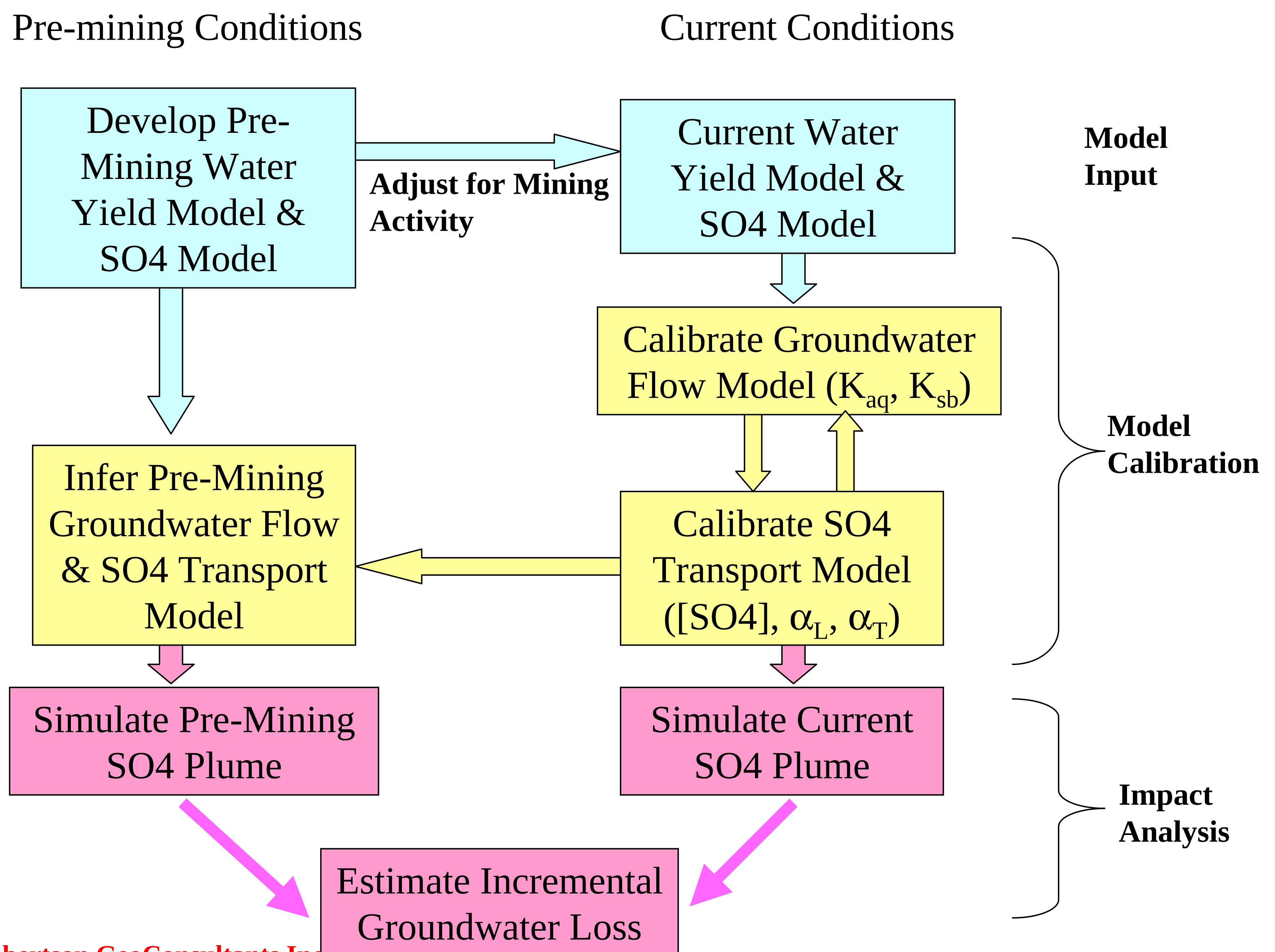
Estimation of Groundwater Impacts
Questa Mine Site

NRDA Meeting
May 2, 2005

Questa Mine Site

- **Yield & Load Estimates**
  - use 2 alternative yield models
  - estimate pre-mining SO4 using Straight Creek data
- **Red River Aquifer Model**
  - Calibration Targets
    - Red River Flows (RI/FS)
    - Observed GWL & sulphate
  - Model Calibration (incl. sensitivity analysis)
- **Estimates of GW Impact**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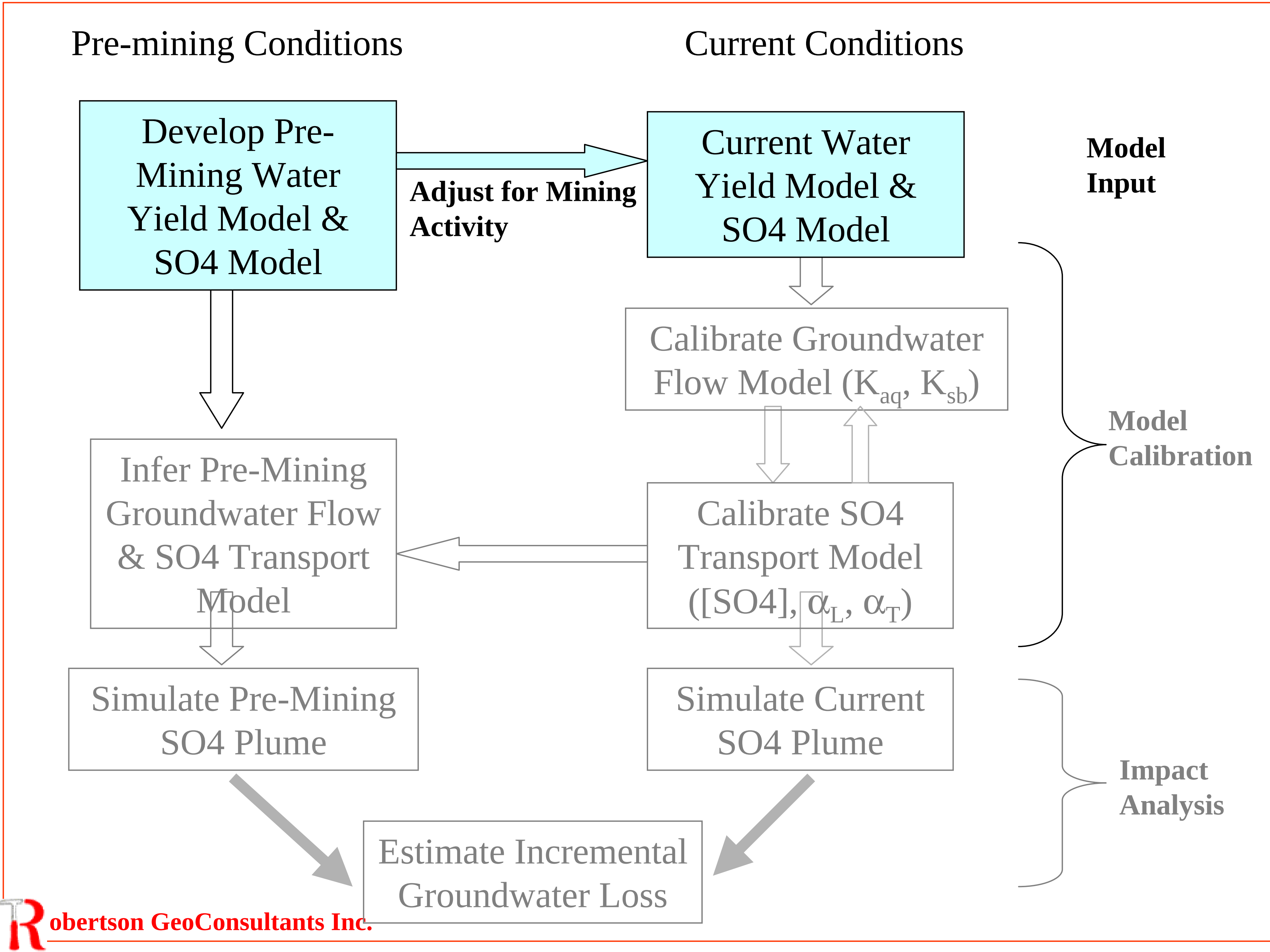
Estimate Incremental Groundwater Loss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Yield Estimates

Approach

use 2 different yield models to bracket uncertainty in this model input parameter:

1. **“High Yield” model based on precipitation and evapotranspiration (McAda & Naus, 2005)**

2. **“Low Yield” model based on observed streamflow in Red River basin (RGC, 2000; Naus & McAda, 2005)**

“High Yield” Model

Method originally developed for Fraser Experimental Forest in California and applied by USGS to Straight Creek (McAda & Naus , 2005)

Yield = MAP - ET

where

MAP = 0.0052*(E) – 27

ET = 18 + 0.28*(MAP-18)

Notes:

- Yield in inches per year
- Mean annual precipitation (MAP) in inches per year
- Actual evapotranspiration (ET) in inches per year
- Elevation (E) in feet

