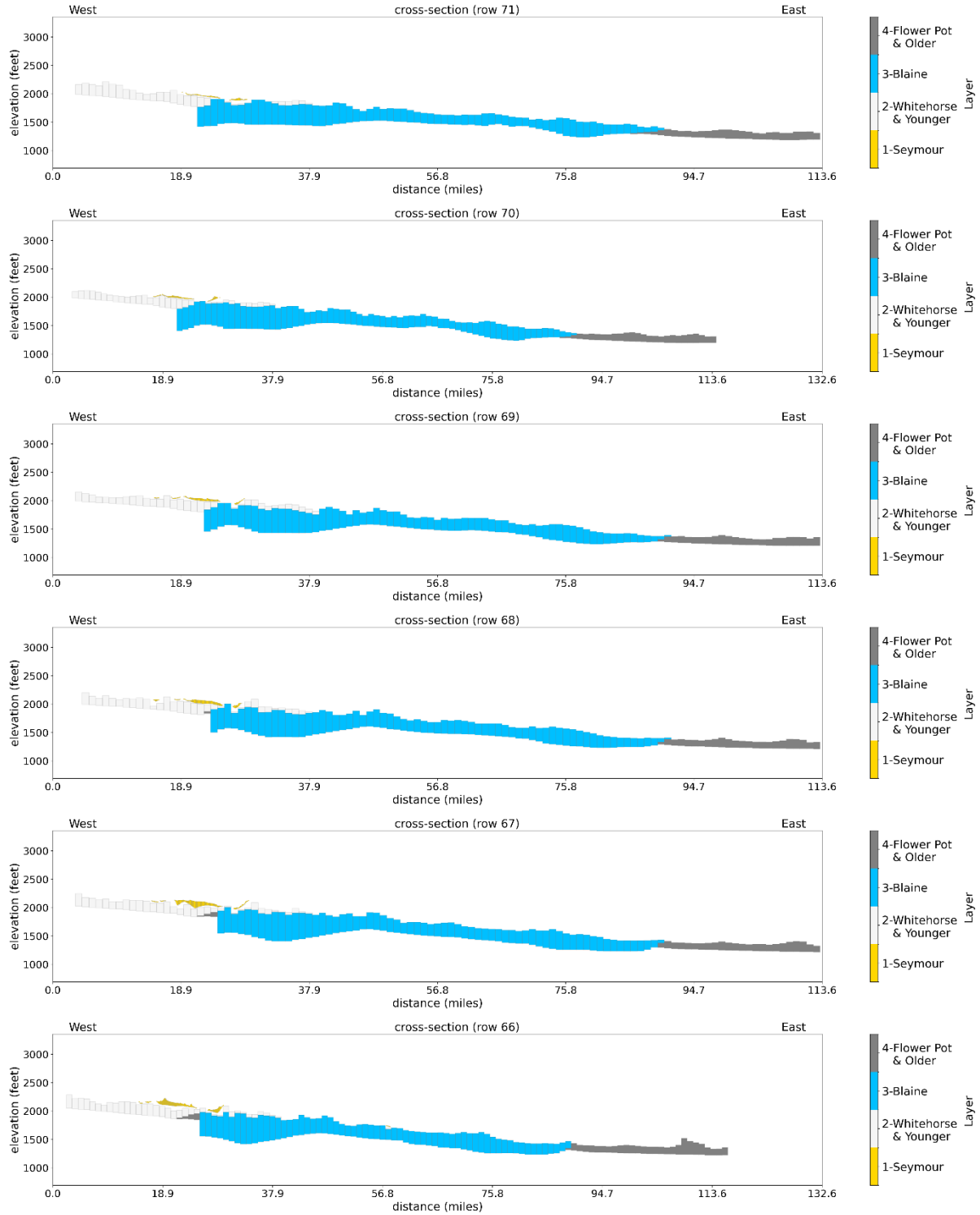
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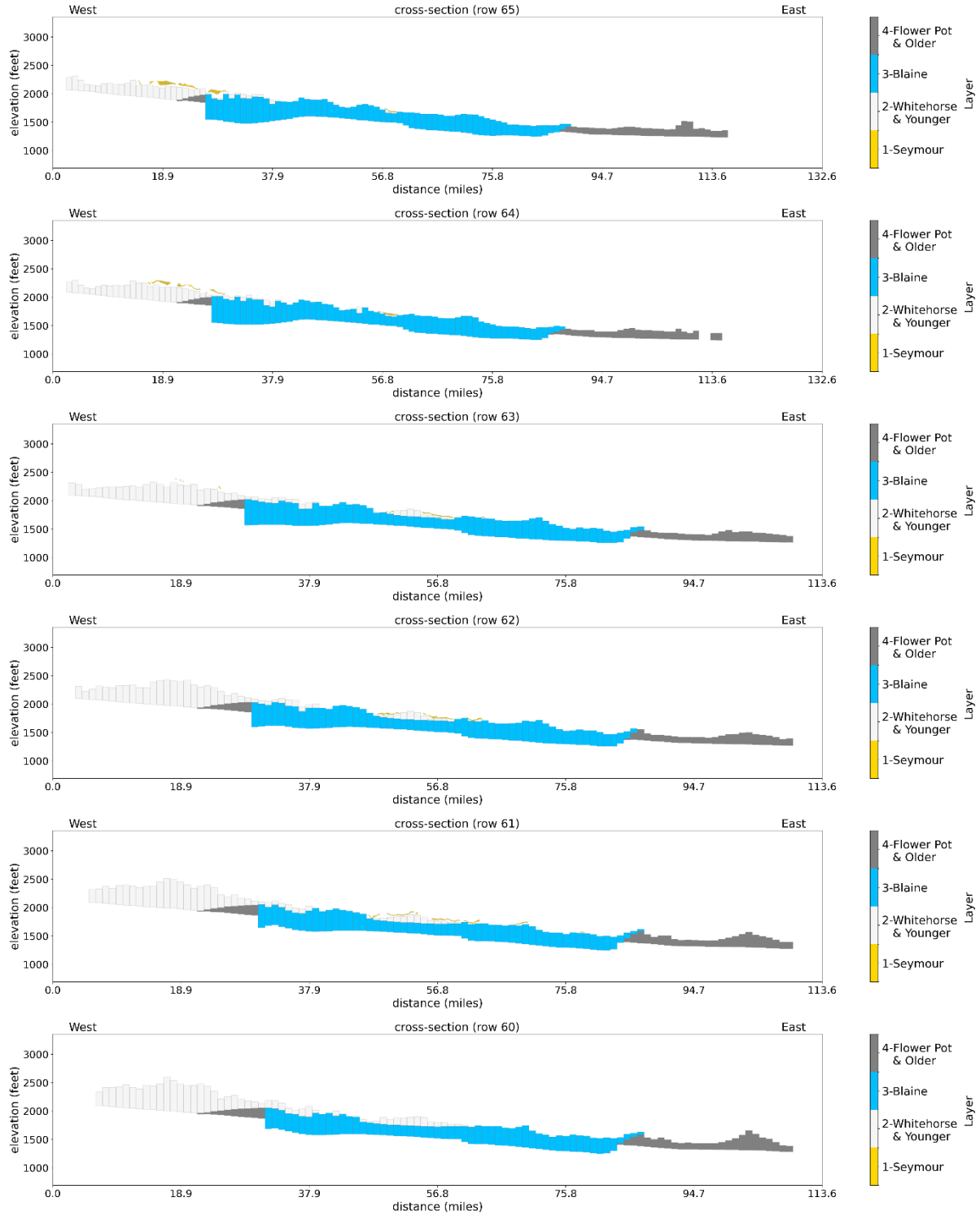
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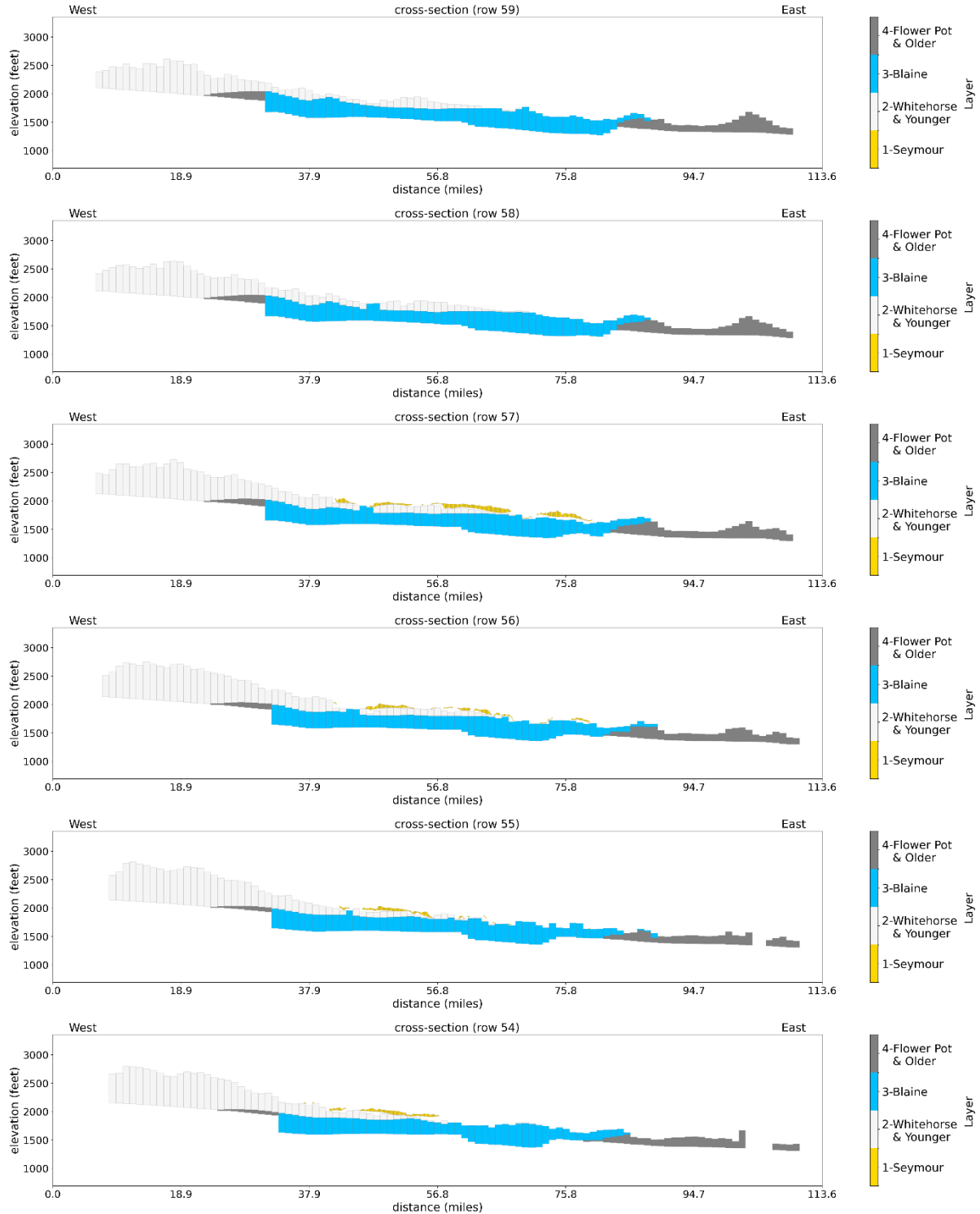
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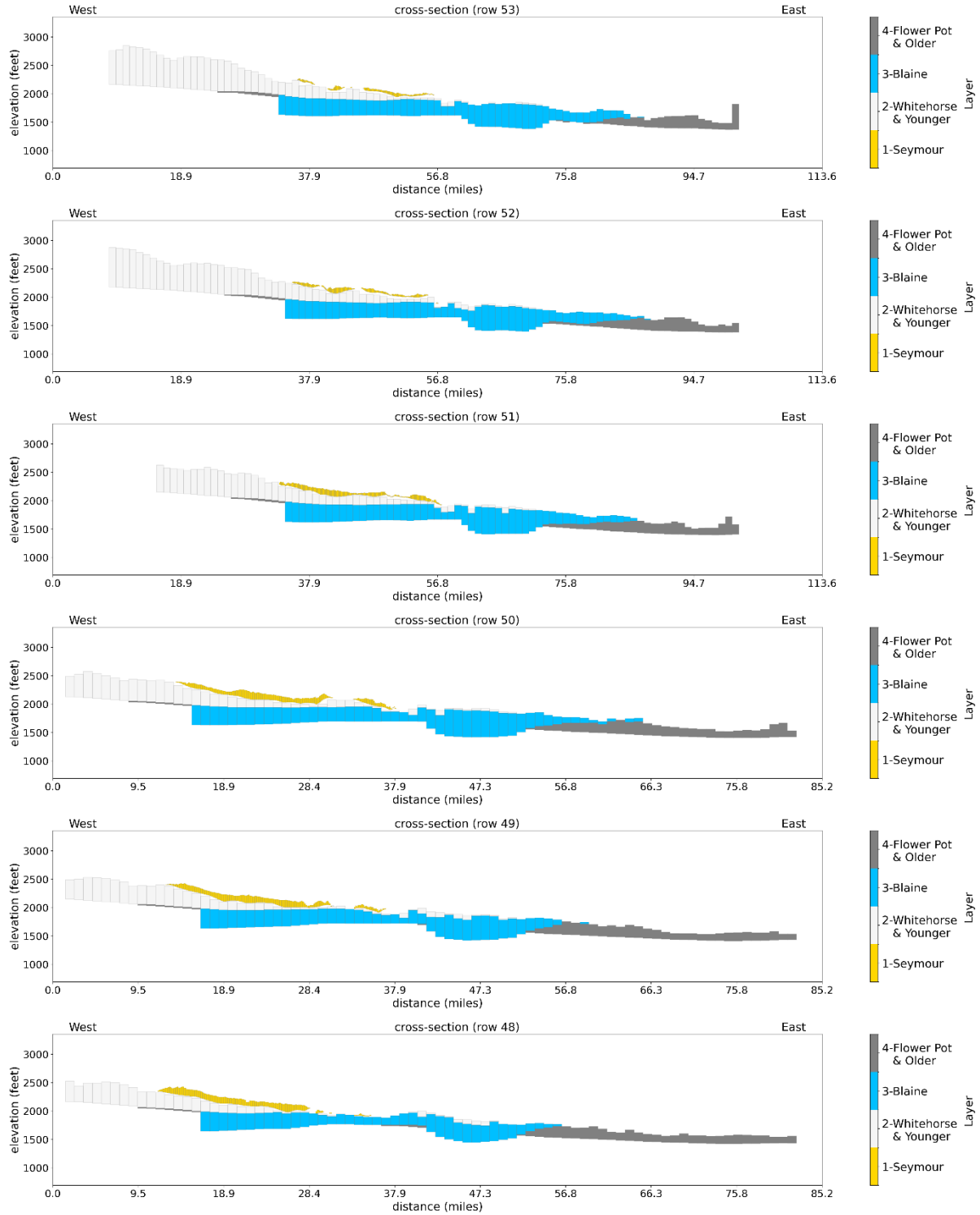
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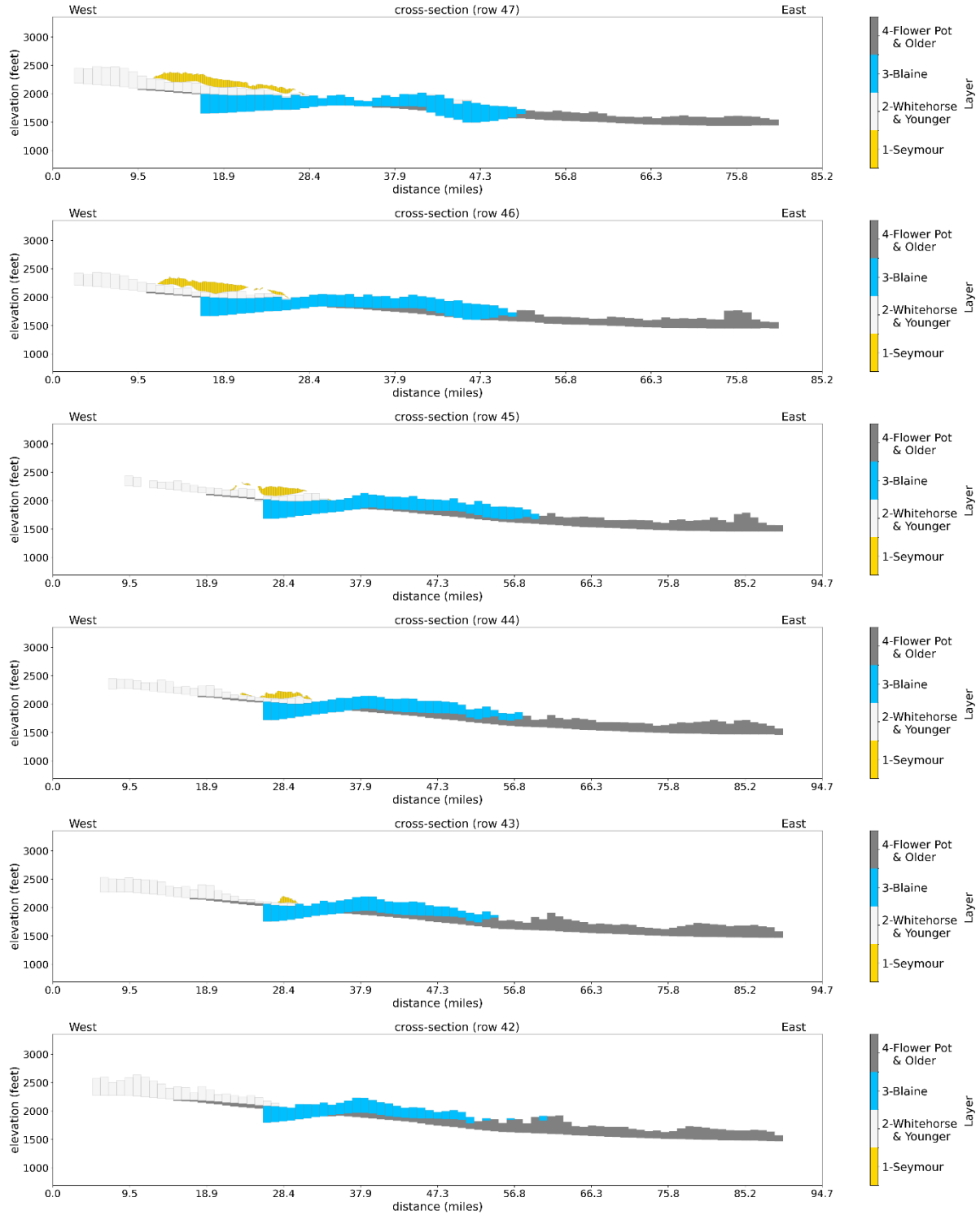
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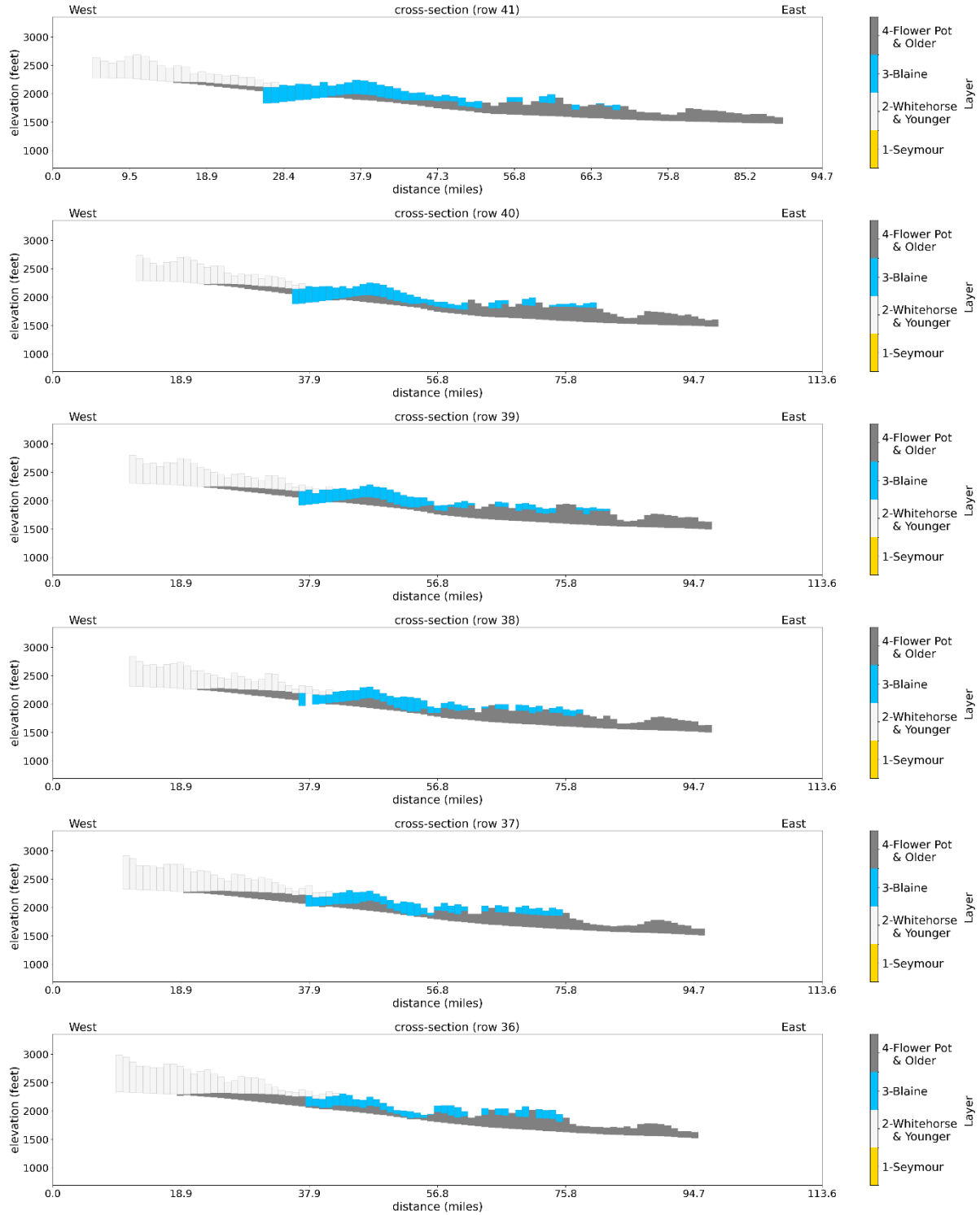
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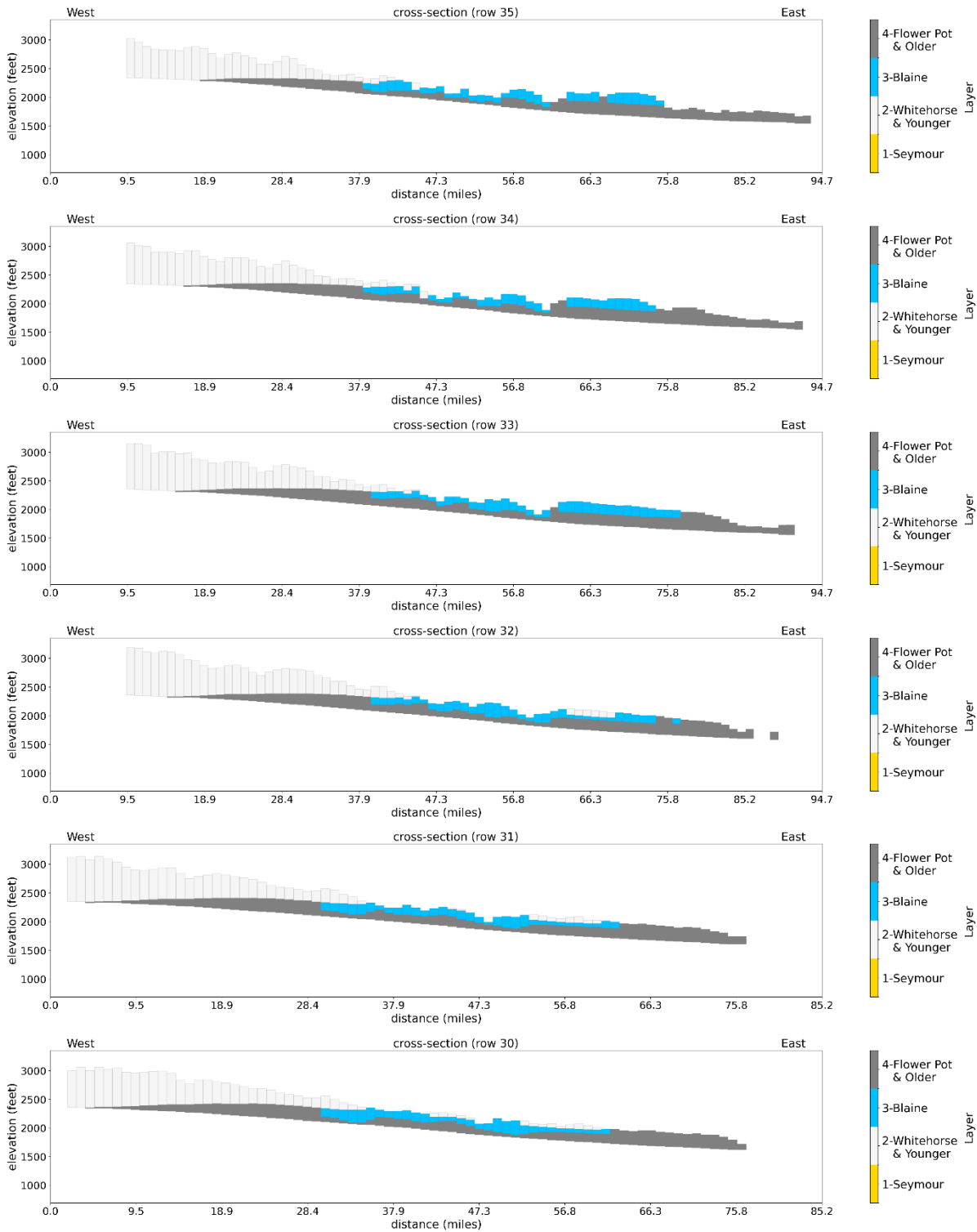
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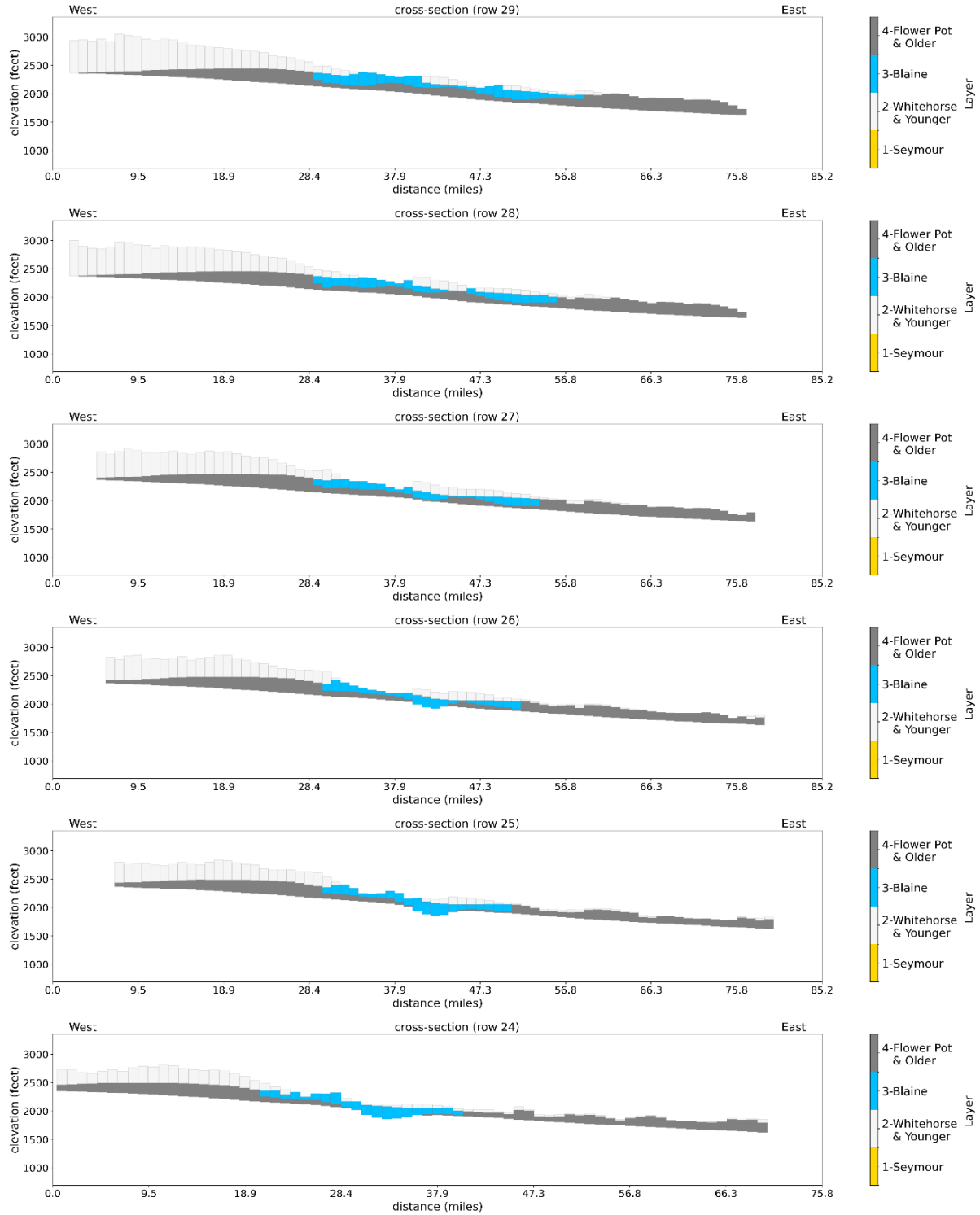
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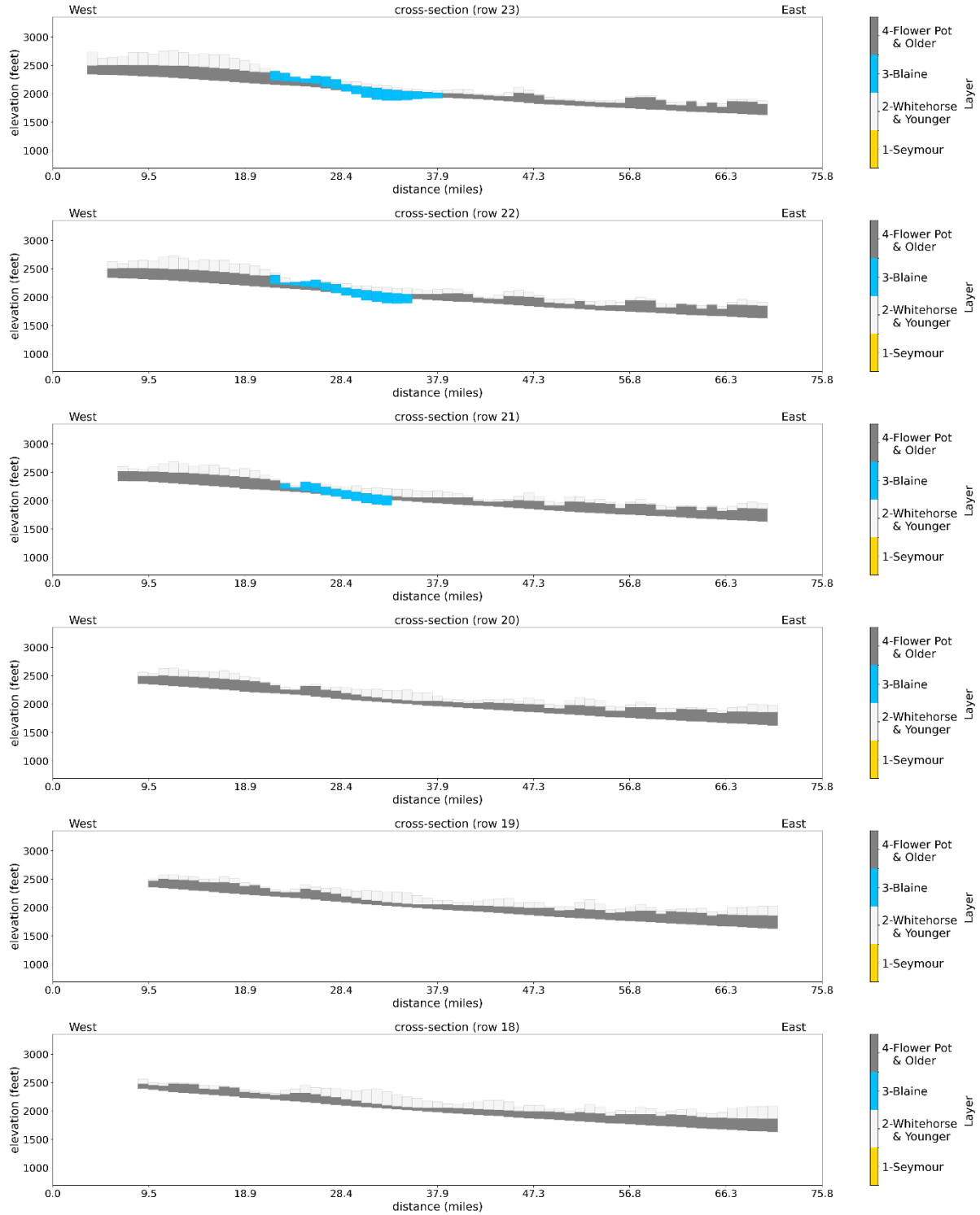
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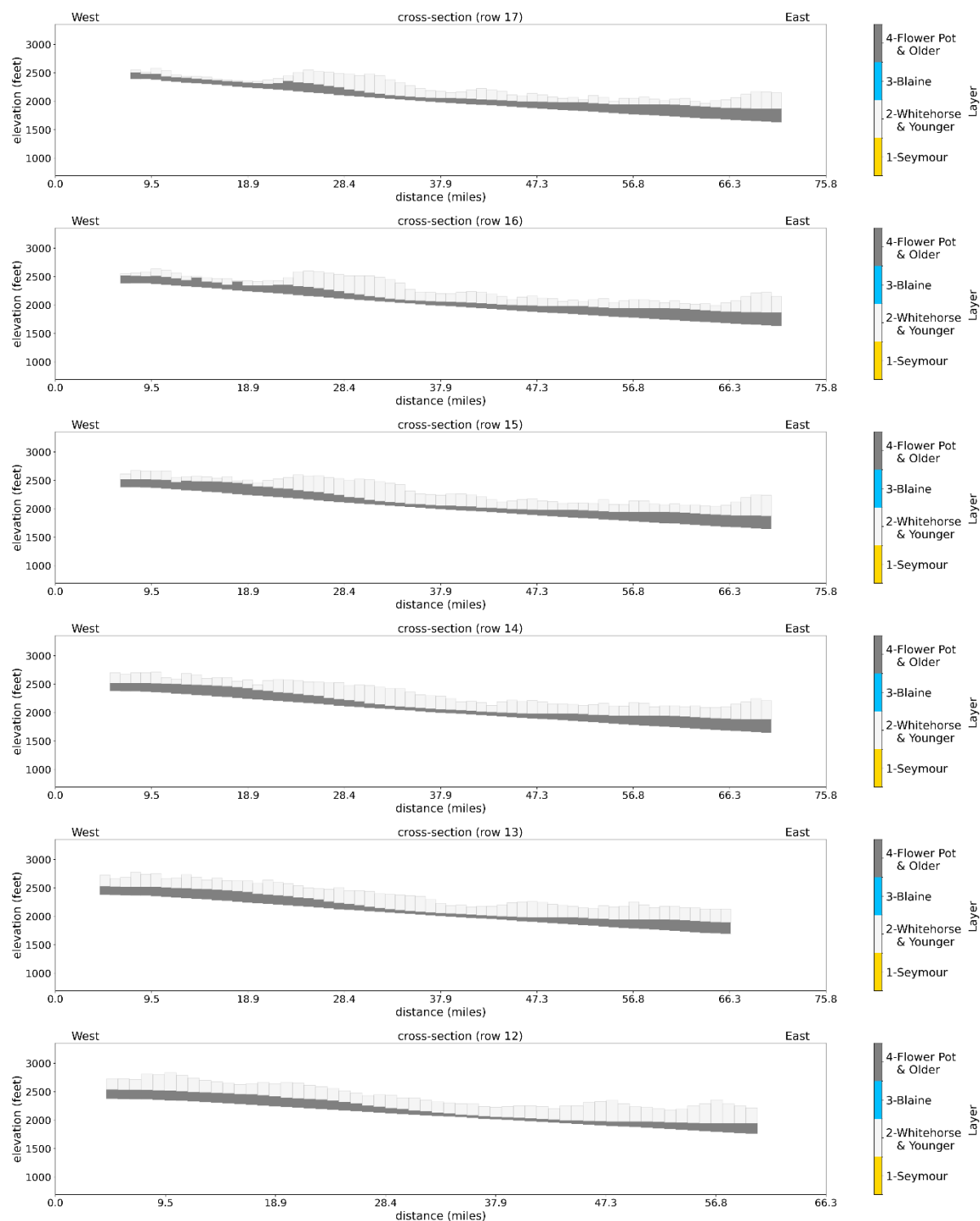
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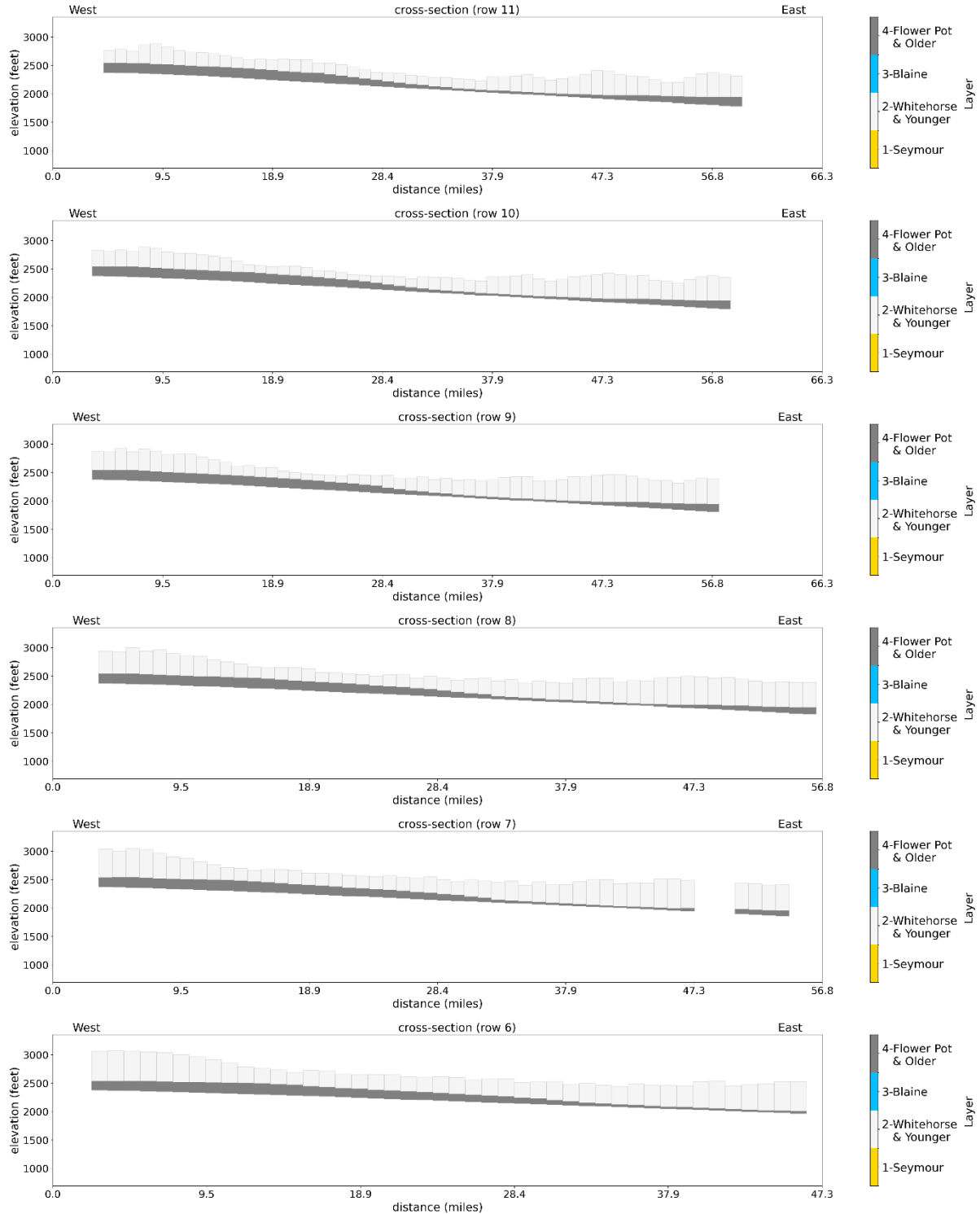
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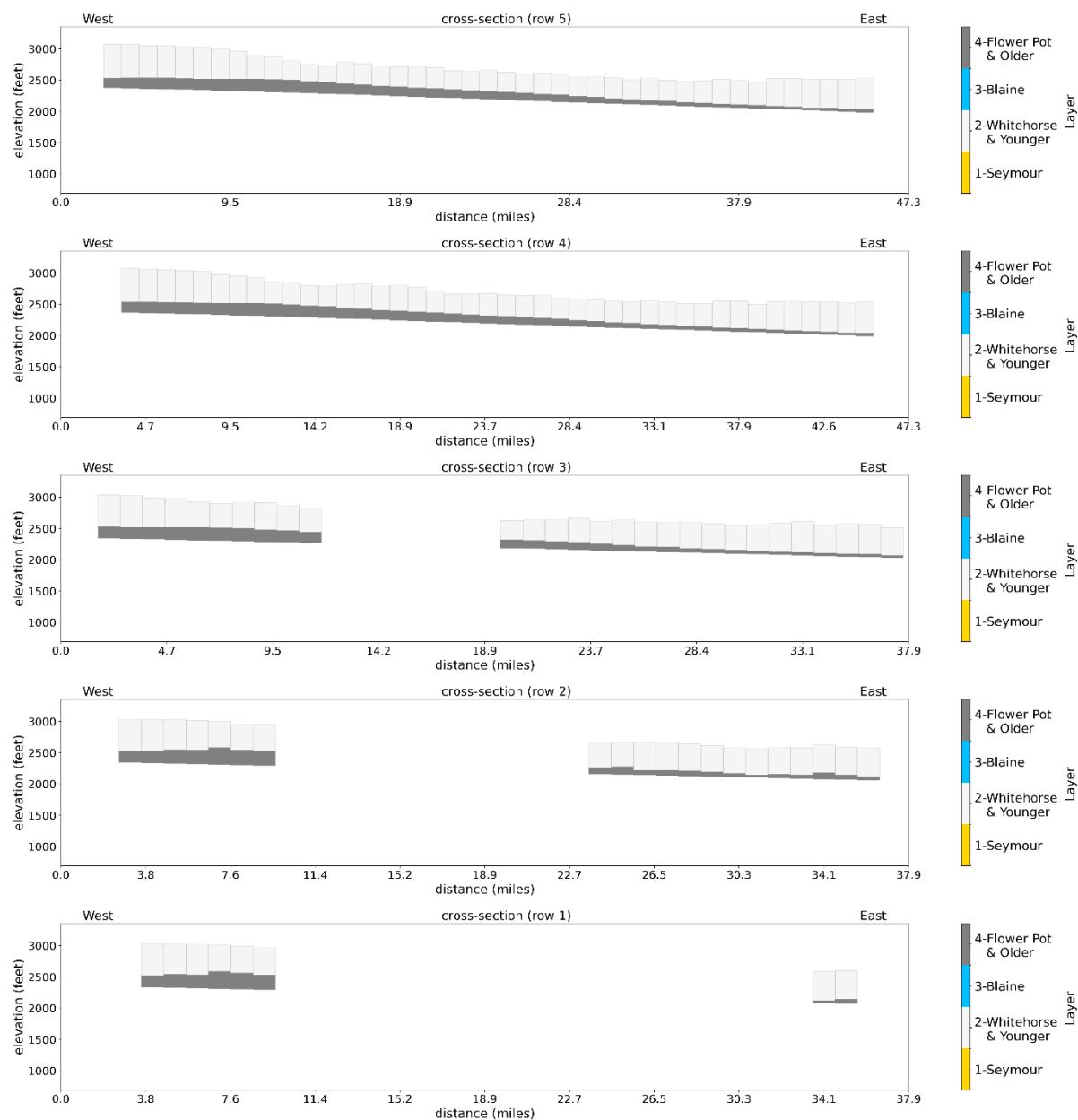
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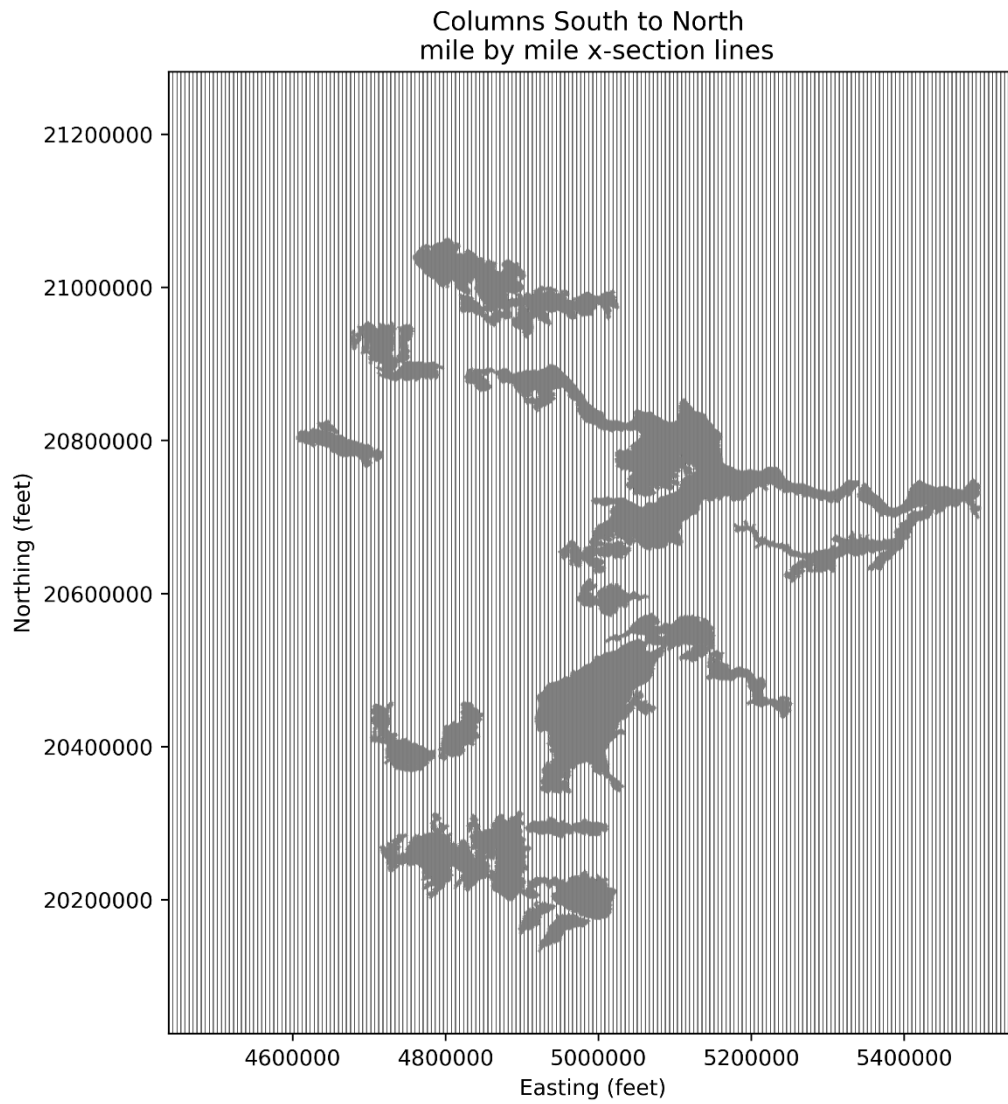
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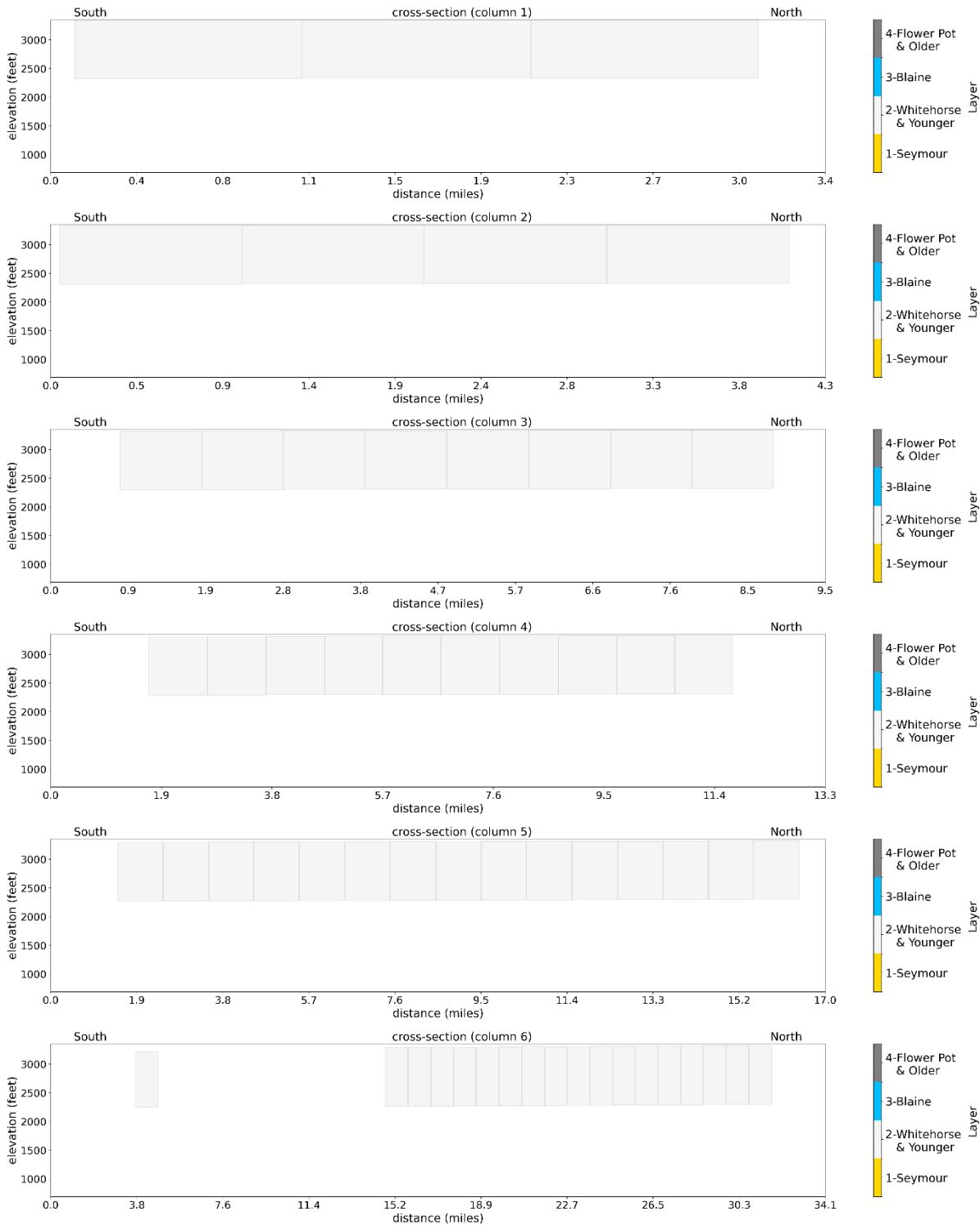
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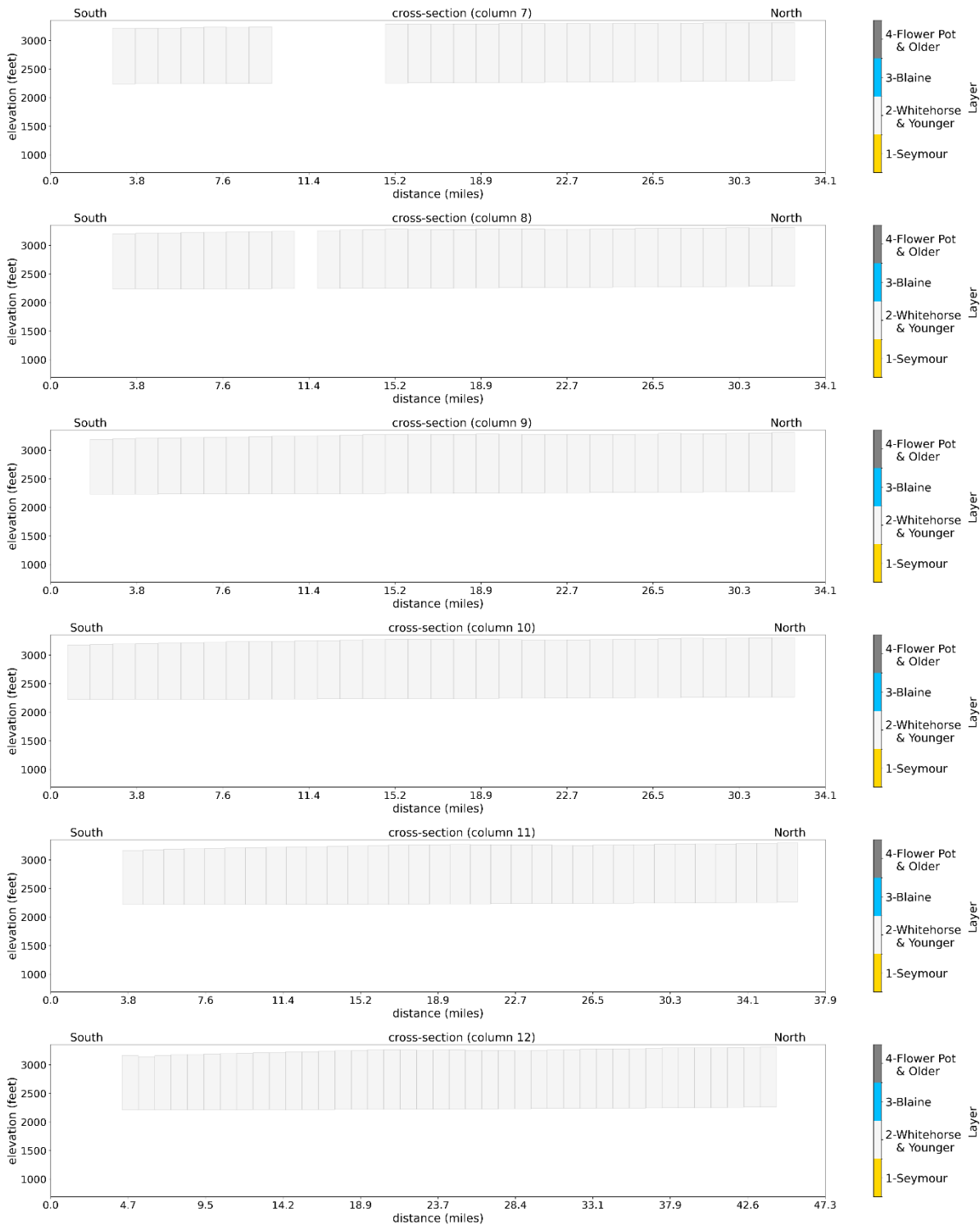
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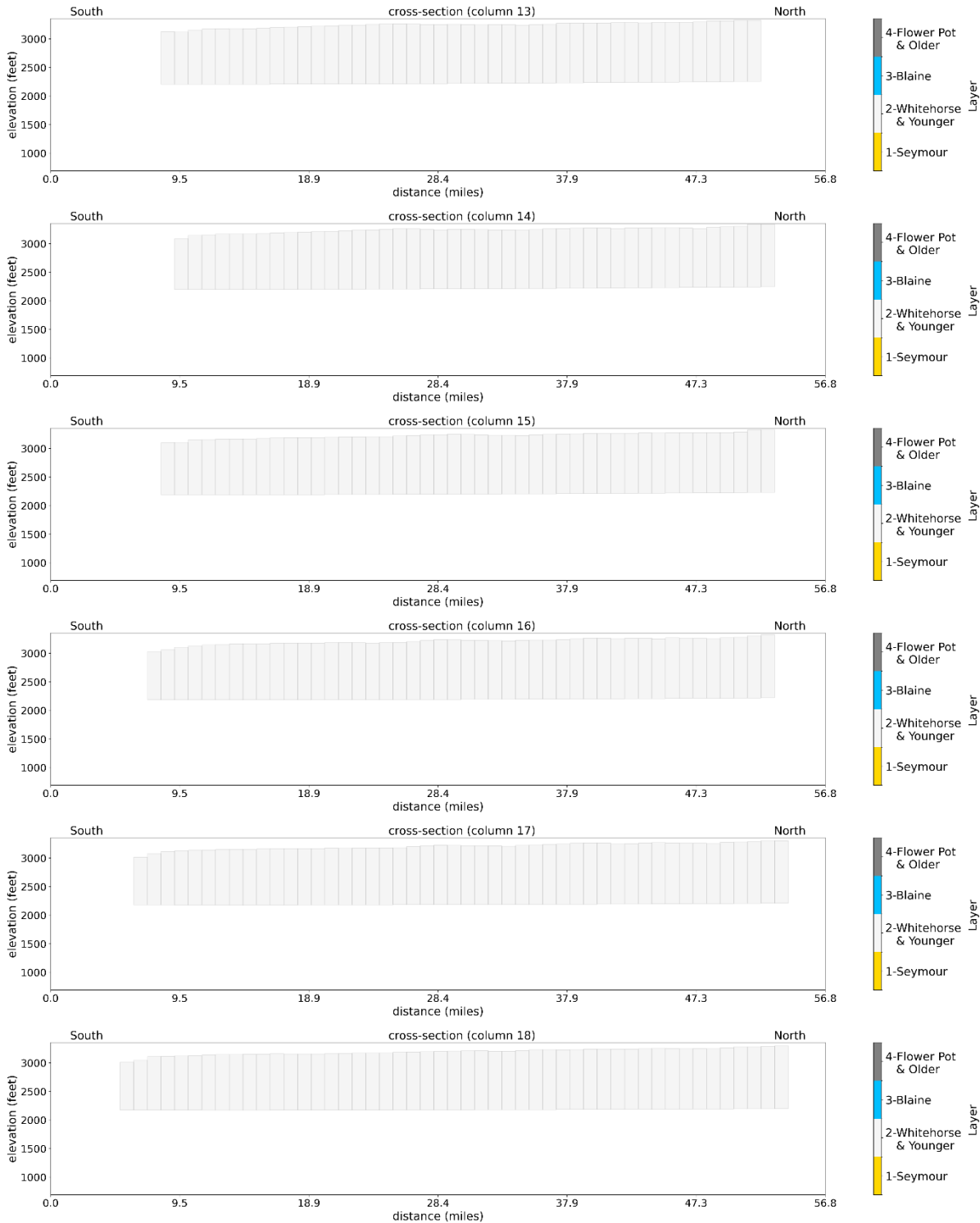
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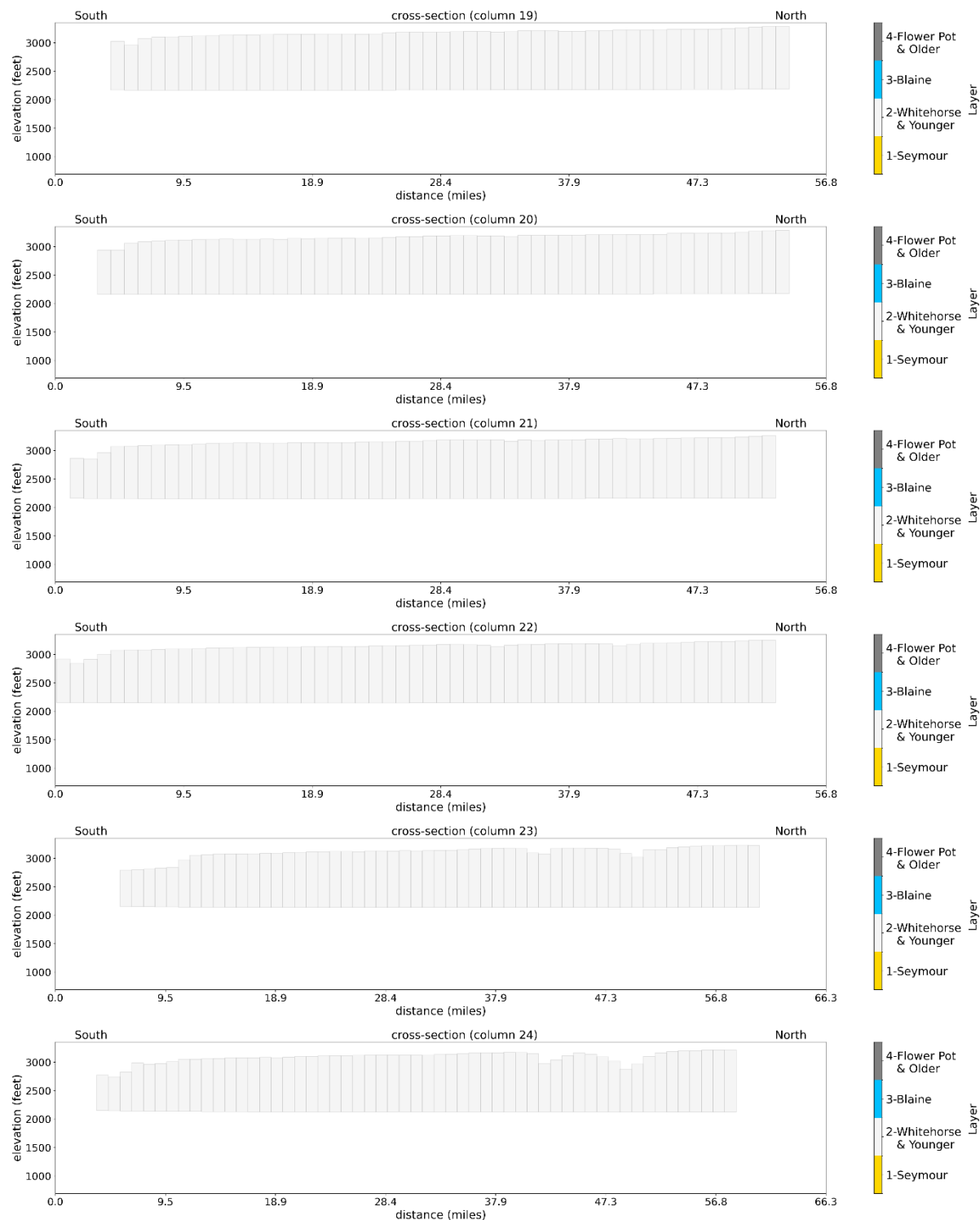
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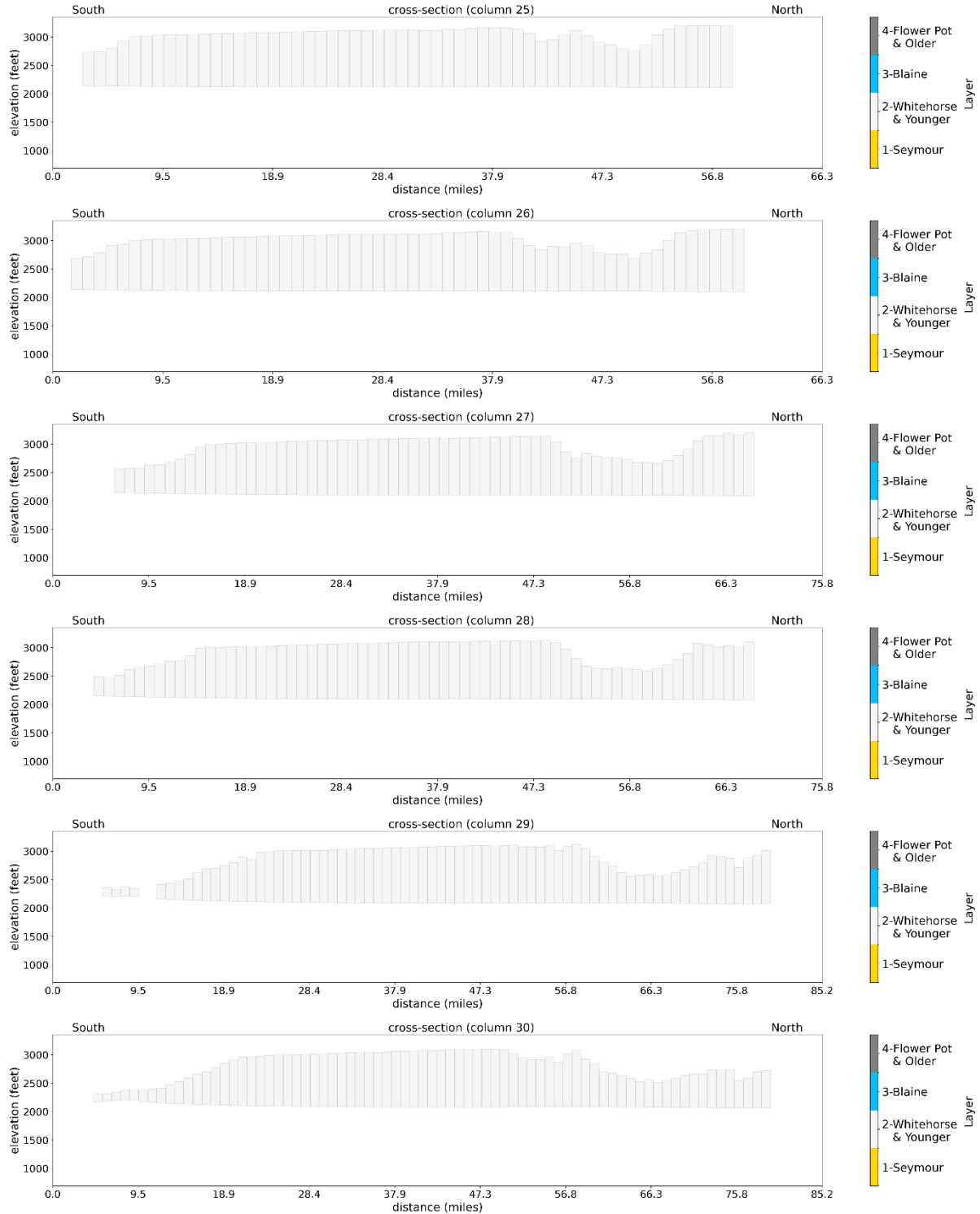
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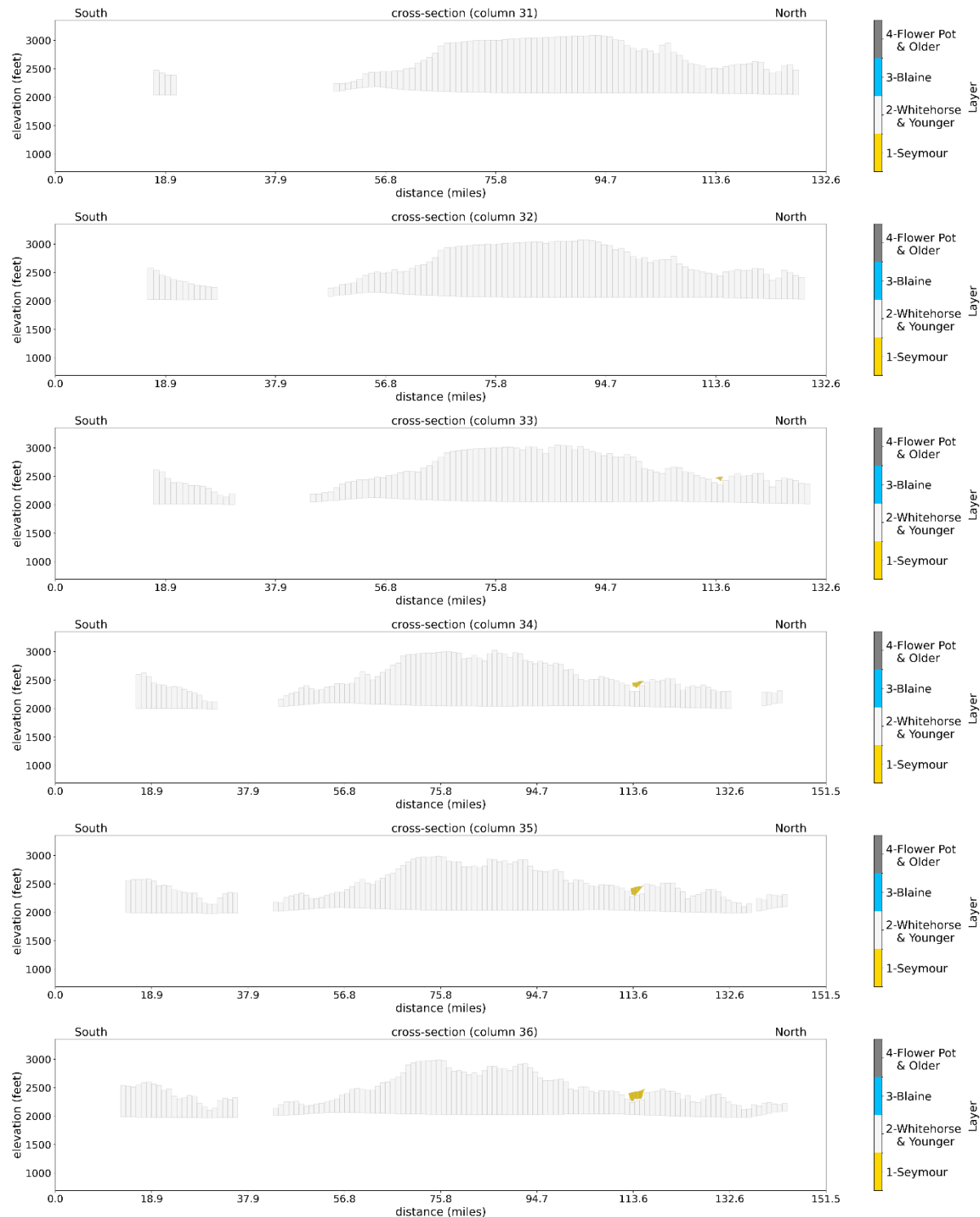
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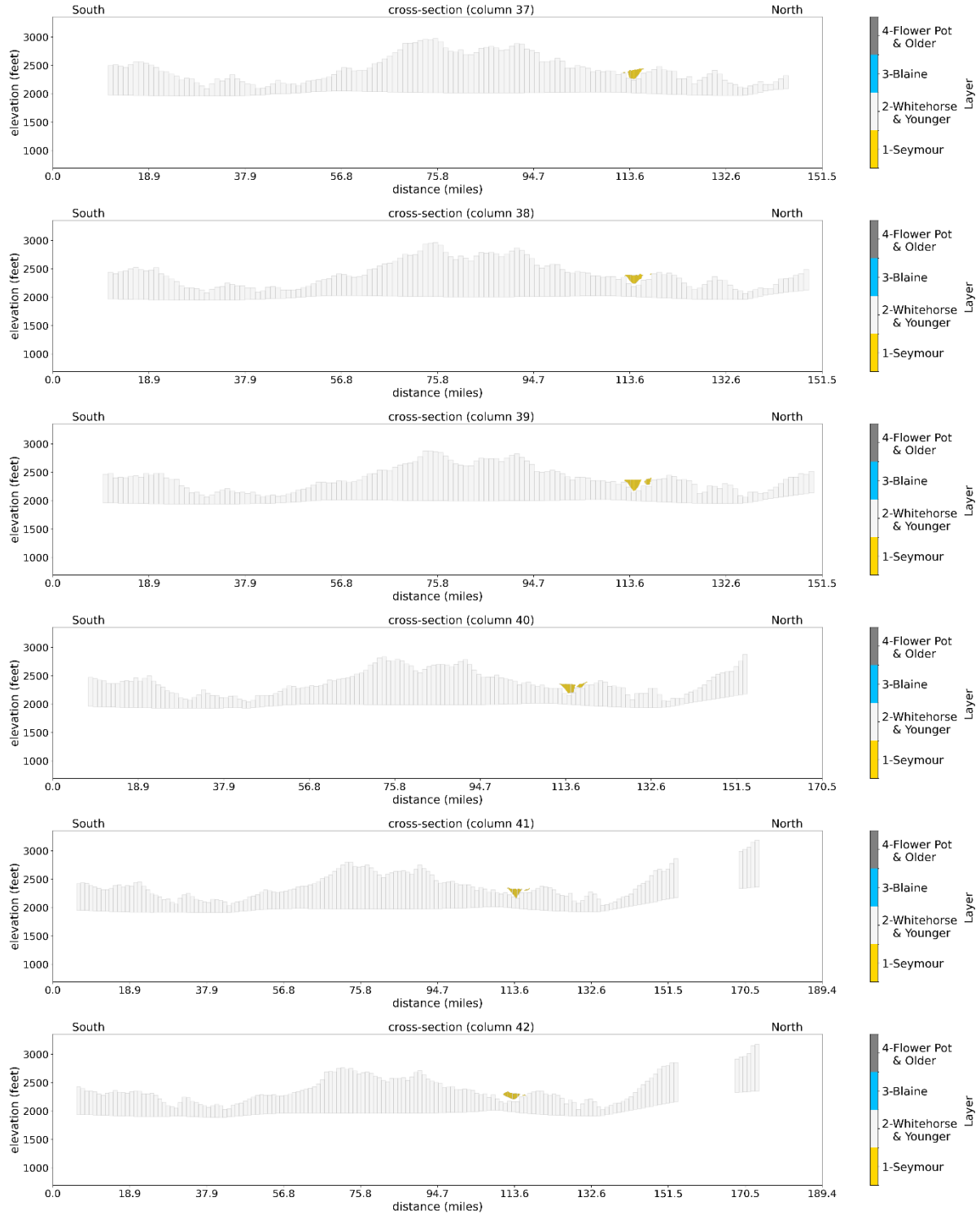
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Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers



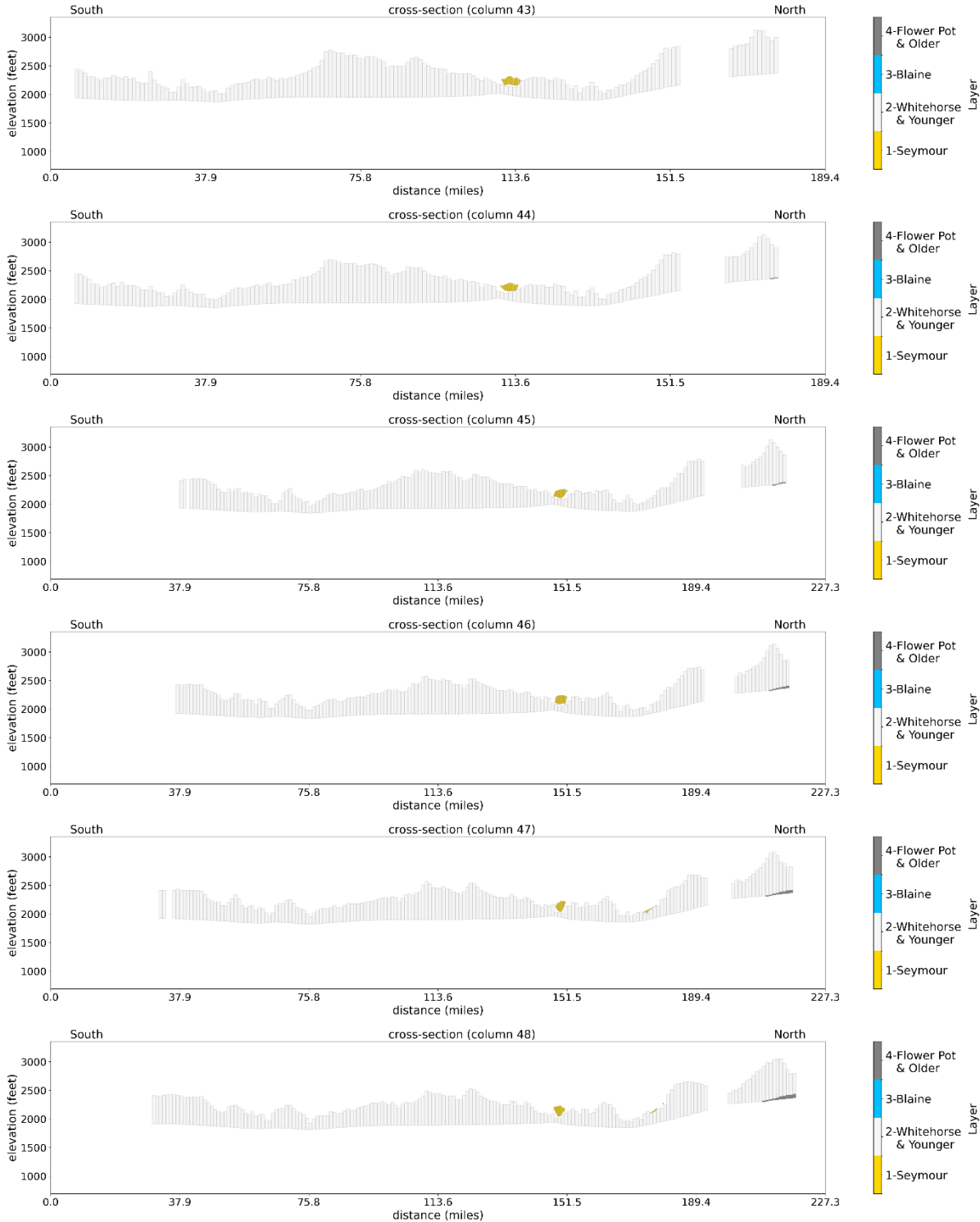
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Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers



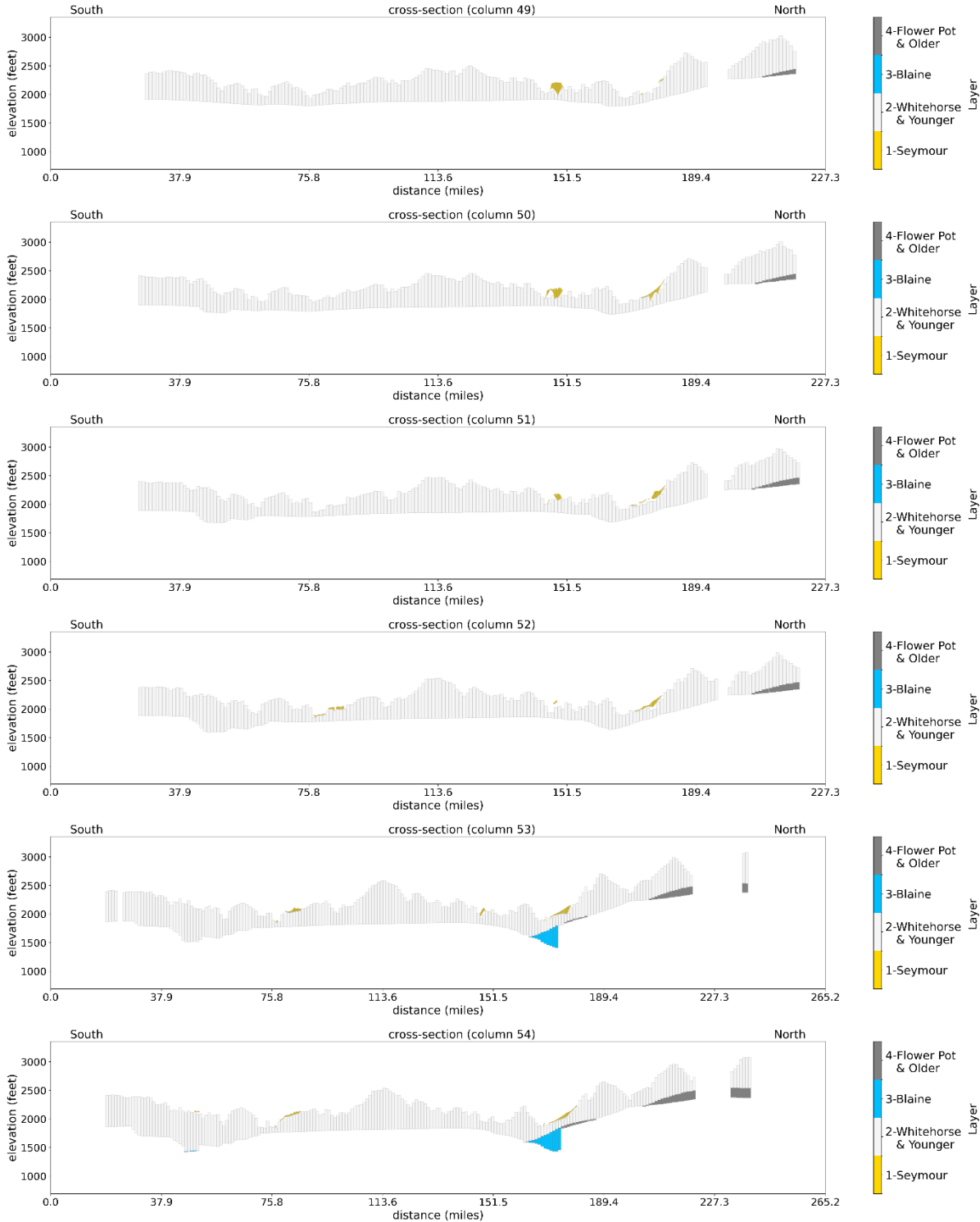
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Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers



