Simulating Groundwater Flow Patterns in Quarry Vicinities Using Numerical Groundwater Flow Model

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GeoHydros, LLC – Reno NV

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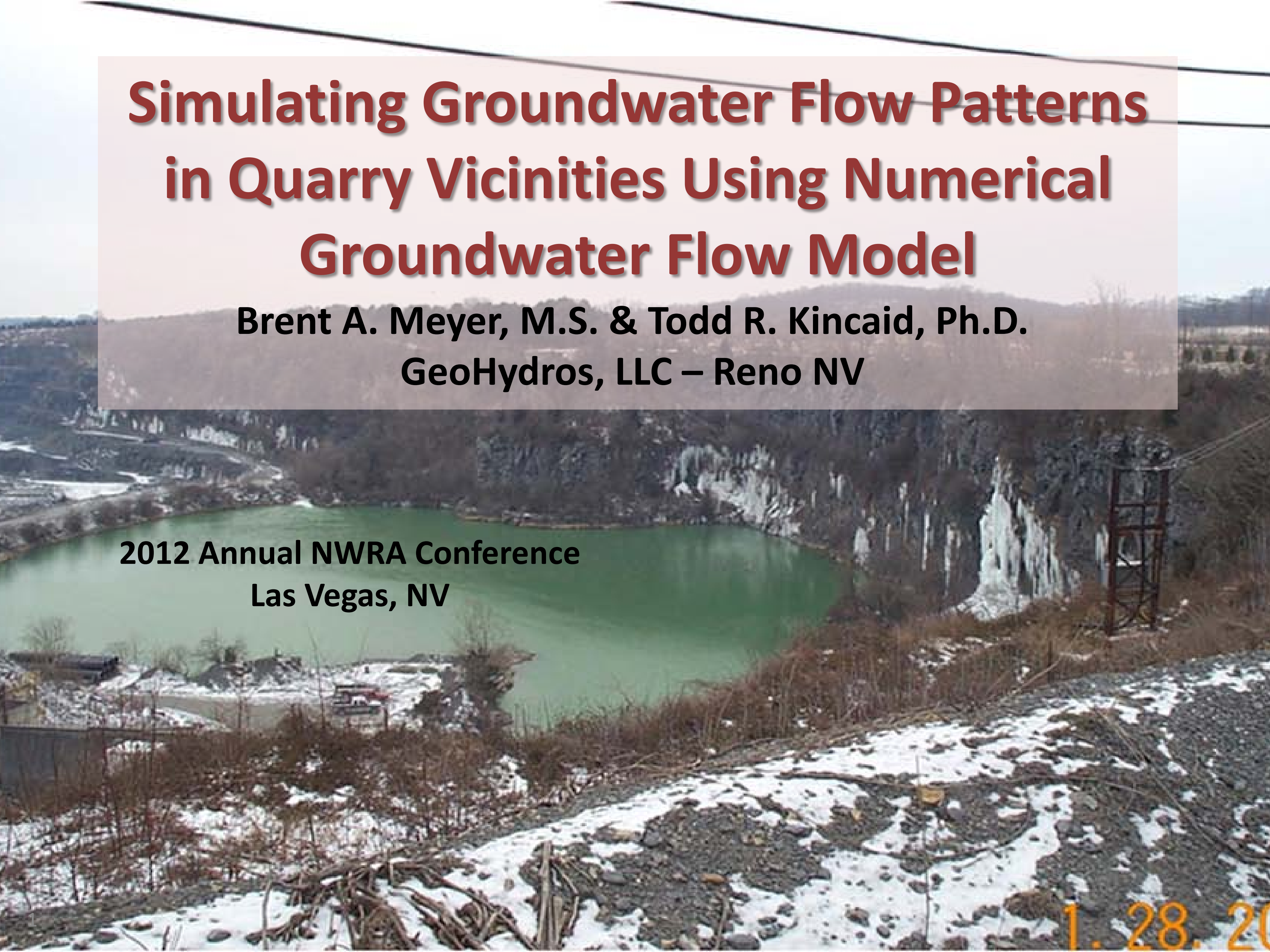
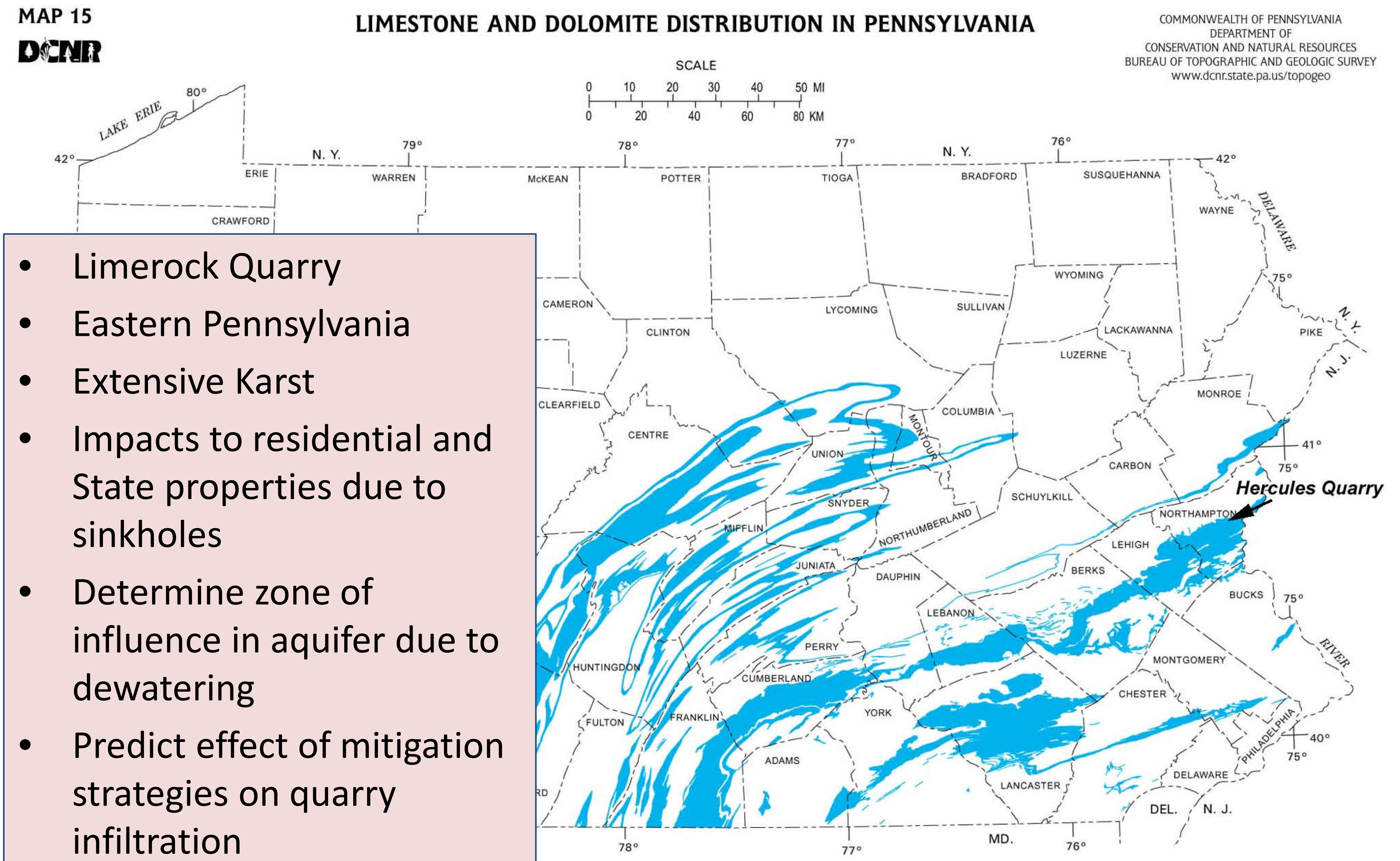
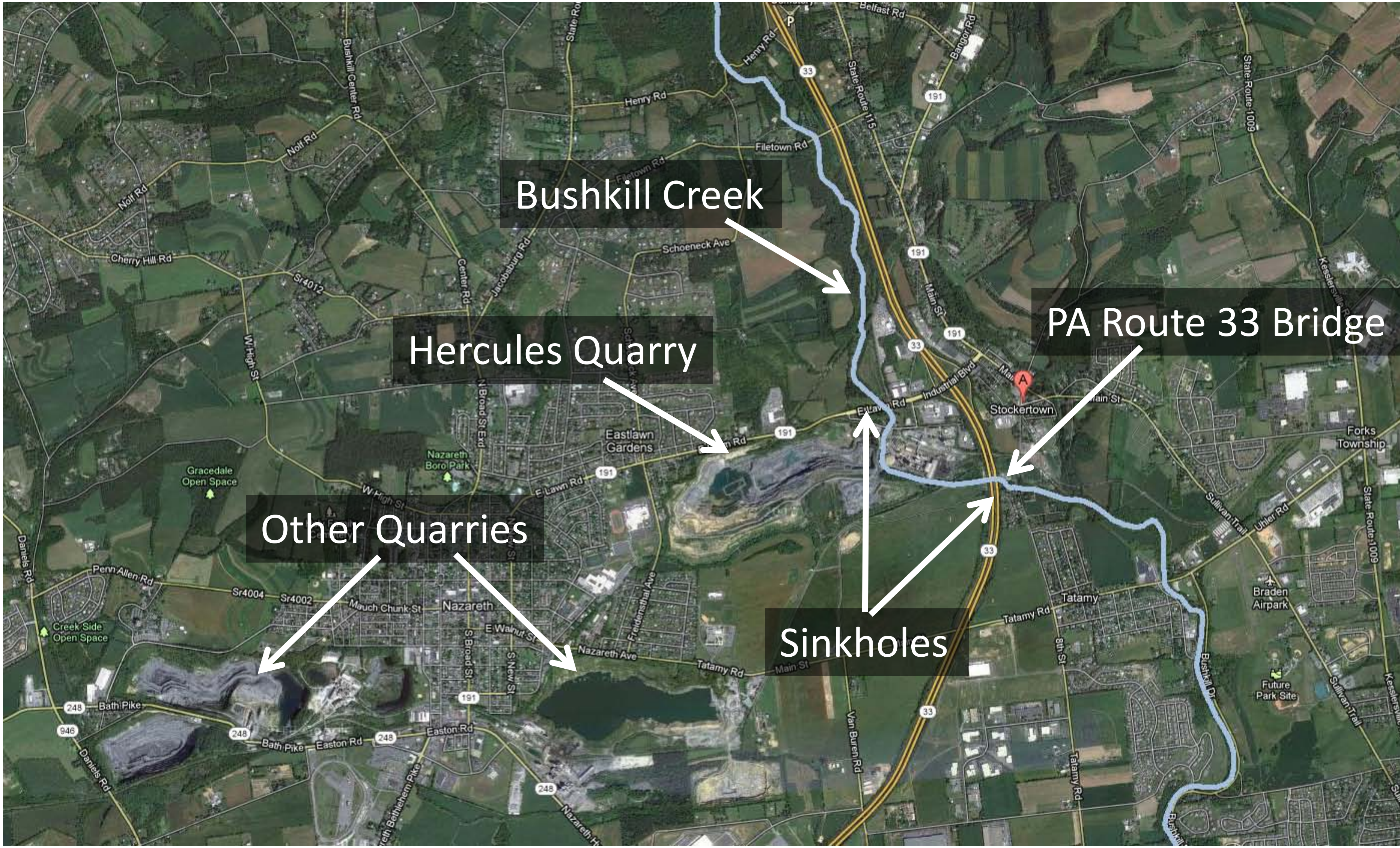