“Low Yield” Model

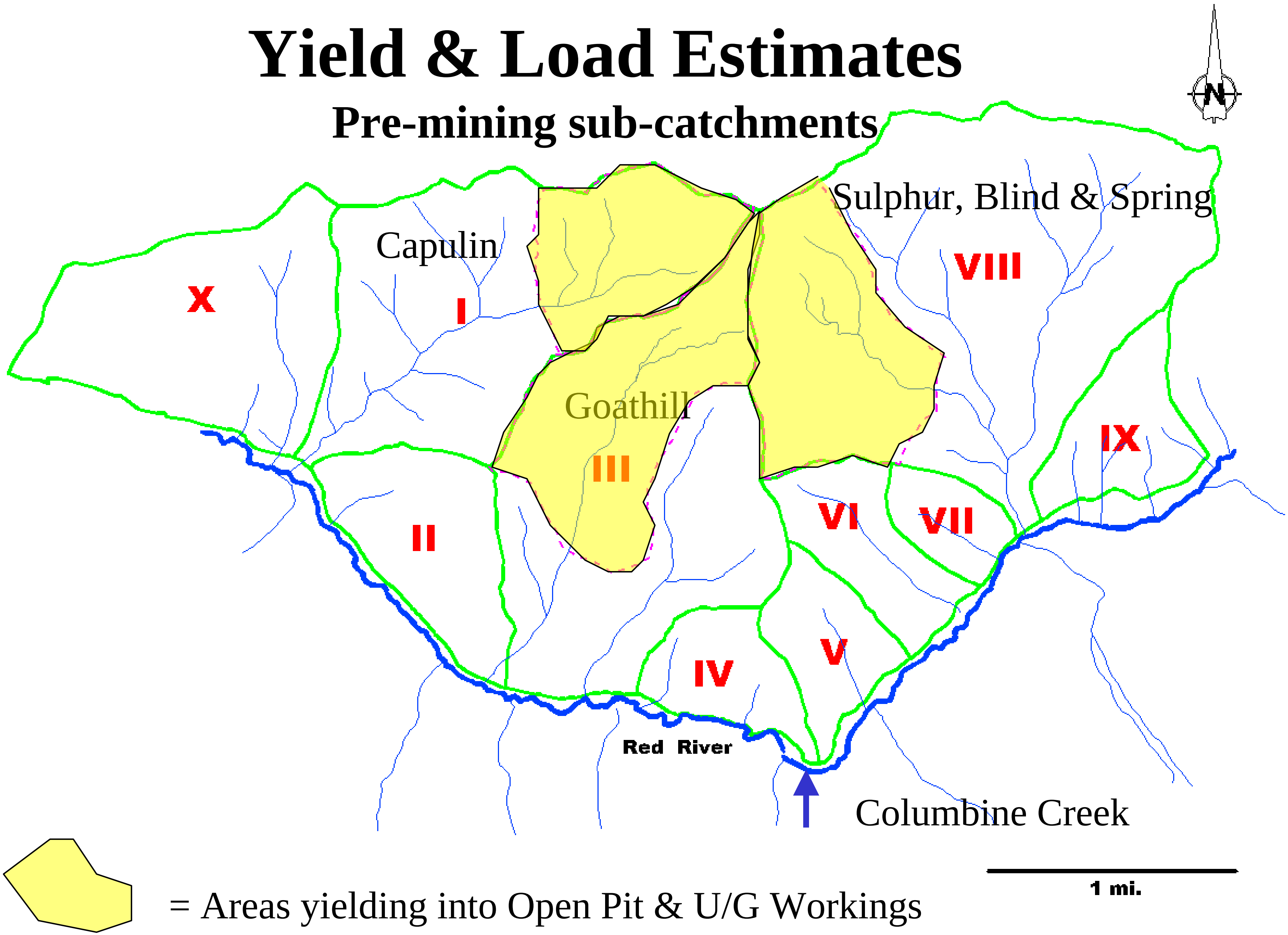
Method originally developed for Red River basin by USGS (Hearne & Dewey, 1972) and later modified for Mine Site Water Balance (RGC, 2000); also used by USGS for Red River water balance study (Naus & McAda, 2005):

$$\textbf{Yield} = 0.00905\,(10^{0.000276\,E}) - 0.9$$

Notes:
- Yield in inches per year
- Elevation (E) in feet

Yield & Load Estimates

Pre-mining sub-catchments

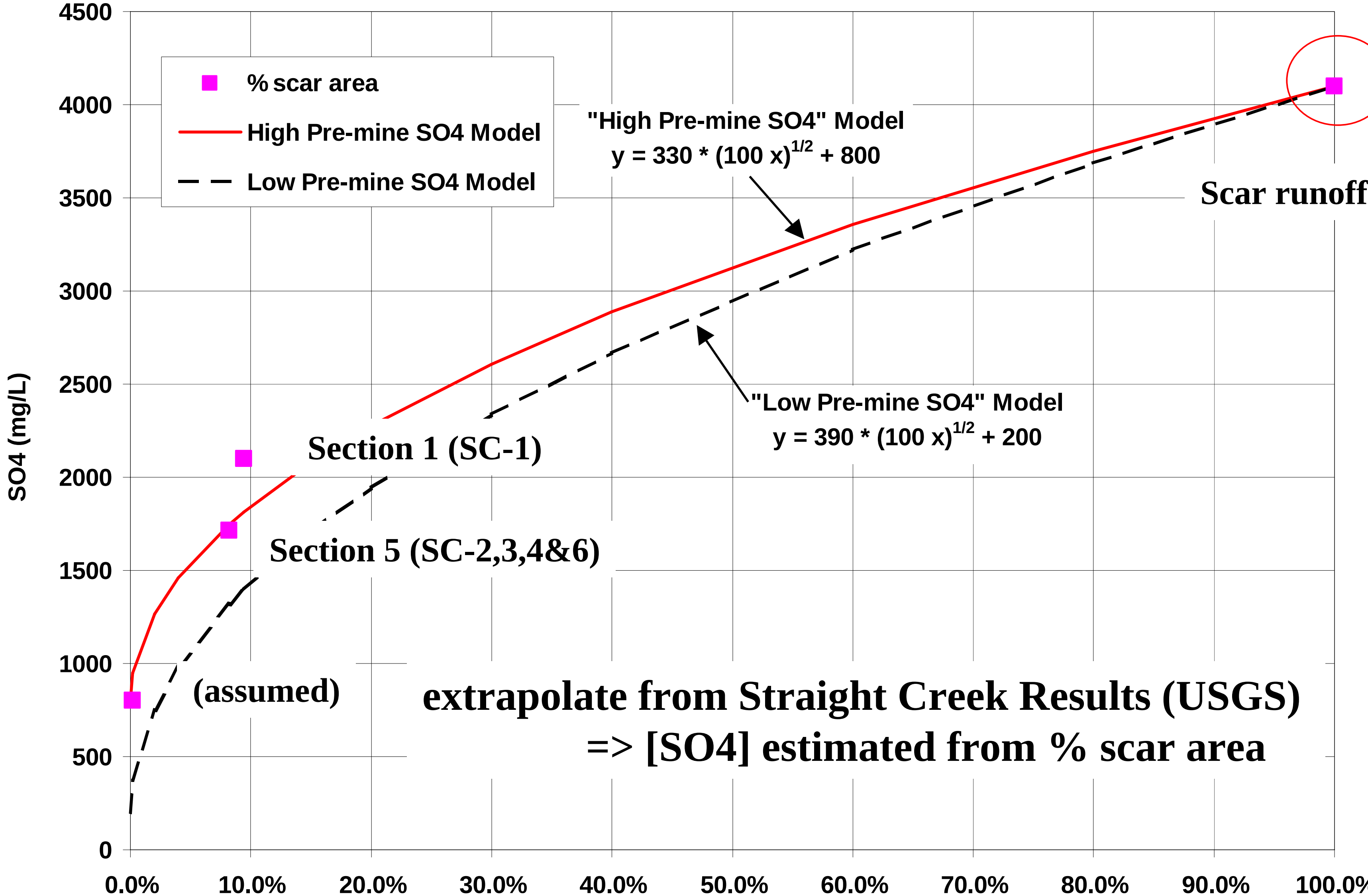


= Areas yielding into Open Pit & U/G Workings

Water Yield Estimates

Basin Number	Basin Name	"Low Yield" Model				"High Yield" Model			
		Pre-Mining		Current		Pre-Mining		Current	
		cfs	gpm	cfs	gpm	cfs	gpm	cfs	gpm
IX	Mine Site Boundary - Sulphur Gulch	0.04	16	0.04	16	0.05	25	0.05	25
VIII	Sulphur Gulch	0.50	226	0.26	116	0.86	386	0.60	270
VII	Sulphur West	0.02	7	0.01	3	0.03	13	0.03	13
VI	Middle Dump	0.05	21	0.02	11	0.08	34	0.08	34
V	Sugar Shack South Dump	0.03	12	0.01	6	0.05	21	0.05	21
IV	Unnamed Drainage	0.02	9	0.02	9	0.03	12	0.03	12
III	Goathill Gulch	0.21	93	0.07	30	0.36	161	0.16	71
II	Unnamed Drainage	0.03	15	0.03	15	0.05	21	0.05	21
I	Capulin	0.23	104	0.10	43	0.39	177	0.22	97
Total		**1.12**	**503**	**0.56**	**250**	**1.89**	**849**	**1.26**	**564**

Pre-Mining SO4



SO4 Load Estimates

Pre-mining Conditions

Basin Number	Basin Name	Low Pre-mine SO4 Model			High Pre-Mine SO4 Model		
		[SO4]	Low Yield SO4 Load	High Yield SO4 Load	[SO4]	Low Yield SO4 Load	High Yield SO4 Load
		mg/L	lbs/day	lbs/day	mg/L	lbs/day	lbs/day
IX	Mine Site Boundary - Sulphur Gulch	200	39	59	800	156	237
VIII	Sulphur Gulch	1,409	3,826	6,533	1,823	4,949	8,452
VII	Sulphur West	2,928	261	445	3,109	277	472
VI	Middle Dump	724	179	299	1,244	307	514
V	Sugar Shack South	2,438	351	611	2,694	388	676
IV	Unnamed Drainage	700	76	99	1,223	132	173
III	Goathill Gulch	1,831	2,041	3,544	2,180	2,430	4,220
II	Unnamed Drainage	1,038	189	263	1,509	275	382
I	Capulin	869	1,085	1,844	1,366	1,707	2,899
Total			**8,047**	**13,697**		**10,621**	**18,023**

