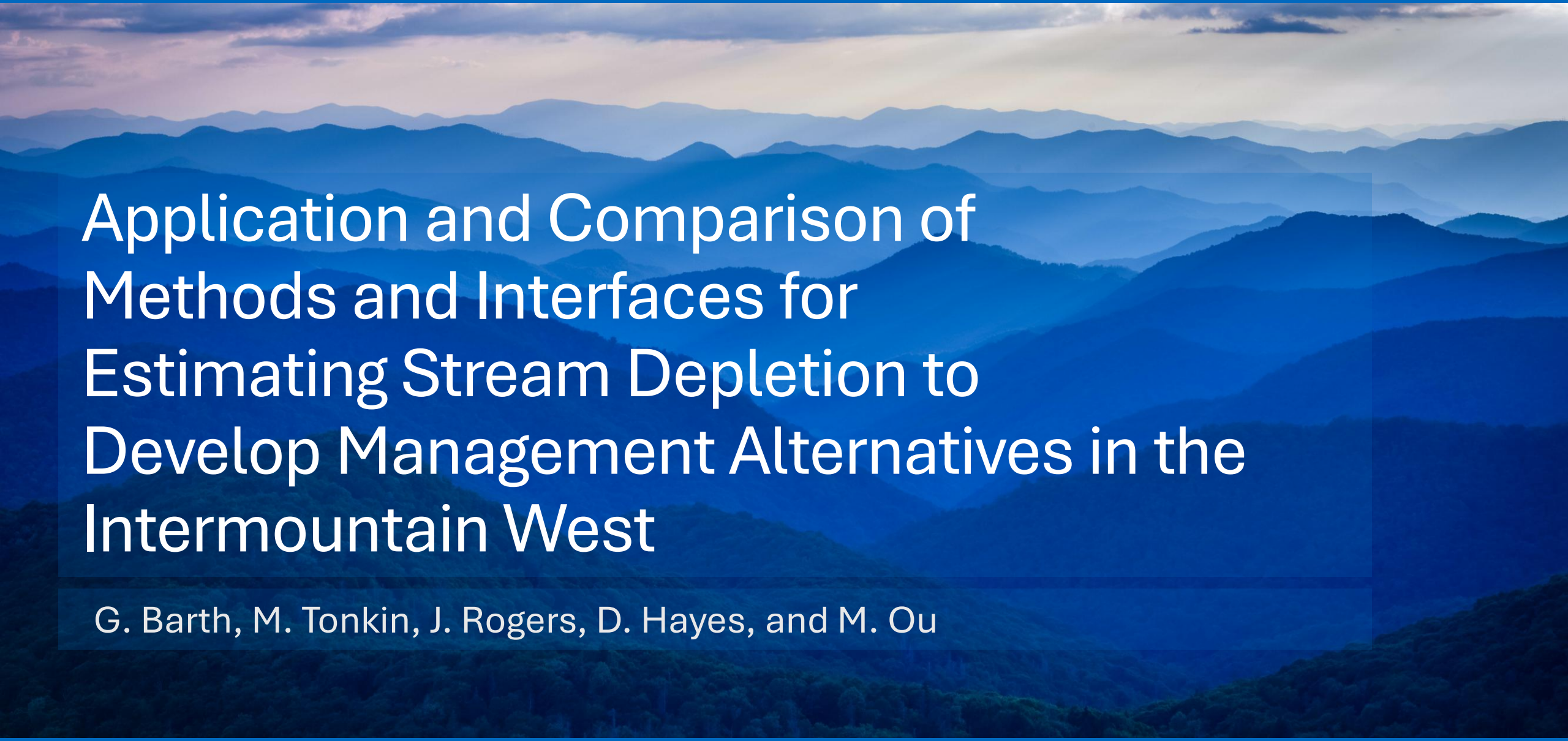


Application and Comparison of Methods and Interfaces for Estimating Stream Depletion to Develop Management Alternatives in the Intermountain West

G. Barth, M. Tonkin, J. Rogers, D. Hayes, and M. Ou

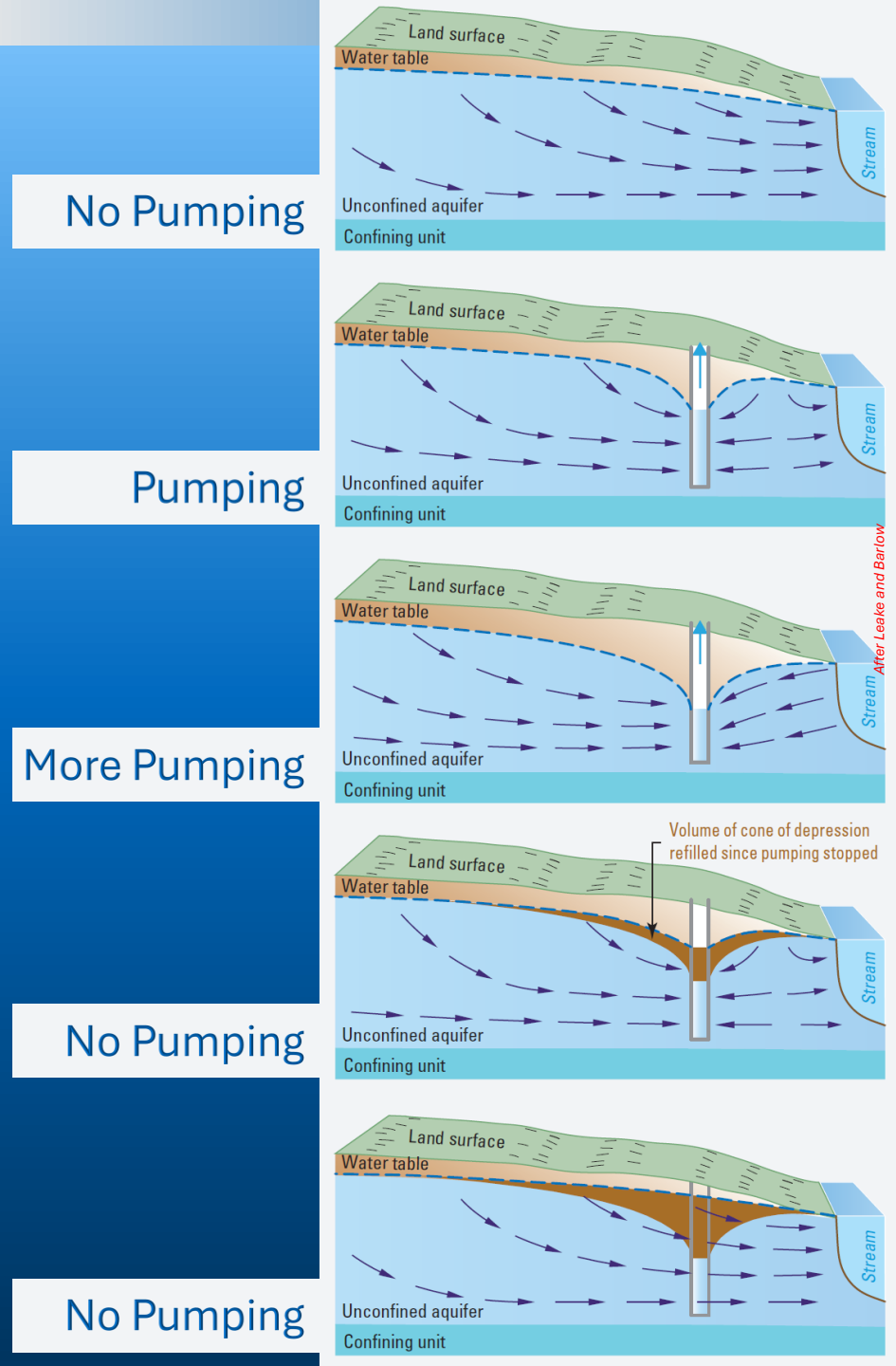
S.S. Papadopulos & Associates, Inc.
Environmental & Water Resource Consultants

Outline

- Motivation
- Methods
  - » Analytical
  - » Numerical
- Interfaces
  - » Capabilities
  - » Examples

Why Estimate Stream Depletion?

- Surface and groundwater typically interact
- Surface water rights are typically senior
- Junior groundwater withdrawal can deplete surface water and ET flows
  - » Need to quantify depletion/capture potential and timing



Stream Depletion Estimation Methods

- Analytical methods
- Numerical methods exploring uncertainty
- Regional numerical models

Analytical Methods

Why Analytical?

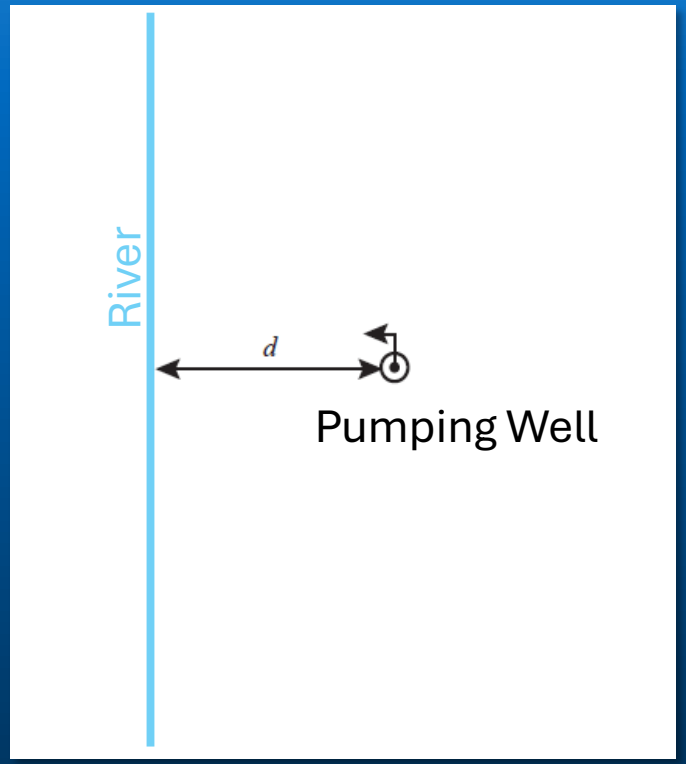
- Screening level
- Using best readily available, limited, information
- Rapid implementation
- Rapid scenario evaluation
- Not wasted effort…

Theis Equation for Drawdown

$$s = \frac{Q}{4\pi T} W(u)$$

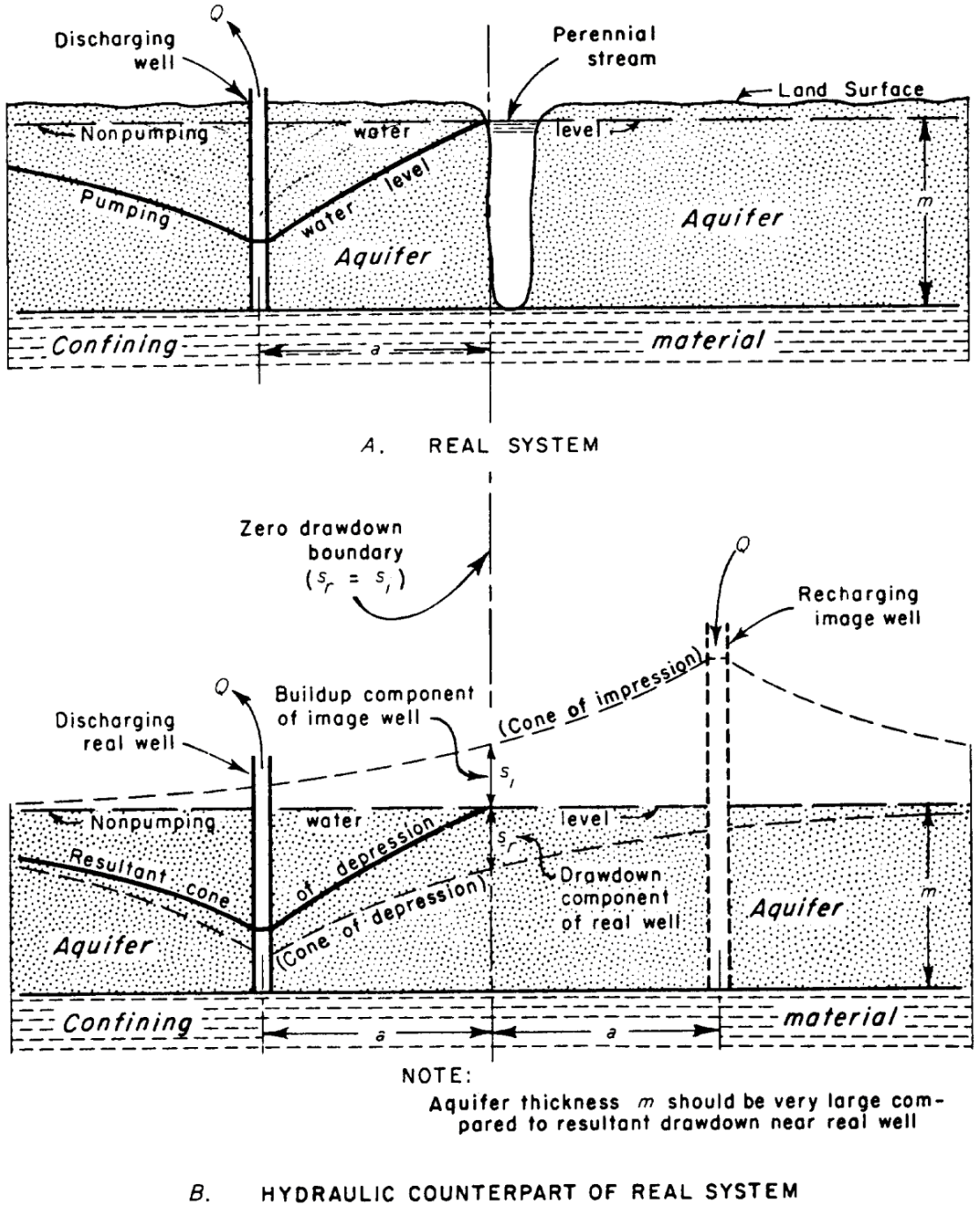
$$u = \frac{r^2 S}{4Tt}$$

- Theis Equation
  - » *s:* drawdown at distance *r*, after time *t*
  - » *Q:* pumping rate
  - » *T:* transmissivity
  - » *W(u):* well function, of *u* (dimensionless time parameter)
  - » *r:* radial distance
  - » *S:* storativity
  - » *t:* time since pumping started
- Unconfined limitations
  - » Short-term predictions, and/or
  - » Relatively small drawdown
- Stream boundary condition:
  - » Straight line approximation of the stream
  - » Image well theory



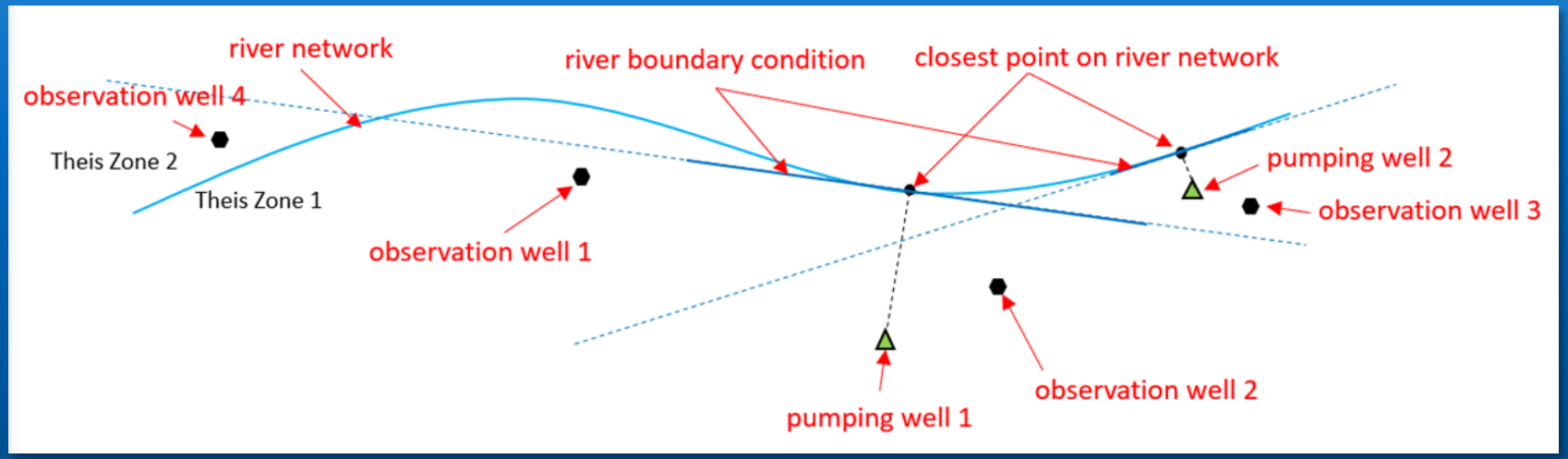
Theis Equation for Drawdown

- Stream boundary condition:
  - » Straight line approximation of the stream
  - » Image well theory (USGS WSP 1536-E)