Site: Stockertown Pennsylvania

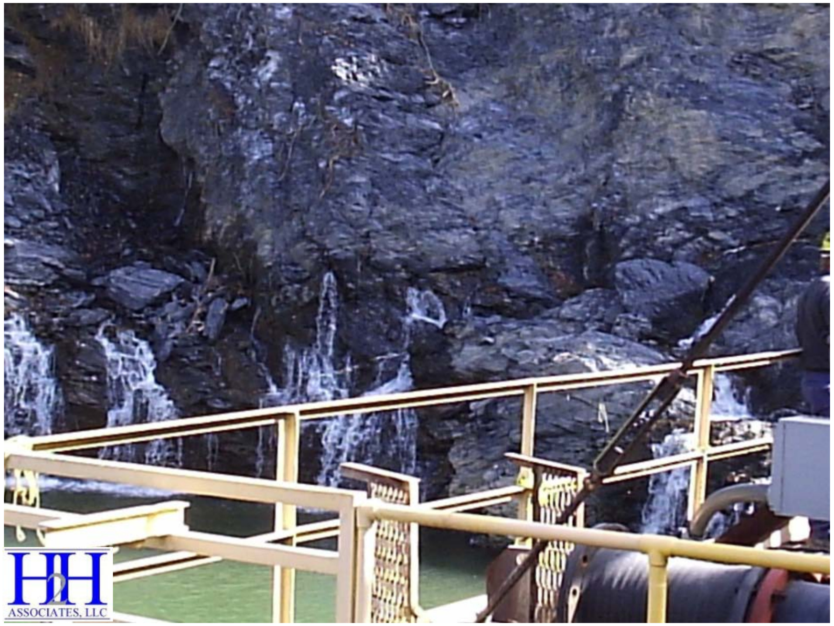


- Limerock Quarry
- Eastern Pennsylvania
- Extensive Karst
- Impacts to residential and State properties due to sinkholes
- Determine zone of influence in aquifer due to dewatering
- Predict effect of mitigation strategies on quarry infiltration

Key Features



Quarry Infiltration: 5-7 MGD



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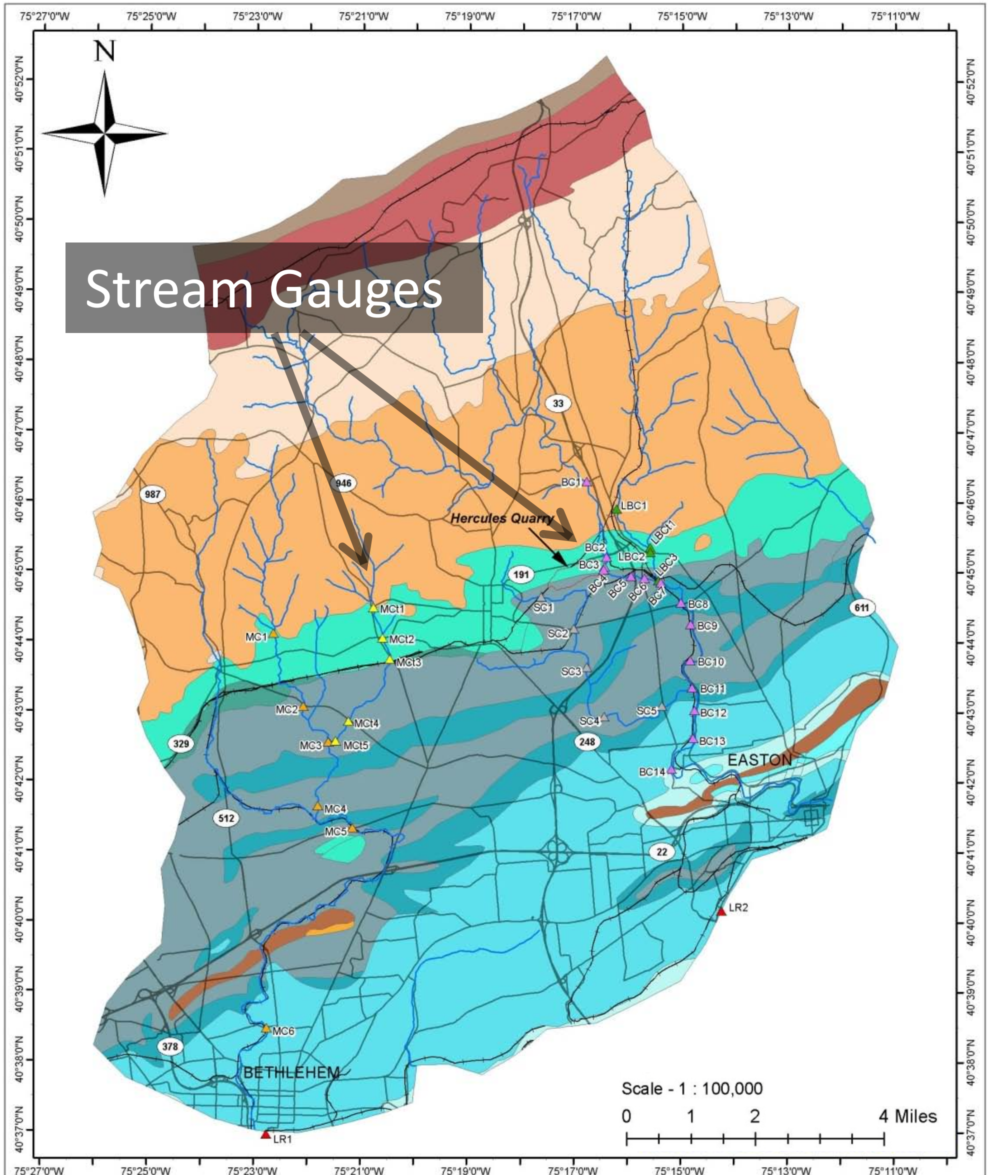
Sinkhole Damage to Property & Infrastructure