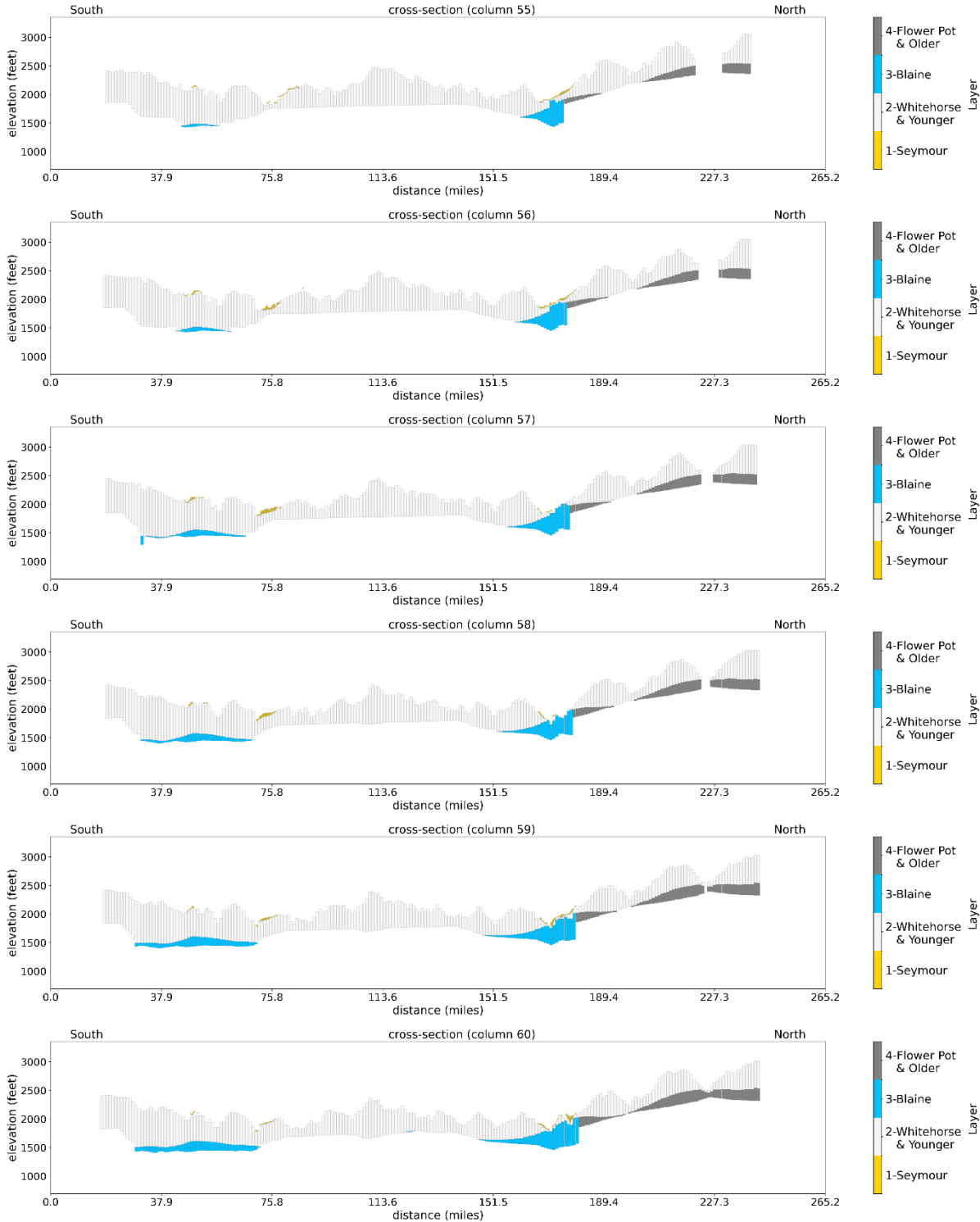
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Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers



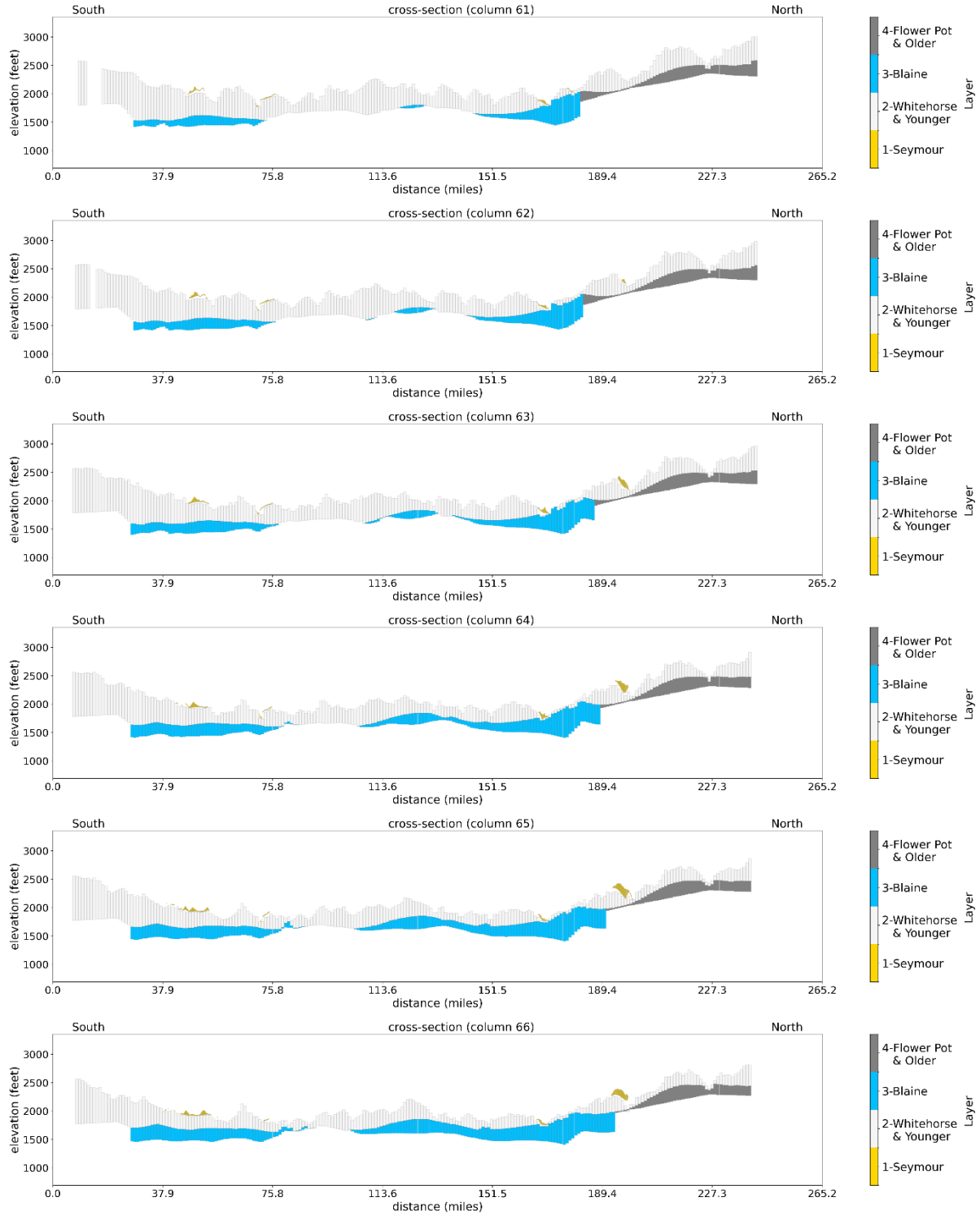
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Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers



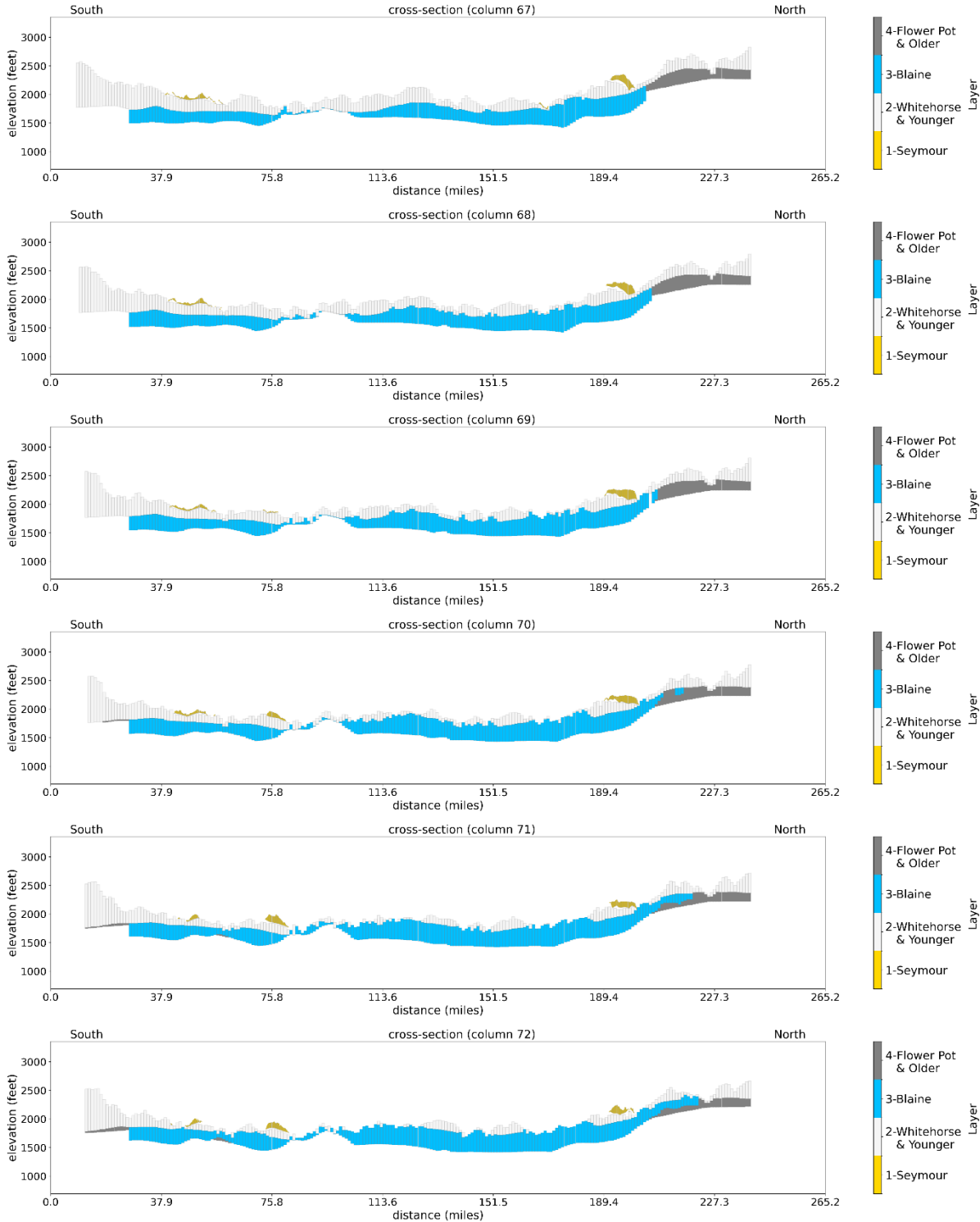
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Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers



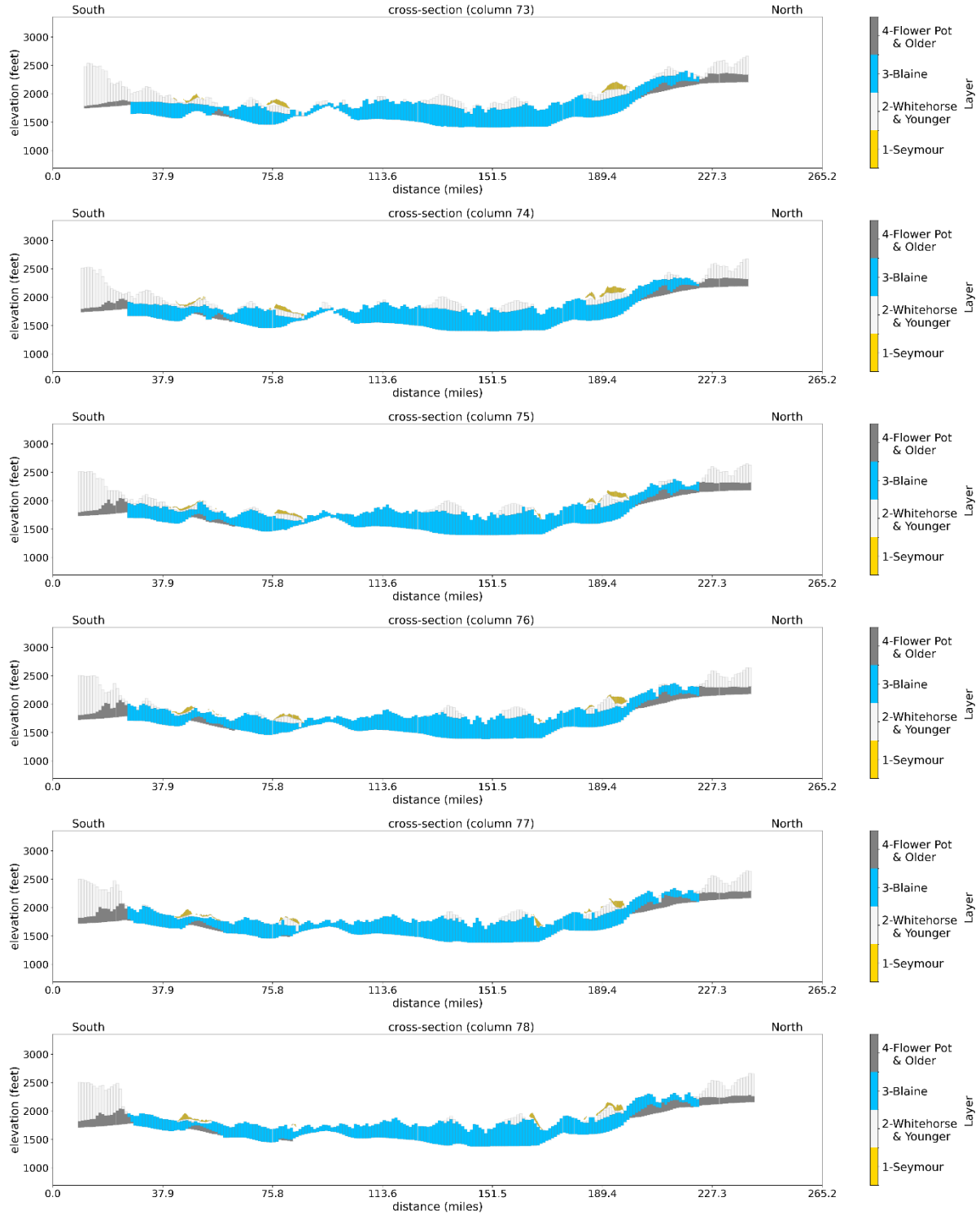
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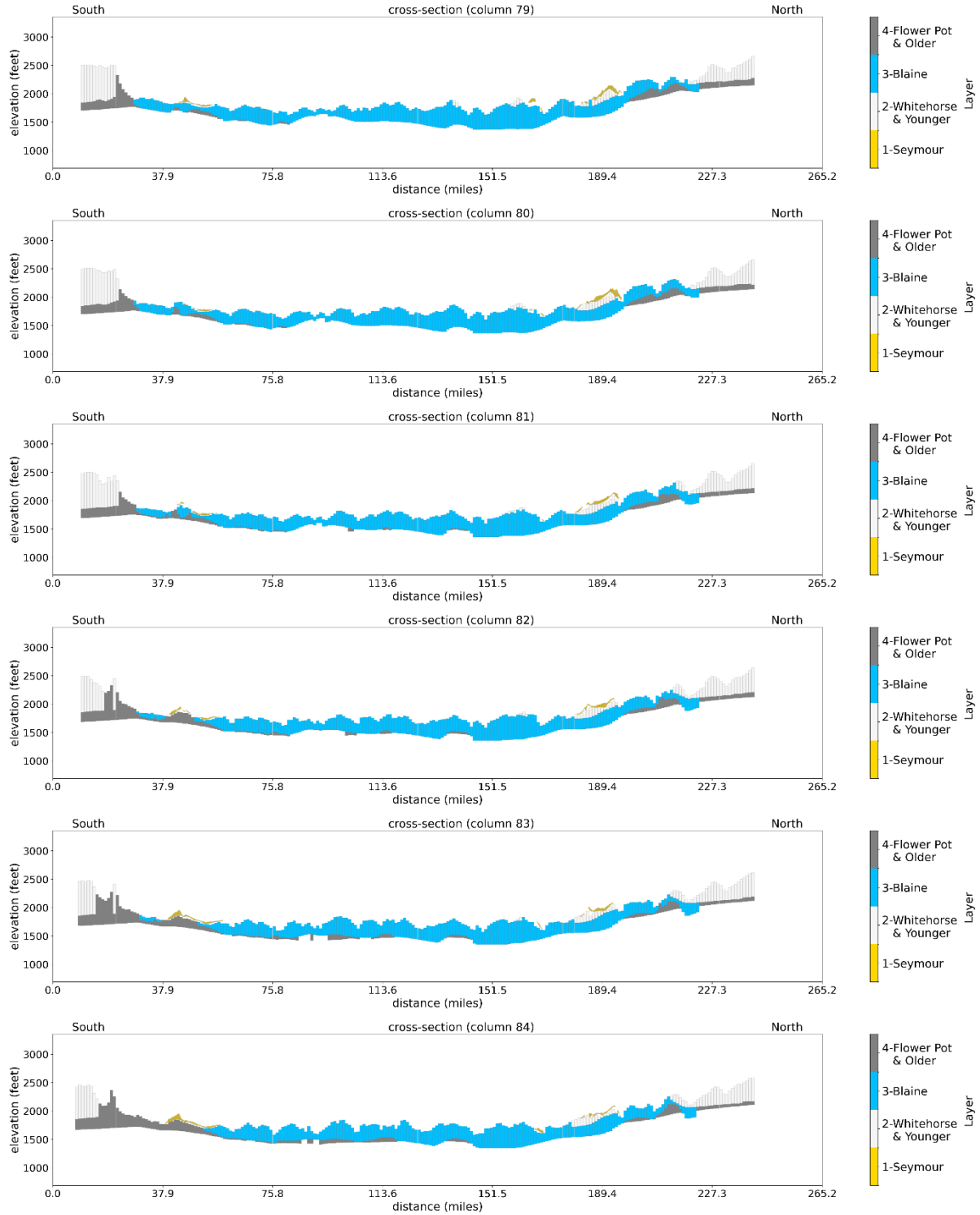
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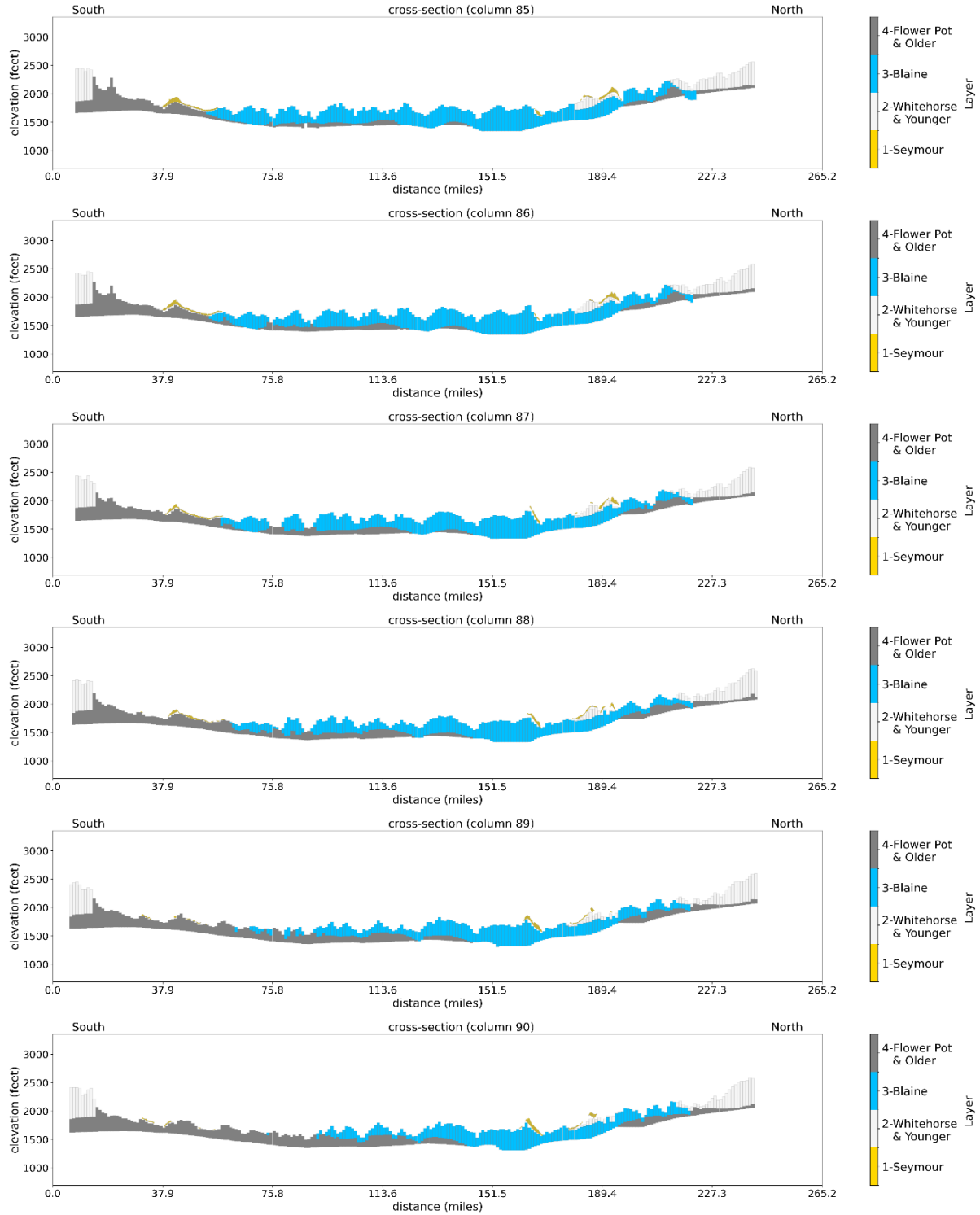
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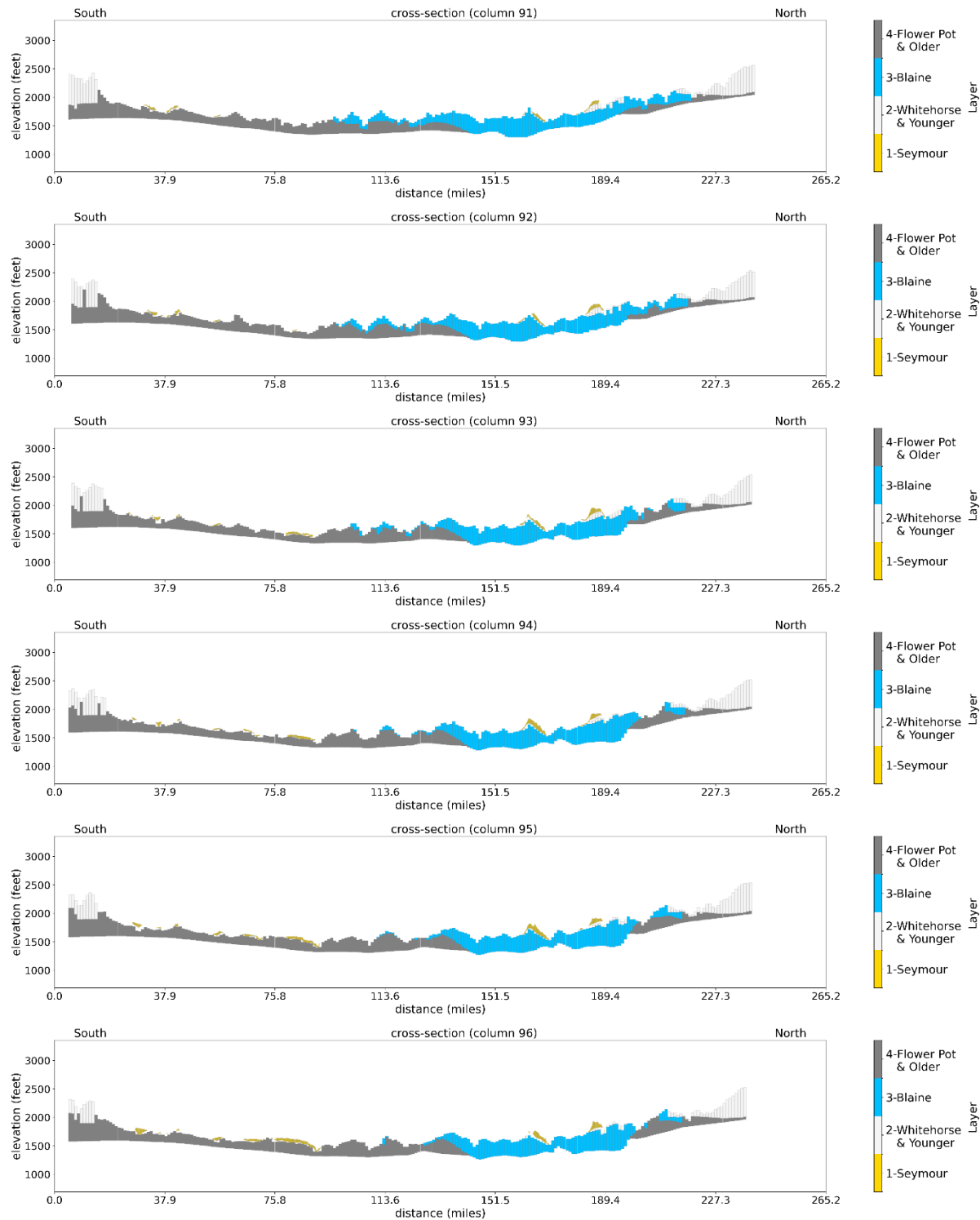
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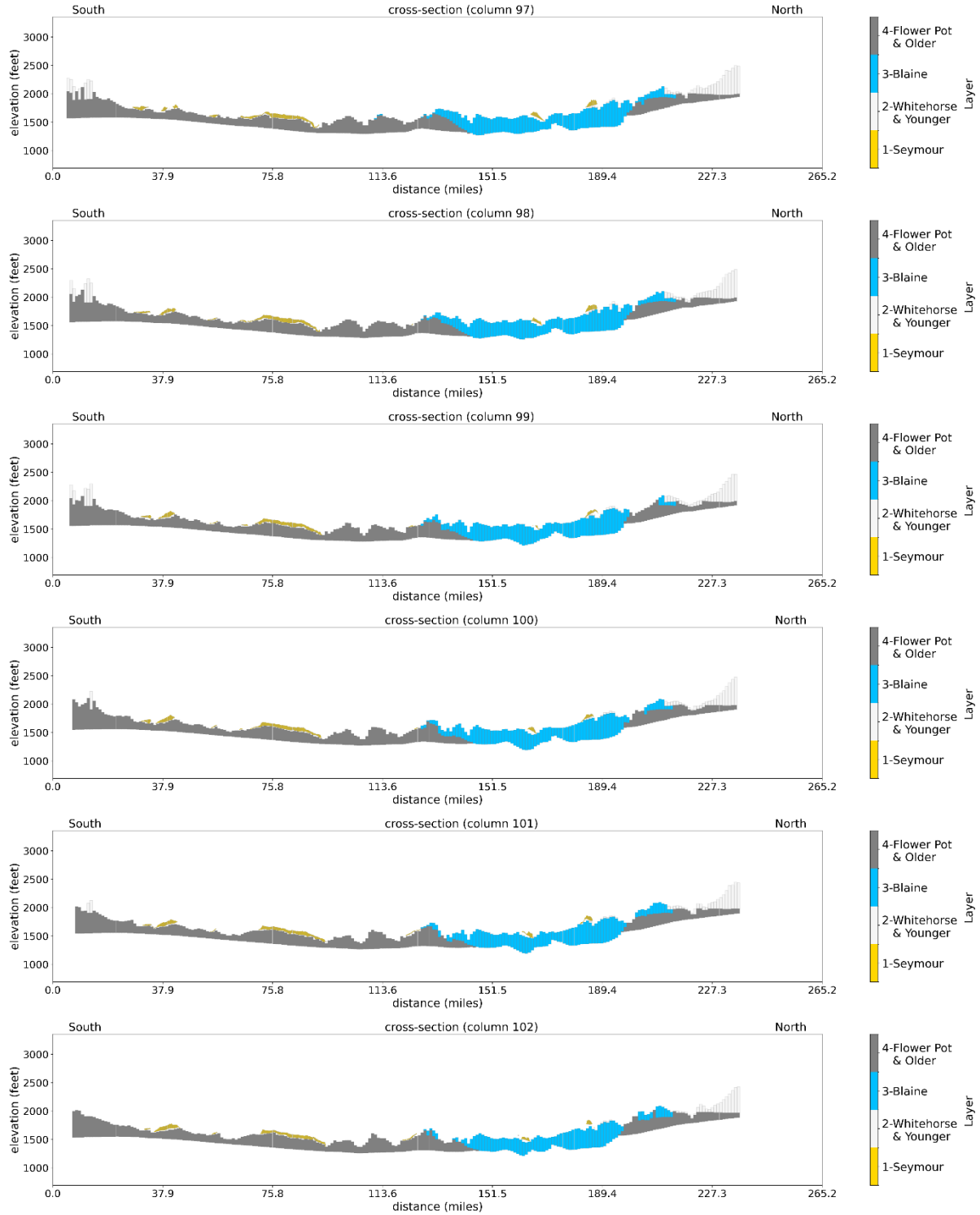
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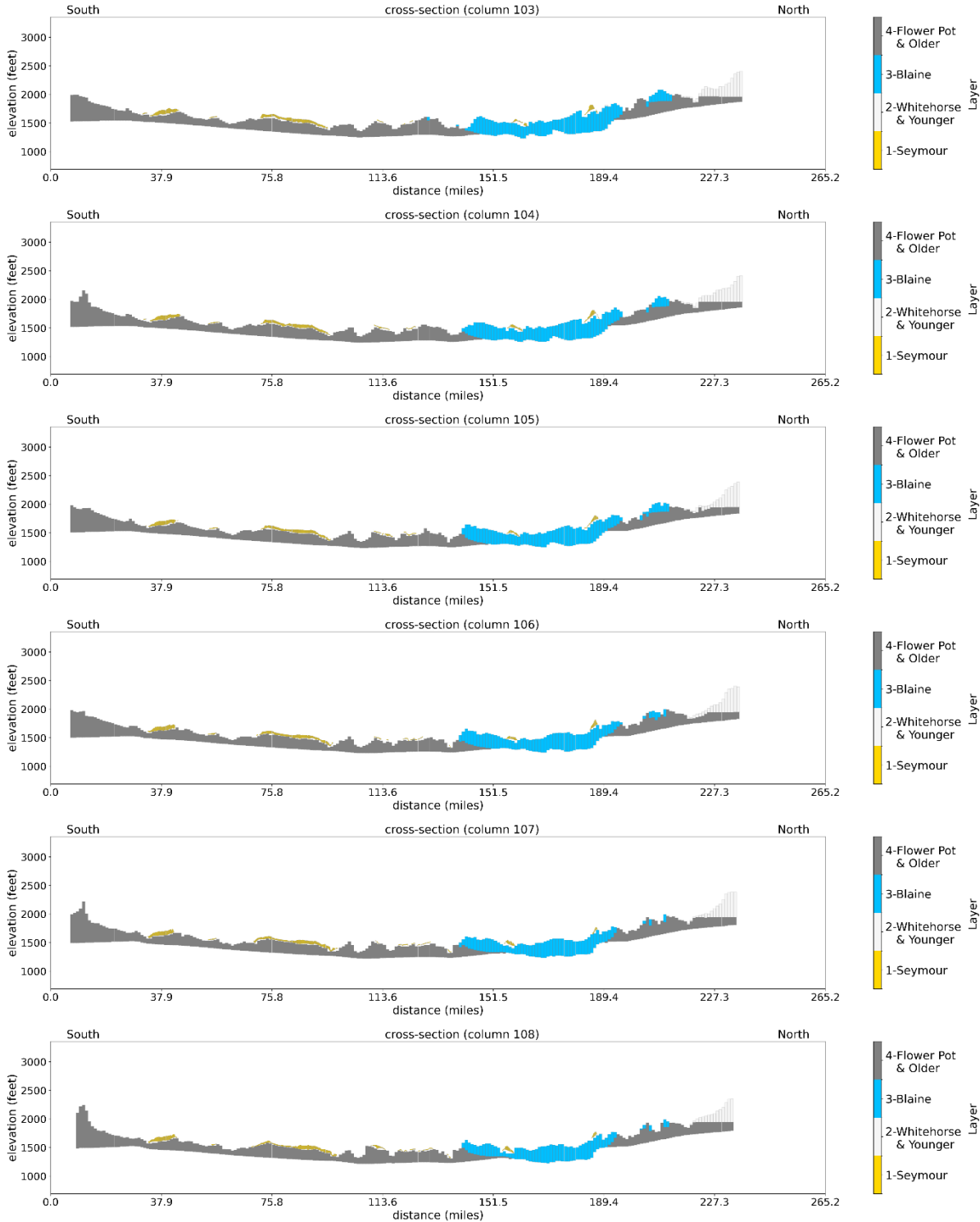
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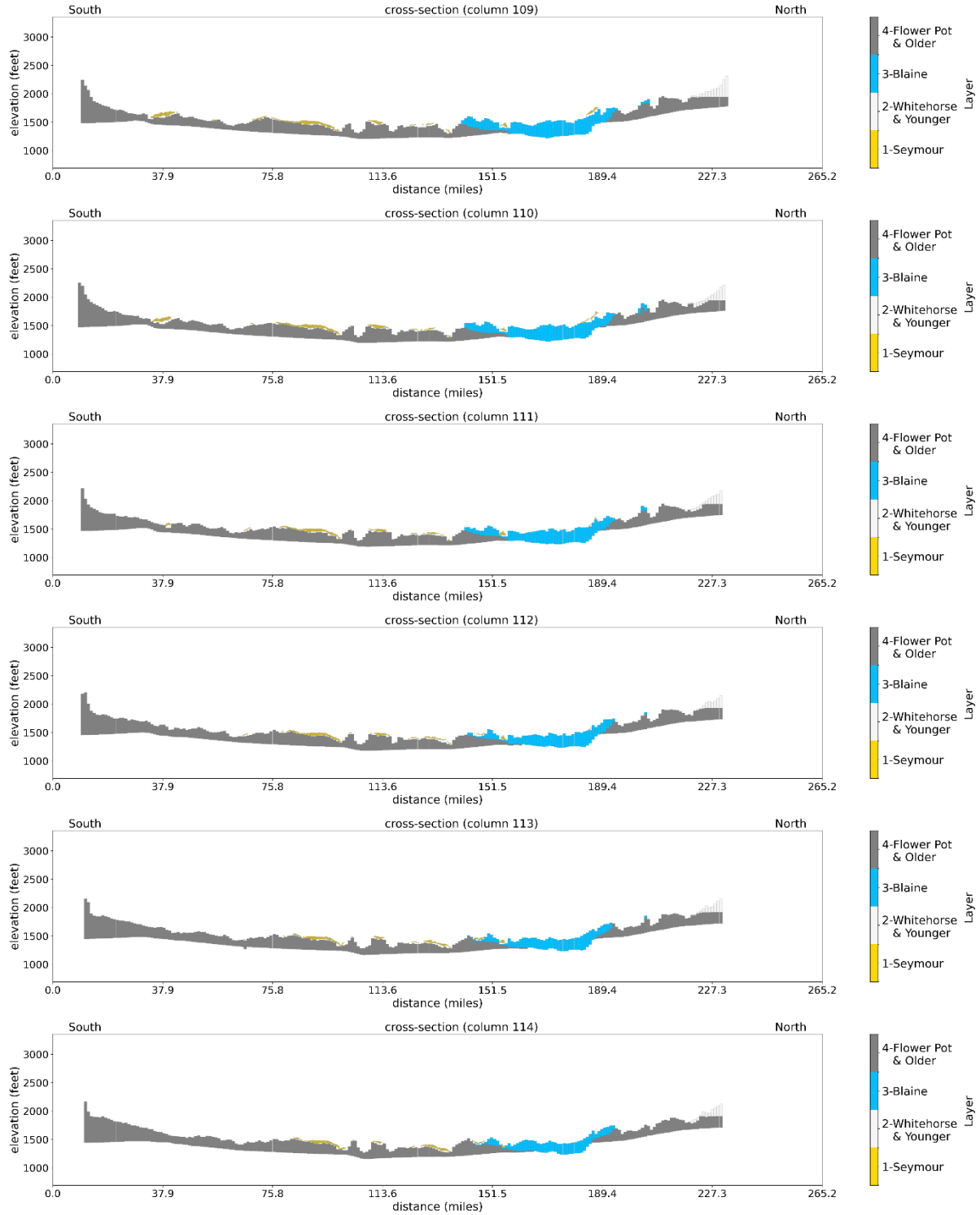
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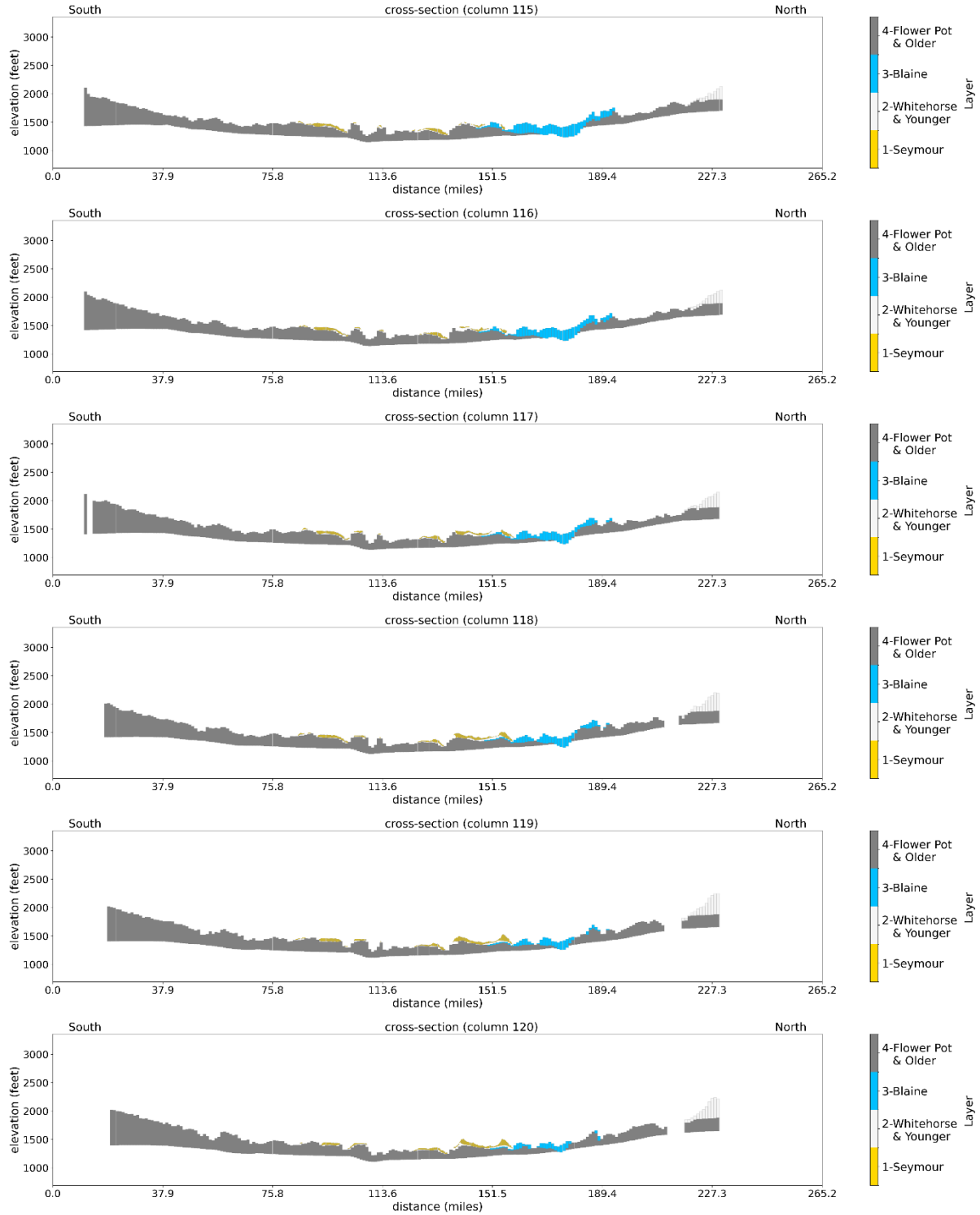
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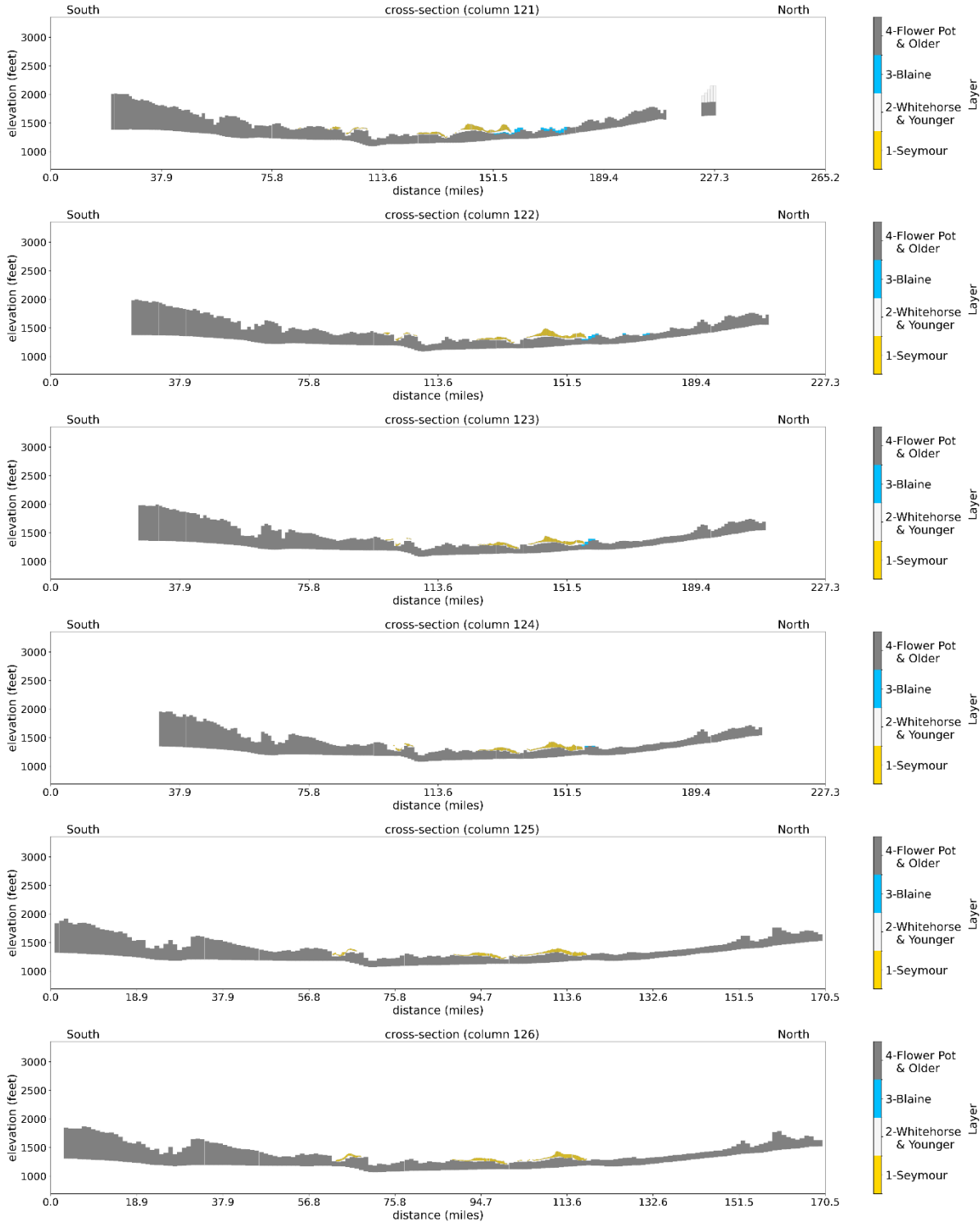
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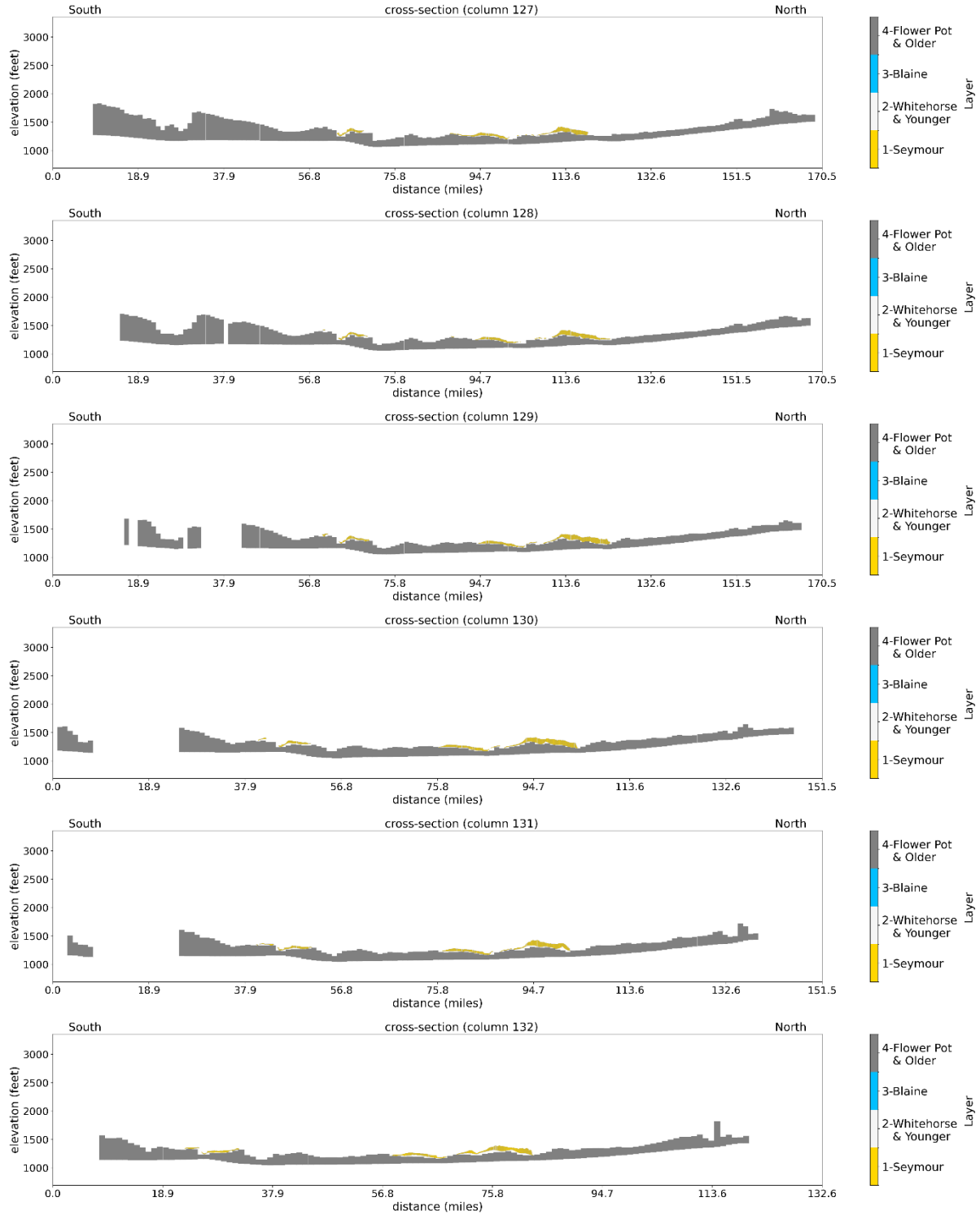
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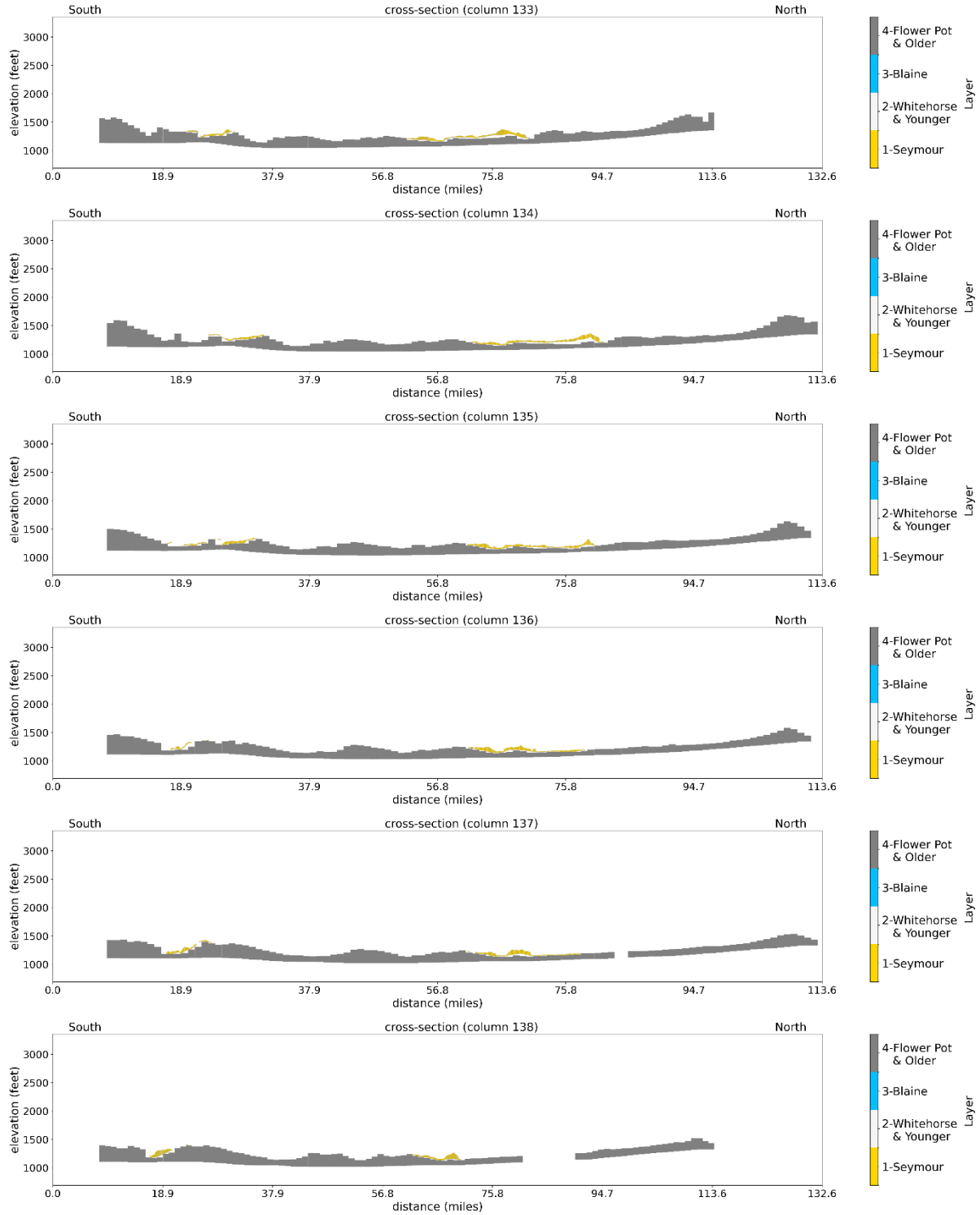
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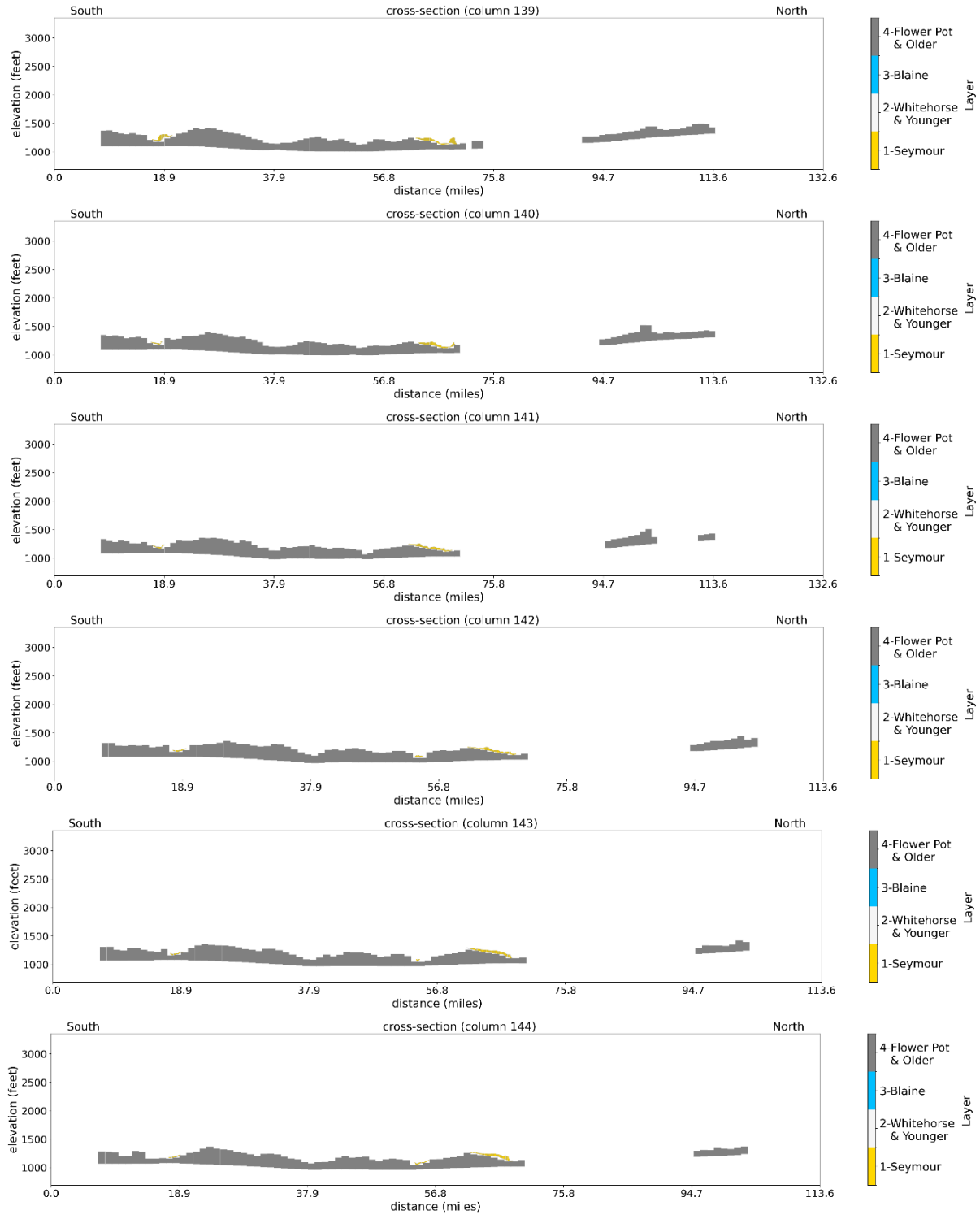
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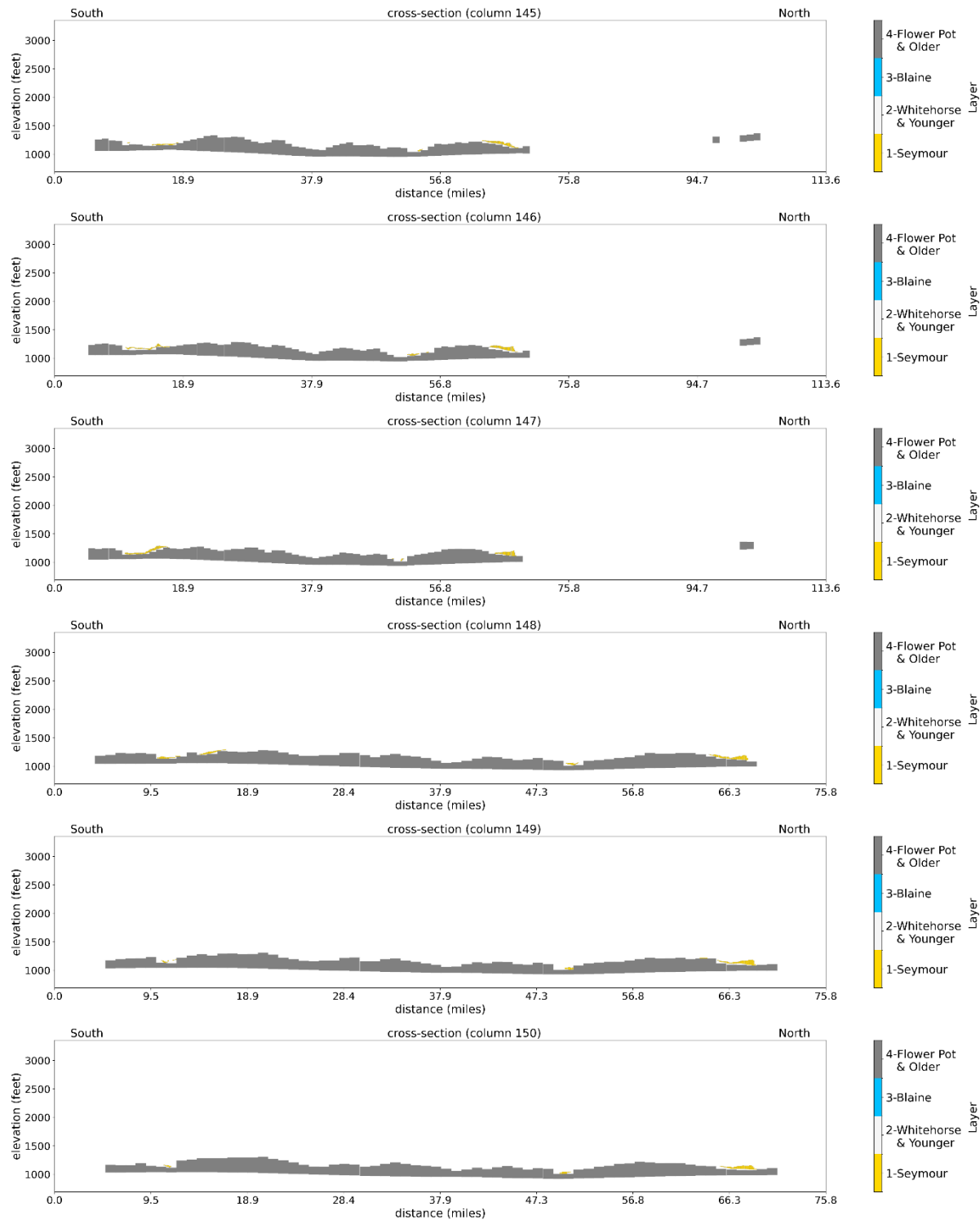