⇒ pre-mining loading influenced by (i) yield model and (ii) pre-mining SO4 model

SO4 Load Estimates

Current Conditions

Basin Number	Basin Name	Low Pre-mining SO4 Model				High Pre-mining SO4 Model			
		Low Yield		High Yield		Low Yield		High Yield	
		[SO4]	SO4 Load	[SO4]	SO4 Load	[SO4]	SO4 Load	[SO4]	SO4 Load
		mg/L	lbs/day	mg/L	lbs/day	mg/L	lbs/day	mg/L	lbs/day
IX	Mine Site Boundary - Sulphur Gulch	200	39	200	59	800	156	800	237
VIII	Sulphur Gulch	6,534	9,144	3,696	12,015	6,534	9,144	3,696	12,015
VII	Sulphur West	6,534	268	3,696	561	6,534	268	3,696	561
VI	Middle Dump	6,534	827	6,534	2,698	6,534	827	6,534	2,698
V	Sugar Shack South	6,534	470	6,534	1,639	6,534	470	6,534	1,639
IV	Unnamed Drainage	700	76	700	99	1,223	132	1,223	173
III	Goathill Gulch	2,644	950	2,644	2,267	2,644	950	2,644	2,267
II	Unnamed Drainage	1,038	189	1,038	263	1,509	275	1,509	382
I	Capulin	1,575	813	1,575	1,837	1,575	813	1,575	1,837
Total			**12,777**		**21,438**		**13,037**		**21,808**

⇒ shaded values represent calibrated [SO4] (based on observation)

⇒ Current loading influenced by yield model & current [SO4]

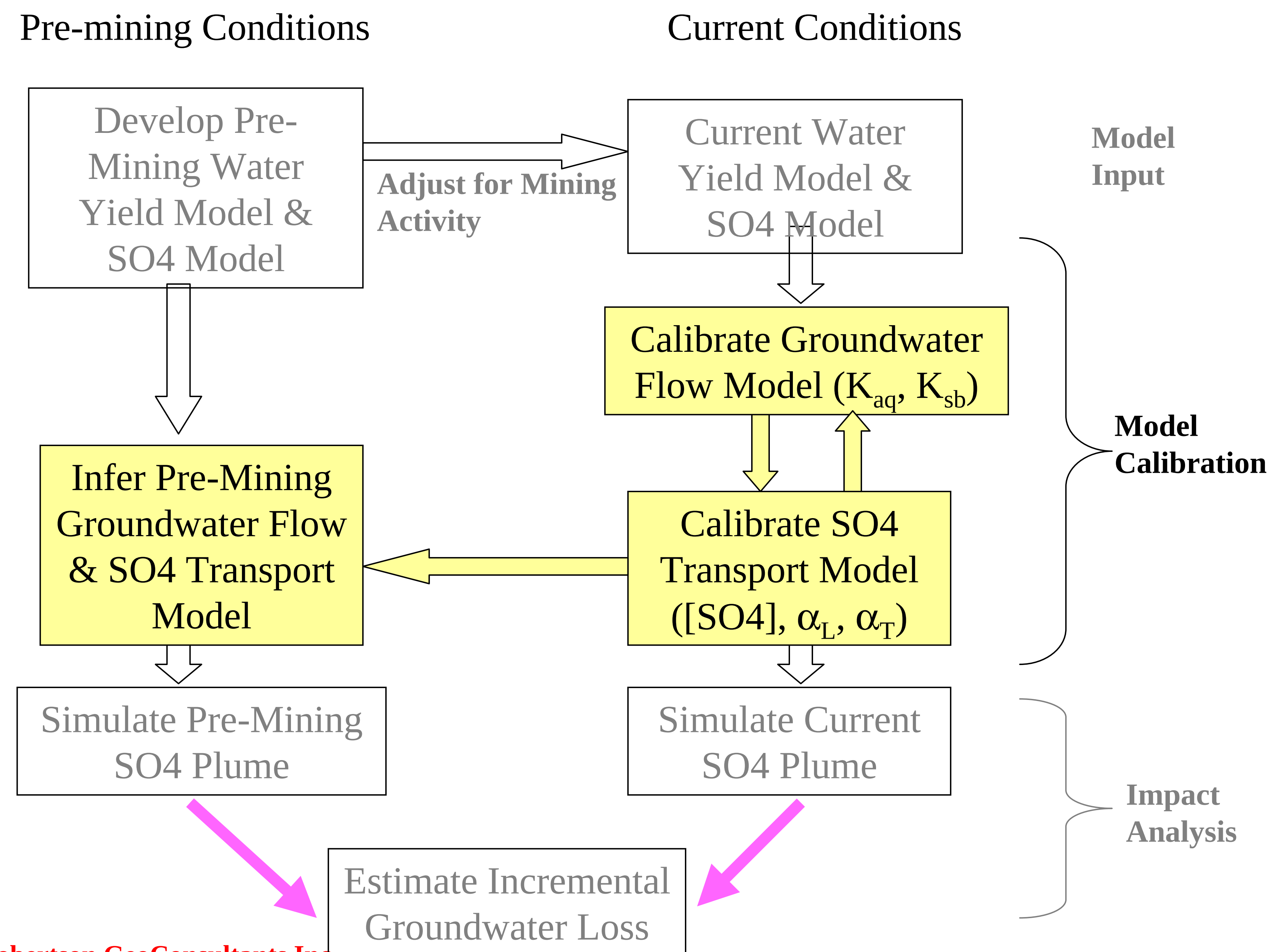
⇒ Pre-mining SO4 model does not influence current SO4 load

Conclusions

SO4 Loading

SO4 Source Model	Low Water Yield	High Water Yield
Current SO4*	13,037	21,808
High Pre-mine SO4	10,621	18,023
Low Pre-mine SO4	8,047	13,697

* Based on model calibration (see below)



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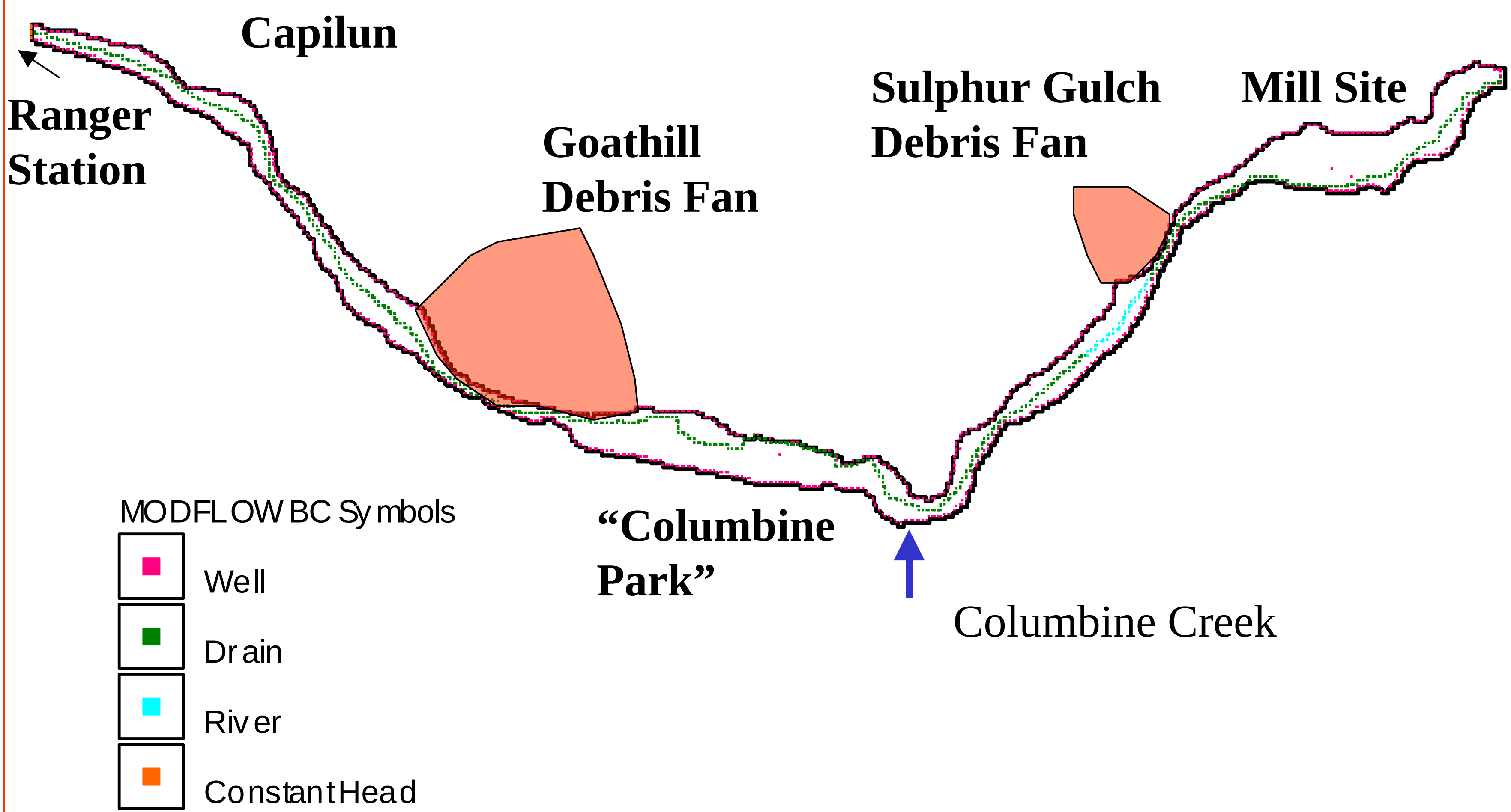
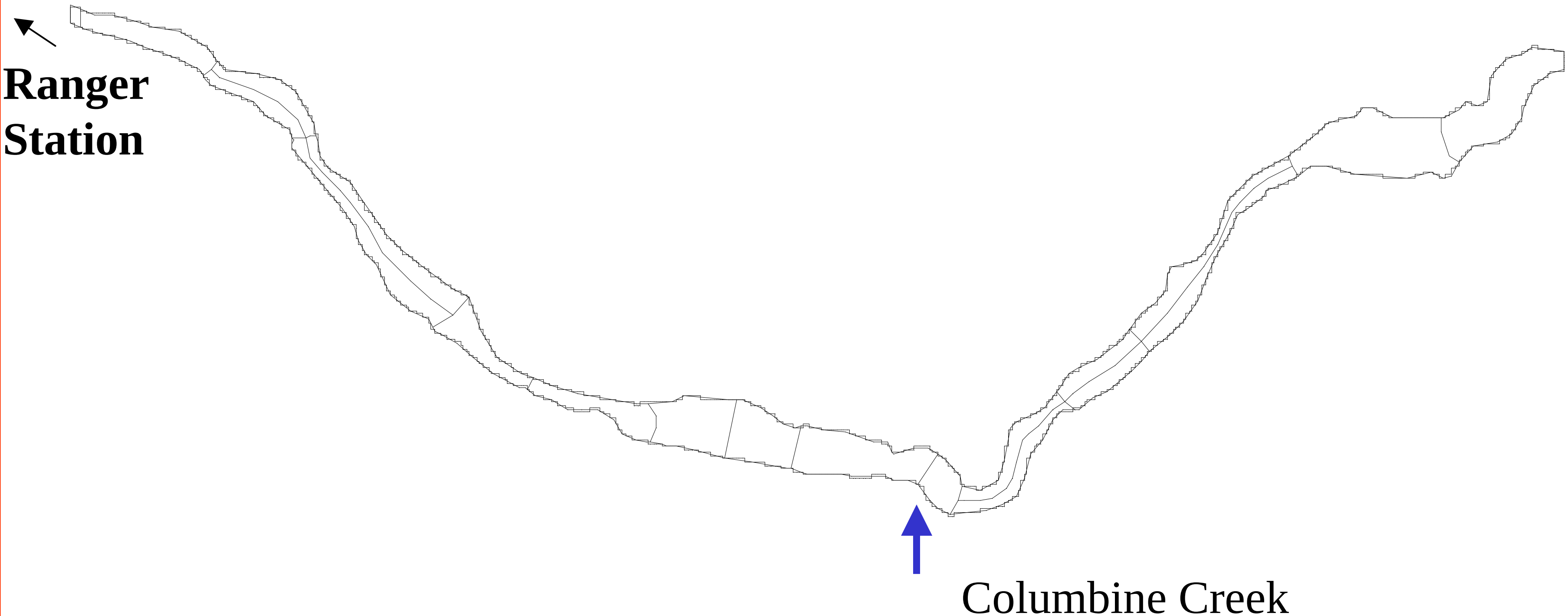
Red River Alluvial Aquifer