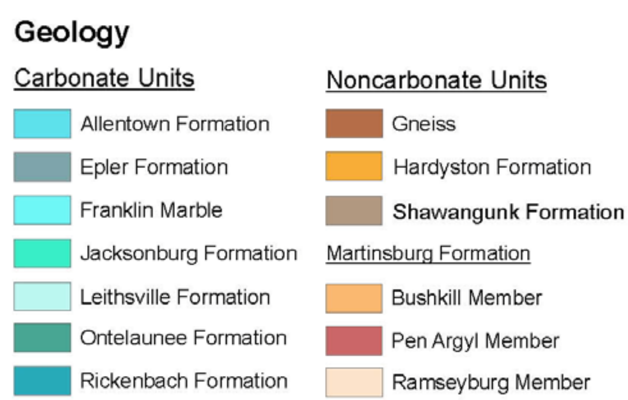
__Cause:__
Presumed to be due to drawdown caused by quarry dewatering.

__Primary modeling objective:__
Delineate dewatering zone of influence.

Geology & Hydrology



- Quarry situated at contact between carbonate and non-carbonate (shale) units.
- Numerous streams loose water to aquifer once they cross into carbonates.
- Extensive and widespread sinkhole development in carbonate region.



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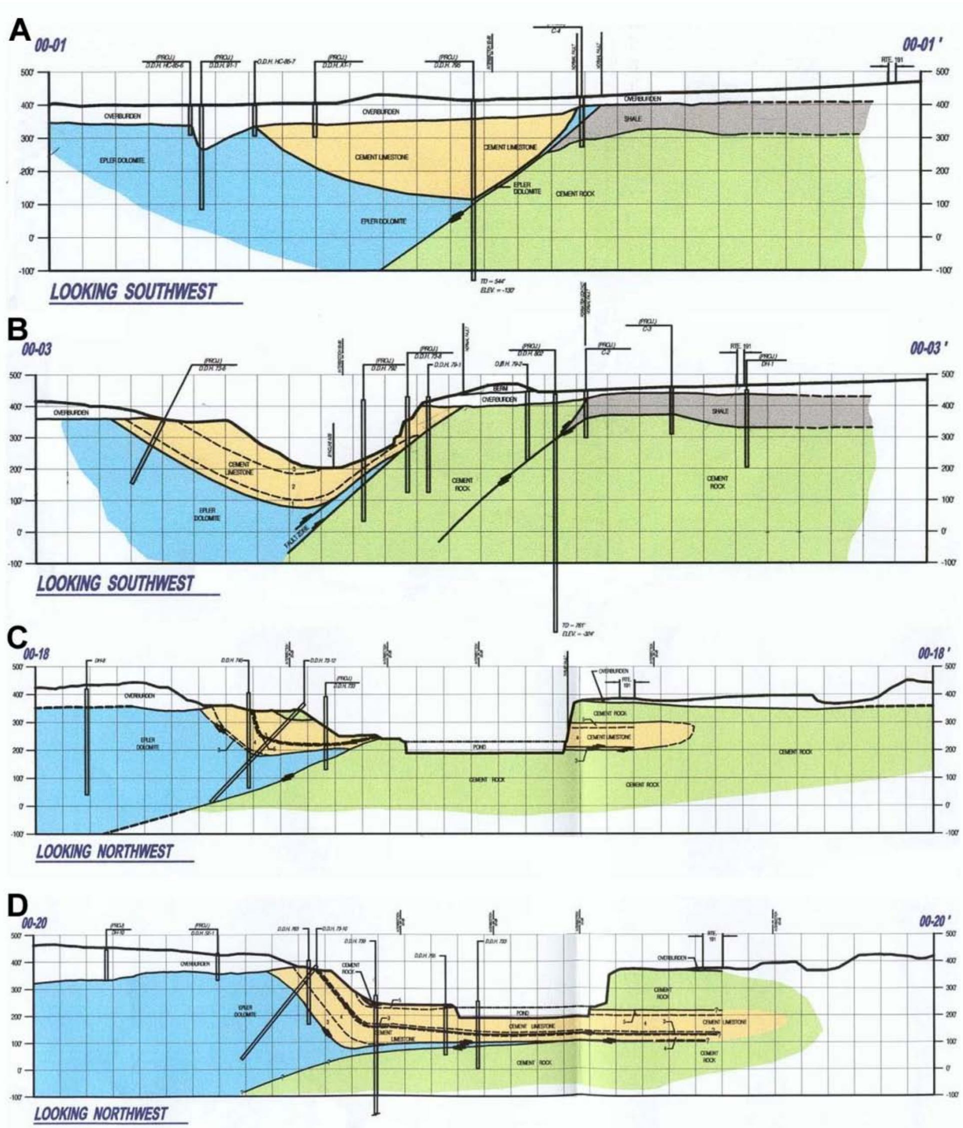
3D Geologic Complexities