Theis Equation for Drawdown

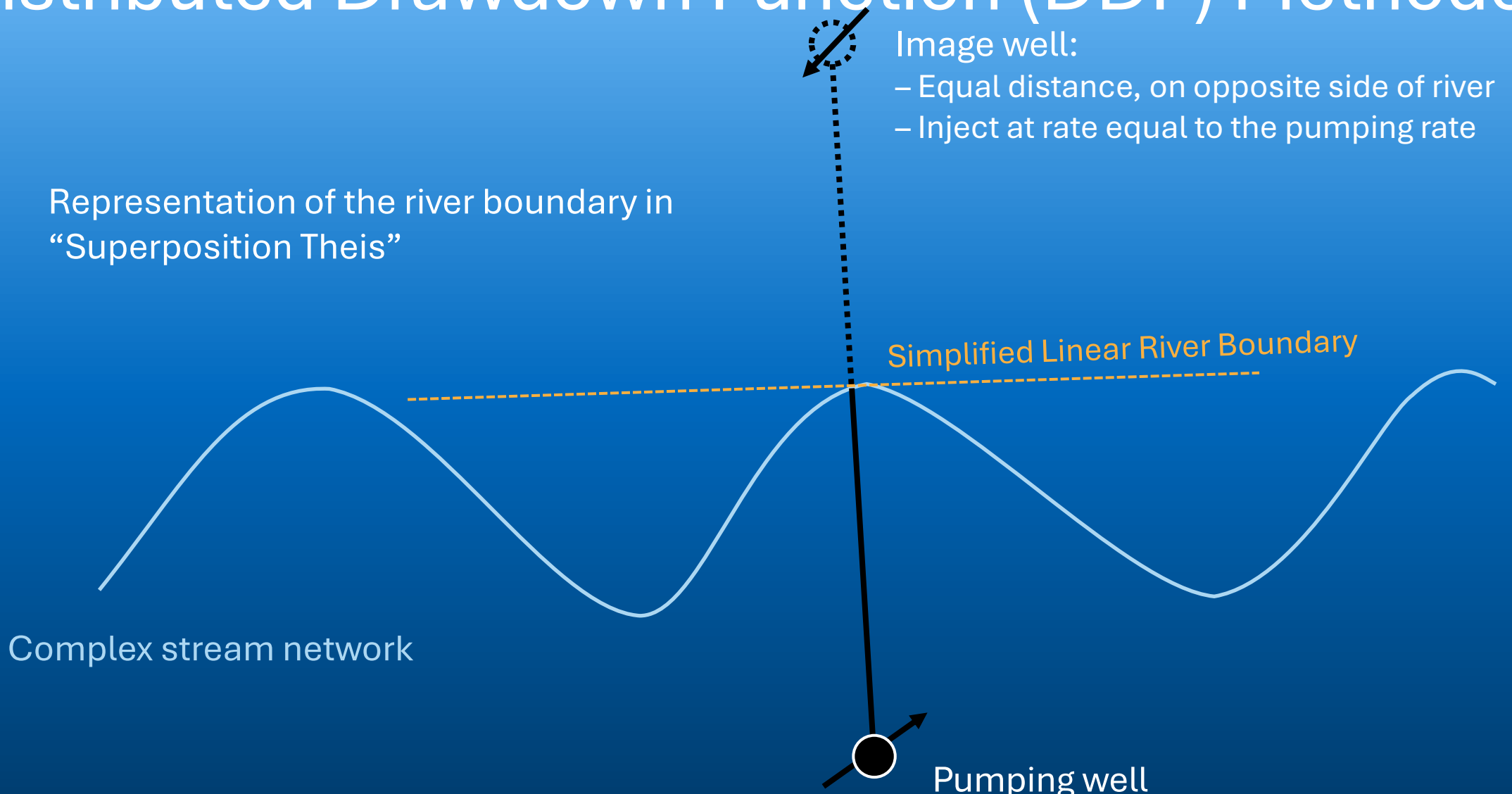
- Stream complexity
  - » Curvature
  - » Stream network
- Multiple Theis calculations
  - » "River" perpendicular to shortest distance
  - » Generate results for each well
- River-boundary restrictions
  - » Which side of river?
- Drawdown output
  - » Time series
  - » Gridded results
- Superposition of solutions
  - » Linearity assumption allows aggregating drawdowns



Distributed Drawdown Function (DDF) Methodology

Image well:
– Equal distance, on opposite side of river
– Inject at rate equal to the pumping rate

Representation of the river boundary in "Superposition Theis"

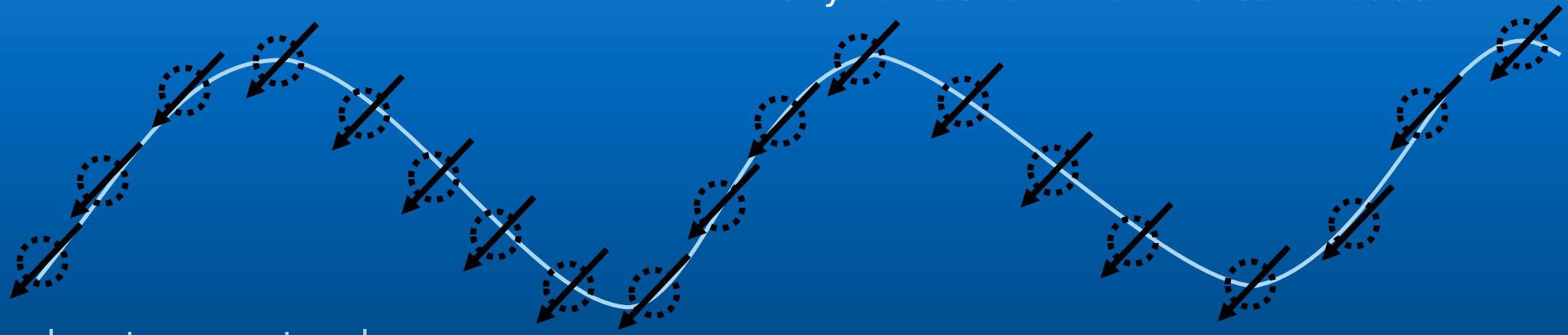


Durbin, T., 2023. Using USGS Program WTAQ and Superposition to Model Stream Depletions, Groundwater 61(4)

DDF Methodology

Representation of the river boundary in DDF

Numerous image wells coincident with any number of uniform stream nodes

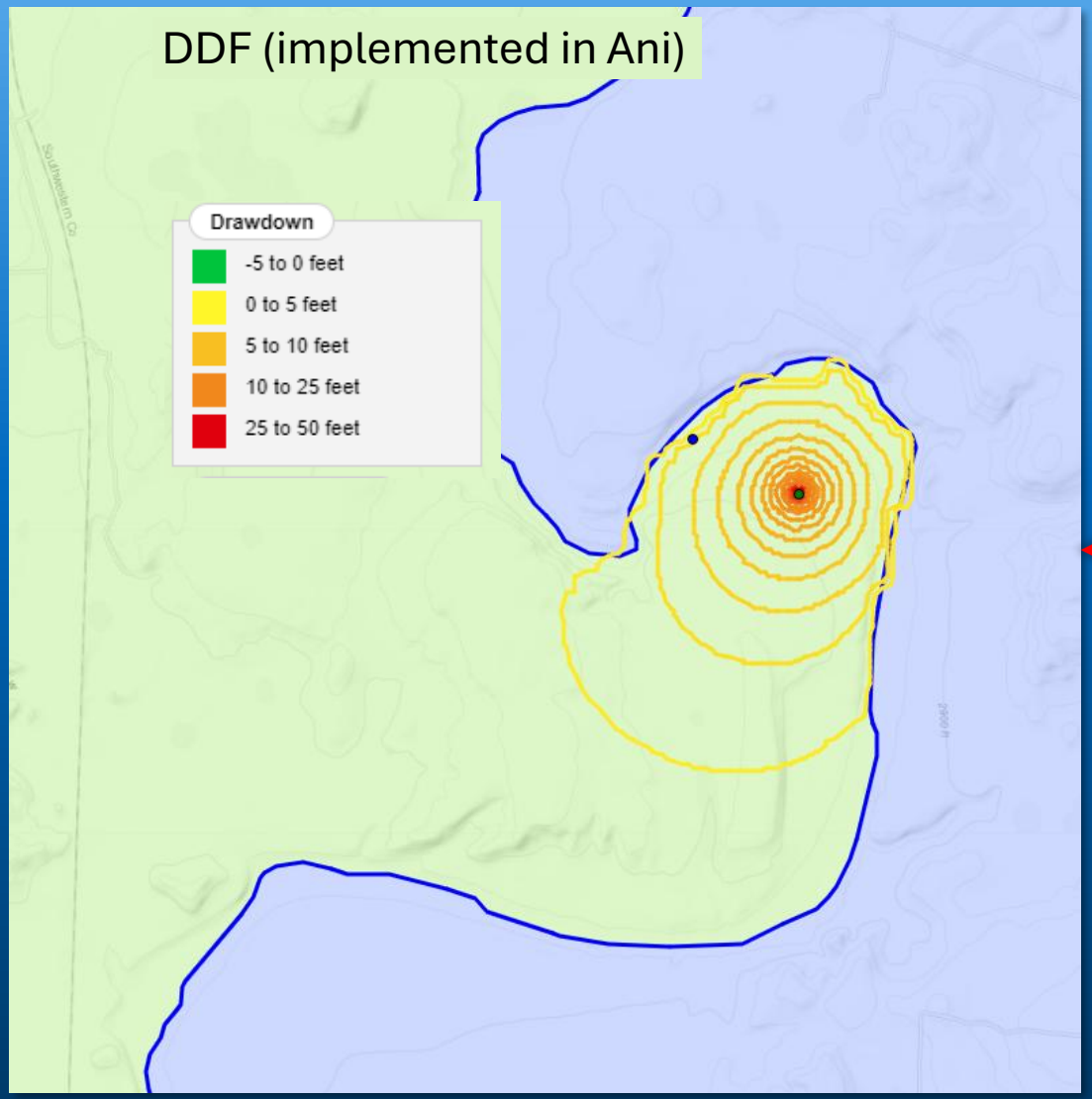


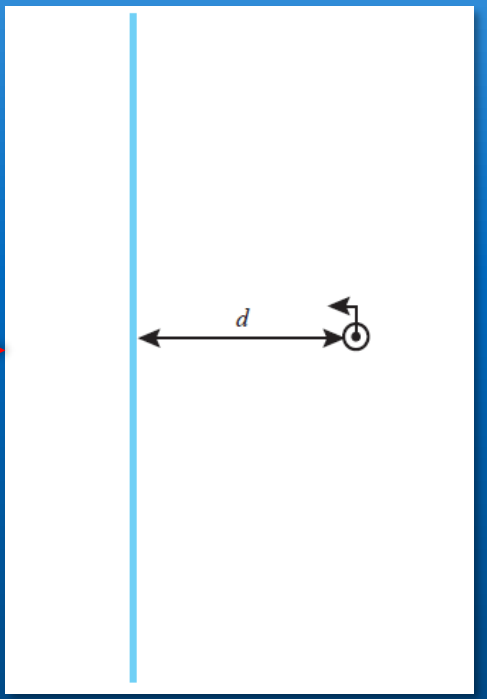
Complex stream network

Pumping well

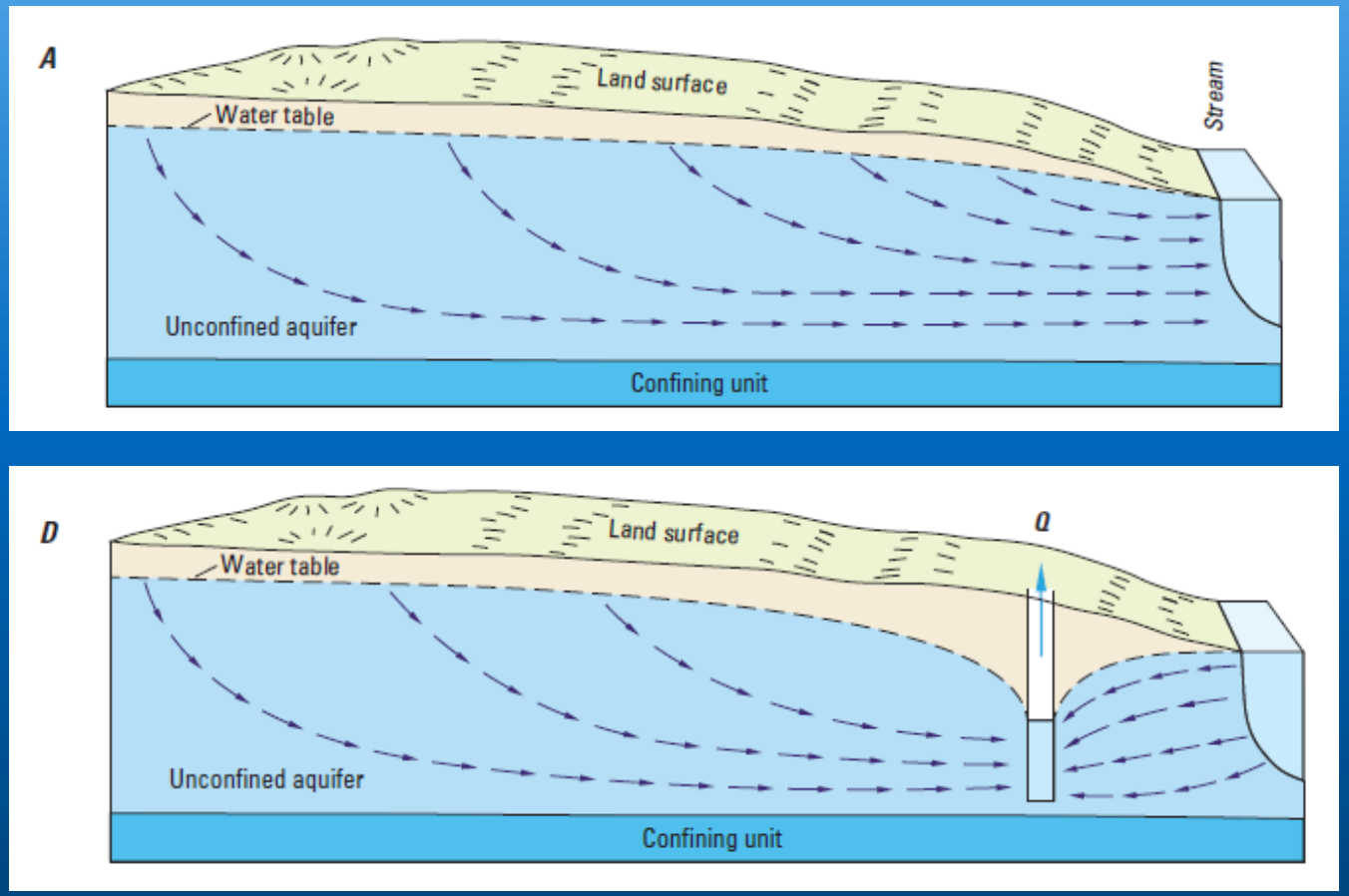
Durbin, T., 2023. Using USGS Program WTAQ and Superposition to Model Stream Depletions, Groundwater 61(4)

Representing Complex River Meanders





Stream Depletion



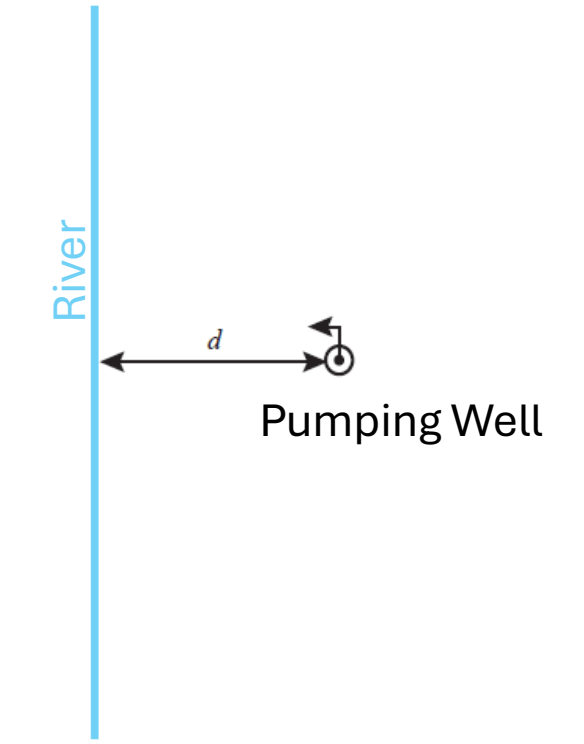
From Barlow and Leake, 2012

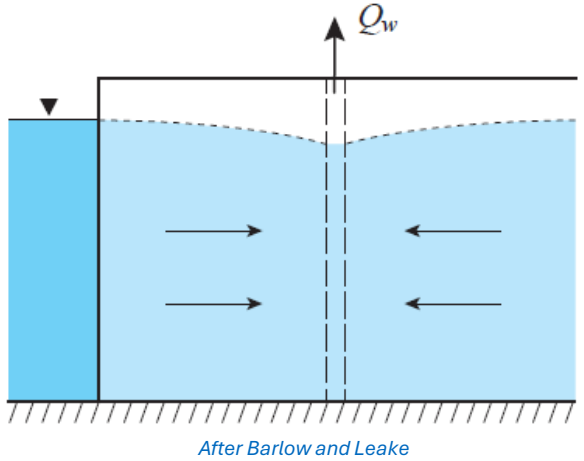
Quantifying Depletion Distribution, Rates and Timing

Analytical Estimate (*Glover Balmer Solution*)