Model Domain and Boundary Conditions



Red River Alluvial Aquifer

Aquifer Reaches (K zones)



GW Flow and Transport Model Parameters and Simplifying Assumptions

- Aquifer w/ variable K (200 - 1,500 ft/day)
- Aquifer w/ variable width
- Aquifer w/ constant depth (~75 ft)
- Single vertical layer (i.e., no vertical dispersivity)
- Allows for injection of sulphate load primarily on upstream boundary and northern side of alluvial aquifer

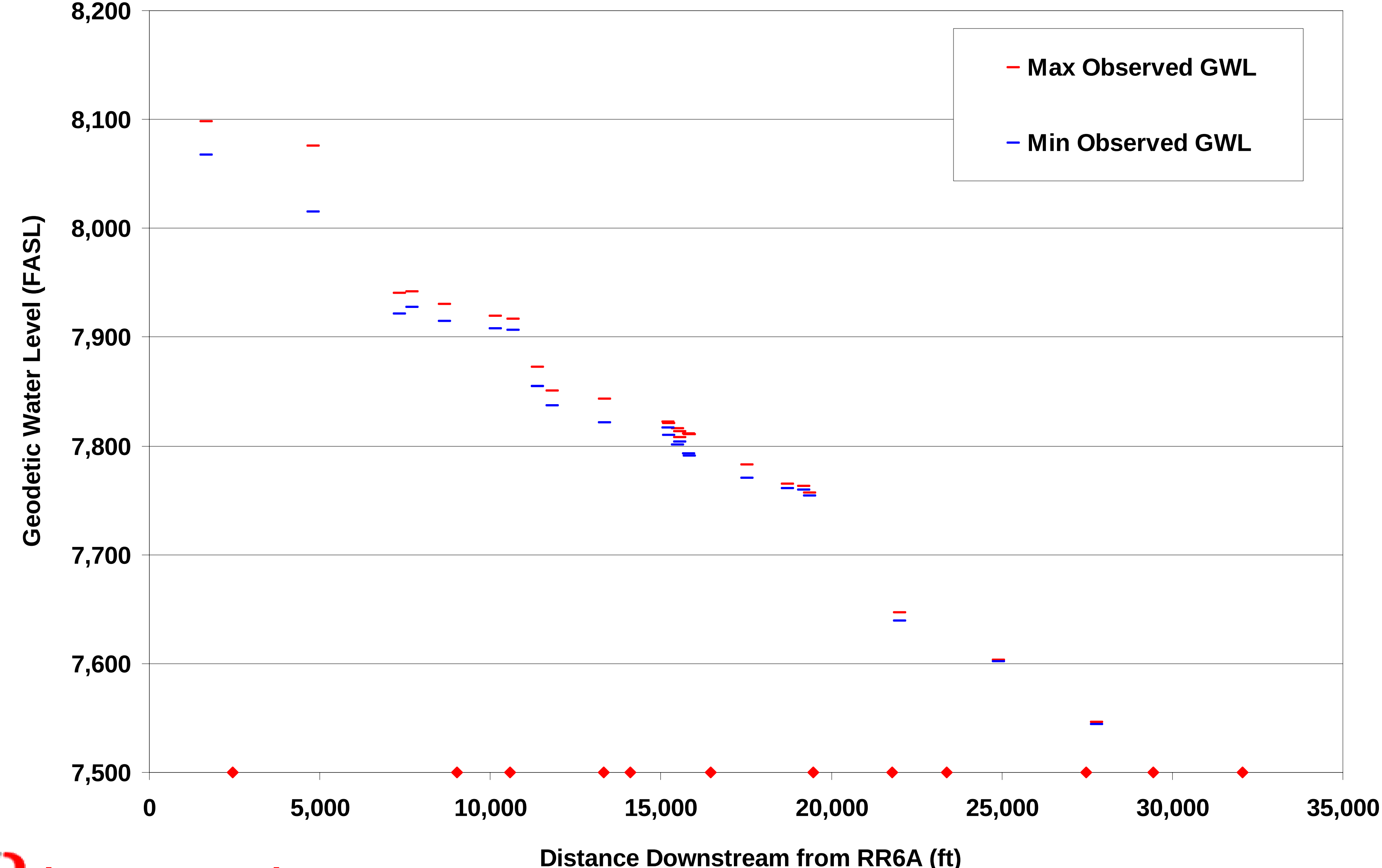
Calibration Targets

for GW Flow & Transport Models

- Comparison of model output with reality (i.e., measured values)
- For flow model:
  - GW discharge to Red River (RI/FS surveys, 2002-2003) – (*primary calibration relied on for flow model assessment*)
  - Range of GW levels (Oct'02 – Sep' 04)
- For flow & transport model:
  - Range of observed Sulphate conc. (Oct'02 – Sep' 04)
  - Sulphate load to Red River

Calibration Targets

Observed Groundwater Levels



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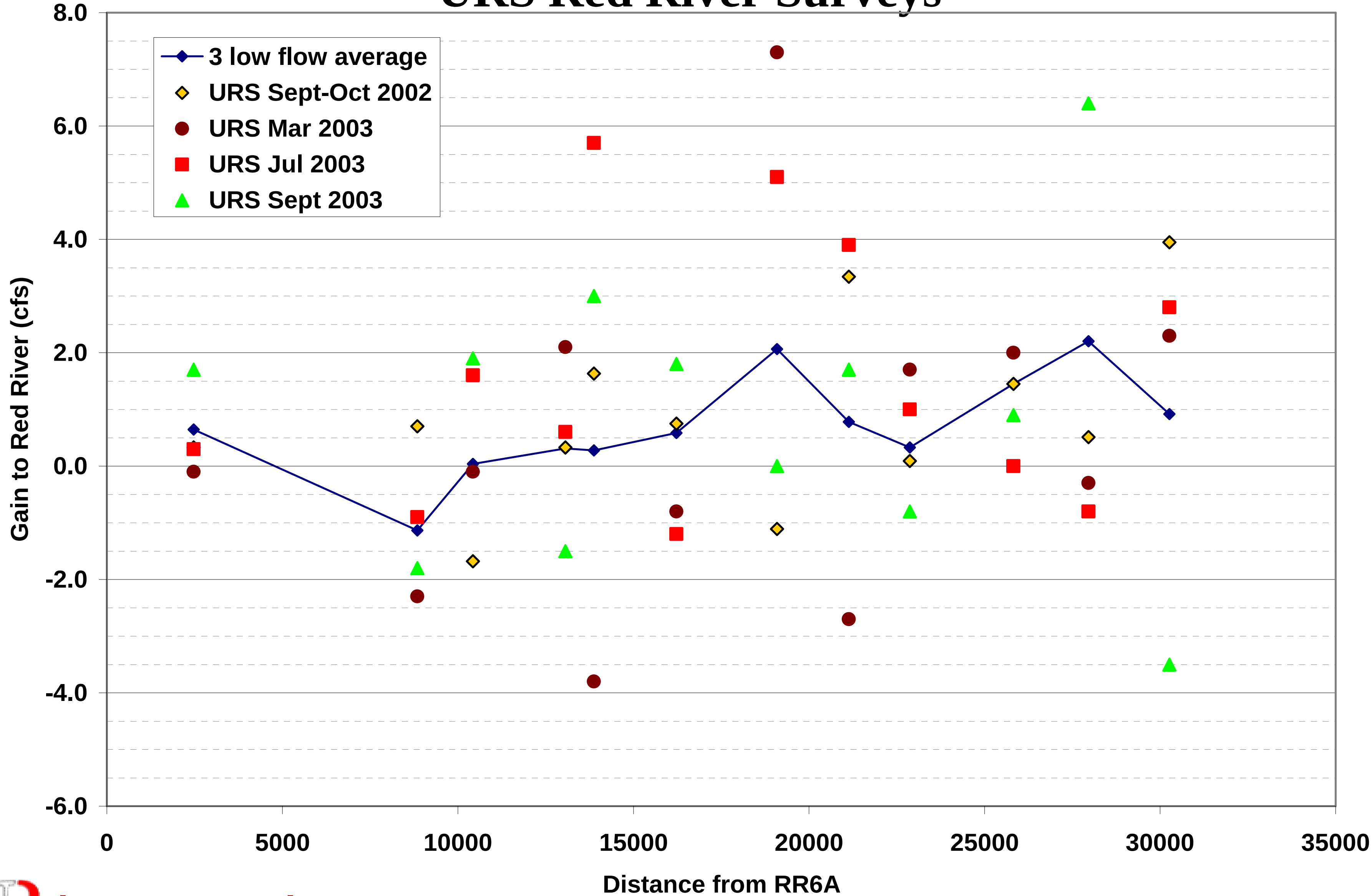
Calibration Targets