- Model was 3D, containing 2 layers representing the ????
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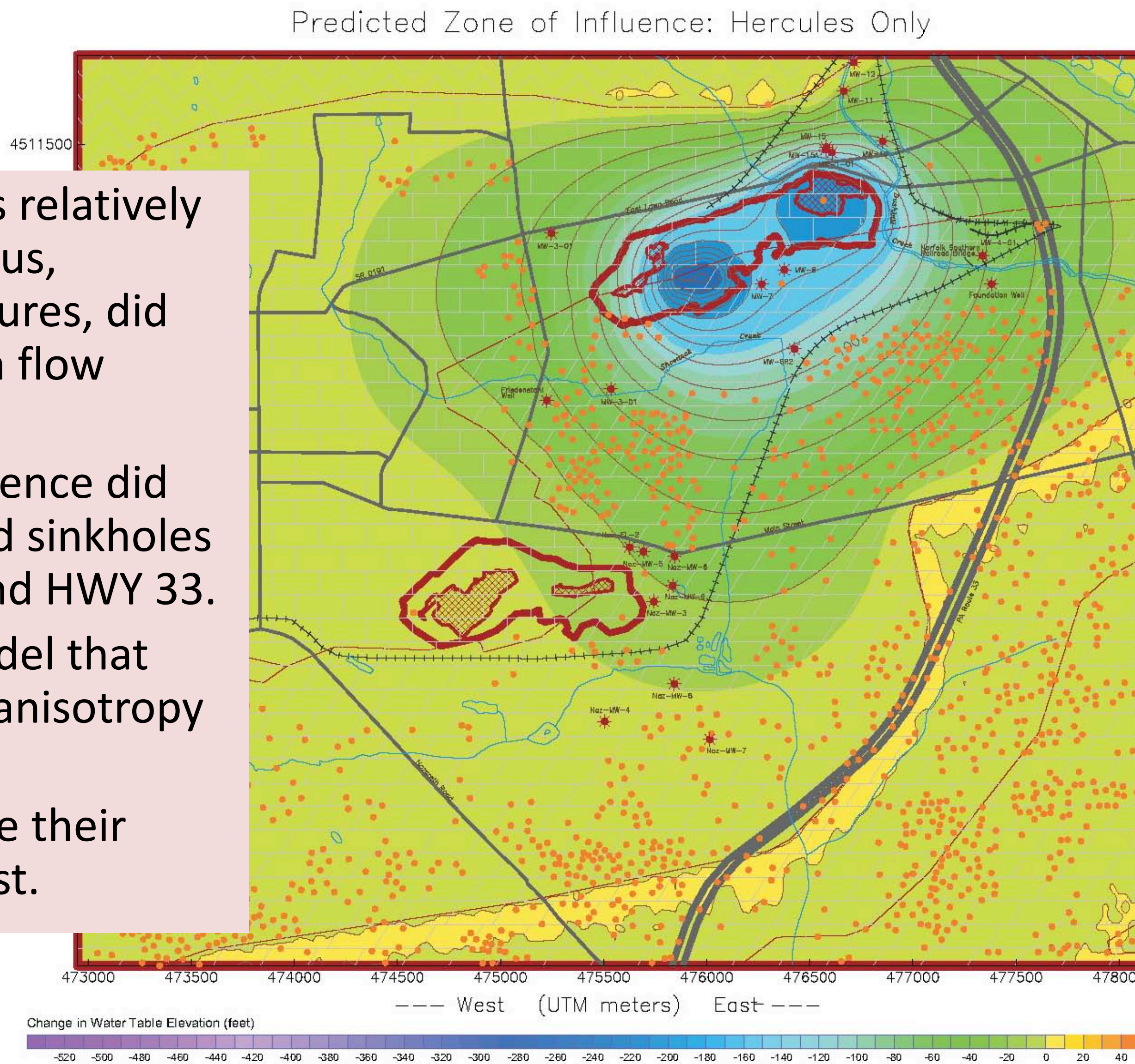
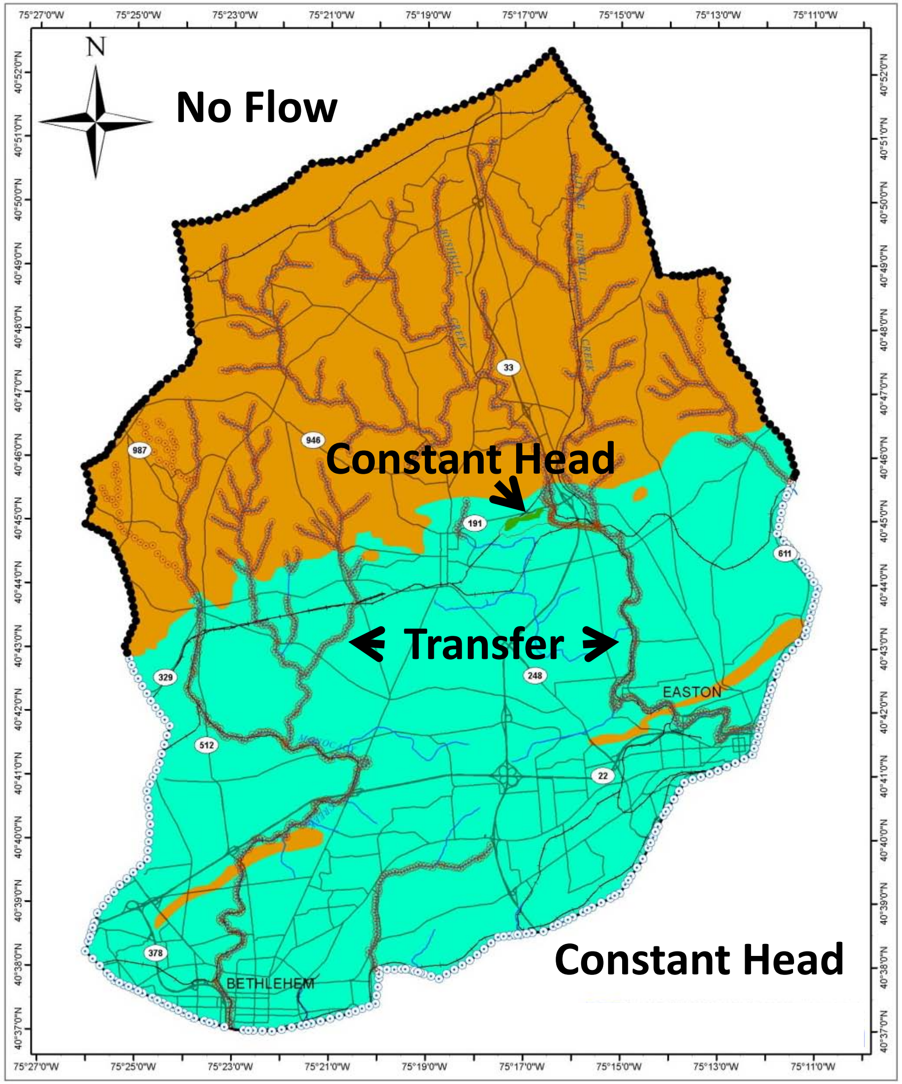
Previous Modeling Limitations



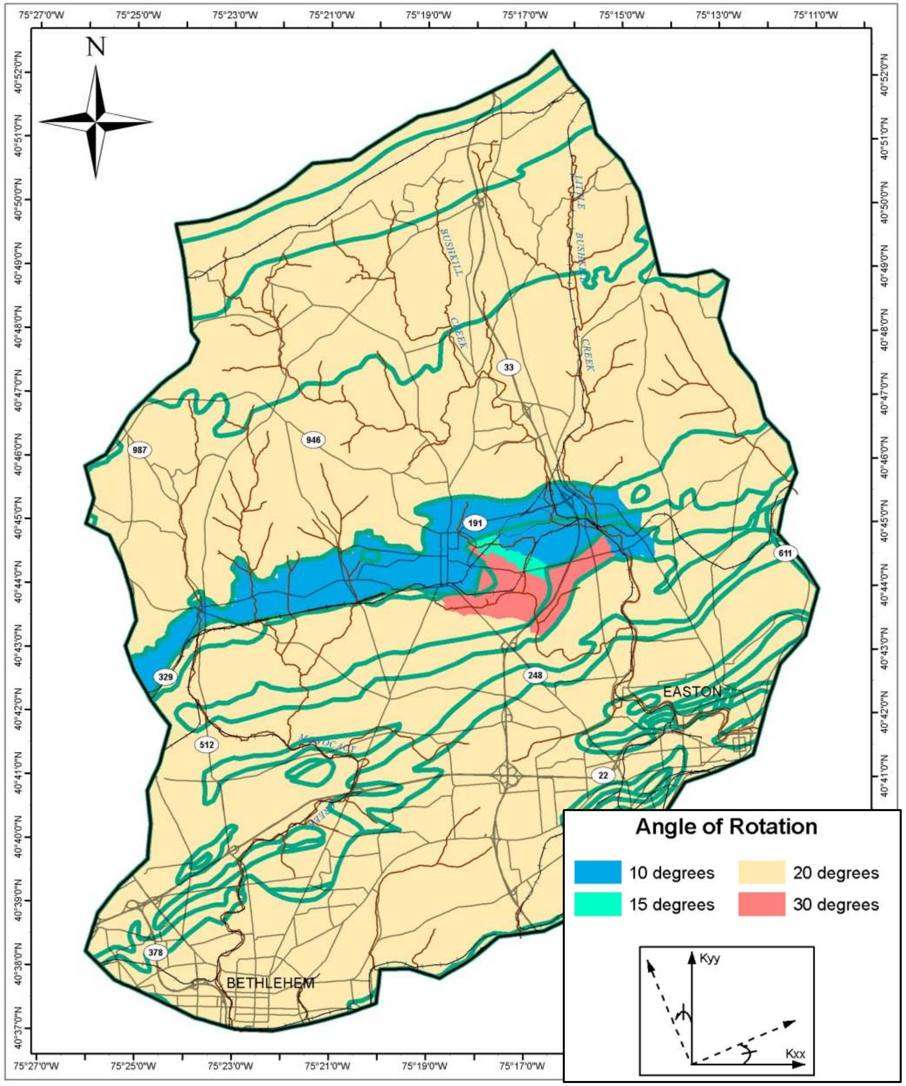
- Previous modeling was relatively simplistic, homogeneous, isotropic, no karst features, did not account for stream flow losses.
- Predicted zone of influence did not extend to observed sinkholes between the quarry and HWY 33.
- USGS completed a model that attempted to address anisotropy due to karst.
- Quarry asked to update their model and include karst.