- ✓ Rapid
- ✓ Do not require significant input data
- ✓ Cost-effective

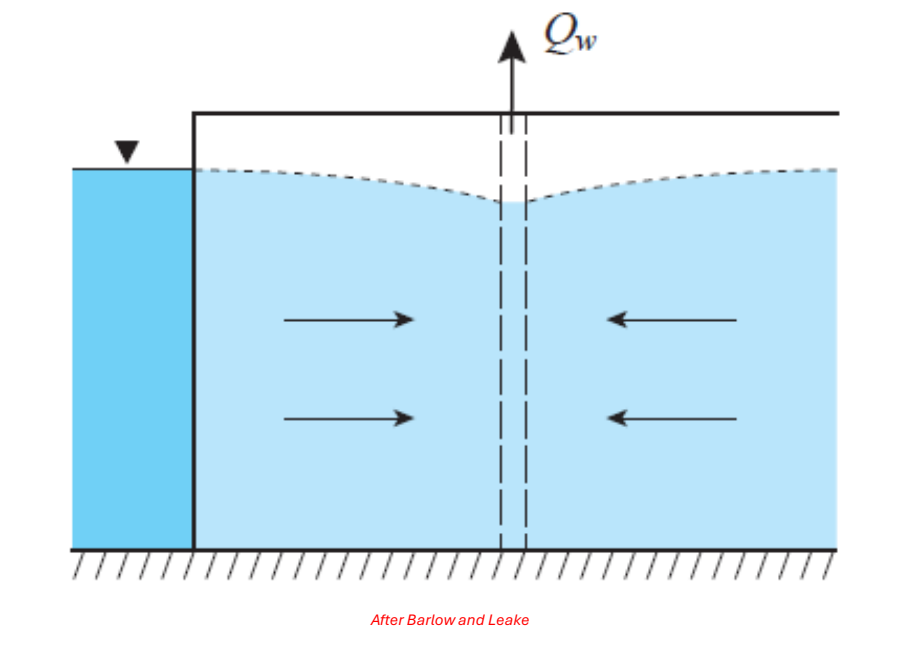
Simplified assumptions (homogenous, idealized aquifer and stream geometry) lead to greater uncertainty in estimates

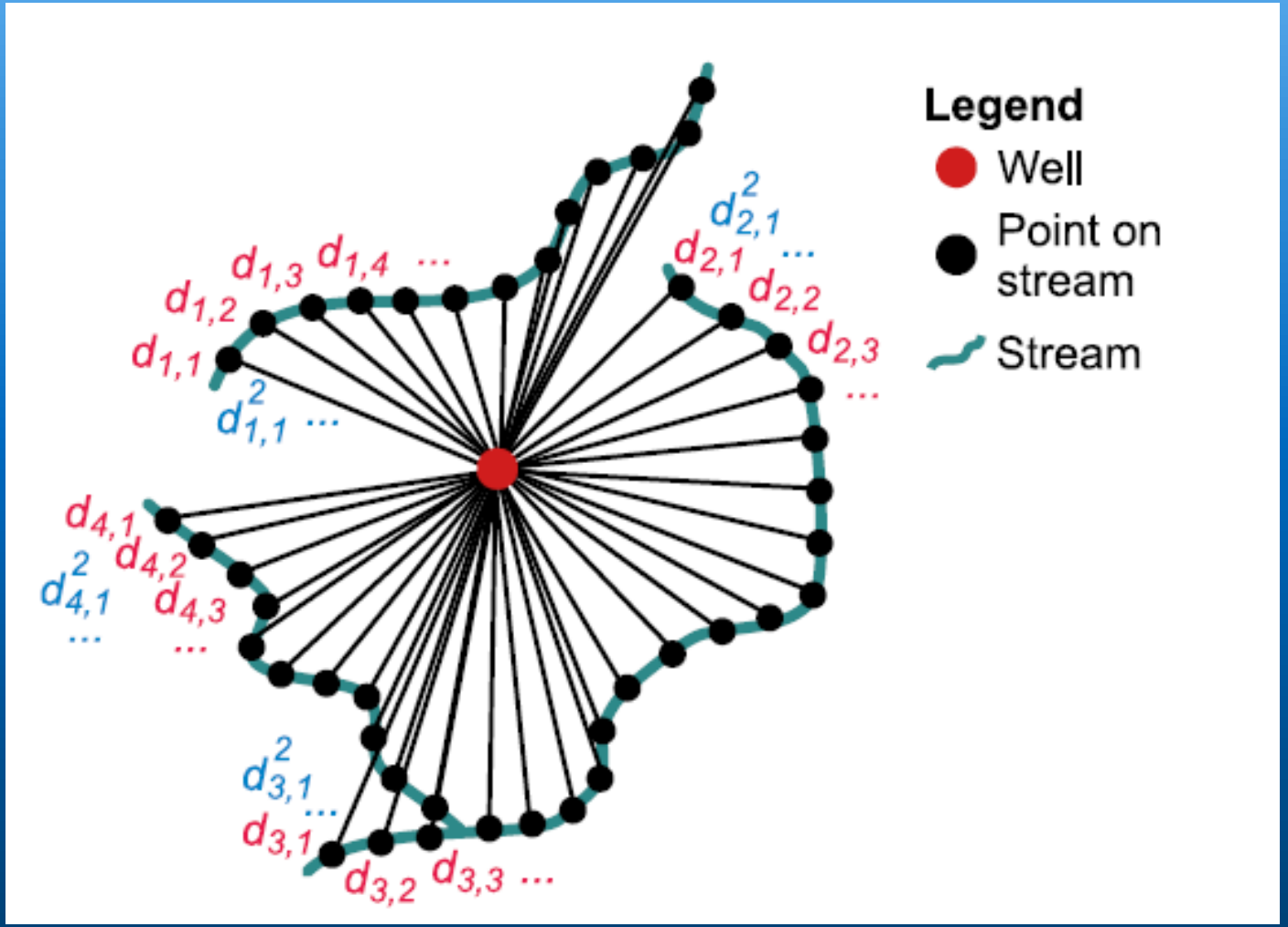




After Barlow and Leake

Analytical Stream Depletion Function (ADF)





Zipper, S. C. et al, 2019. Rapid and Accurate Estimates of Streamflow Depletion Caused by Groundwater Pumping using Analytical Depletion Functions, Water Resources Research, 55, 5807-5829.

Numerical Solutions

Regional Modeling

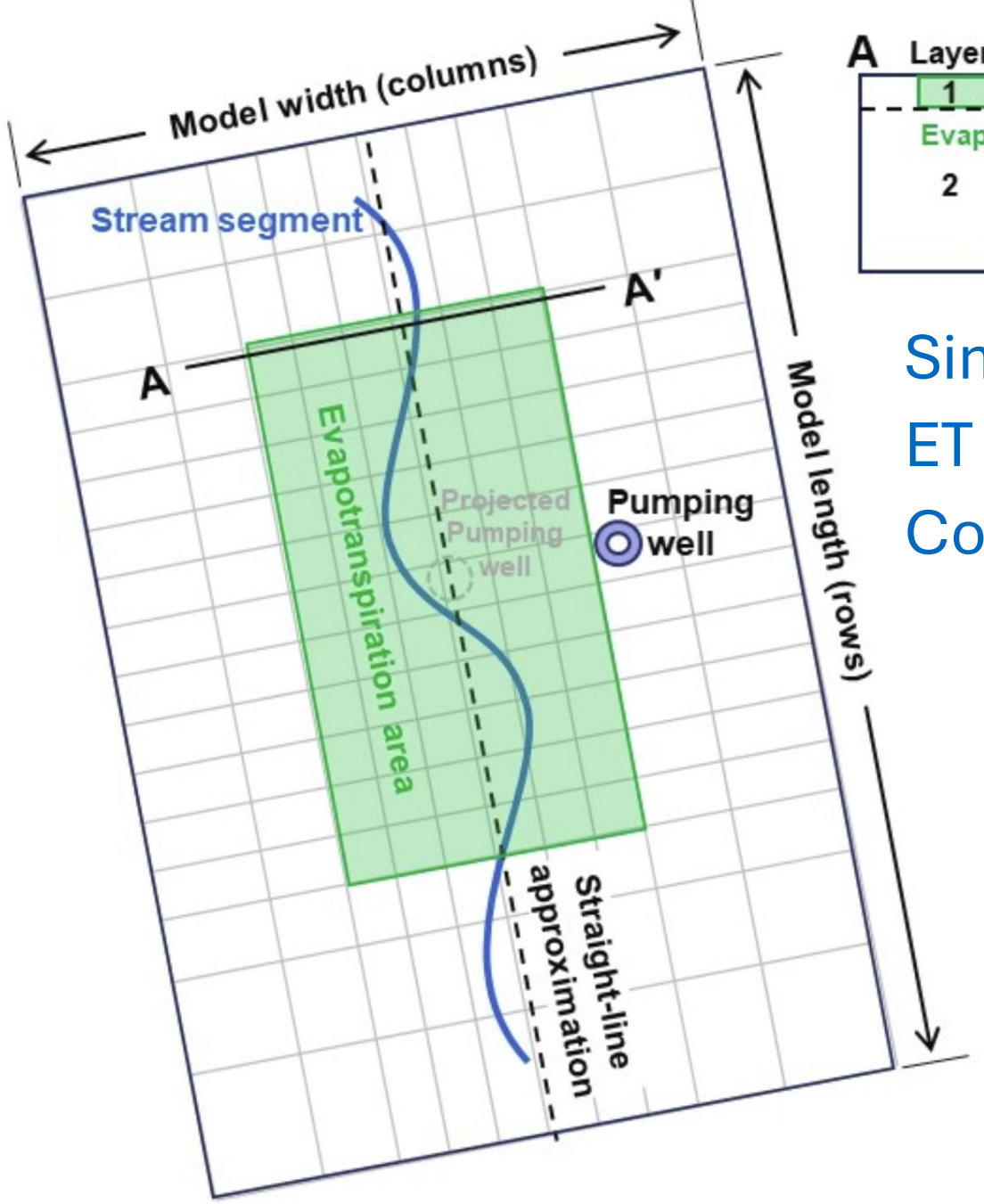
- System complexity (spatial/temporal)
- Baseline simulation: existing conditions
- Scenario simulation: proposed conditions (e.g., additional pumping)
- Differencing to identify changes
  - » Seepage to/from streams
  - » Evapotranspiration
  - » Transboundary or other fluxes
  - » Water levels

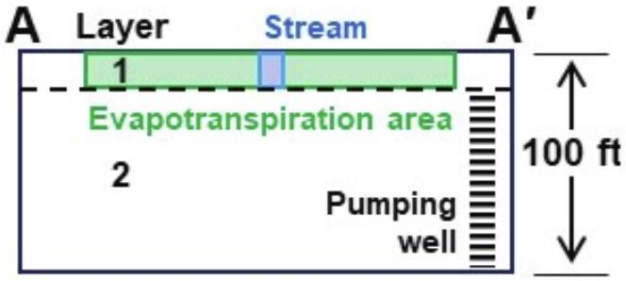
Intermediate Numerical Methods

- Analytical methods do not consider the effect of evapotranspiration (ET), including ET capture or enhancement:
  - » Where large areas of riparian and phreatophyte vegetation exist
  - » Distribution, rates, and volumes of capture can vary widely
  - » Can be a large component of the water budget.
- CaptureMF6 (Halford, 2024) accounts for ET processes, while maintaining a relatively simple approach using site specific conditions

CaptureMF6

- CaptureMF6
  - » EXCEL™
  - » VBA
  - » Modflow-6 models.
- Capabilities
  - » Incorporate phreatophyte ET; and,
  - » Monte-Carlo-type uncertainty analysis.
- MF6 models created:
  - » aquifer dimensions,
  - » stream proximity to groundwater extraction,
  - » area subject to ET





Simple stream

ET footprint

Combined effect

- Stream depletion
- ET capture

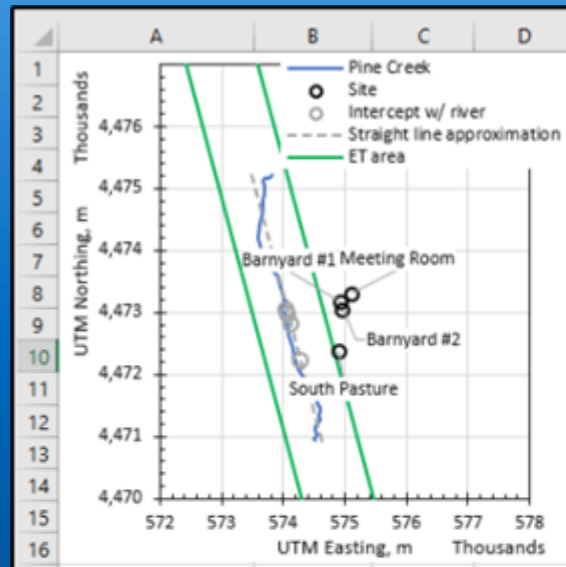
From HalfordHydrology.com

Figure 1.— Simplified MODFLOW6 template for analyzing stream and evapotranspiration capture from proposed pumping.

CaptureMF6

- Multiple models using combinations of inputs
- Inputs are defined with ranges:
  - » Hydraulic conductivity (Kx)
  - » Specific yield (Sy)
  - » Maximum ET rate (ETr)
  - » ET extinction depth (ETd)

Example CaptureMF6 input worksheet



AQ-ET_dimensions	Value	AQ-ET_units
AQ width =	8.0	mi
AQ length =	30.0	mi
Min. cell width =	100.0	ft
Cell multiplier =	1.20	
ET area =	3,000	acres
ET width =	0.7	mi
ET length =	6.7	mi

N models = 135

Tag	Min	Max	Cnt	unit_Plus
NPF.dKx-ftPd_KX	9.00	23.00	5	ft/d
STO.dStorCoeff_SY	0.10	0.20	3	d'less
EVT.year_ETR	0.47	0.86	3	ft/yr
EVT.dETdepth_ETD	3.00	9.00	3	ft

Total = 6.6

Grid Make

N-rows = 83

N-columns = 77

MF write

Process MF6 results

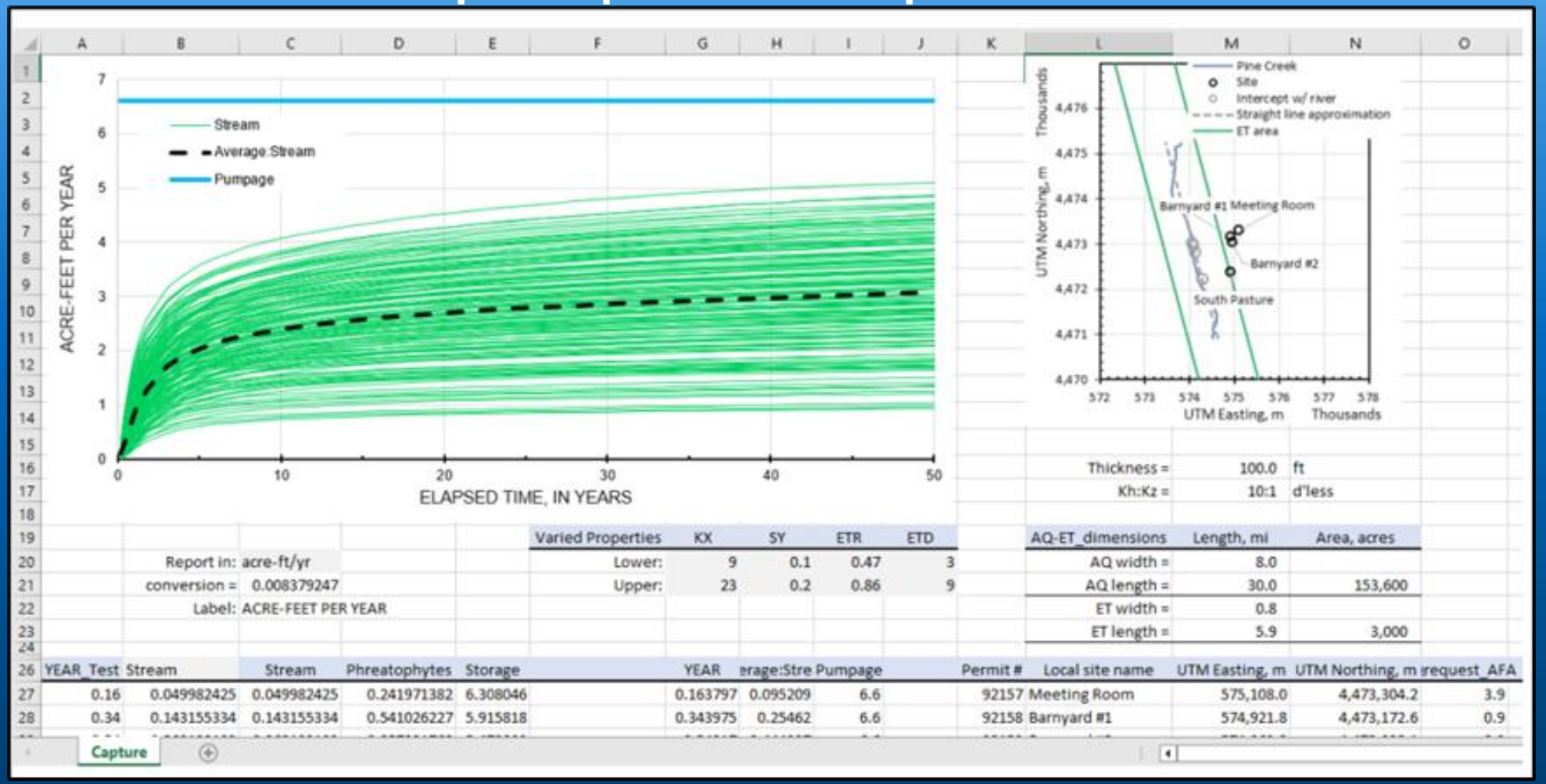
X-Stream segment	Pine Creek	Permit #	Local site name	UTM Easting, m	UTM Northing, m	Qrequest_AFA
573,828	4,475,229	92157	Meeting Room	575,108.0	4,473,304.2	3.9
573,778	4,475,178	92158	Barnyard #1	574,921.8	4,473,172.6	0.9
573,700	4,475,157	92159	Barnyard #2	574,963.2	4,473,038.1	0.9
573,681	4,475,105	92160	South Pasture	574,906.7	4,472,375.6	0.9
573,687	4,475,057					
573,689	4,474,945					