URS Red River Surveys



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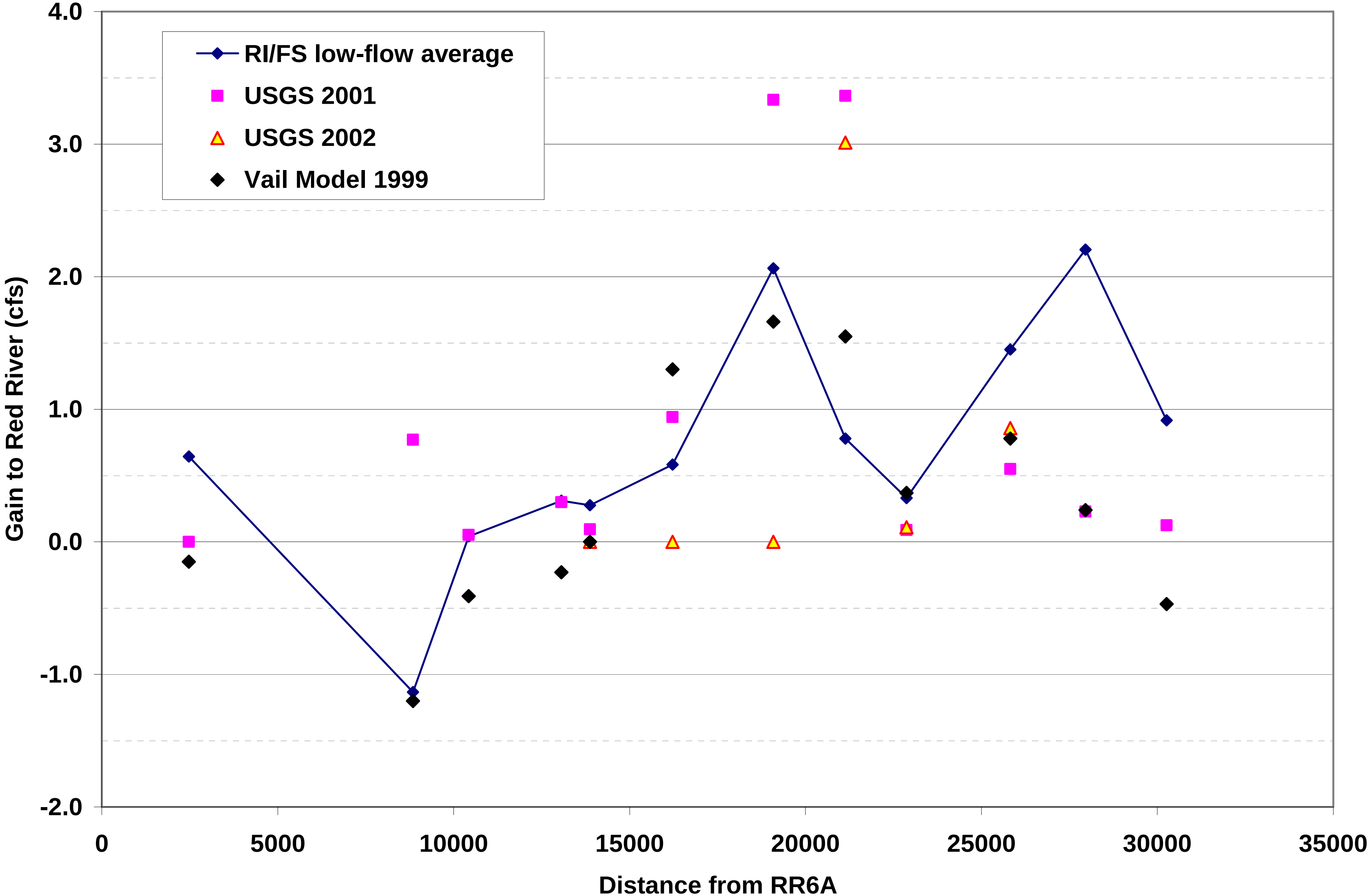
Comparison to Other RR Surveys



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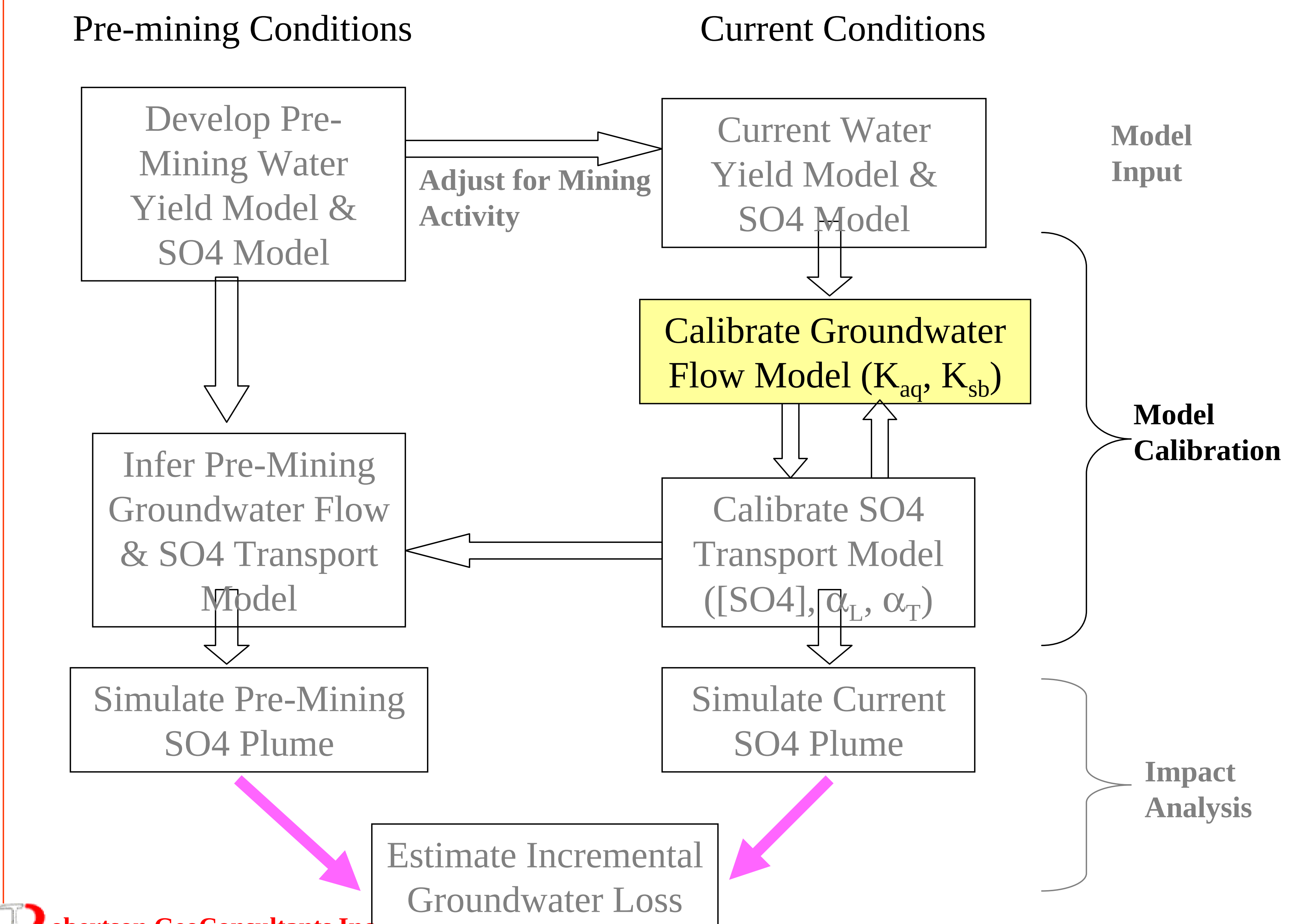
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Calibration of GW Flow Model

Run ID	Description
RR18_2	High Yield Model (Current Conditions)
RR24_1	Low Yield Model (Current Conditions)

⇒Adjust hydraulic parameters ($K_{aquifer}$ & $K_{streambed}$) until good match with observed flows (to Red River) and GW levels is achieved