Model Design: Streams & Anisotropy

Boundary Conditions



Anisotropy Assignment



Model Design: Karst Conduits

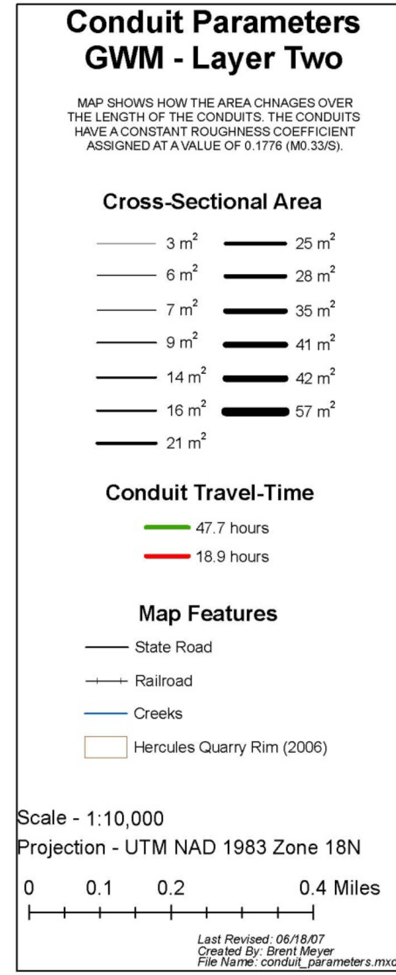
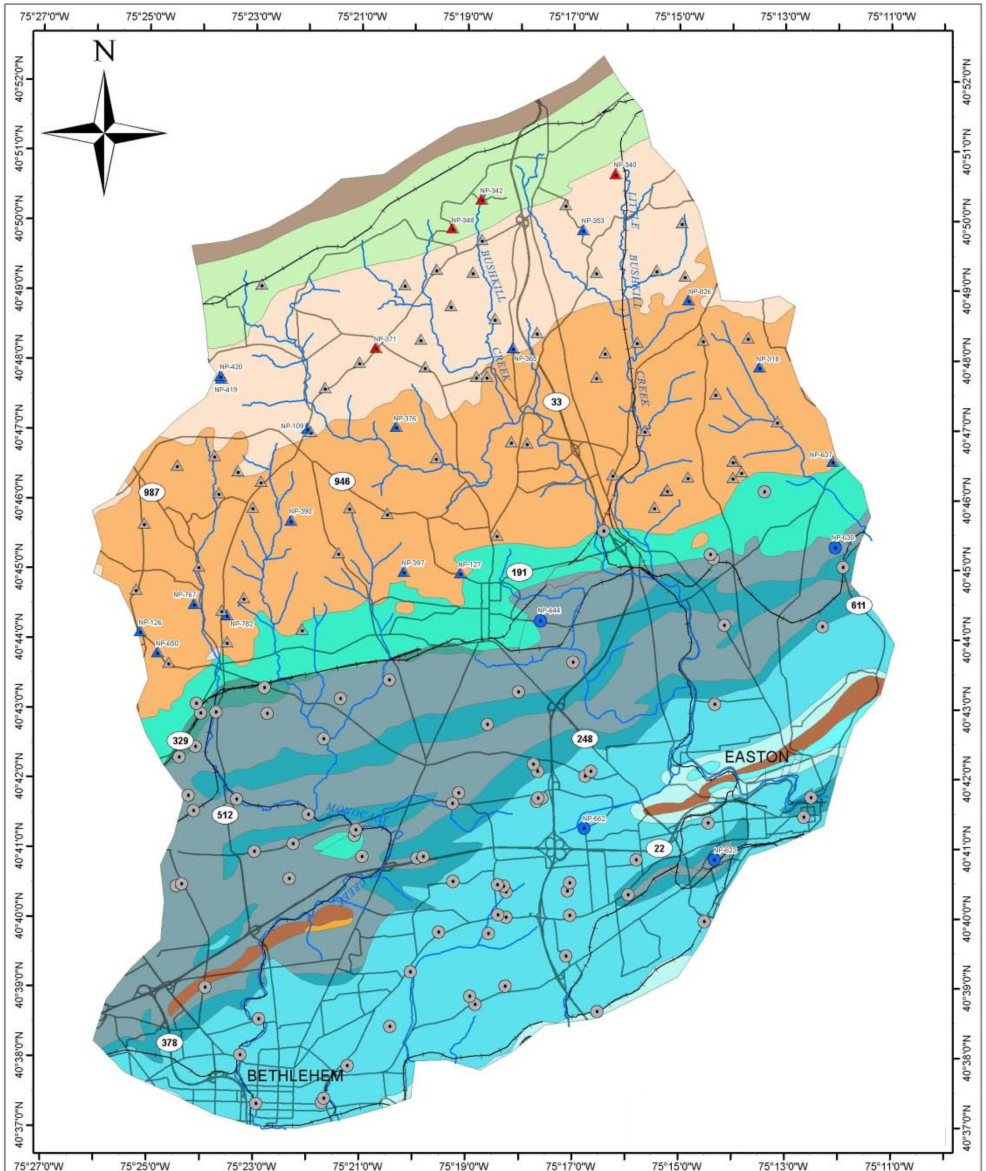


FIGURE 15: Location and size of conduits connecting the Bushkill Creek with the exposure of the Epler Formation in the Hercules Quarry floor relative to the inferred travel time along the main conduit flow paths, Stockertown Pennsylvania.

- Model was designed using the software FEFLOW™
- Conduits were assigned as 1D linear features
- Connected seeps in quarry floor to sinkholes in creek where connection and velocity was established by tracing.
- Conduit flow simulated using the Manning-Strickler eq.
- Matrix flow simulated using the Darcy eq.

Model Calibration: Acceptability by Area



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WELL CALIBRATION

- Within acceptable range
- Below acceptable range
- Above acceptable range

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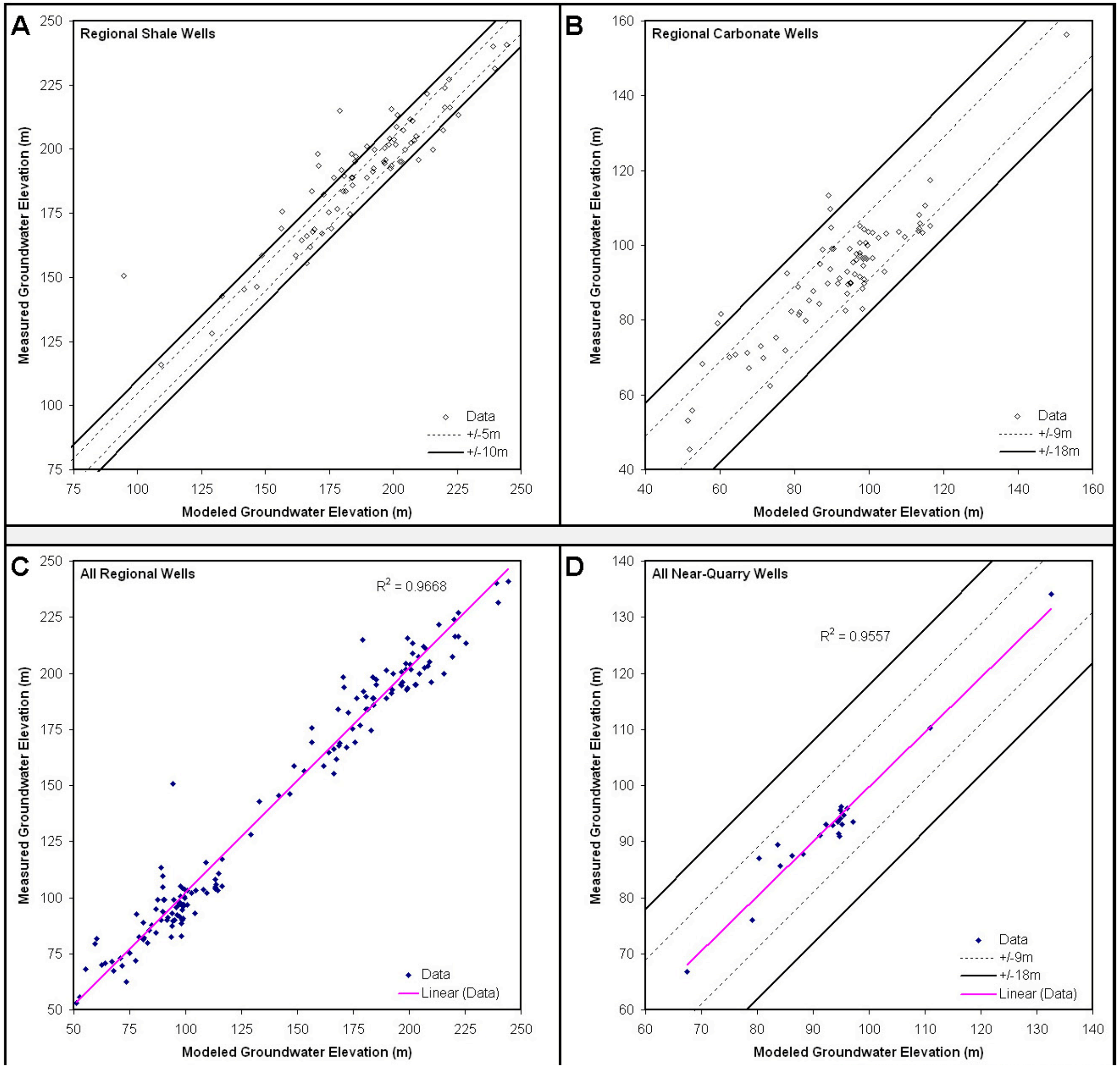
Model Calibration: Heads by Area