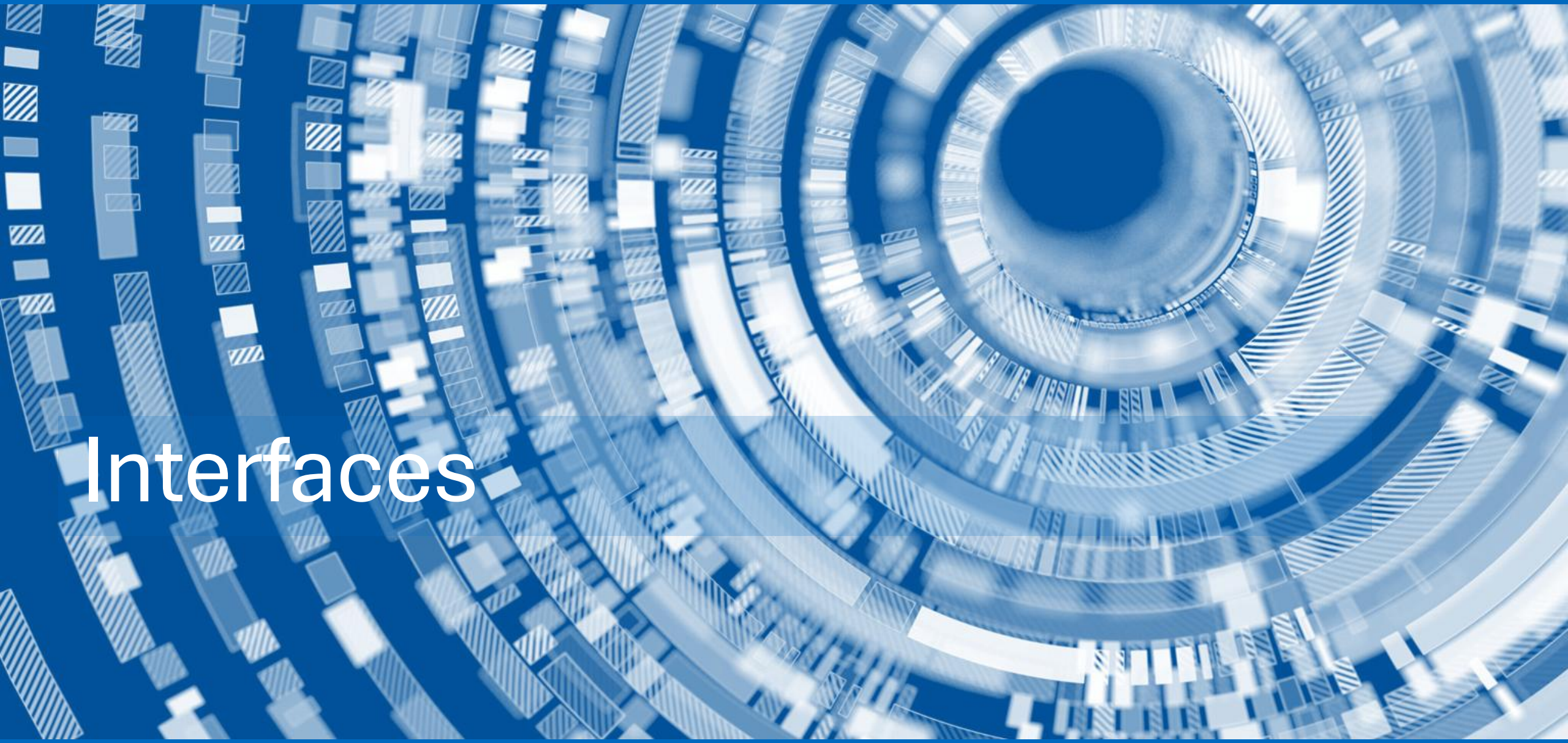
SITE

CaptureMF6 Output

- Monte Carlo type analysis
- Ensemble of results

Example CaptureMF6 output worksheet



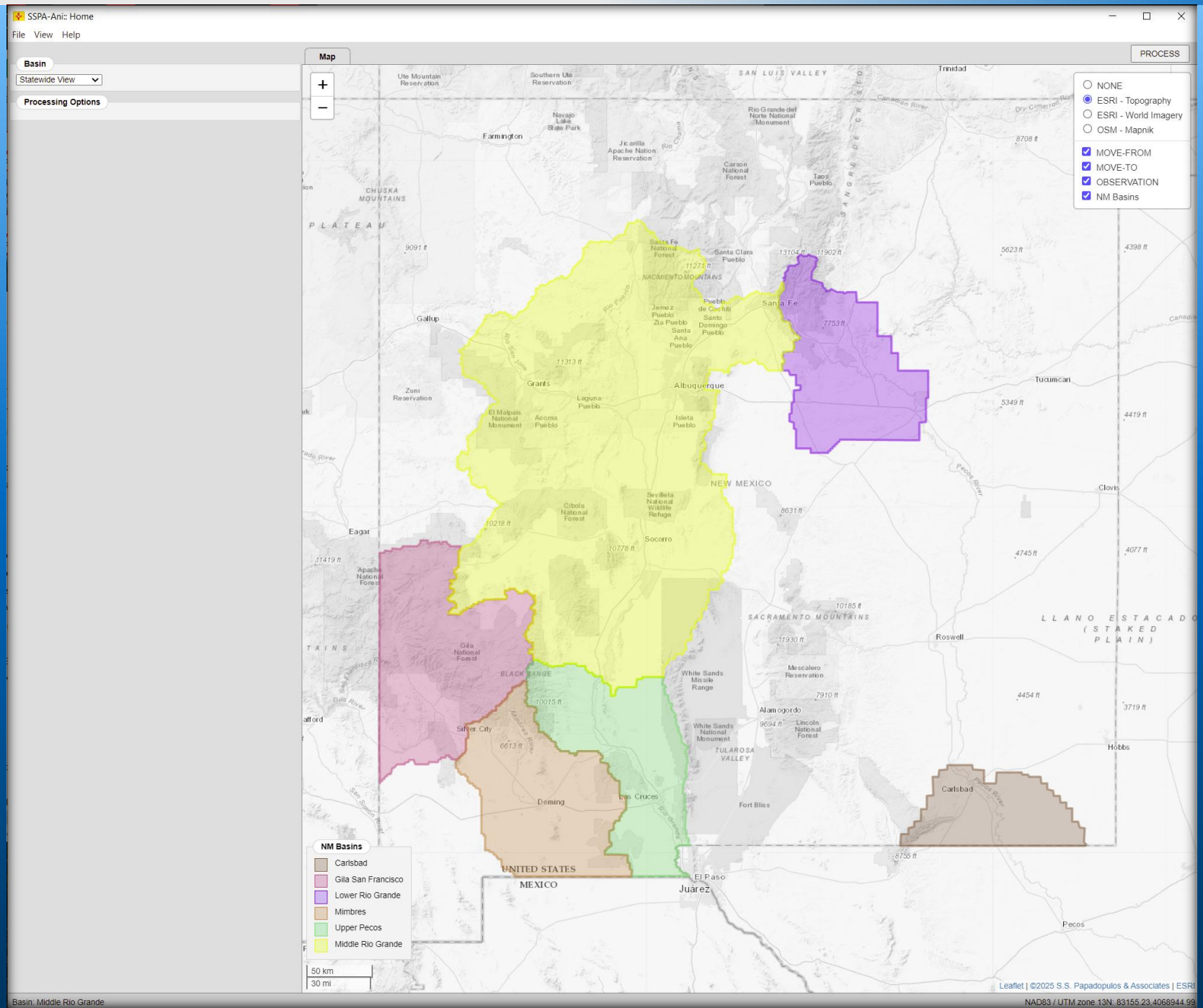

Interfaces

Customized Map-Based Interfaces

- Rapid scenario configuration: explore options
- Graphical and tabular summaries
- Spatial and temporal insights
- Analytical solutions implemented on river networks
- Regional numerical models incorporating complex hydrogeology

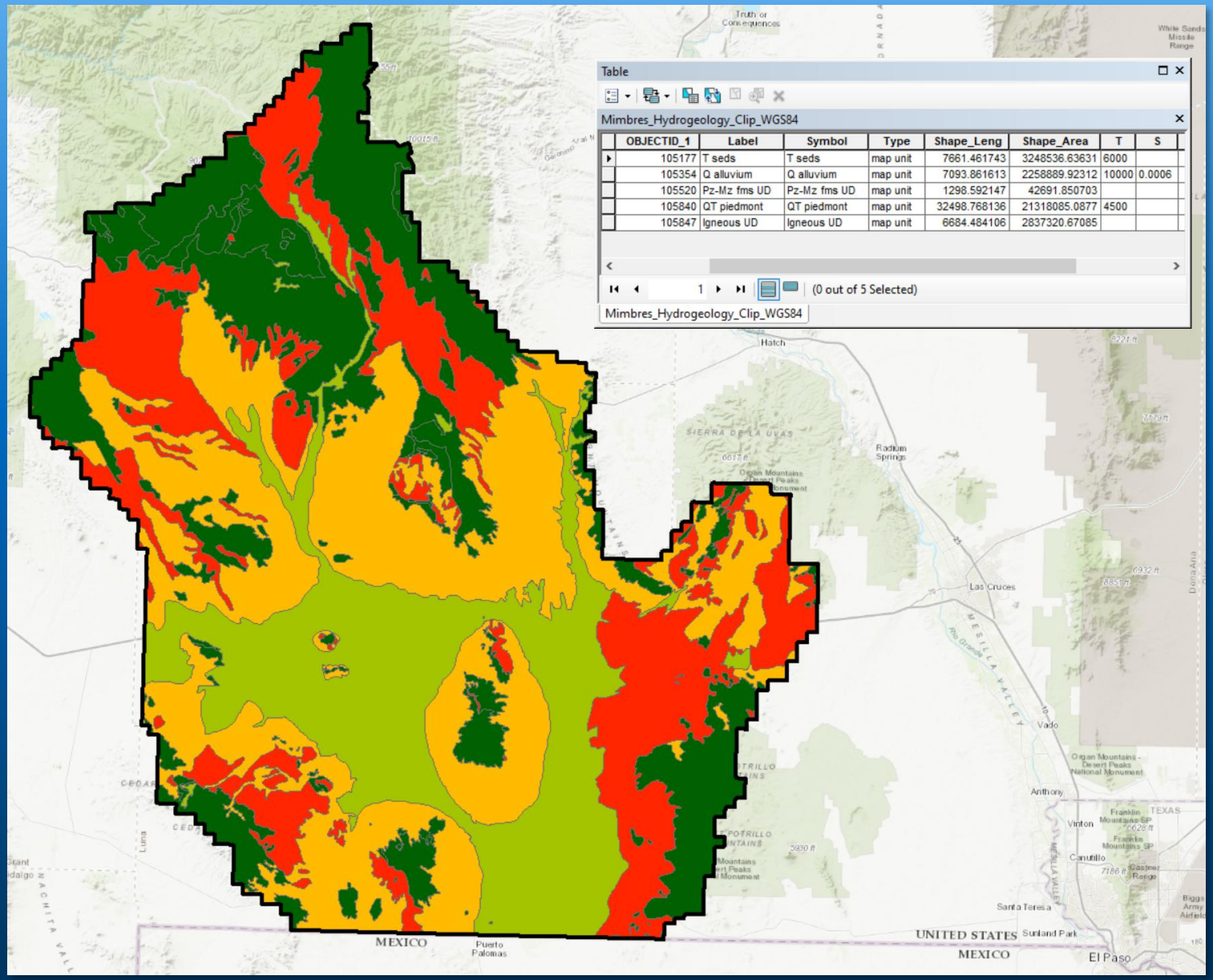
Ani
“ahh-Knee”
(Analytical Interface)

- Statewide New Mexico Map
- Select basins by clicking on individual polygon



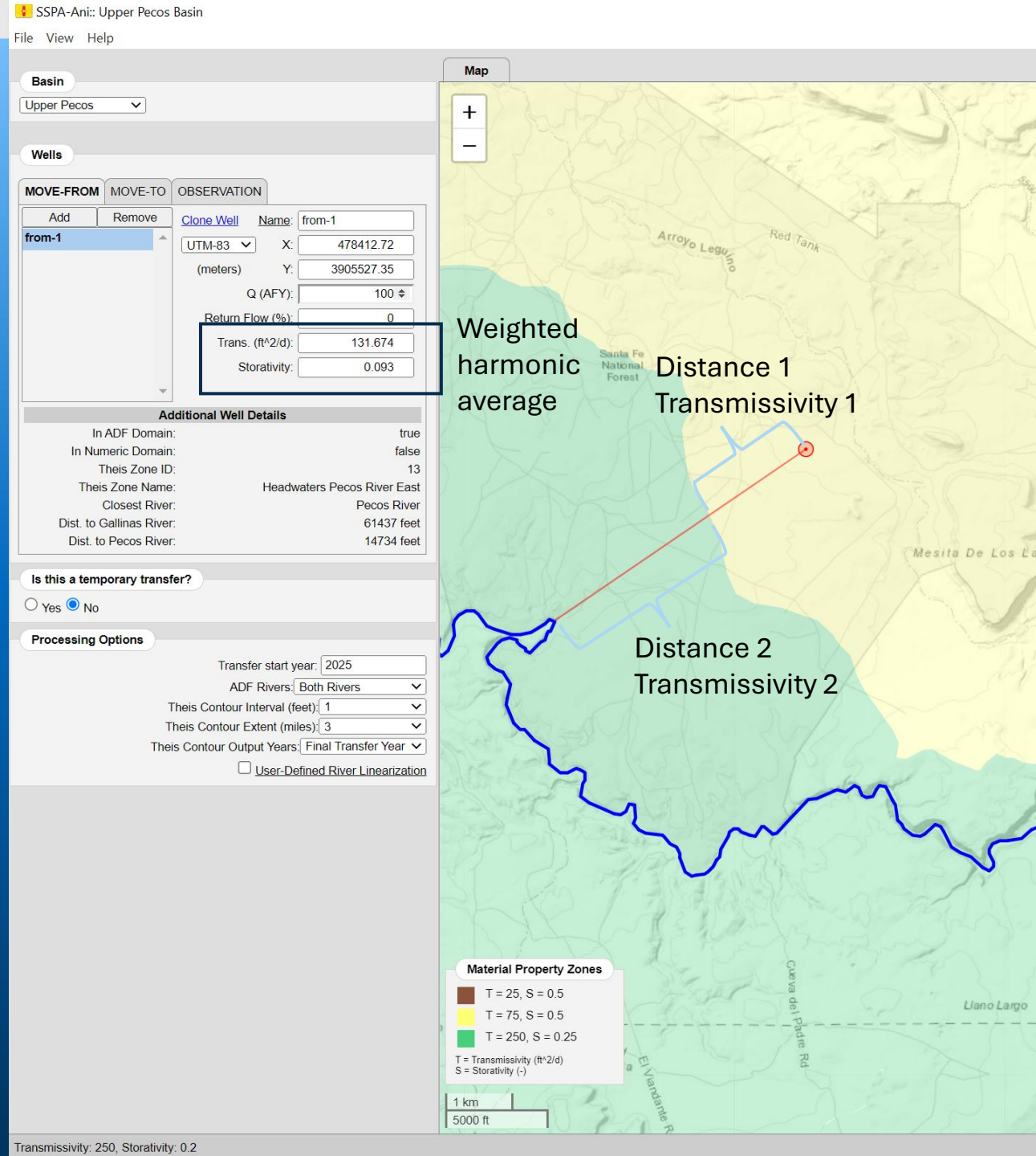
Basin Data Example

- Mimbres Basin
- Lumped/simplified properties
- 5 hydraulic property categories

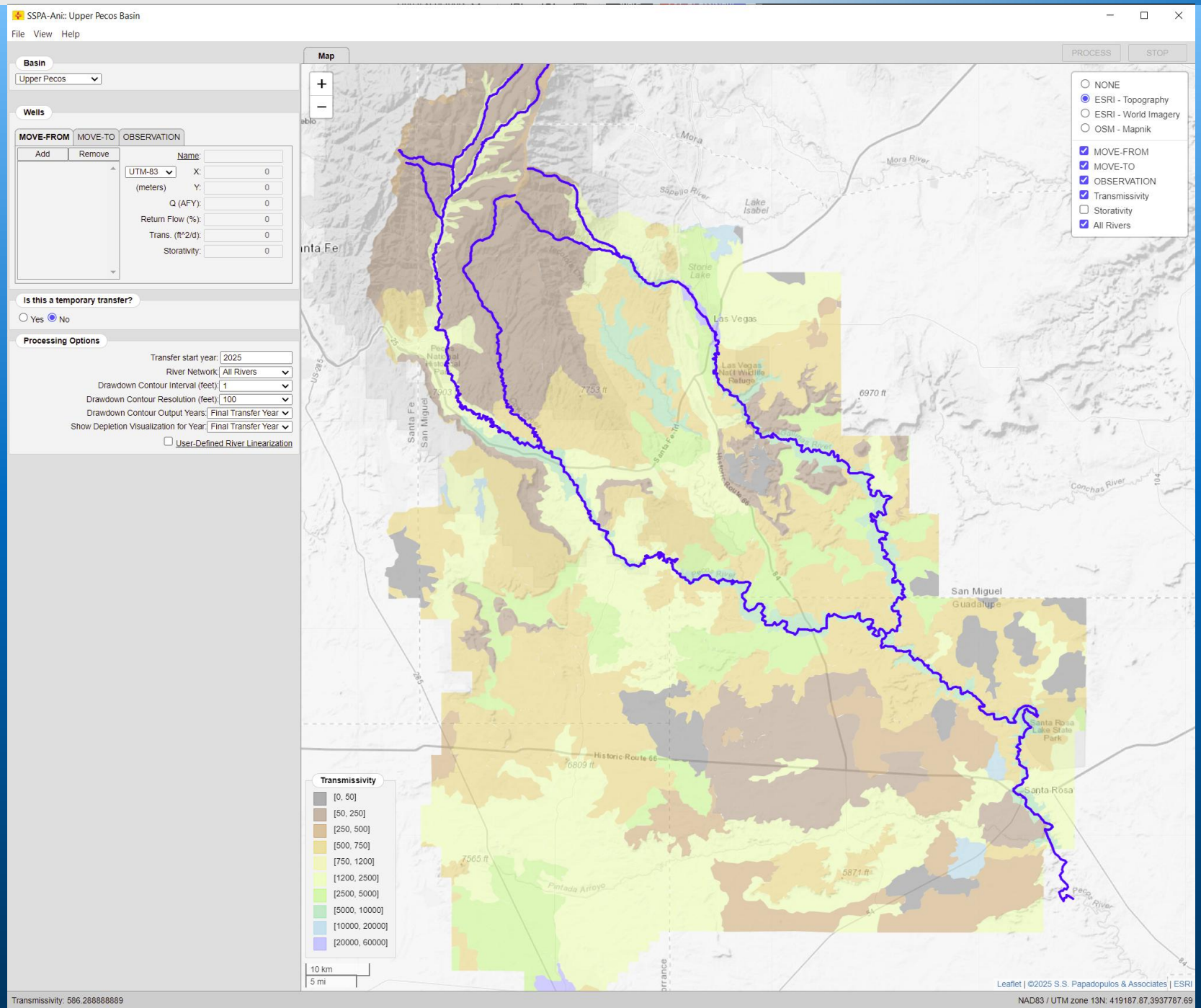


Spatial Transmissivity Weighting

- Aquifer properties from distance-weighted harmonic average
- User needs to critically evaluate T,S
- Manual override available