Calibration of Flow Model

Hydraulic Parameters

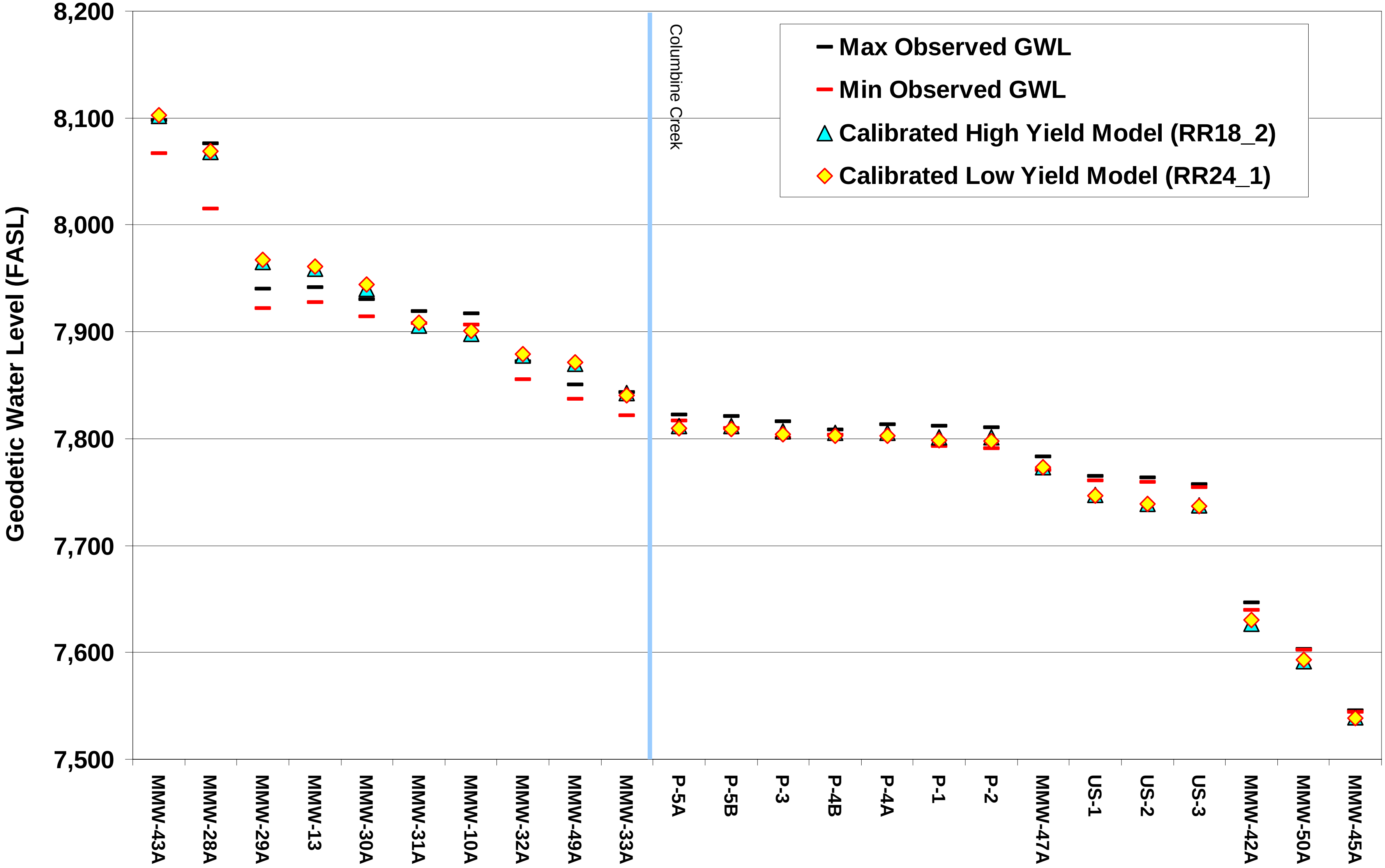
Aquifer Reach[1]	Calibrated High Yield Model RR18_2		Calibrated Low Yield Model RR24_1	
	K (ft/d)	C (ft^2/d) [2]	K (ft/d)	C (ft^2/d) [2]
6A - 7	600	600	900	900
7 - 8'	700	700	800	800
8' - 8	700	70	600/1000	80
8 - 8A	800	800	600/1000	800
8A - 10	1200	1200	900/1500	1200
10 - 10A	800	800	800	800
10A-11A1	600	100	700	700
11A1-11A	600	600	700	700
11A - 11B	250	250	250	250
11B - 11C	700	700	800	800
11C - 12	700	700	800	800
12 - 13	800	800	600/1000	800
13-14	300	300	300/500	400
14-14'	300	300	200	200
14'-15	26	26	26	26

Notes:

[1] reaches coincide with RI/FS flow stations of RR surveys

[2] $C = K_{streambed}$ * river width

Calibration of GW Flow Model



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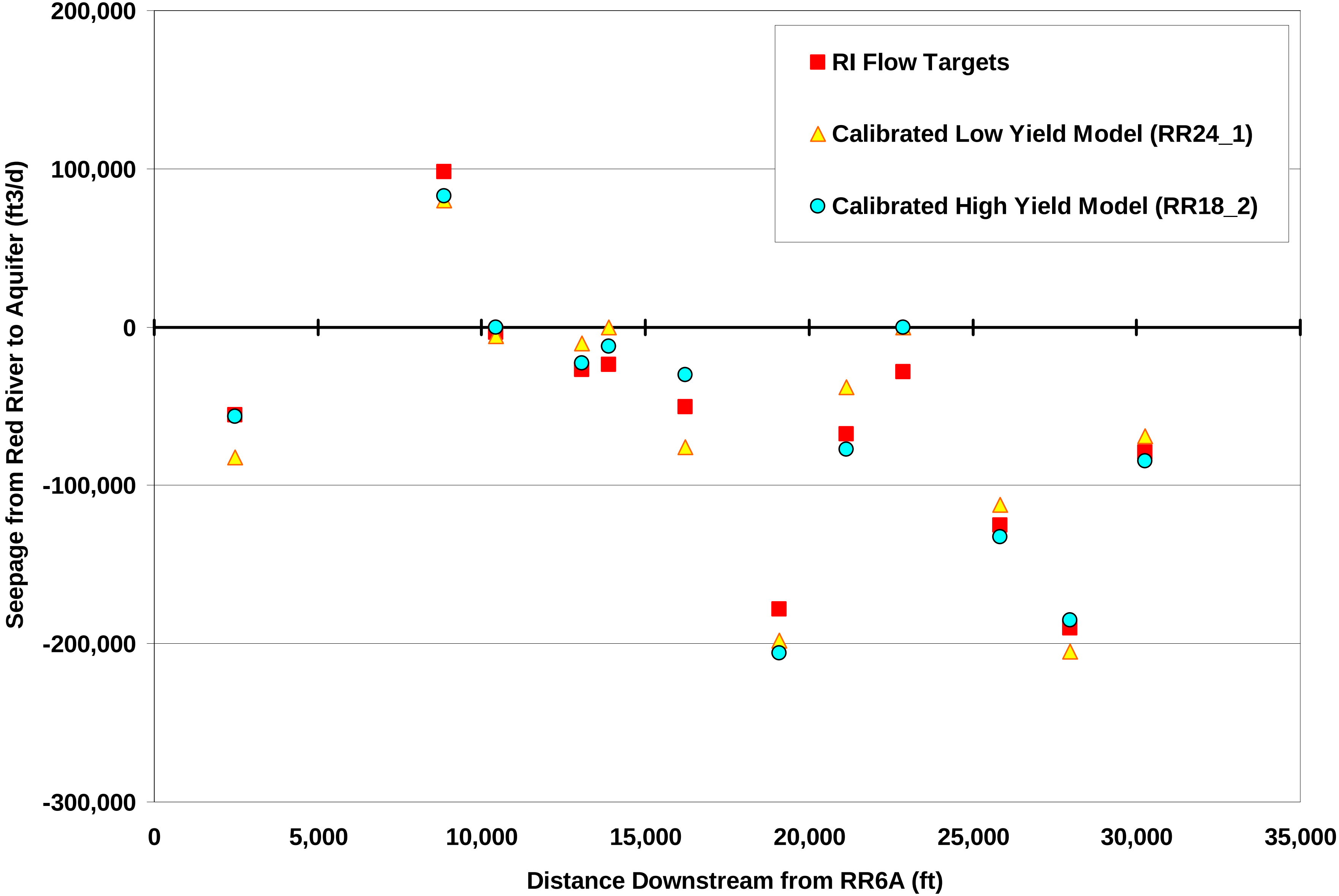