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Model Calibration: Stream Flows

Table 6. Comparison of estimated and simulated losses and gains to and from the aquifer.

Station	Estimated Gain/Loss m^3/s (cfs)	Model Gain/Loss m^3/s (cfs)	Geologic Unit / Comments
Monocacy Creek			
MC1	0.06 (2.1)	0.06 (2.2)	Martinsburg
MC2	-0.06 (-2.1)	-0.05 (-1.7)	Jacksonburg-Epler
MC3	0.0	0.02 (0.6)	Epler
MC4	0.03 (1.2)	0.02 (0.8)	Epler-Rickenbach
MC5	0.27 (9.7)	0.03 (1.0)	Epler-Rickenbach / Unaccounted for inputs?
MC6	1.62 (57.3)	-0.07 (-2.6)	Epler-Allentown / Unaccounted for inputs?
Total	*1.93 (68.2)*	*0.01 (0.3)*	*Possible unaccounted for inputs, i.e. quarry discharges, springs, etc.*
Monocacy Creek Tributary			
MCt1	0.03 (0.9)	0.04 (1.5)	Martinsburg
MCt2	0.01 (0.4)	0.04 (1.2)	Jacksonburg
MCt3	0.08 (2.7)	0.00 (-0.1)	Jacksonburg / Unaccounted for inputs?
MCt4	-0.05 (-1.8)	-0.09 (-3.2)	Epler
MCt5	-0.05 (-1.9)	0.00 (-0.2)	Epler
Total	*0.01 (0.3)*	*-0.02 (-0.6)*	
Bushkill Creek			
BC1	0.44 (15.6)	0.44 (15.7)	Martinsburg
BC2	0.01 (0.2)	-0.01 (-0.3)	Jacksonburg
BC3	-0.01 (-0.3)	-	Jacksonburg
BC6	-1.37 (-48.3)	-1.45 (-51.3)	Epler / Quarry Discharge: Stream gains 82.2 cfs between BC3 & BC6
BC7	-0.19 (-6.8)	-0.13 (-4.4)	Epler
BC8	-0.09 (-3.2)	-0.07 (-2.6)	Rickenbach
BC9	0.15 (5.2)	-0.01 (-0.4)	Epler-Rickenbach
BC10	-0.20 (-7.0)	-0.02 (-0.6)	Epler
BC11	0.36 (12.8)	-0.01 (-0.4)	Epler-Rickenbach
BC12	0.02 (0.7)	0.0	Allentown-Rickenbach
BC13	0.03 (1.0)	0.02 (0.7)	Allentown
BC14	0.07 (2.4)	0.05 (1.8)	Allentown
Total	*1.54 (54.5)*	*1.15 (40.5)*	
Little Bushkill Creek			
LBC1	0.27 (9.7)	0.24 (8.5)	Martinsburg
LBC2	-0.01 (-0.4)	0.03 (1.0)	Martinsburg-Jacksonburg
LBC3	-0.05 (-1.8)	-0.07 (-2.5)	Jacksonburg-Epler
Total	*0.21 (7.5)*	*0.20 (7.0)*	
Little Bushkill Creek Tributary			
LBCt1	0.01 (0.4)	0.01 (0.2)	Martinsburg-Jacksonburg
Schoeneck Creek			
Total	*0.0*	*0.00 (-0.1)*	Martinsburg-Jacksonburg
Lehigh River			
LR2	2.50 (88.3)	1.60 (56.4)	Allentown / Estimated input – poor confidence in estimated value
Total Lehigh River Boundary			Allentown-Leithsville
	>2.50 (>88.3)	1.74 (61.5)	Estimated input – poor confidence in estimated value
Total Delaware River Boundary			Epler-Allentown-Leithsville-Gneiss-Franklin
	NR	0.67 (23.8)	Currently not possible to estimate real inputs

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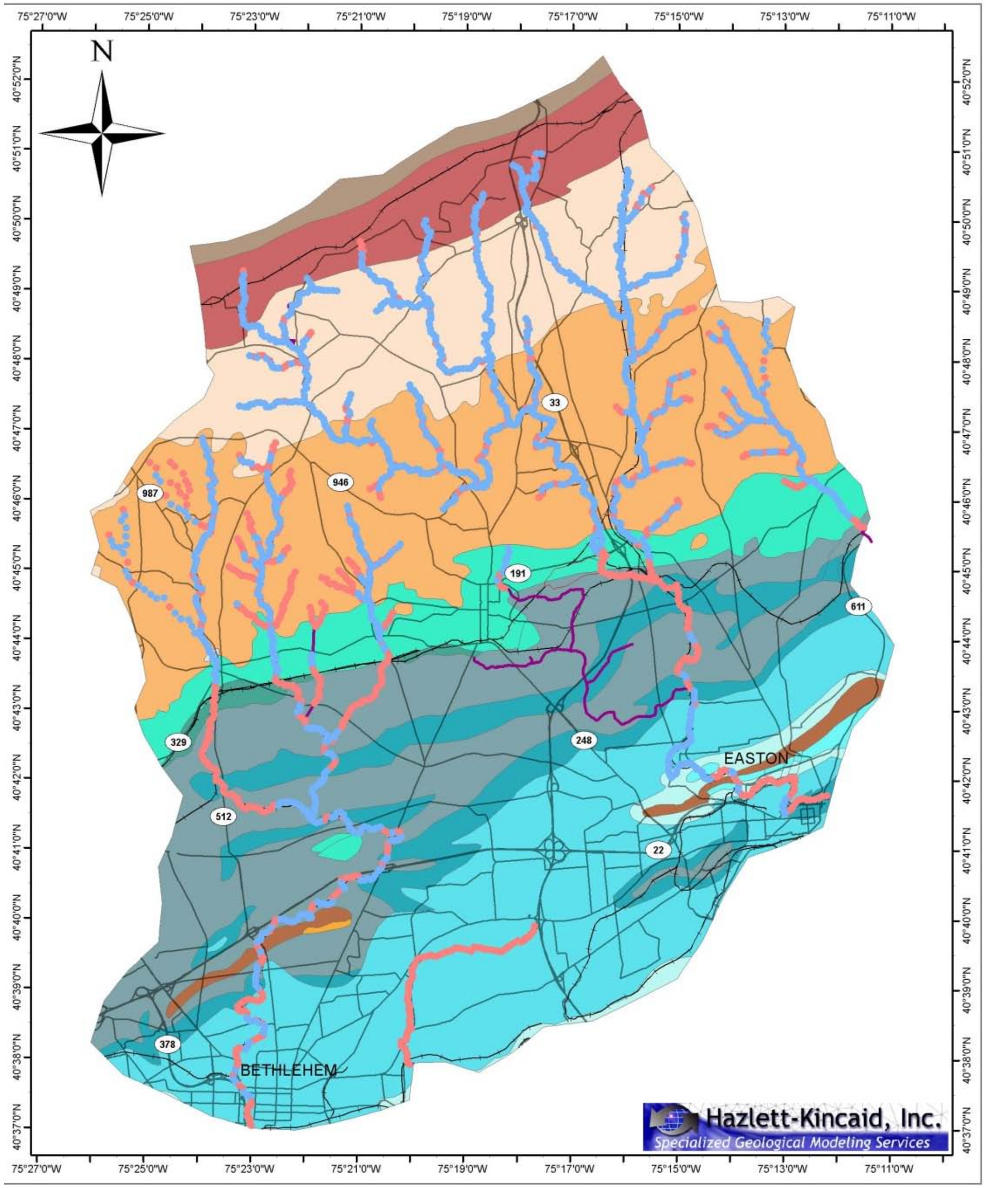
Model Results: Stream Flows