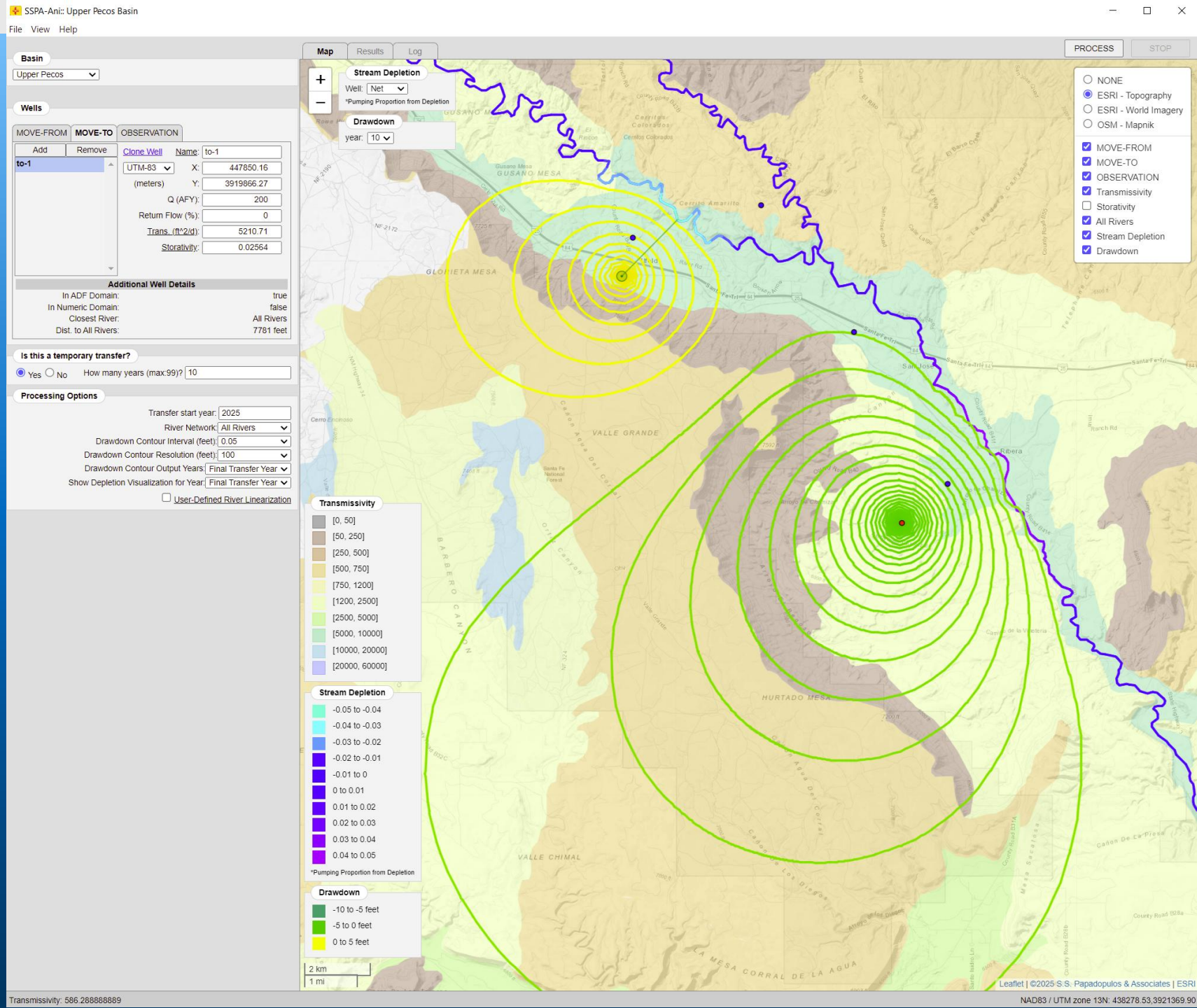


Upper Pecos Basin



Upper Pecos Example

- Move-From downstream
- Move-To upstream
- Same pumping rate
- 10-year transfer
- Drawdown at 10 years



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Upper Pecos Example

- Move-From downstream
- Move-To upstream
- Same pumping rate
- 10-year transfer
- Color coded depletion-accretion segments

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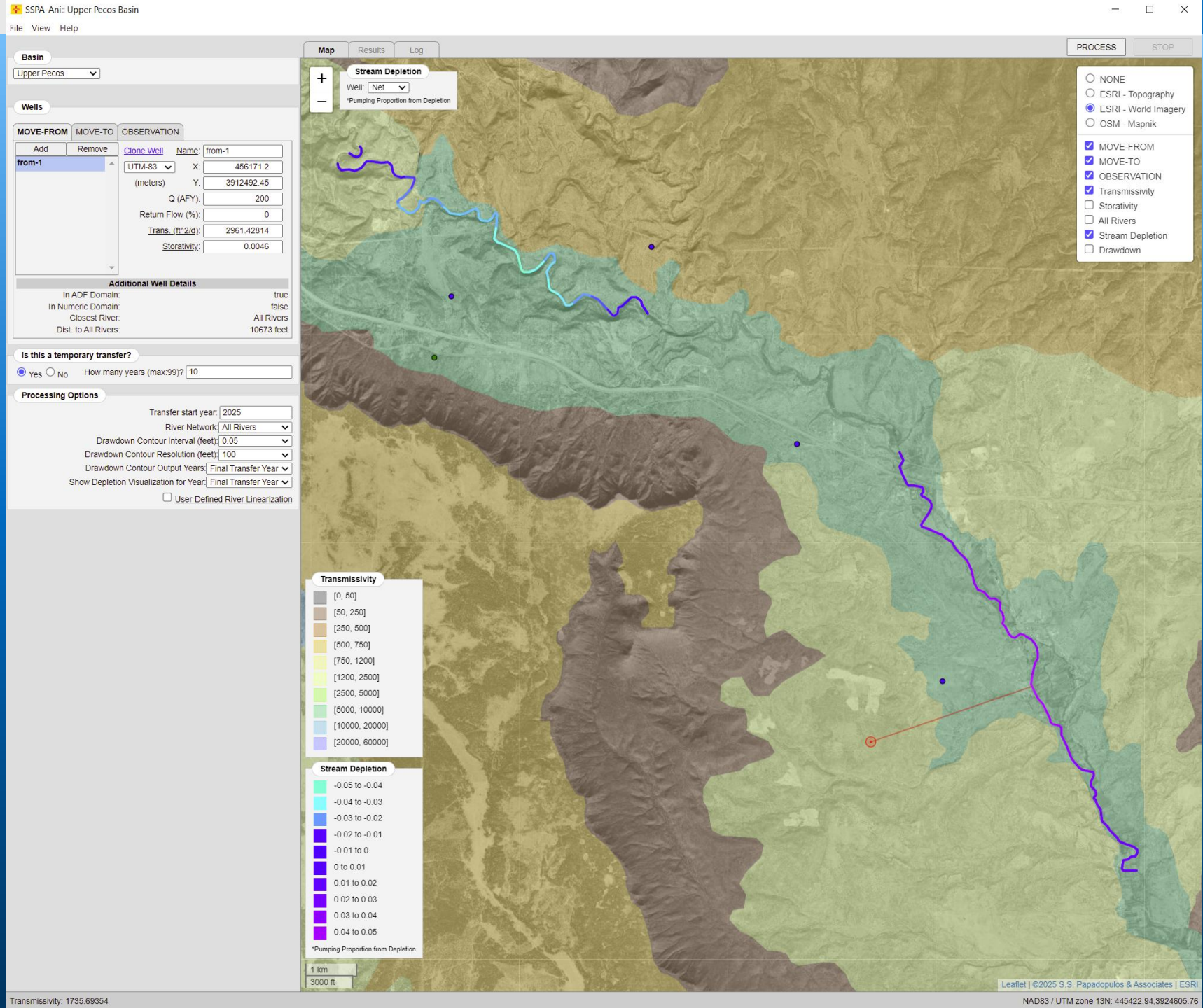
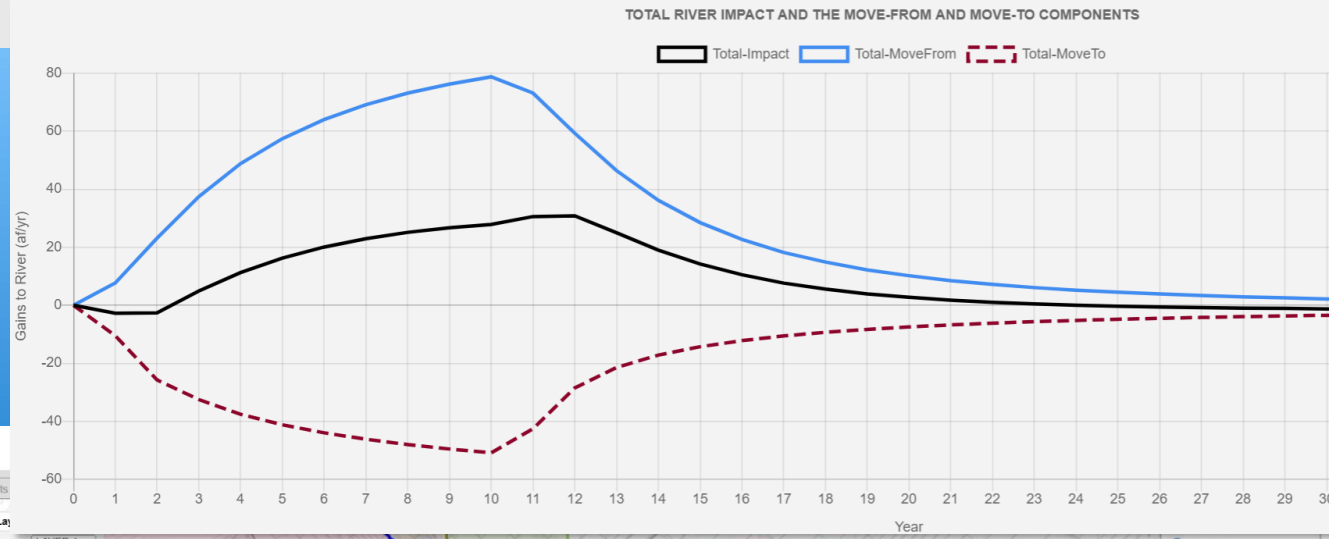
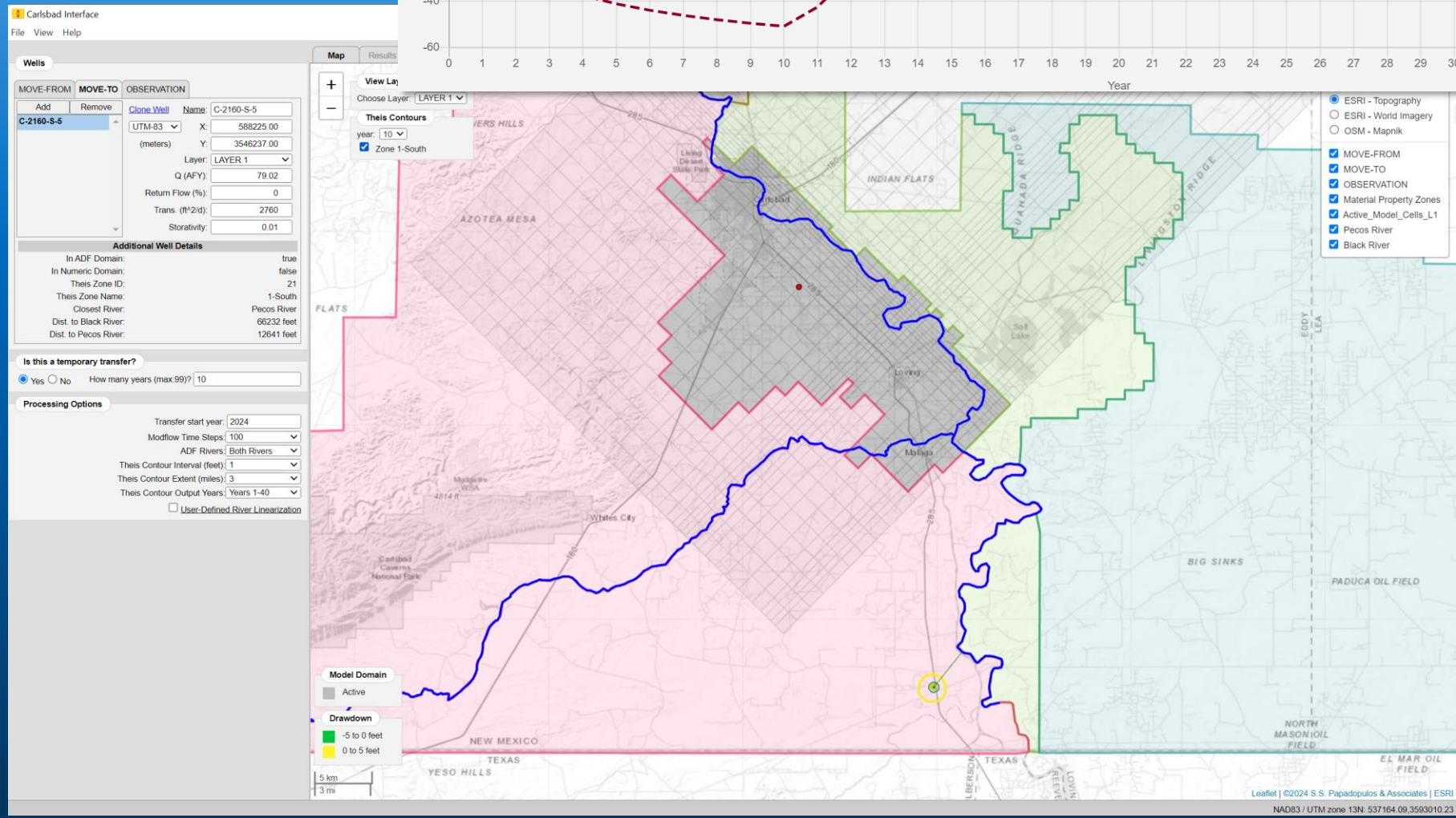


Hybrid Interface

- Numerical groundwater model (MODFLOW)
- Analytical methods (ADF)
- Output from both methods are combined for the results