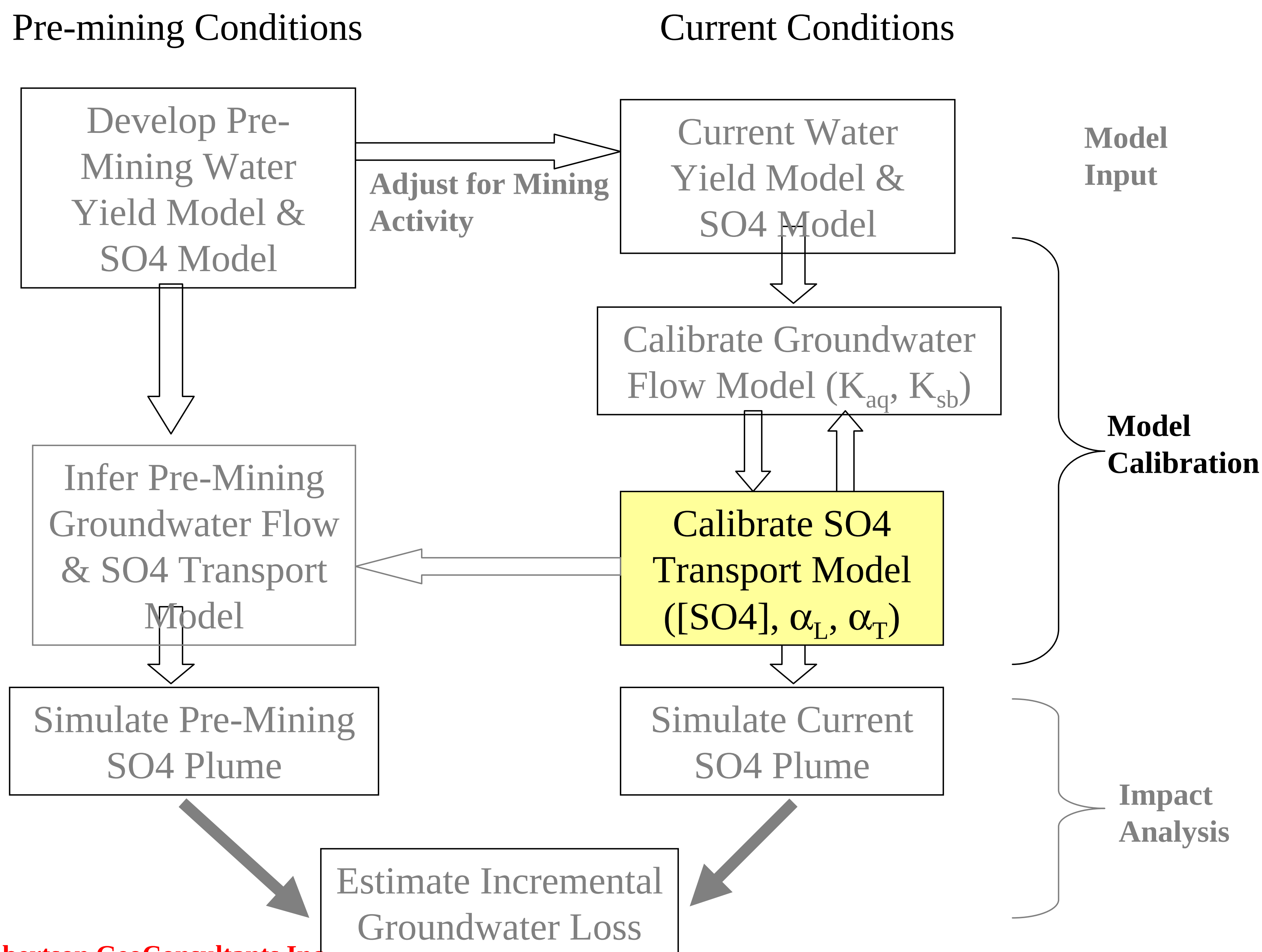
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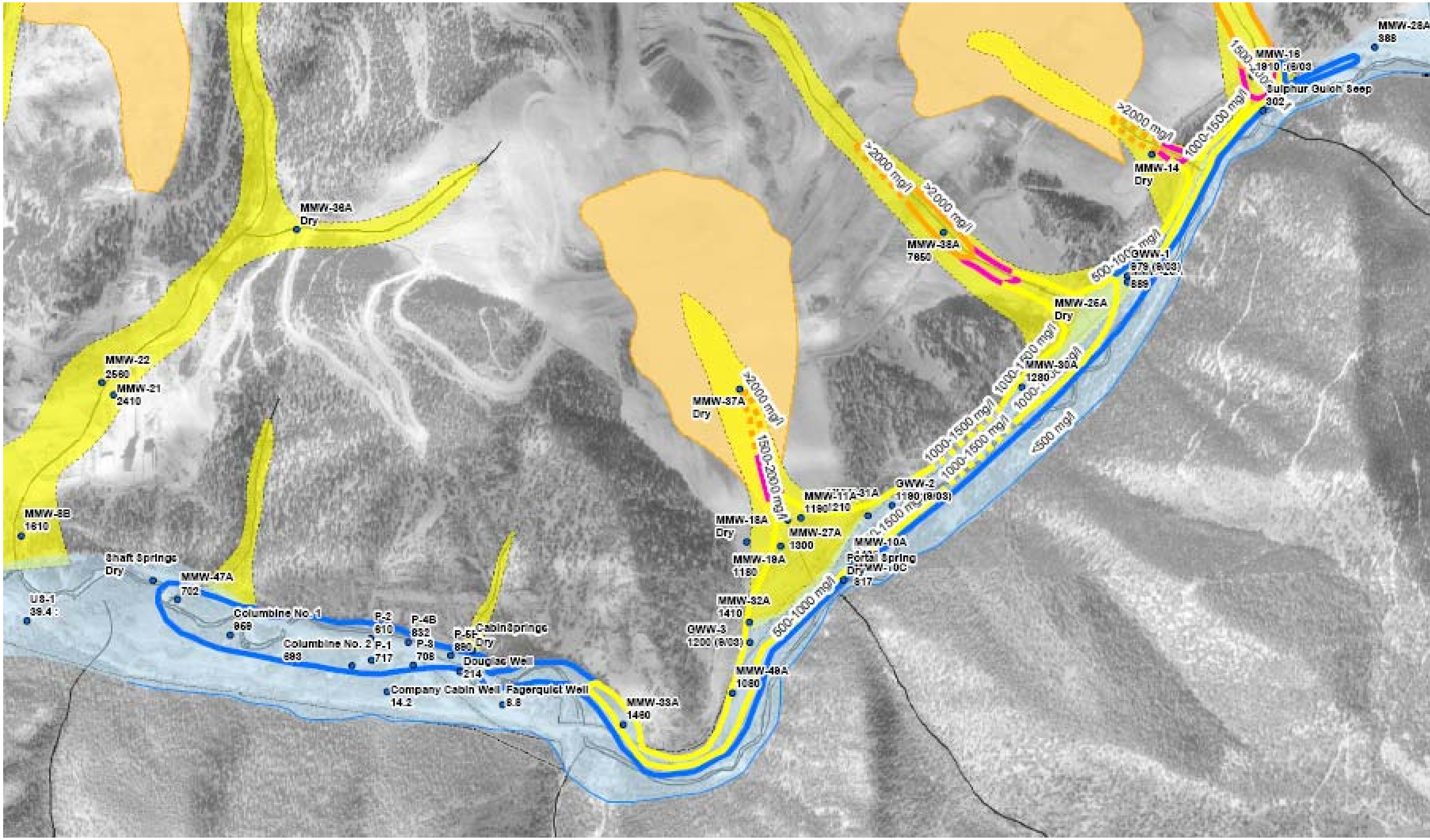
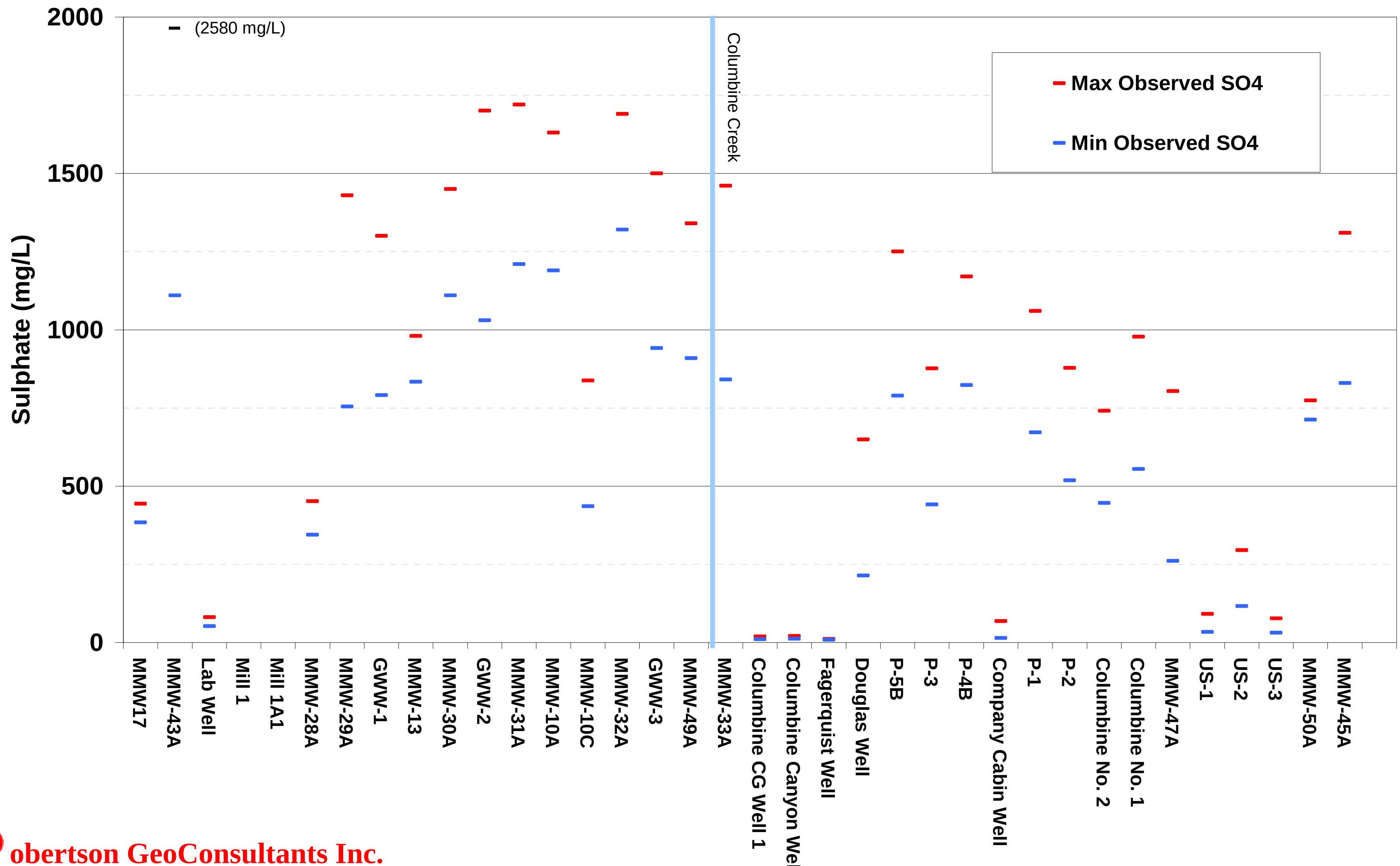
Sulphate Concentrations in RR Aquifer