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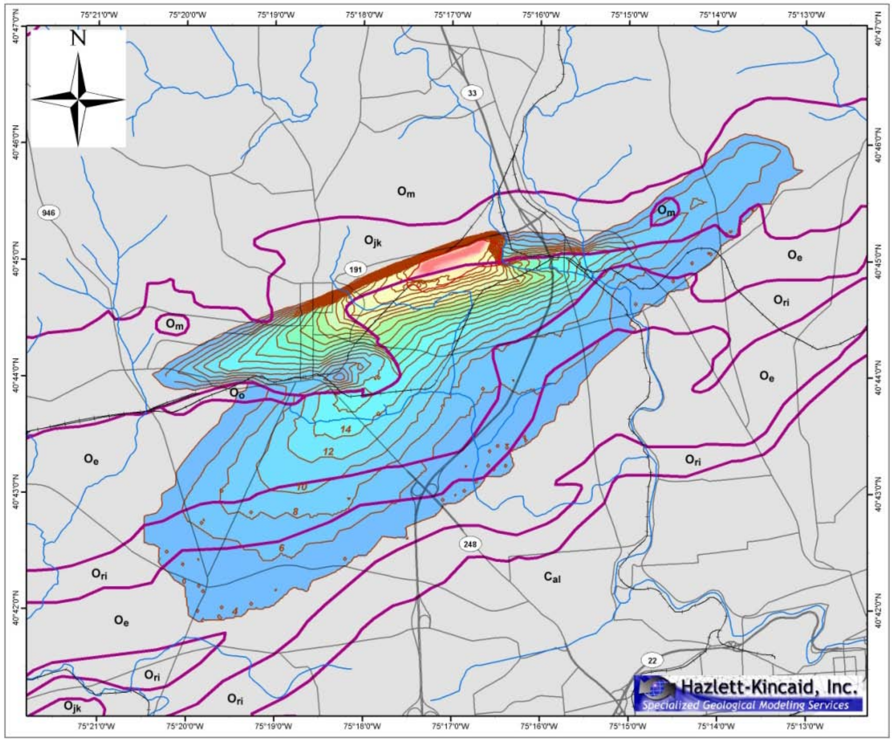
Flux Features

- Losing Or Dry Creek Node
- Gaining Creek Node
- Dry Creek excluded From GWM

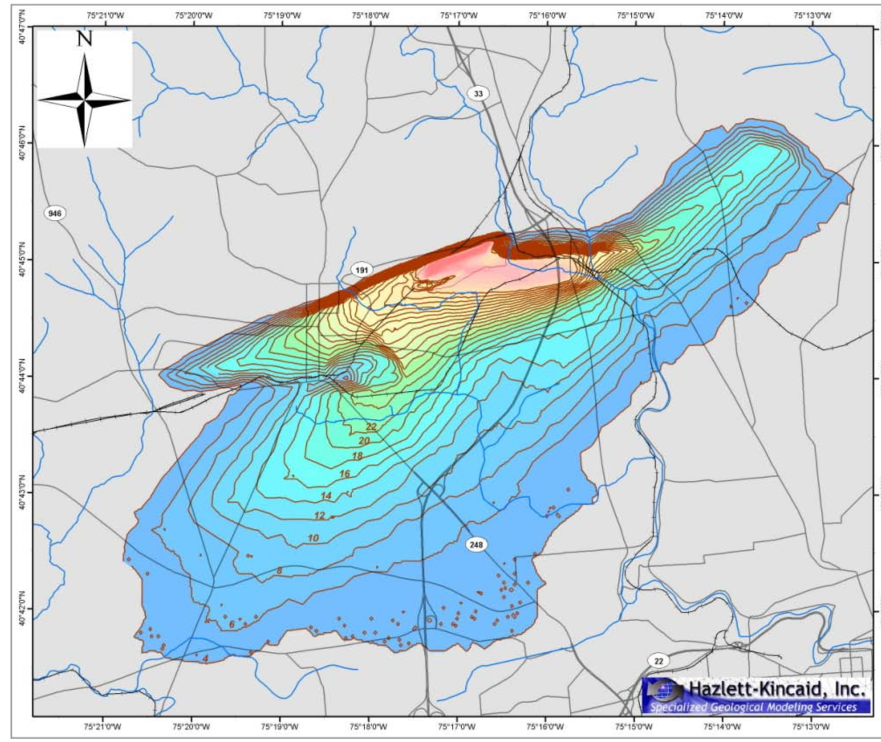
Model Results: Lined vs. Unlined Stream

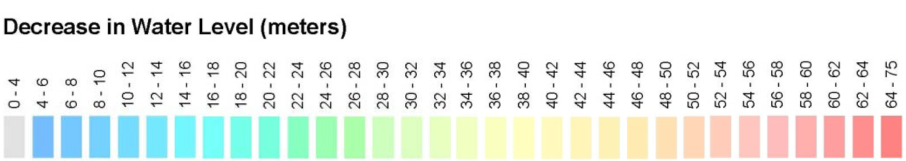
Model-Simulated Zone of Influence

Unlined Stream Scenario (Calibrated Model)