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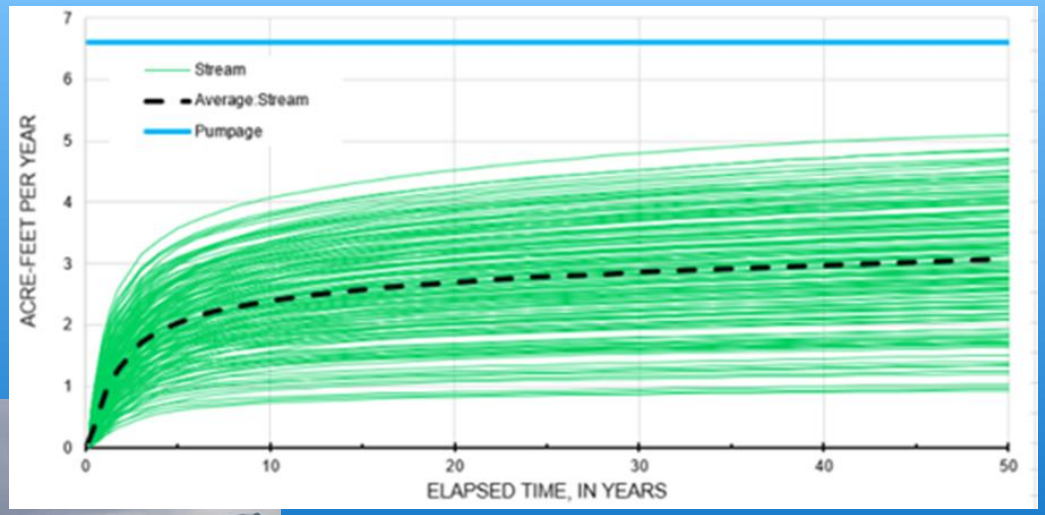
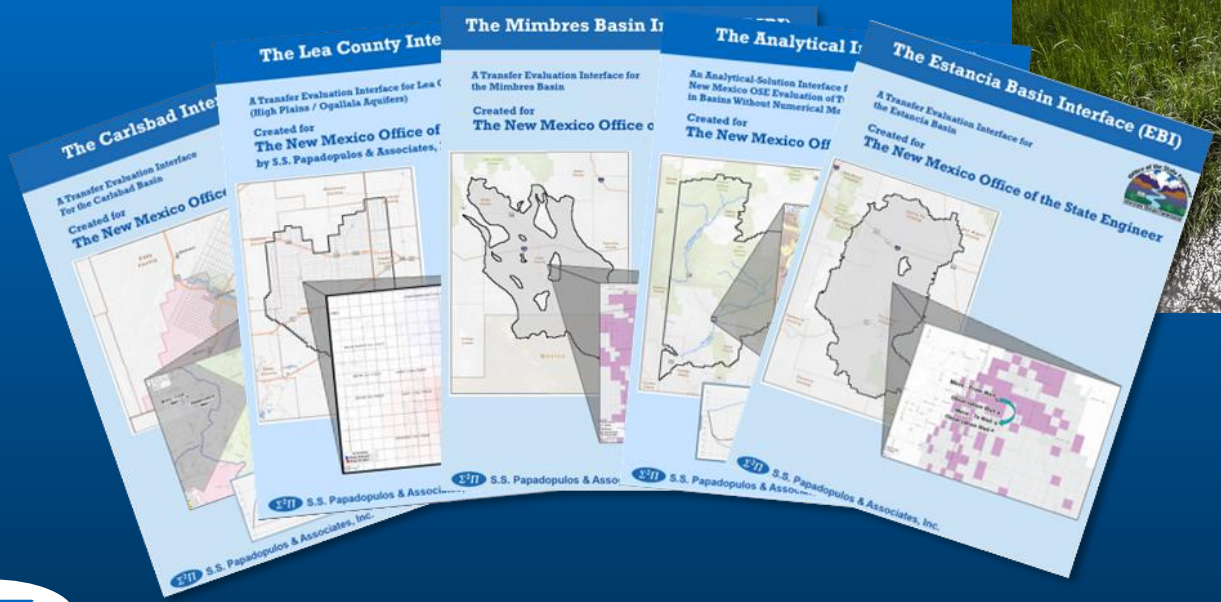
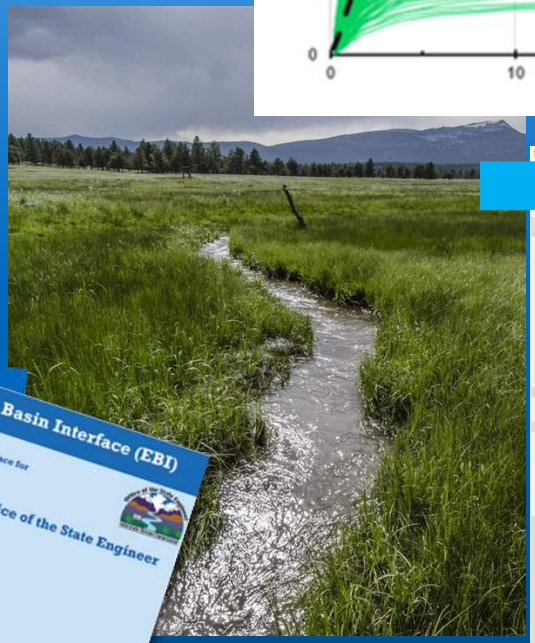
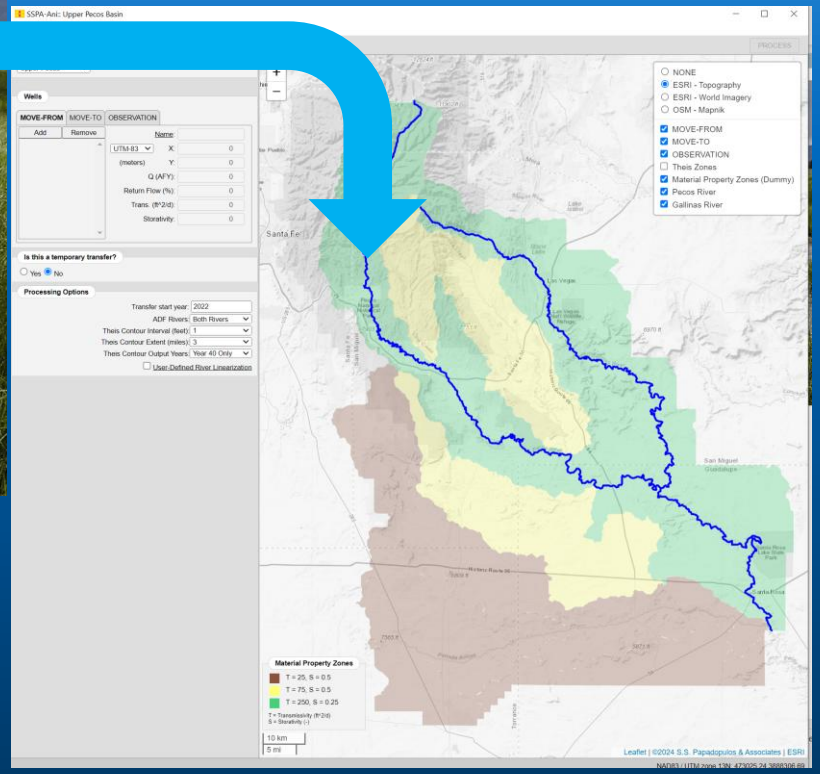
Summary

- Estimate stream depletion (pumping impacts)
- Incorporate variability
  - » Spatial
  - » Scenario
  - » Parameter
- Rapidly assess options









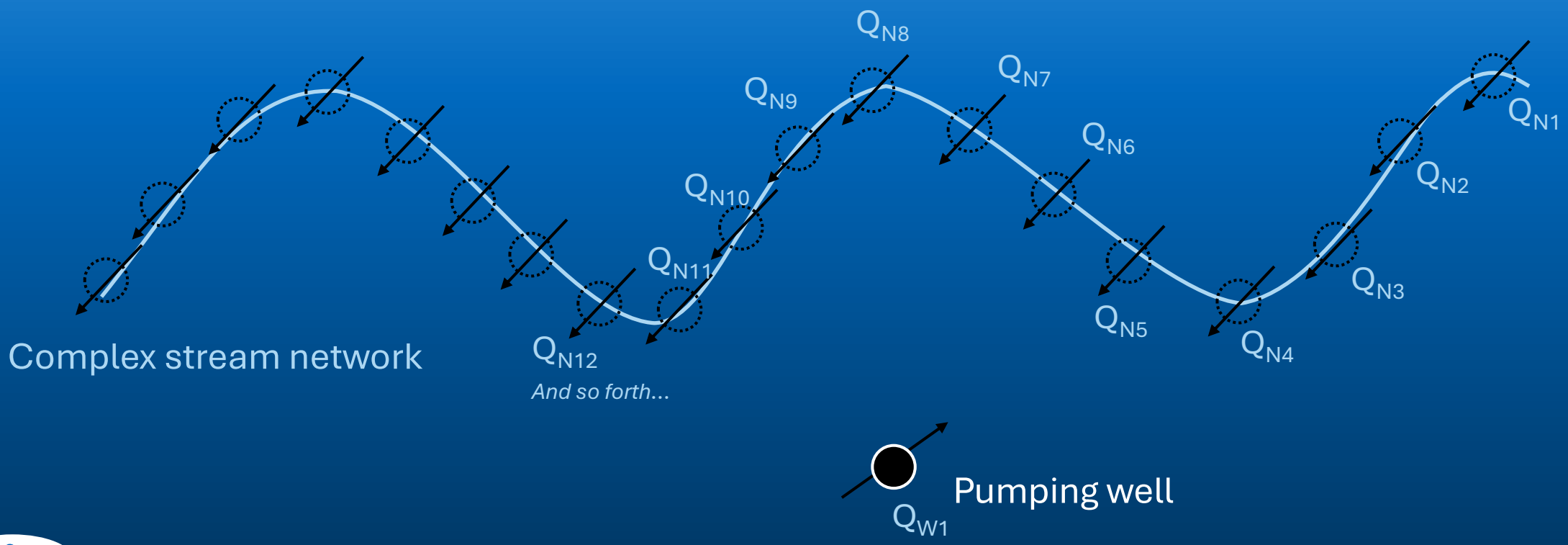
Analytical Interface (Ani)

Questions?

DDF Methodology

Representation of the river boundary in DDF

DDF solves a system of linear equations for the injection coincident with the stream nodes such that the drawdown at the stream boundary is zero.



DDF Methodology

Aggregated head change at given location is calculated as:

$$\Delta h = \sum_{i=1}^{N} Q_i d(r)_i + \sum_{w=1}^{M} Q_w d(r)_w$$

Where:

Q_i is the injection at each node (solved by DDF)

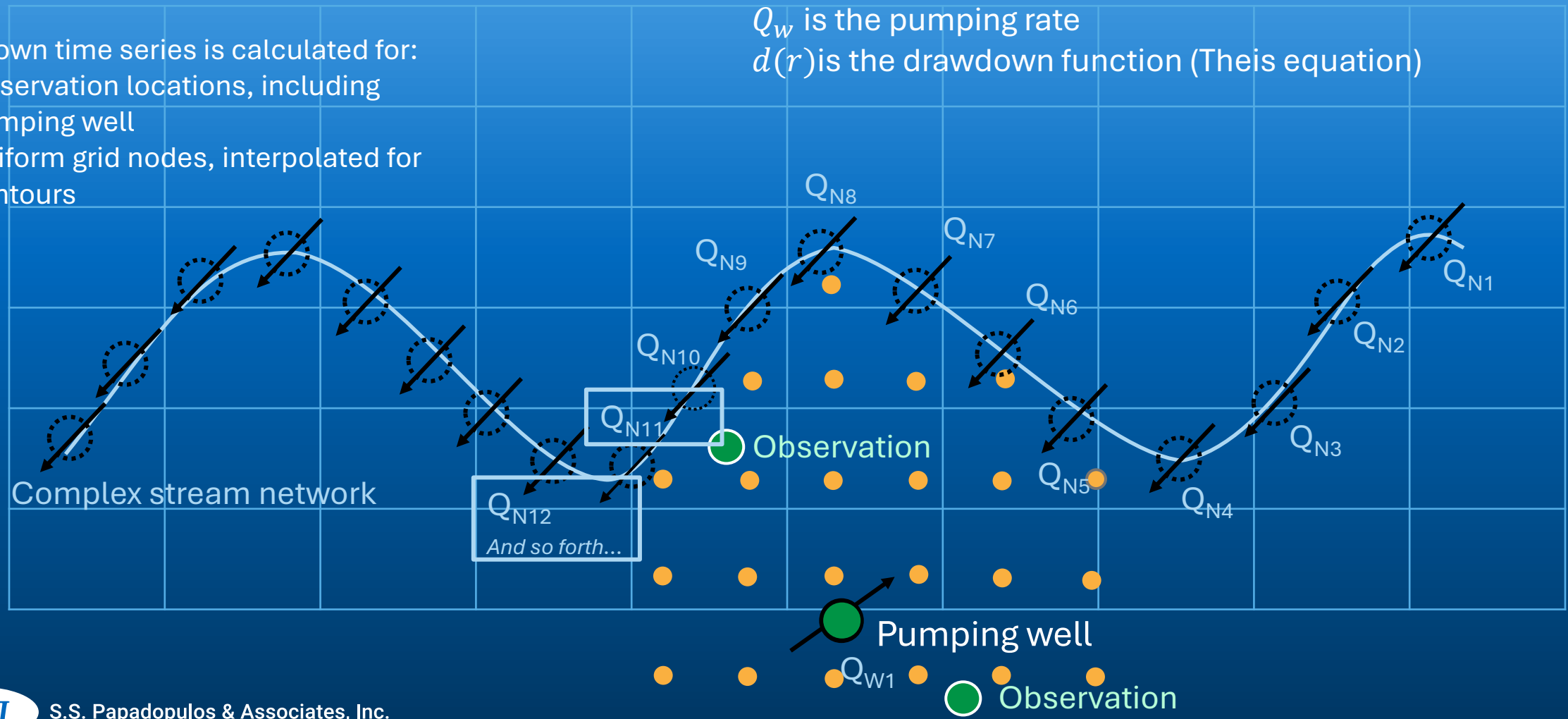
Q_w is the pumping rate

$d(r)$is the drawdown function (Theis equation)

Drawdown time series is calculated for:

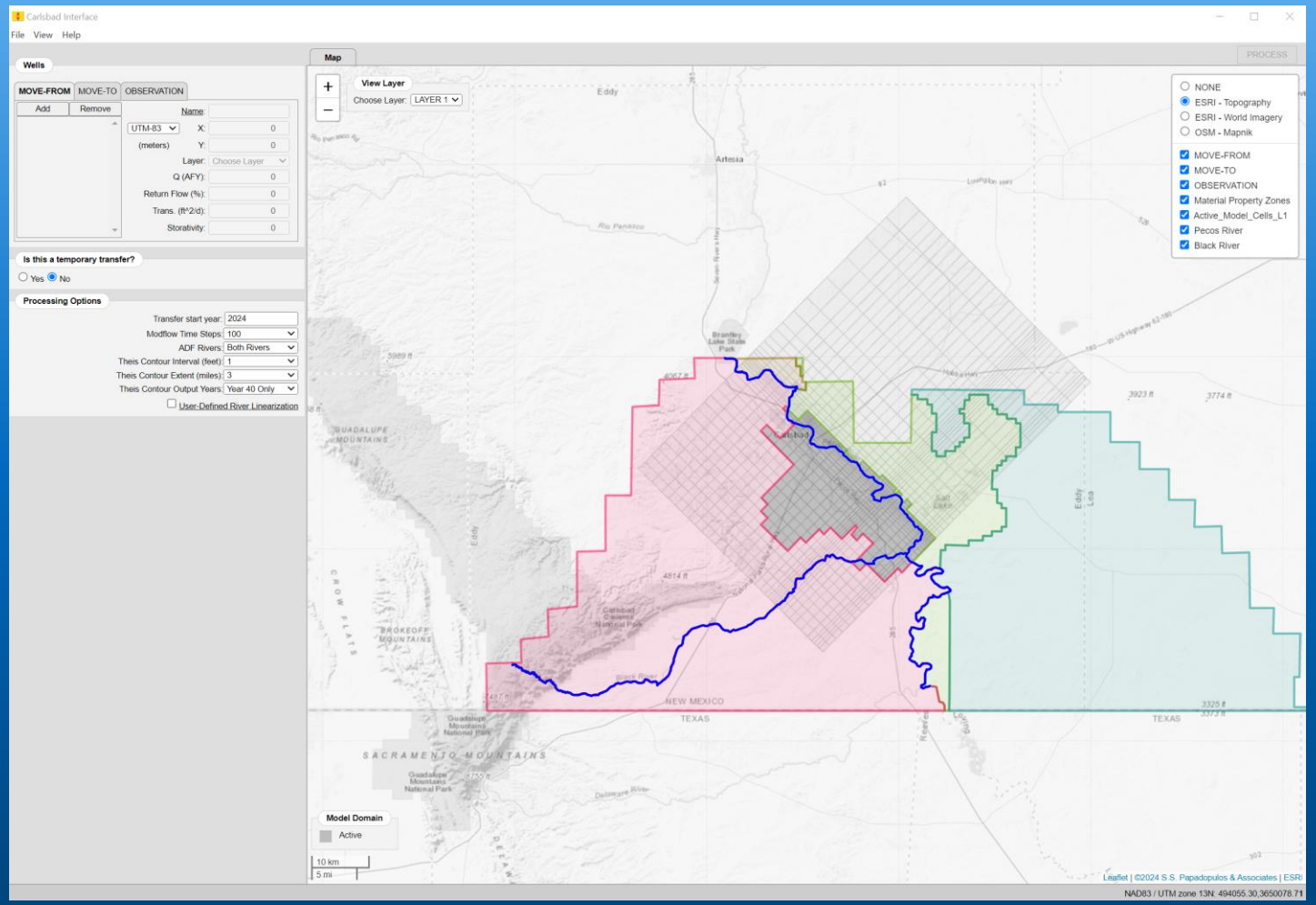
(1) Observation locations, including pumping well