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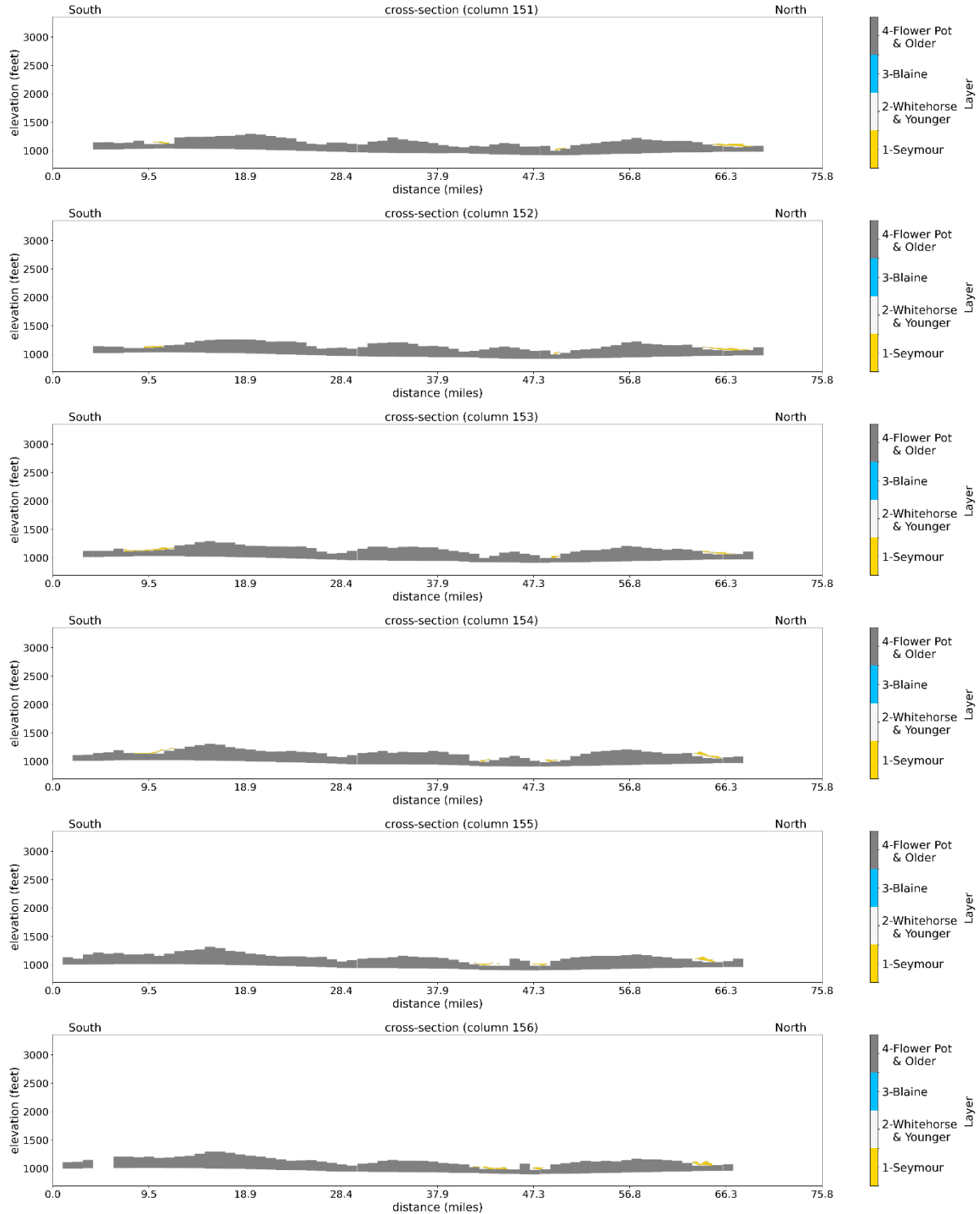
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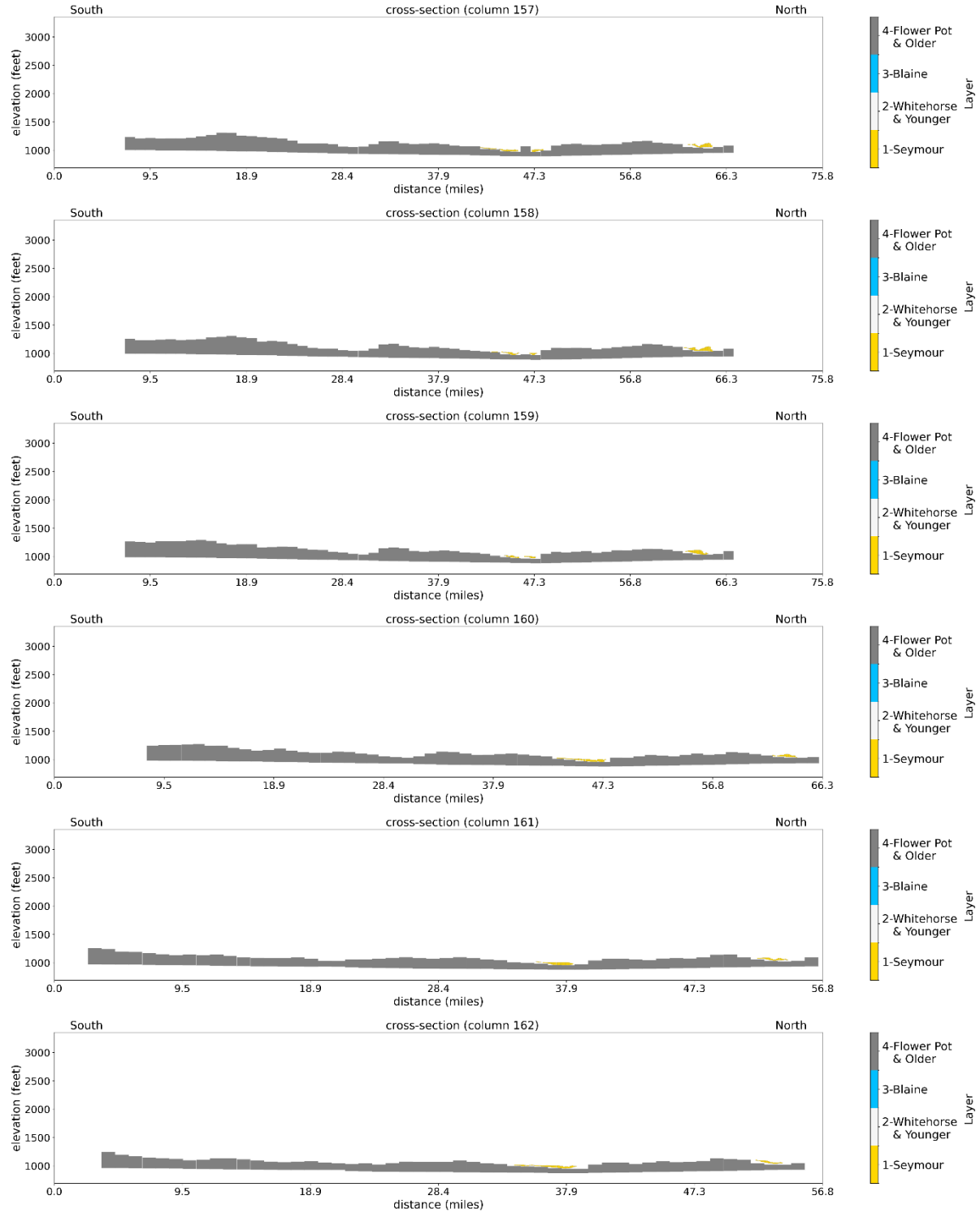
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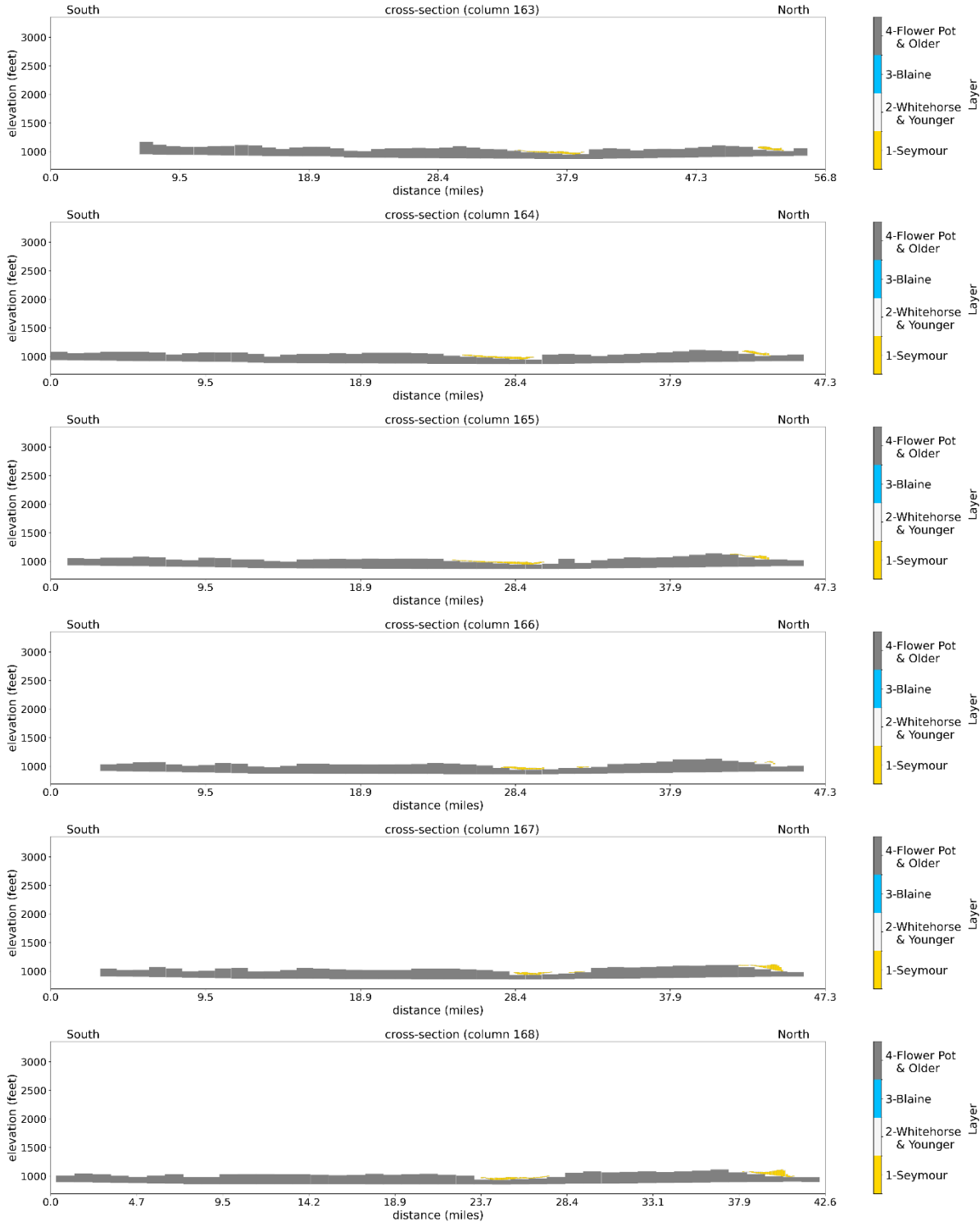
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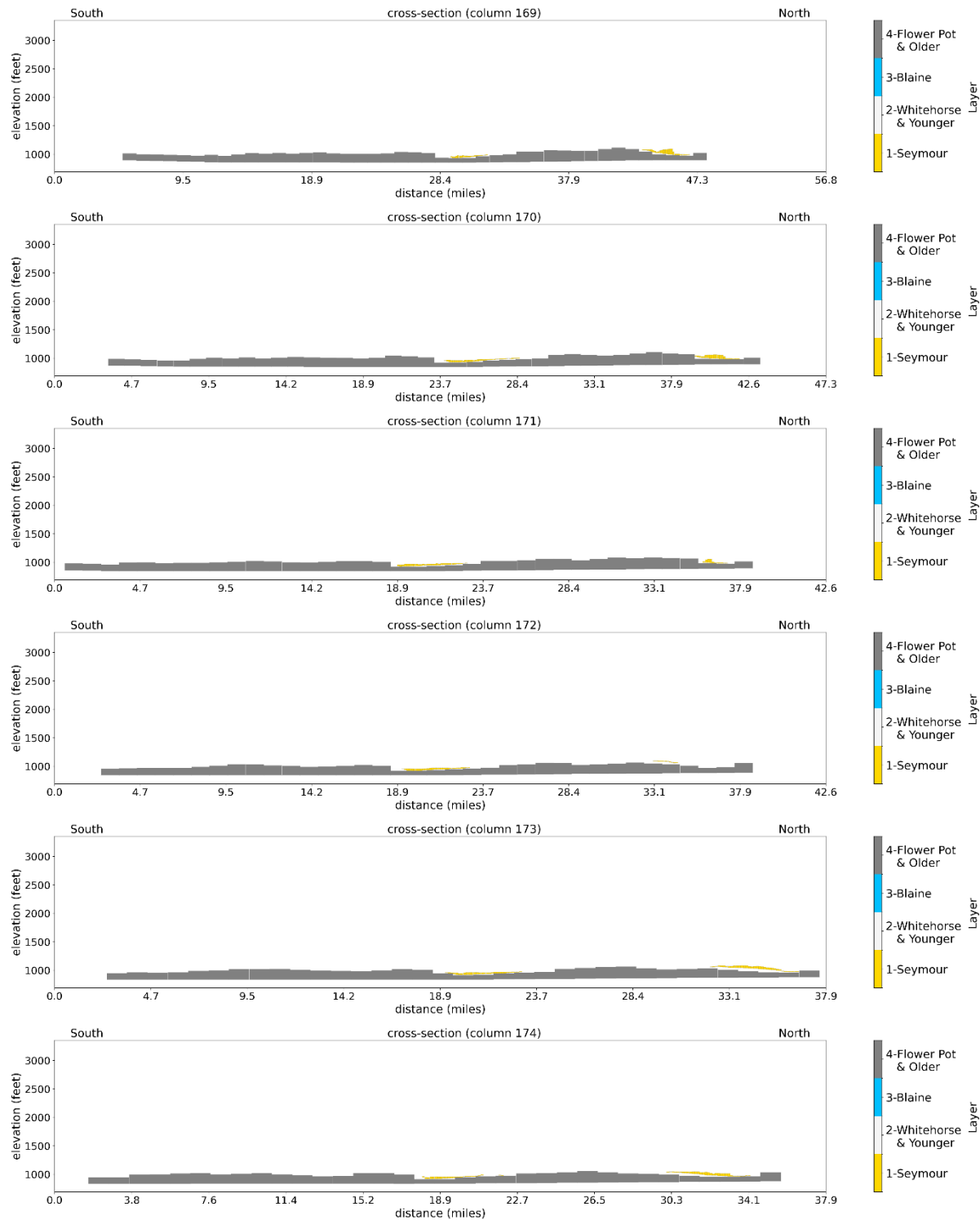
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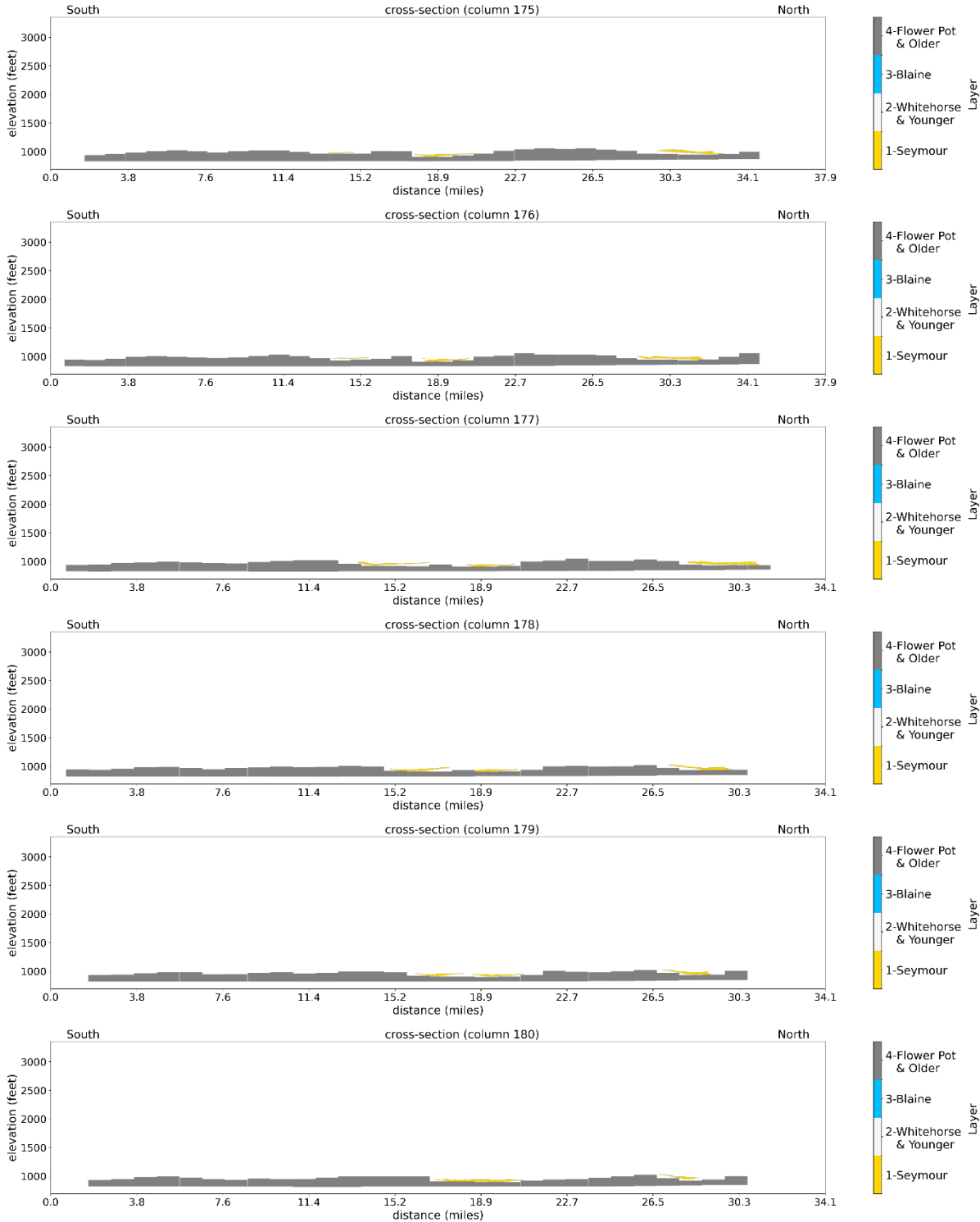
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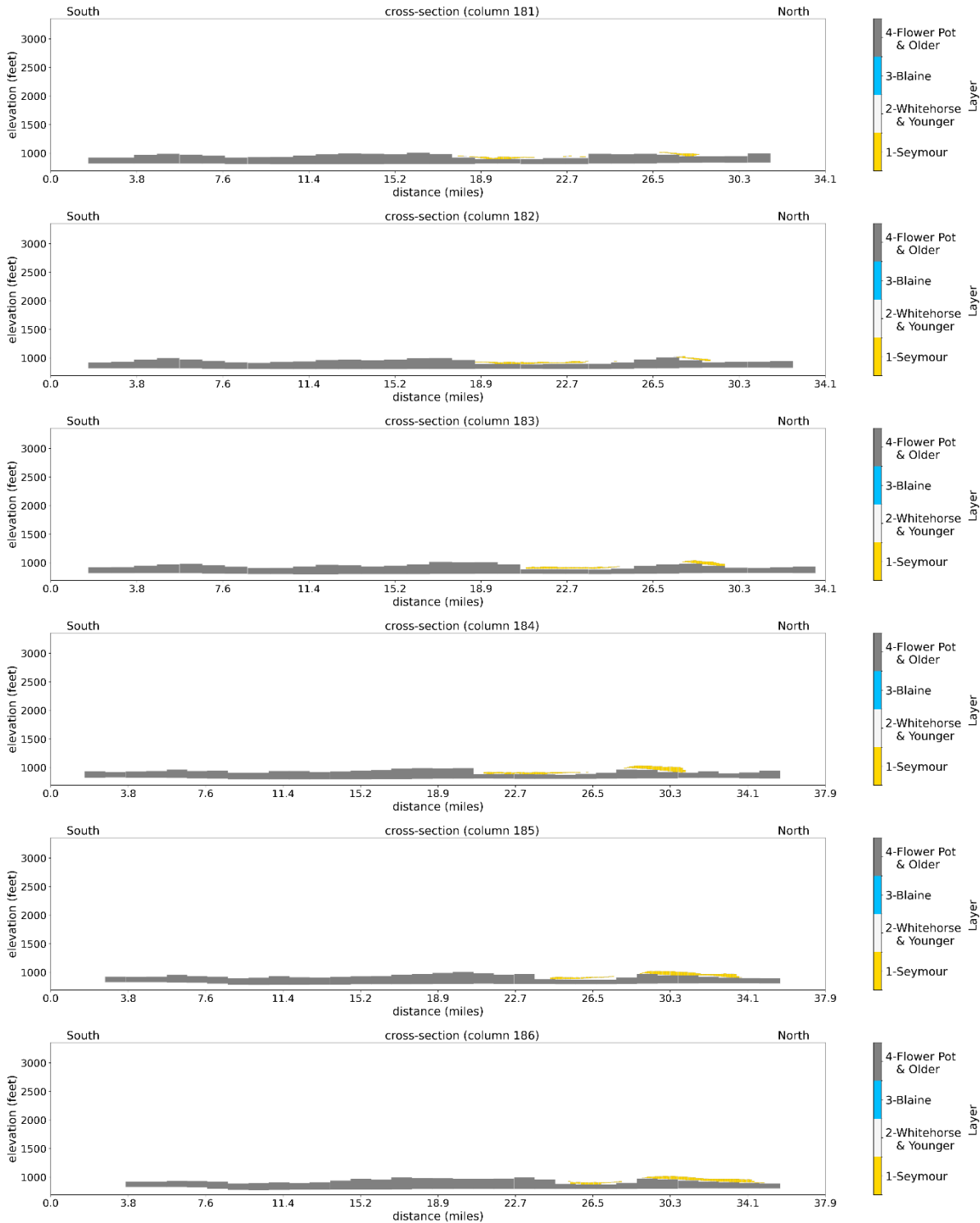
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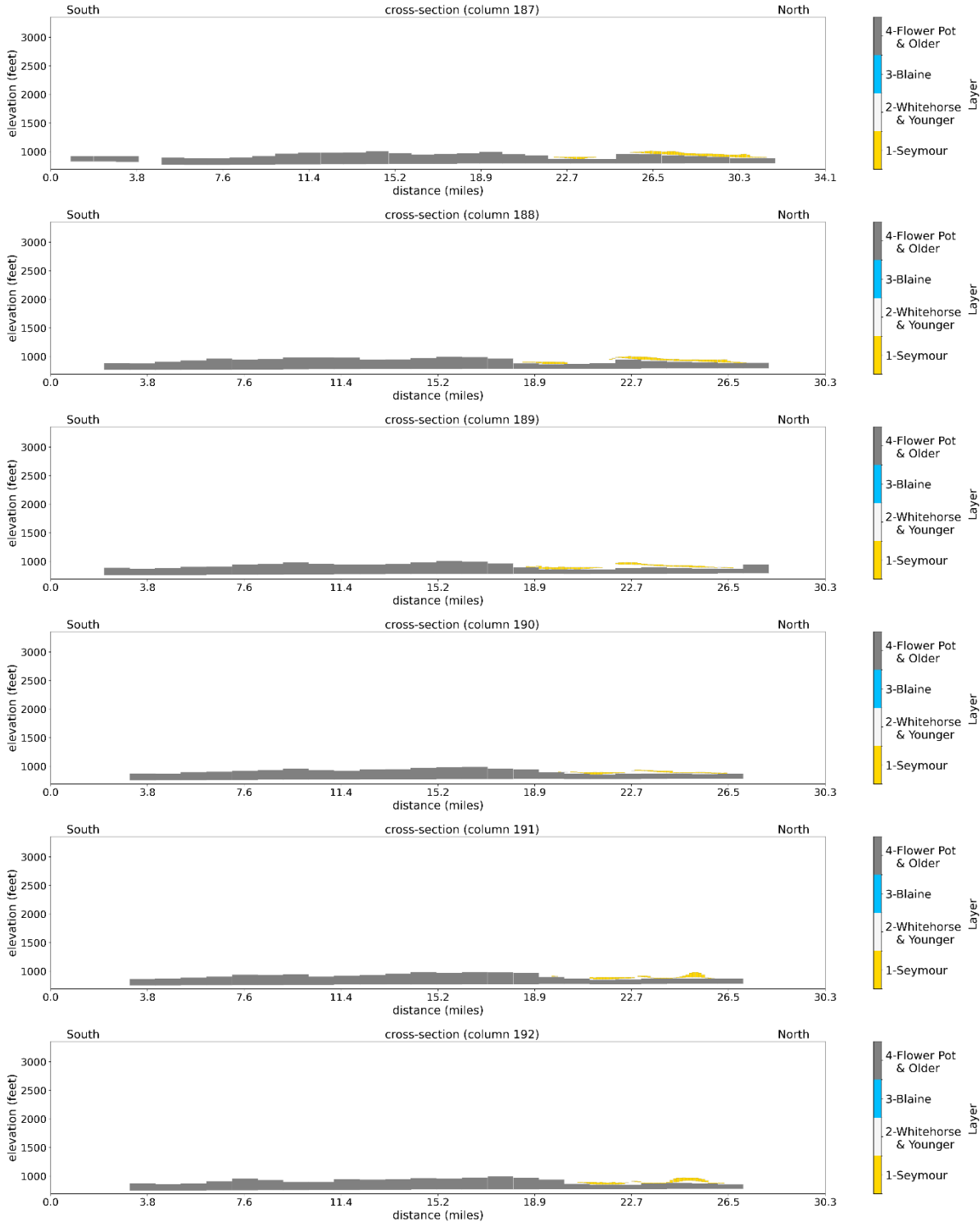
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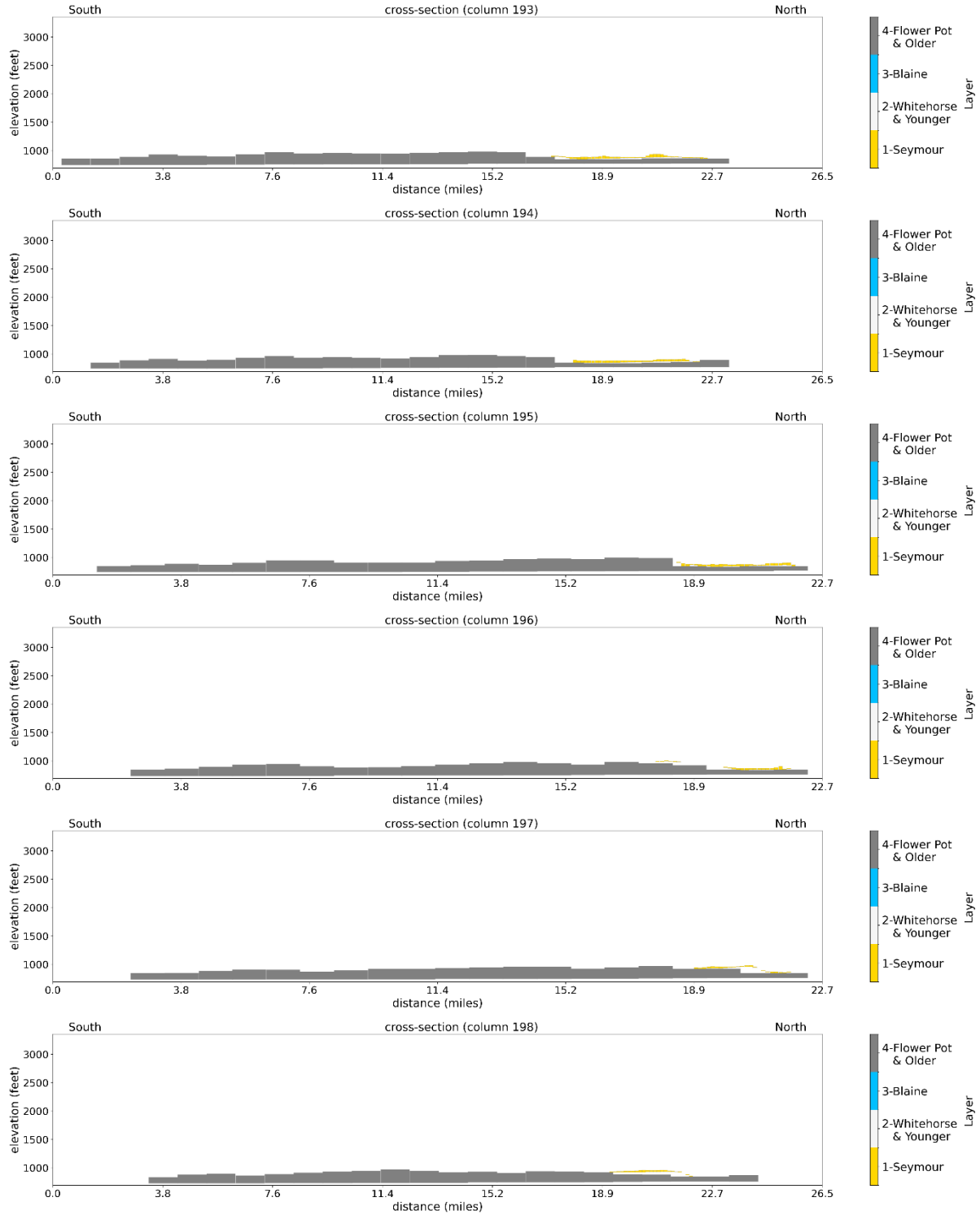
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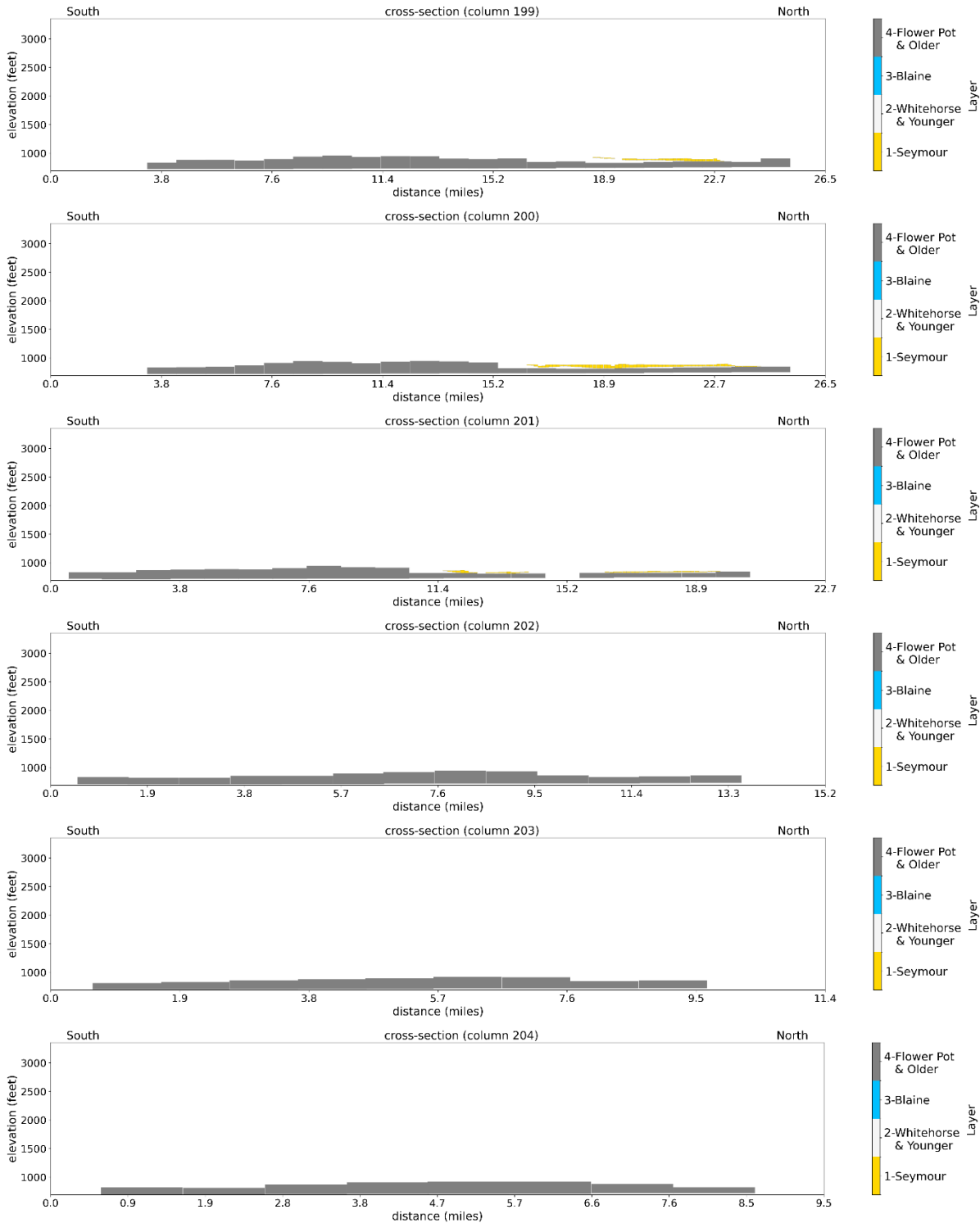
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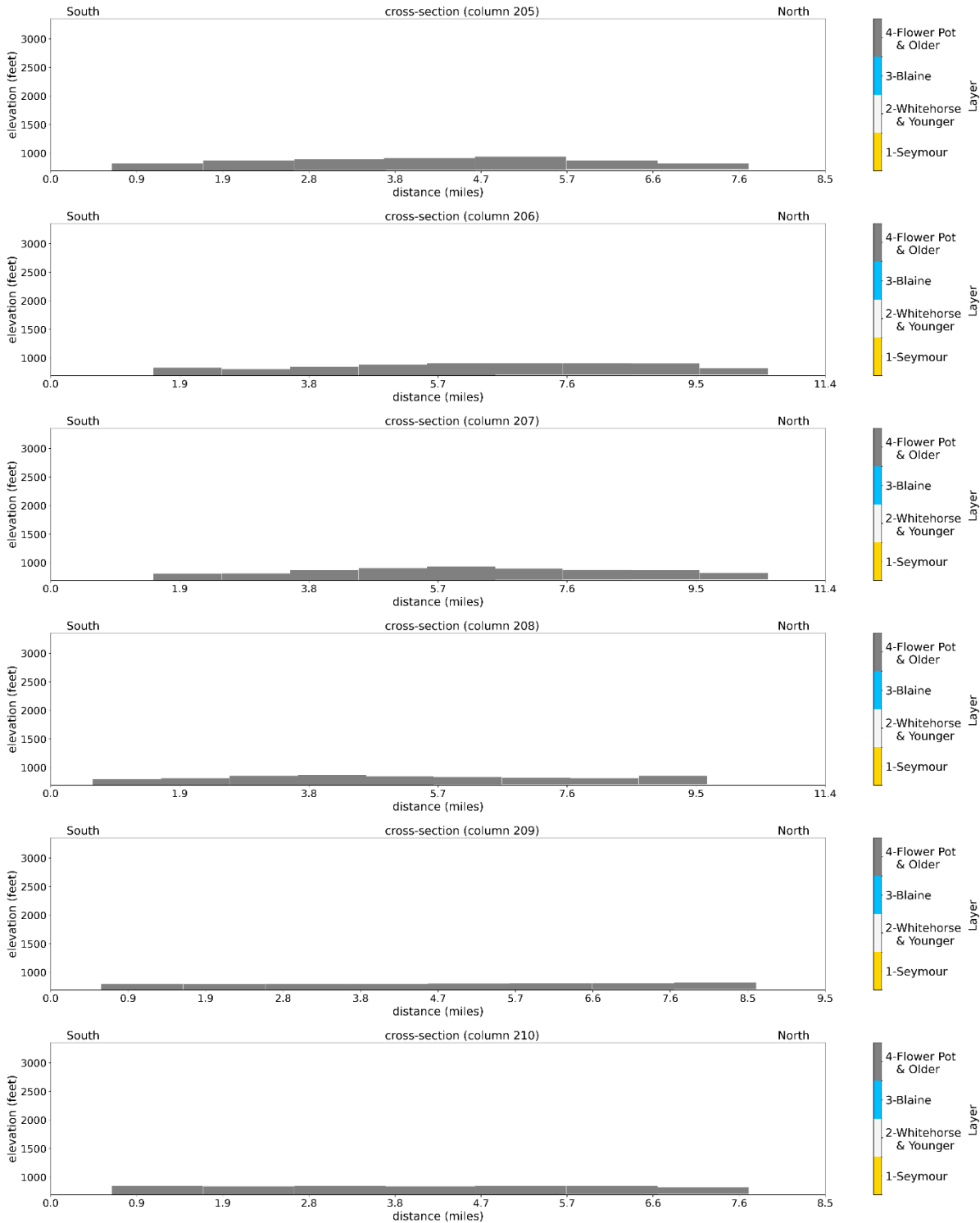
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Final Report: Groundwater Availability Model for the Seymour and Blaine Aquifers