Lined Stream Scenario





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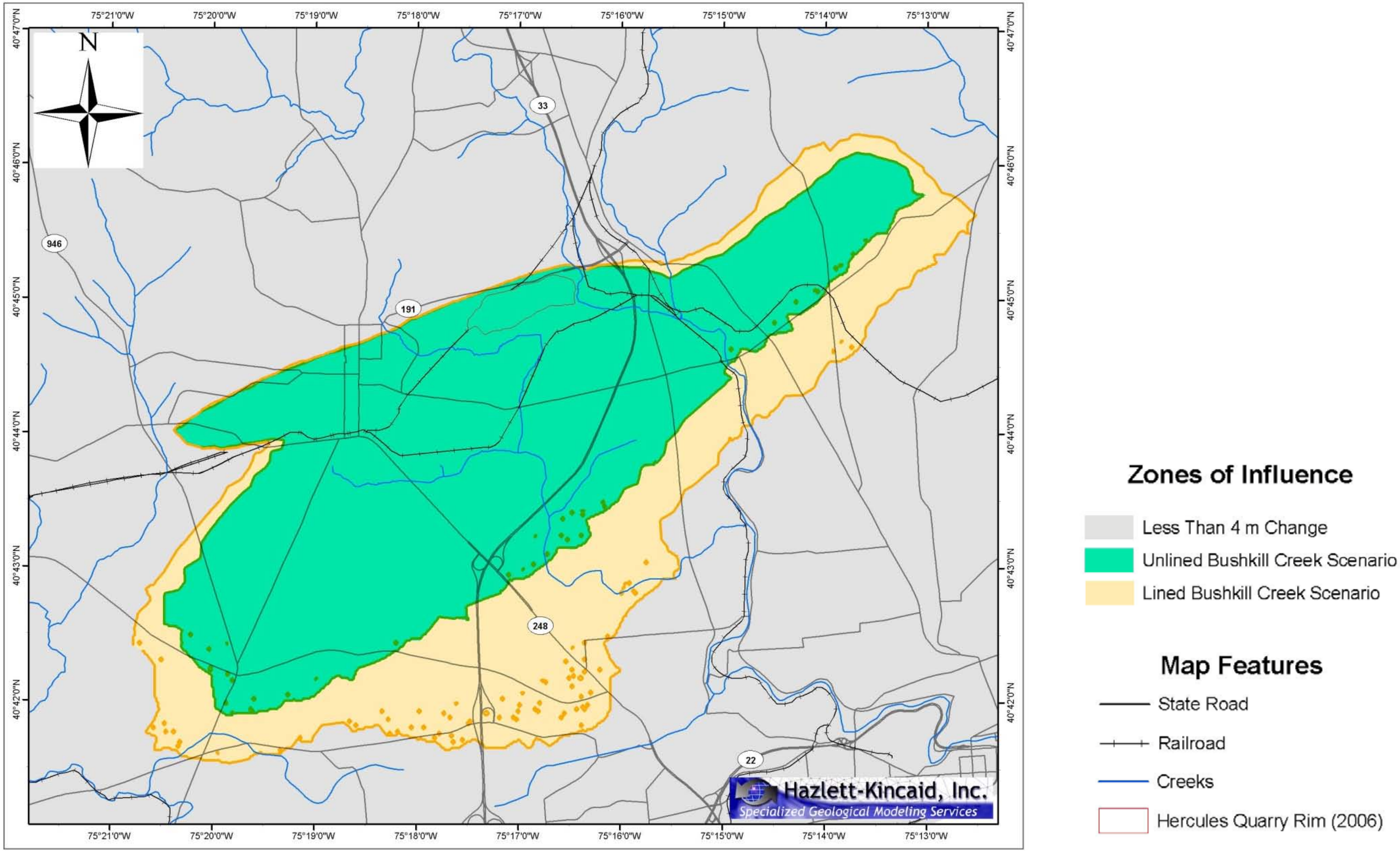
Model Results: Lined vs. Unlined Stream

Model-Simulated Zone of Influence



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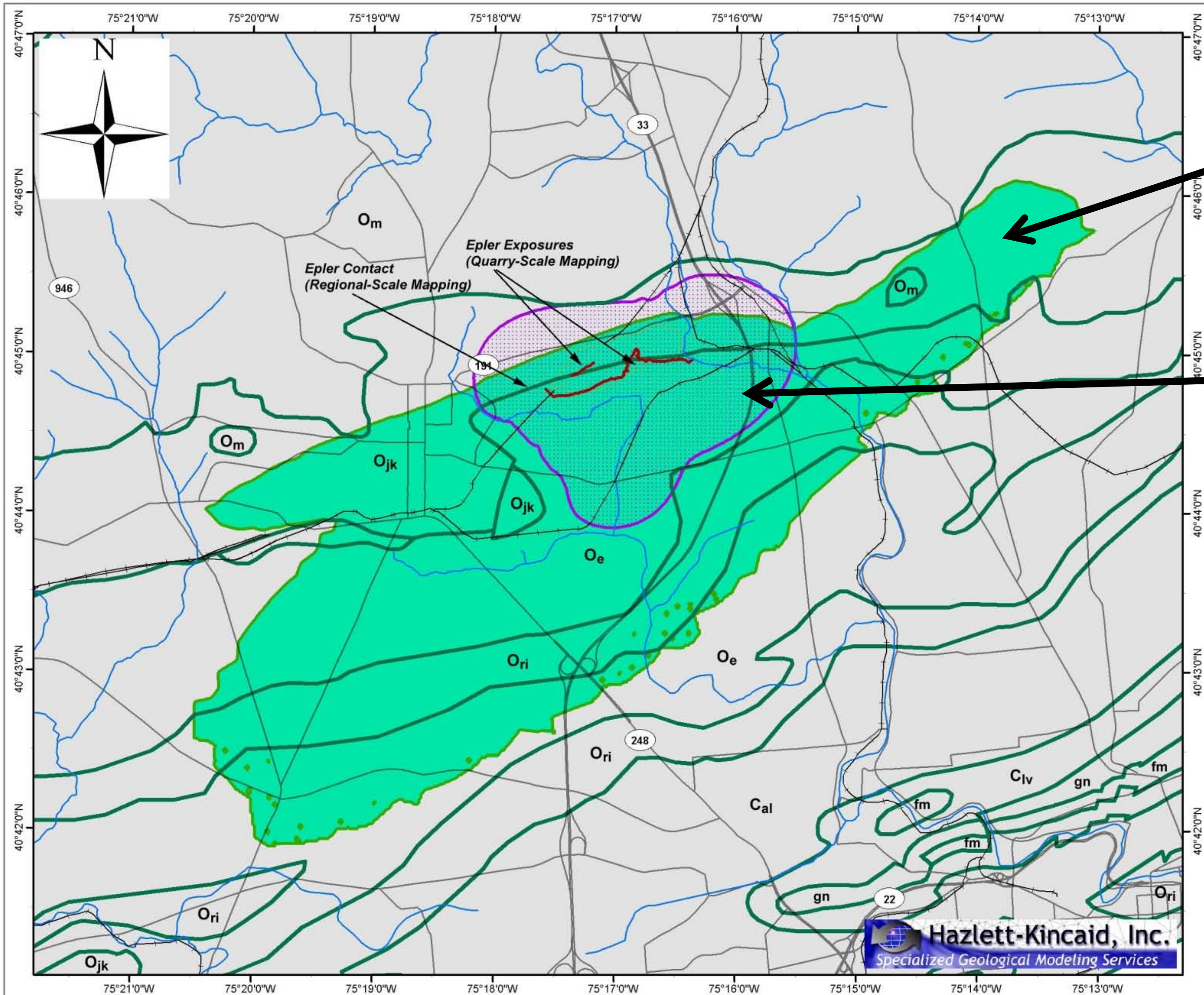
Scenario Analyses

Table 7. Magnitude and source of Quarry discharge simulated for the current conditions, stream lining, and two versions of the build down model scenarios.

Scenario	Components of Simulated Quarry Discharge m^3/s (cfs)						
	Total	Jacksonburg	Epler	Aquifer	River	Streambed	Sinkholes
Current Conditions	2.47 (87.4)	0.14 (4.8)	2.34 (82.5)	0.54 (19.1)	1.93 (68.3)	0.41 (14.5)	1.52 (53.8)
1 – Lined Stream	1.18 (41.6)	0.11 (4.0)	1.06 (37.6)	1.18 (41.6)	0.00	0.00	0.00
2a – Build Down	3.26 (115.2)	0.19 (6.8)	3.07 (108.4)	1.00 (35.5)	2.26 (79.7)	0.74 (26.0)	1.52 (53.8)
2b – Build Down	3.81 (134.7)	0.20 (7.0)	3.62 (127.7)	0.72 (25.4)	3.09 (109.2)	0.57 (20.1)	2.52 (89.1)
3 – Plugged Epler	0.59 (21.0)	0.18 (6.4)	0.41 (14.63)	*NC*	*NC*	*NC*	*NC*

- Used model to simulate how mitigation strategies and potential quarry build-down scenarios would likely change the magnitude and source of discharge into the quarry.
- Ultimately recommended that sealing the quarry floor would have a significantly greater effect on reducing both quarry discharge and the zone-of-influence in the aquifer than other mitigation strategies.

Comparing Predictions: Zone of Influence



Model with karst, anisotropy, and stream flows

Simplistic Model homogeneous, isotropic

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Summary

- Model successfully incorporated observed karst conduit features and inferred anisotropies as well as observed stream flow gains and losses.
- Incorporating the hydrogeologic complexities fostered a strong calibration to observed heads and stream flows.
- Strong calibration and incorporation of observed complexities increased confidence in the predictions with the State.
- Simulated zone of influence was accepted by State and used as a basis for negotiating terms for consent order-driven mitigation of impacts from sinkhole development associated with dewatering.
- Model also proved to be a useful tool for evaluating future design and build-down scenarios.

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