(2) Uniform grid nodes, interpolated for contours



Graphical Interfaces

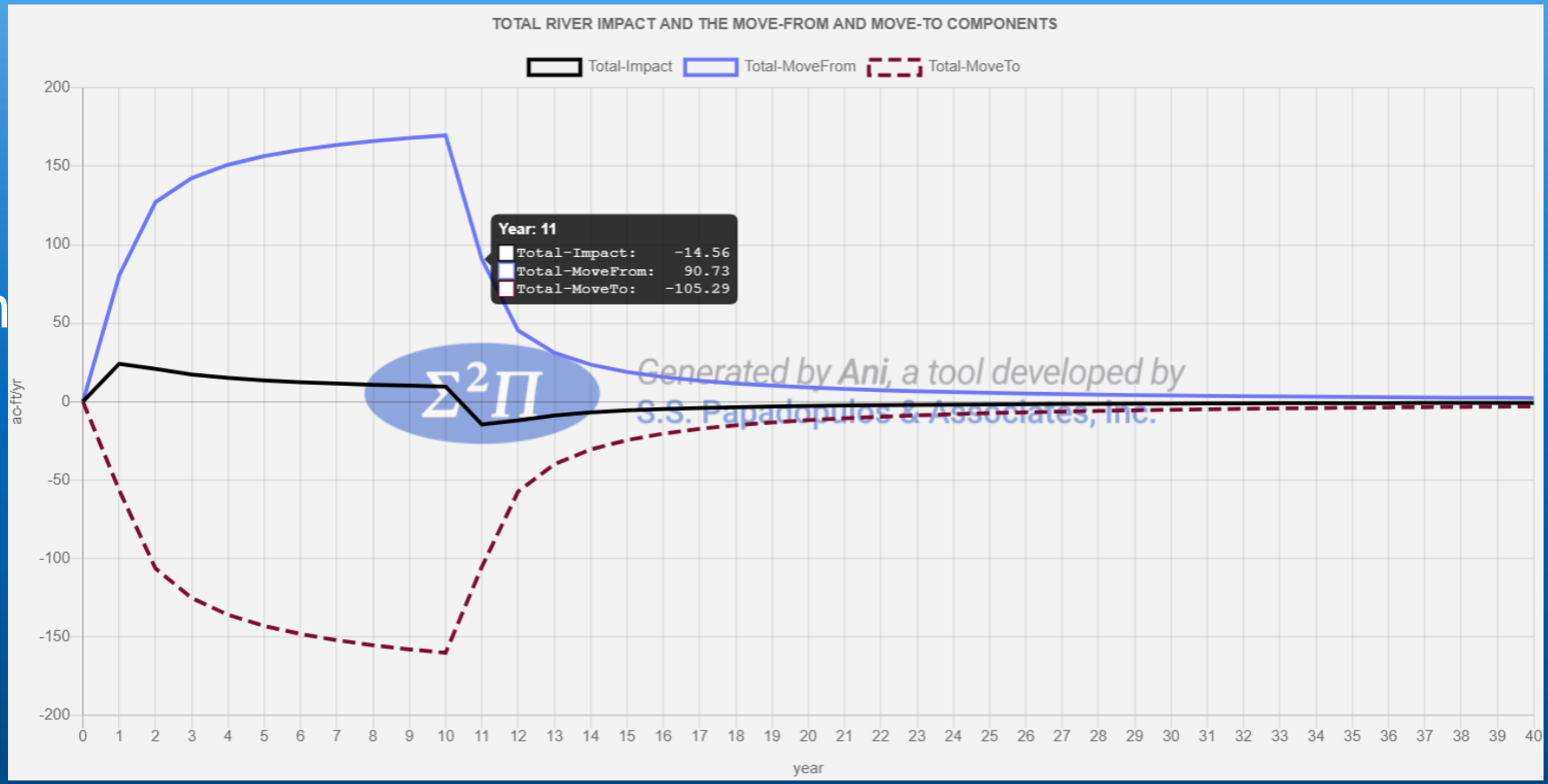
- Provide user access:
  - » Intuitive interface
  - » Dialog entries
  - » Extensive messaging
  - » *Users must understand the outputs*
- Packaged analyses, e.g.,
  - » Governing equations (**Theis, Glover Balmer**)
  - » **Numerical models** (flow, transport)
  - » Empirical models (Blaney Criddle)
  - » Statistical models (ungauged basin flow)
  - » Results visualization
- Published/private data accessed behind the scenes (local or cloud)



Hybrid Analytical-GW Model Interface

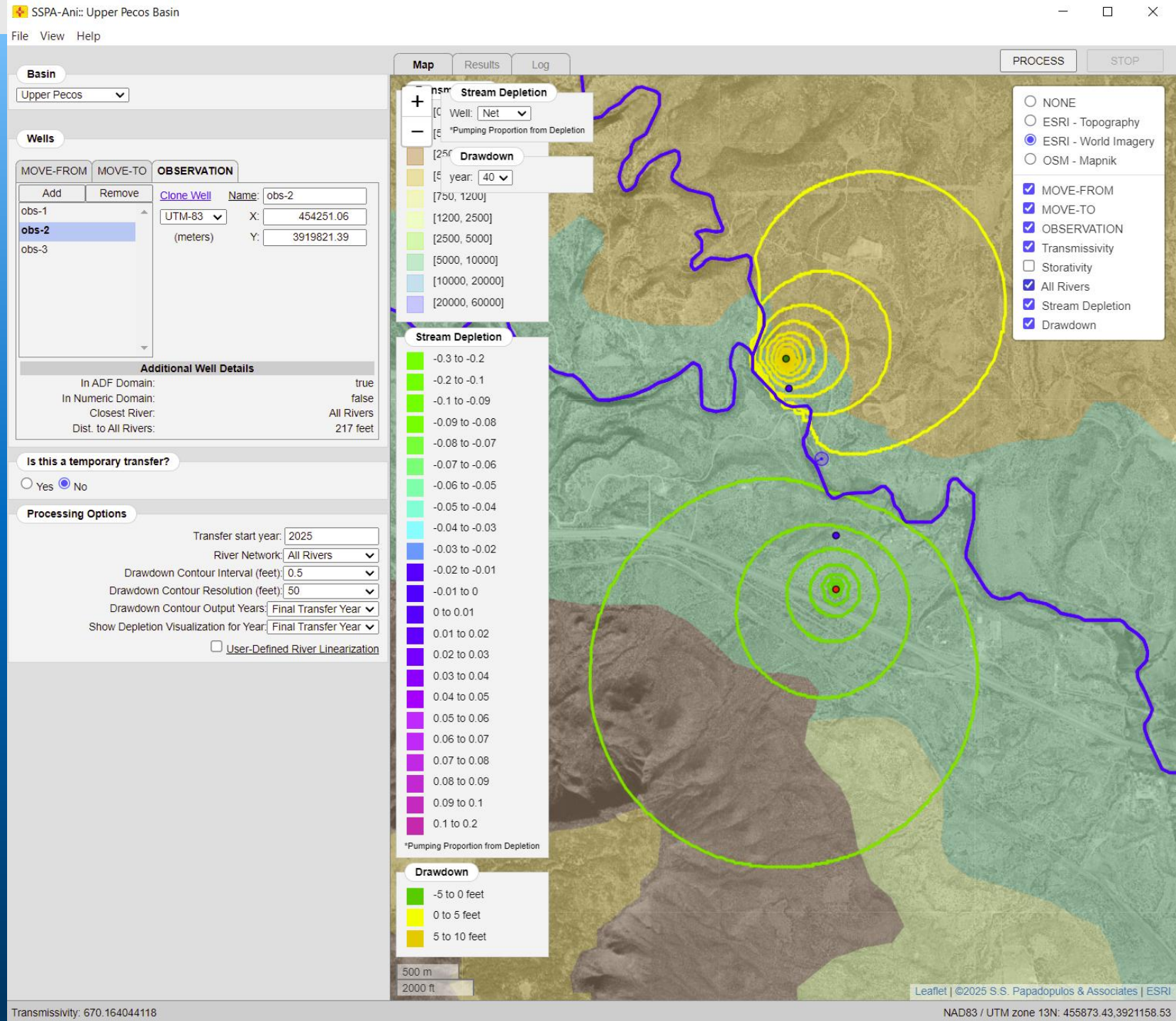
Upper Pecos Example

- Move-From downstream
- Move-To upstream
- Same pumping rate
- Permanent transfer



Upper Pecos Example II

- Move-From downstream
- Move-To upstream
- Same pumping rate
- Permanent transfer
- Drawdown at 10 years



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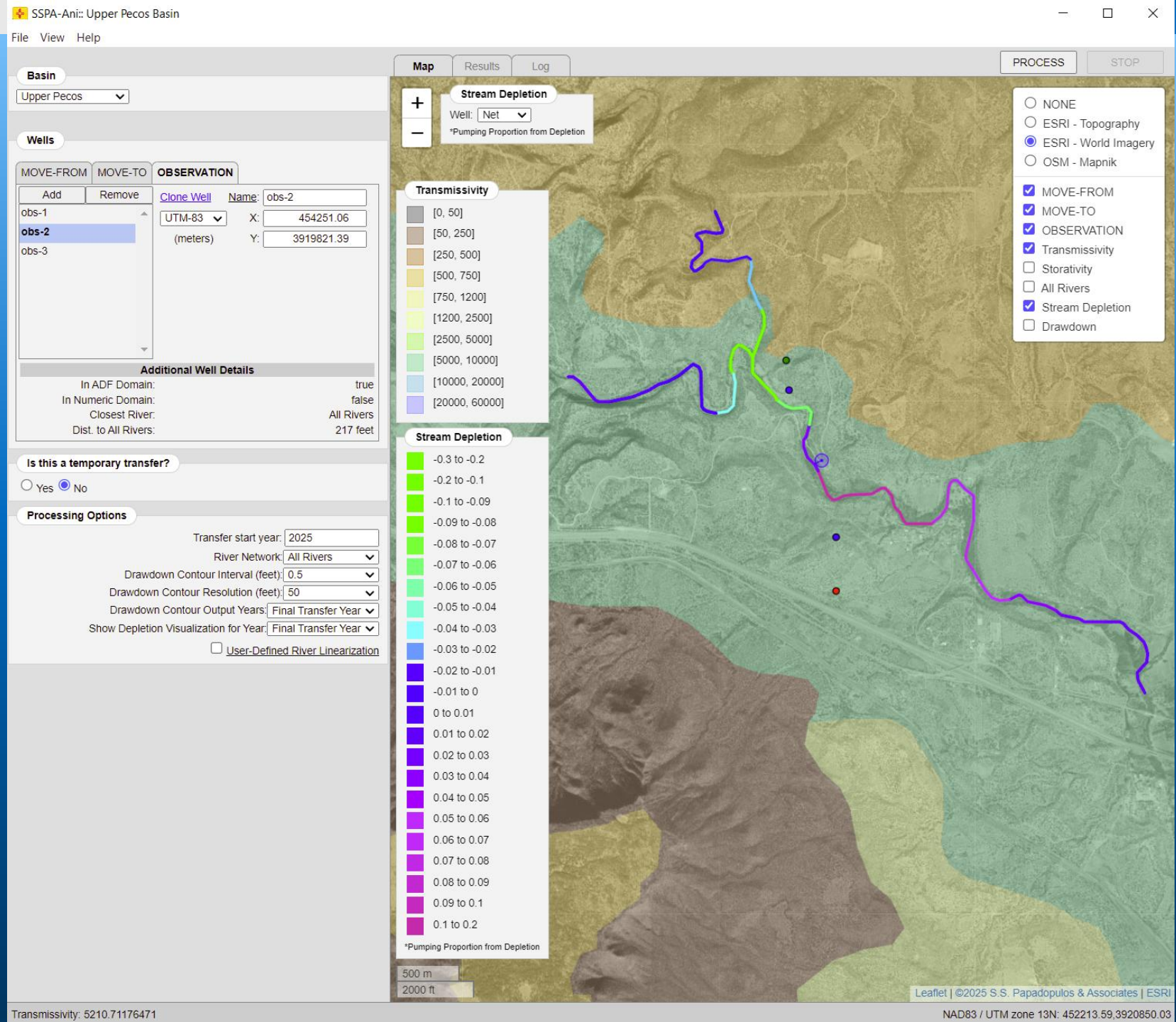
Upper Pecos Example II

- Move-From downstream
- Move-To upstream
- Same pumping rate
- 10-year transfer
- Color coded depletion-accretion segments



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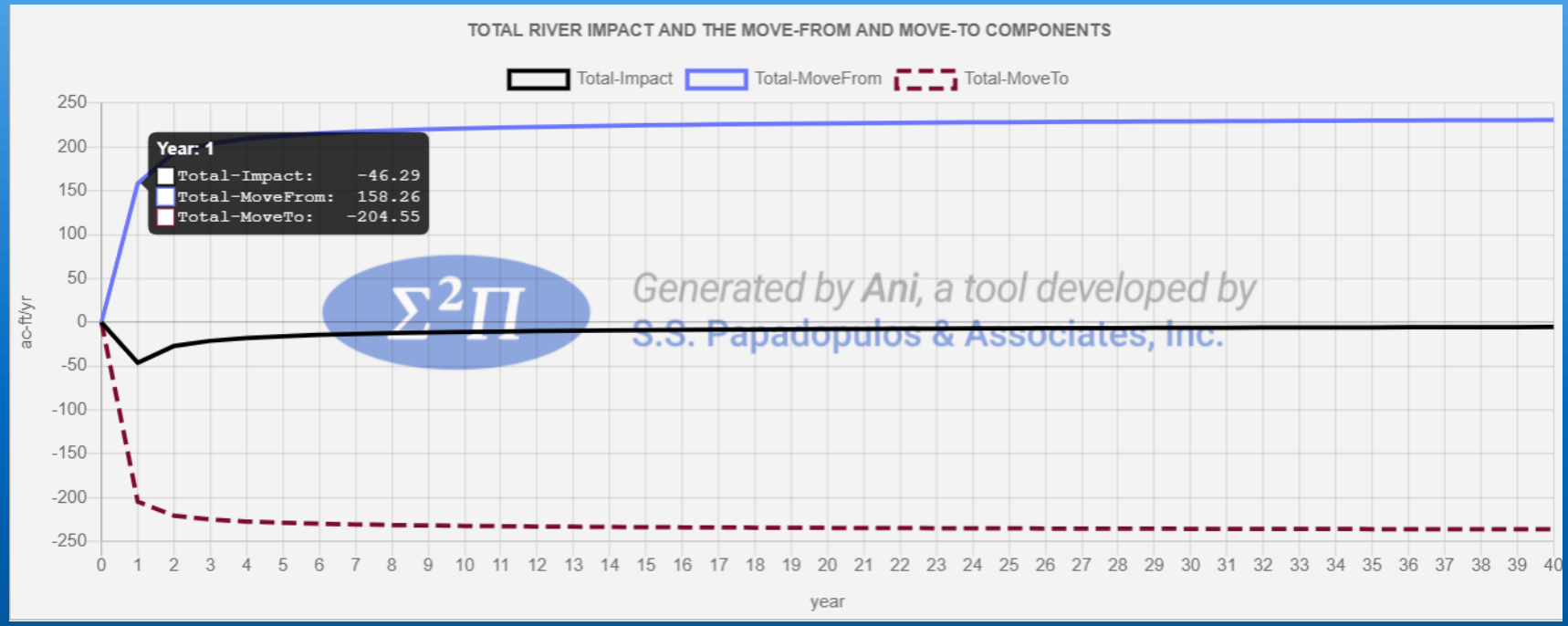
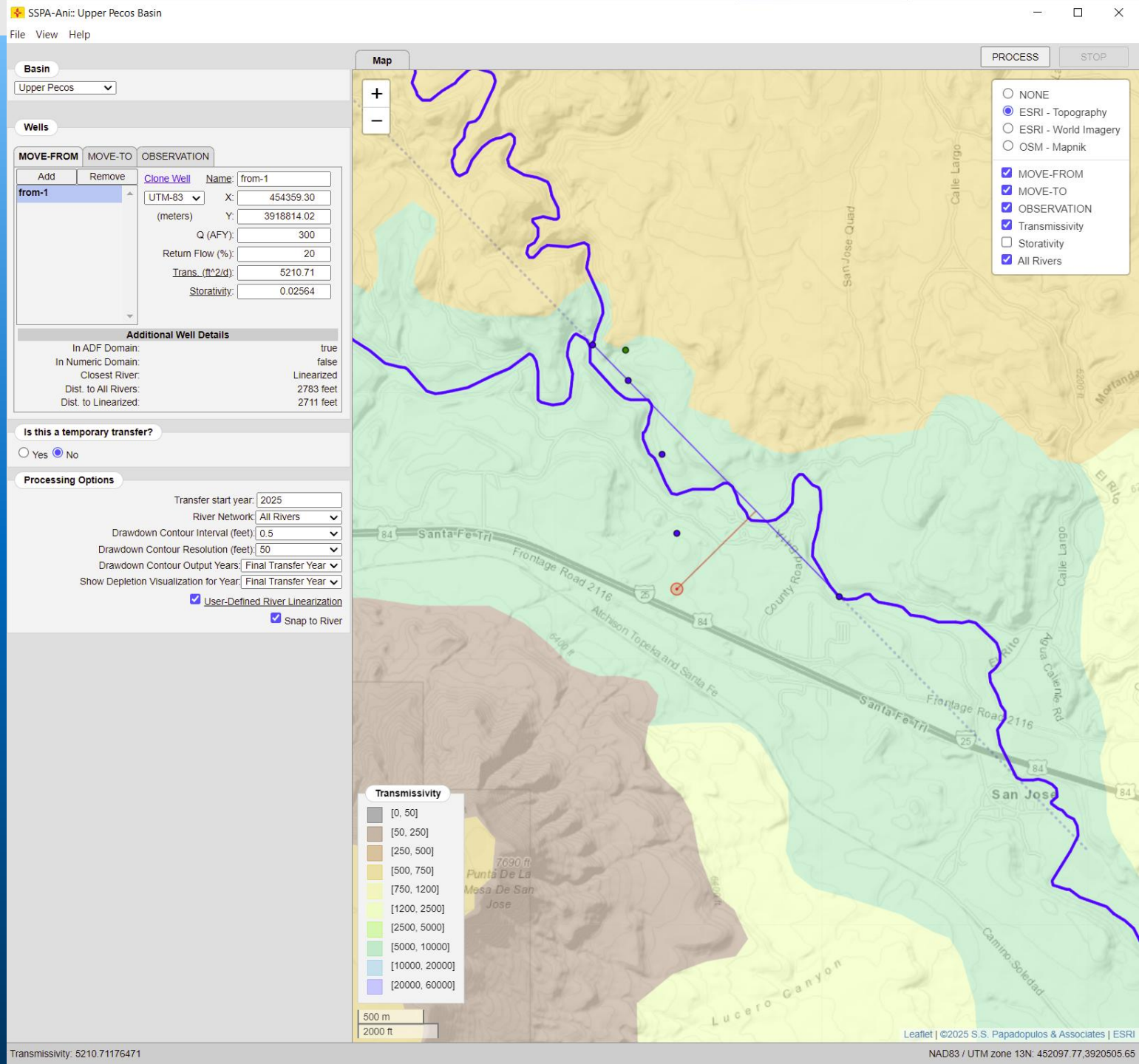
Upper Pecos Example II

- Move-From downstream
- Move-To upstream
- Same pumping rate
- Permanent transfer