13 Appendix C: Processed Water Levels

Appendix C provides hydrographs of measured water levels and rolling-average trends for each observation location. Given the number of figures included, Appendix C is provided as a standalone PDF attachment.

14 Appendix D: Hydrographs

Appendix D provides hydrographs of measured and simulated water levels for all high-frequency monitoring wells (those with more than five measurements and a record length of at least five years, as described in Section 5.2.1). Given the number of figures, Appendix D is provided as a standalone PDF attachment.

Each figure shows the well locations within the aquifer alongside a hydrograph panel for each well. The panels display the base realization of the posterior ensemble (dark blue line), the full range of posterior ensemble realizations (light blue lines), the prior ensemble (gray lines), the model bottom (dashed line), and observed water level measurements as weighted calibration targets (red dots) and unweighted observations (black dots). Unweighted observations are measurements with reported water levels below the model bottom. Since the model cannot simulate heads below the aquifer base, they were excluded from calibration but retained on the hydrographs to show where the framework limits reproduction of the observed record. Simulated water levels extend through the predictive period to 2080. The key evaluation criterion is whether the range of simulated groundwater elevations encompasses the observed values, indicating that the posterior ensemble captures the observed variability at that location.

15 Appendix E: Water Budget By Counties

Appendix E presents simulated water budgets by county for the calibrated model. Each county is a single ZONEBUDGET zone spanning all four model layers, so budgets are for all layers combined and include storage change. The inter-county flow term is lateral exchange with adjacent counties in all layers; these terms cancel when summed over all counties. Values are in acre-feet per year.

16 Appendix F: Water Budget By GCDs

Appendix F presents simulated water budgets by Groundwater Conservation District (GCD) in Texas, plus areas of Texas counties outside any district ("NoDistrict"). Each district is a single ZONEBUDGET zone spanning all four model layers, so budgets are for all layers combined and include storage change. The inter-district flow term is lateral exchange with adjacent districts in all layers; exchange with the Oklahoma portion of the model is reported separately. Values are in acre-feet per year.