Upper Pecos Example II

- Implementing a linear river



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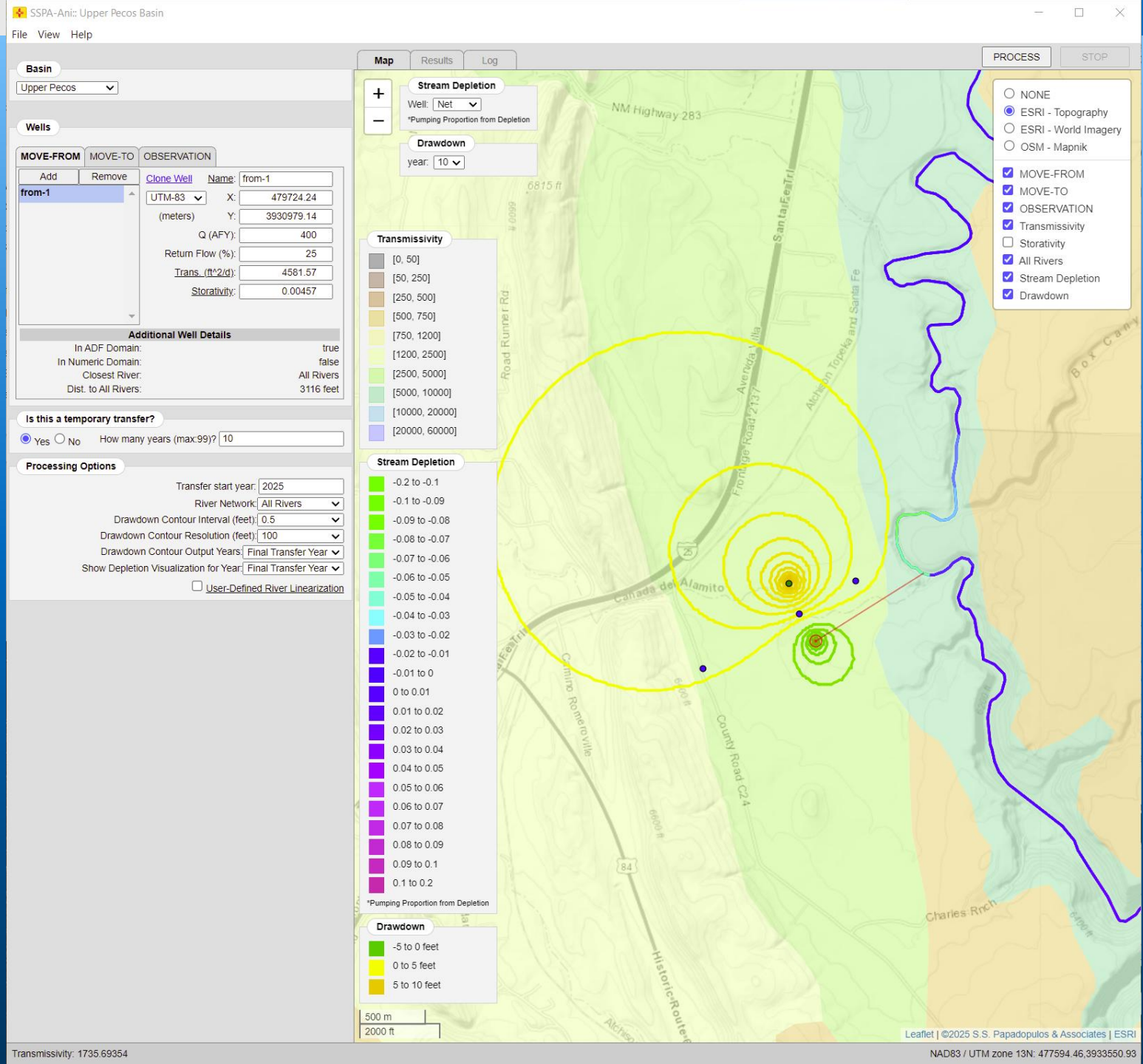
Upper Pecos Example III

- Move-From downstream
- Move-To nearby/upstream
- Different effective pumping rate
- 10-year transfer
- Drawdown at 10 years



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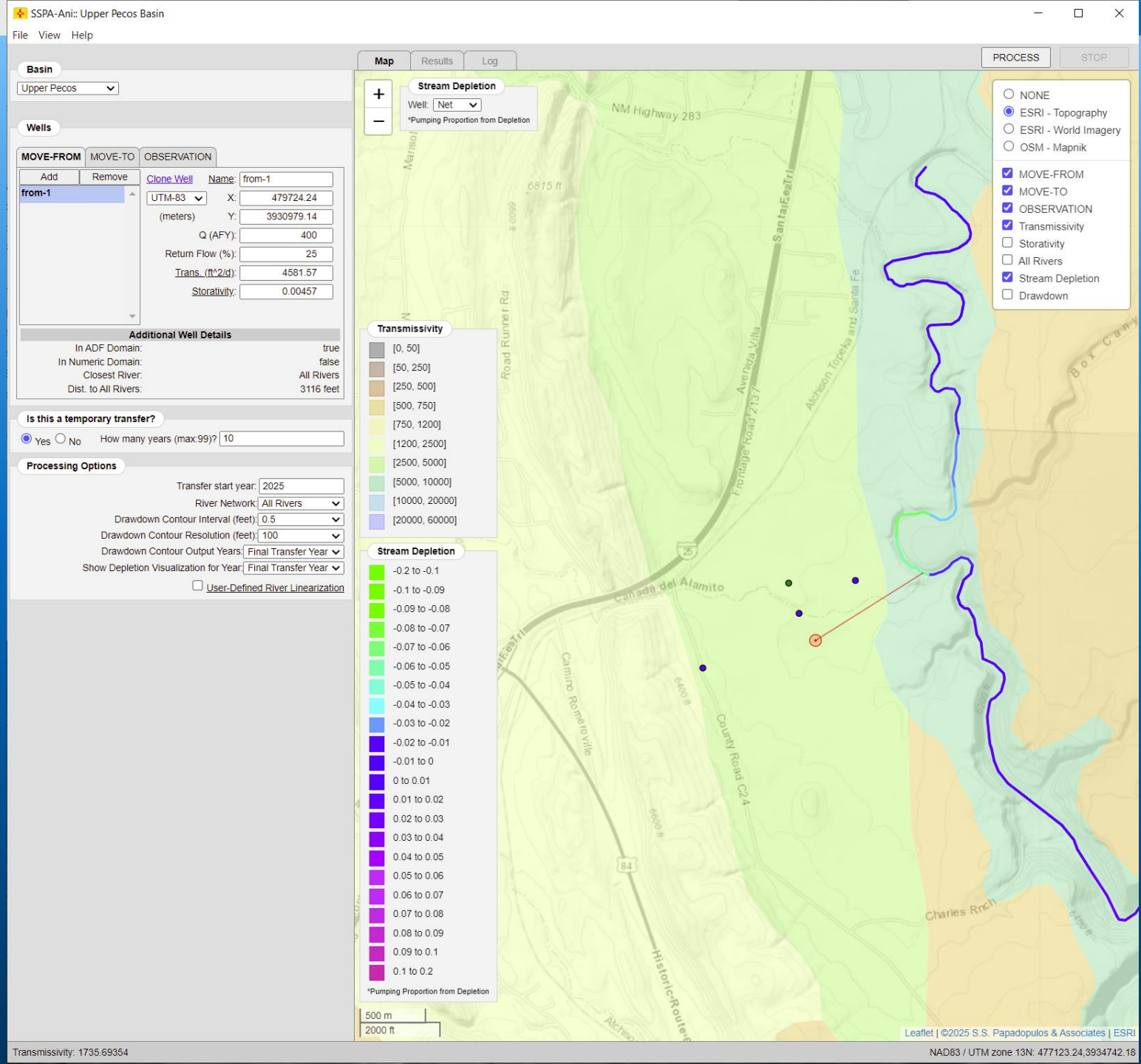
Upper Pecos Example III

- Move-From downstream
- Move-To nearby/upstream
- Different effective pumping rate
- 10-year transfer
- Color coded depletion-accretion segments



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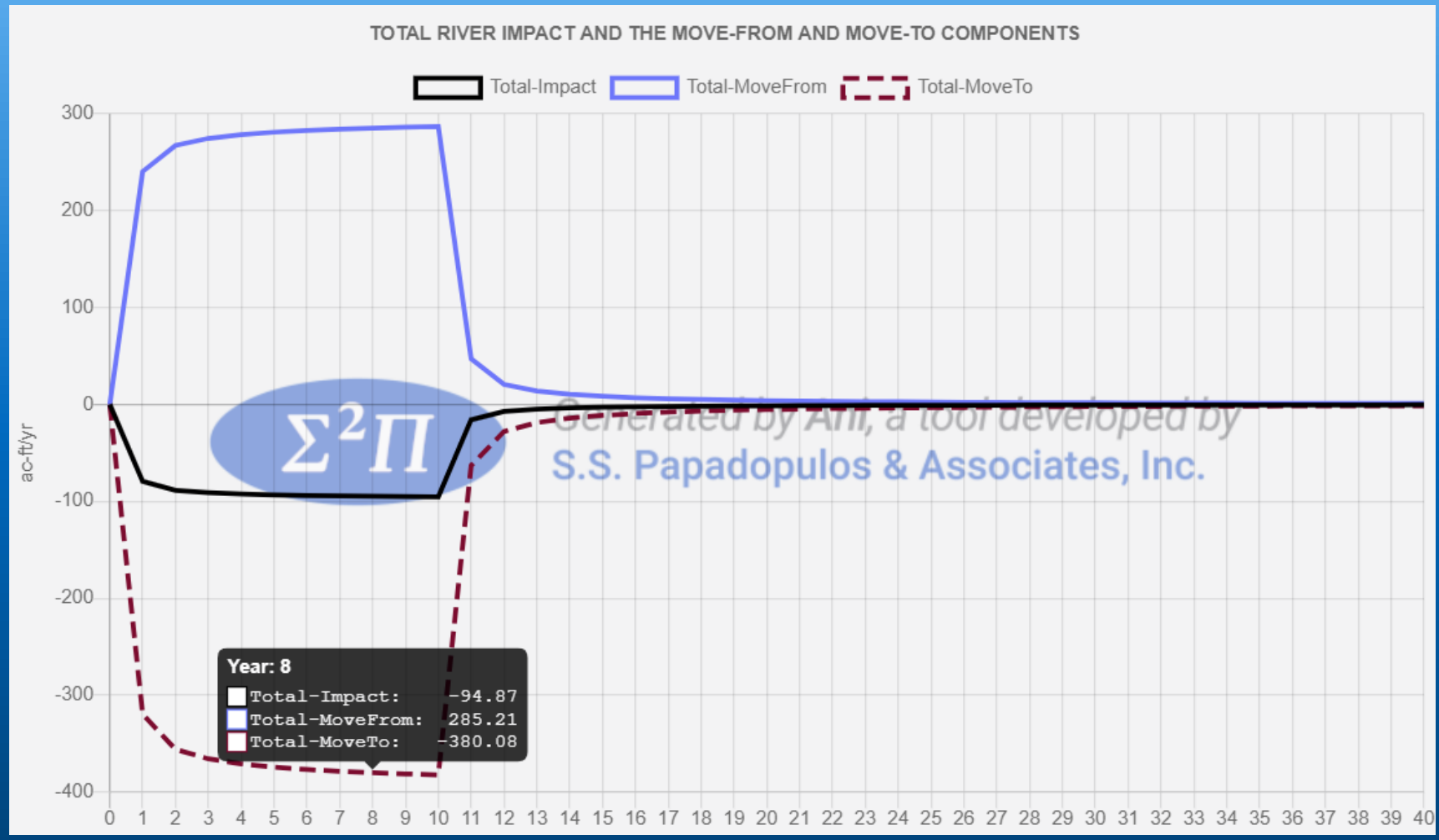
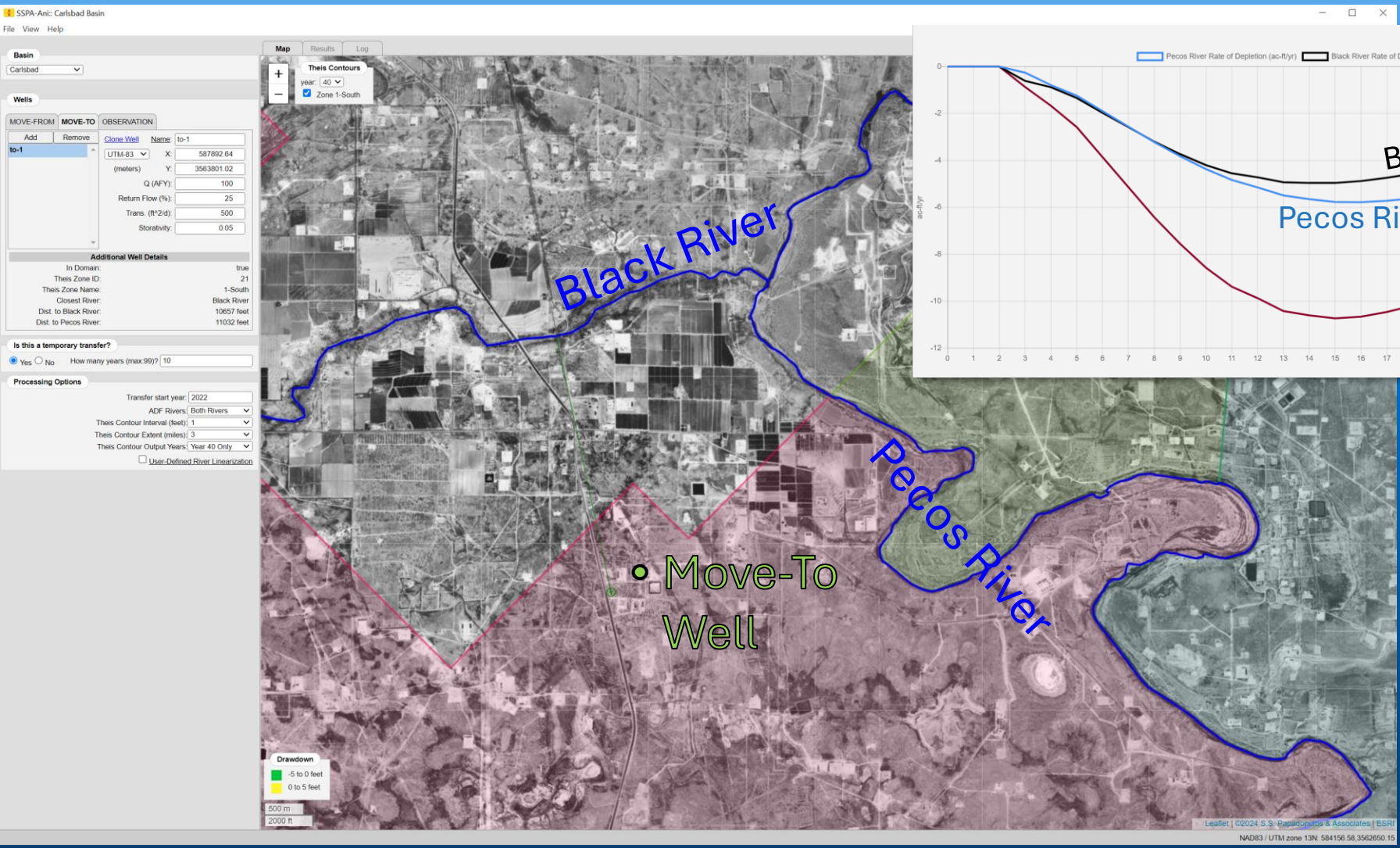
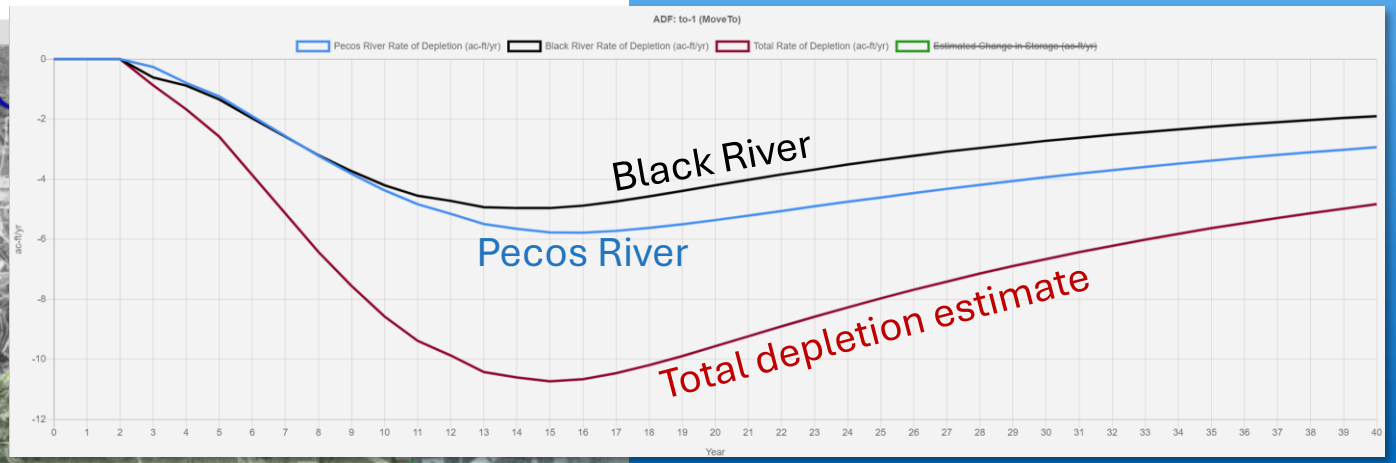
Upper Pecos Example III

- Move-From downstream
- Move-To nearby/upstream
- Different effective pumping rate
- 10-year transfer
- Drawdown at 10 years



Ani: Estimated Depletion by Stream





ADF can aggregate by SW feature to inform location of estimated depletion.

Combining Analytical-Numerical

- Move-From assessed with numerical
- Move-To assessed with: analytical