Calibration of Transport Model

Observed Sulphate Concentrations



Calibration of Transport Model

Key Factors influencing [SO4] in Red River aquifer:

- Sulfate Loading
  - Source sulfate concentrations*
  - Flow yield from mine site*
- "Spreading" or dispersion in RR aquifer
  - longitudinal dispersivity (α_L)*
  - transverse dispersivity (α_T)*

* = To be varied during model calibration and sensitivity analysis

Calibration Parameters

- (High vs Low Flow Yield)
- Current [SO4] on Mine Site:
  - Low [SO4]
  - Intermediate [SO4]
  - High [SO4]
- Dispersivity
  - low dispersivity (α_L= 10ft; α_T =1 ft)
  - high dispersivity (α_L= 20ft; α_T =2 ft)

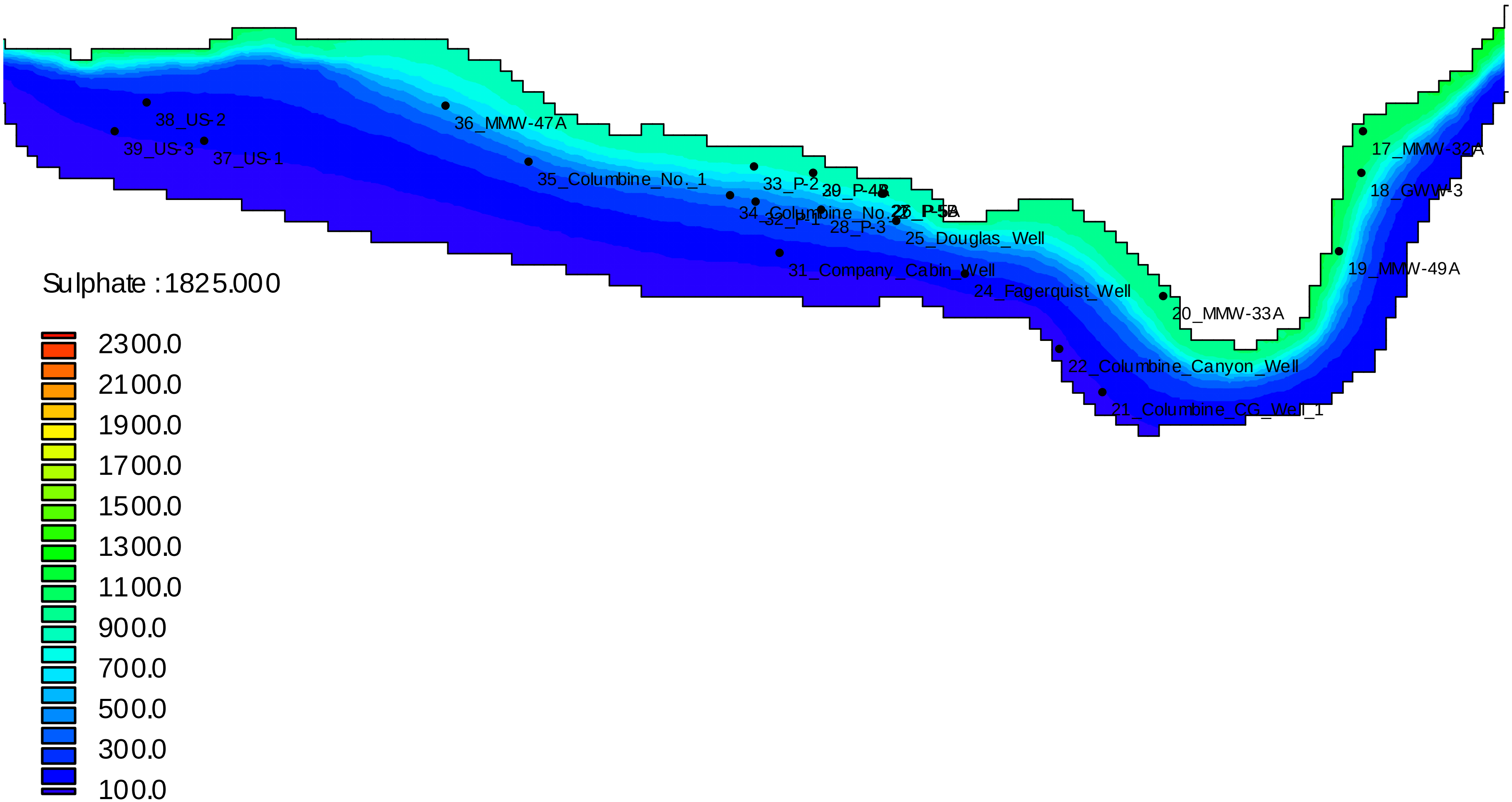
Current [SO4] along front rock piles

Observed [SO_4] in colluvial groundwater beneath the front rock piles draining towards the Red River aquifer varies from 3,696 mg/L (MW39A) to 6,534 mg/L (MW38A)

Current [SO4] Model	Sub-watershed [SO_4] (mg/L)			
	Sulphur Gulch	Sulphur West	Middle Pile	Sugar Shack South Pile
Low	3,696	3,696	3,696	3,696
Intermediate	3,696	3,696	6,534	6,534
High	6,534	6,534	6,534	6,534

Simulated SO4 Plume (Current Conditions)

Low Yield Model



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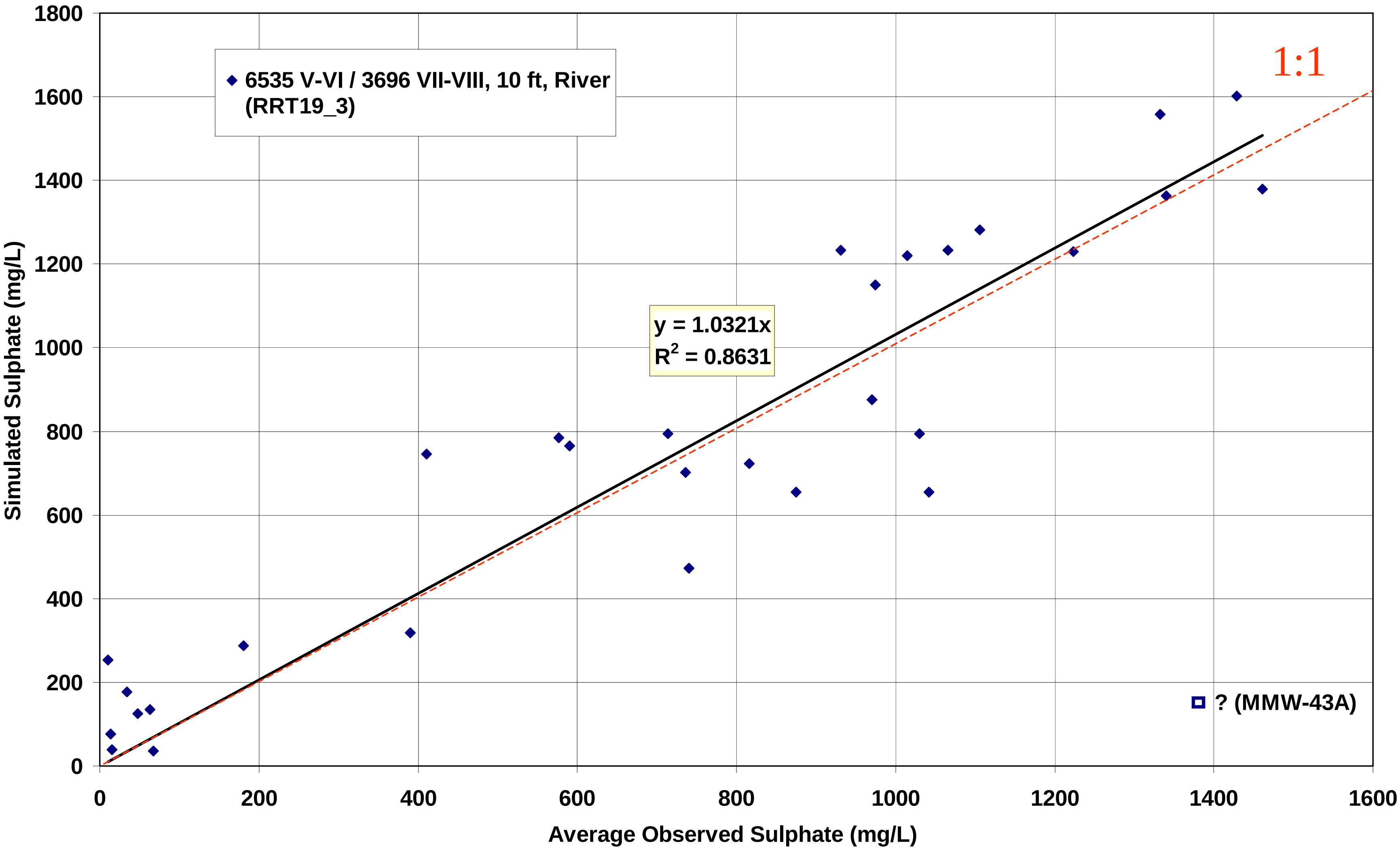
High Yield Model - Calibration



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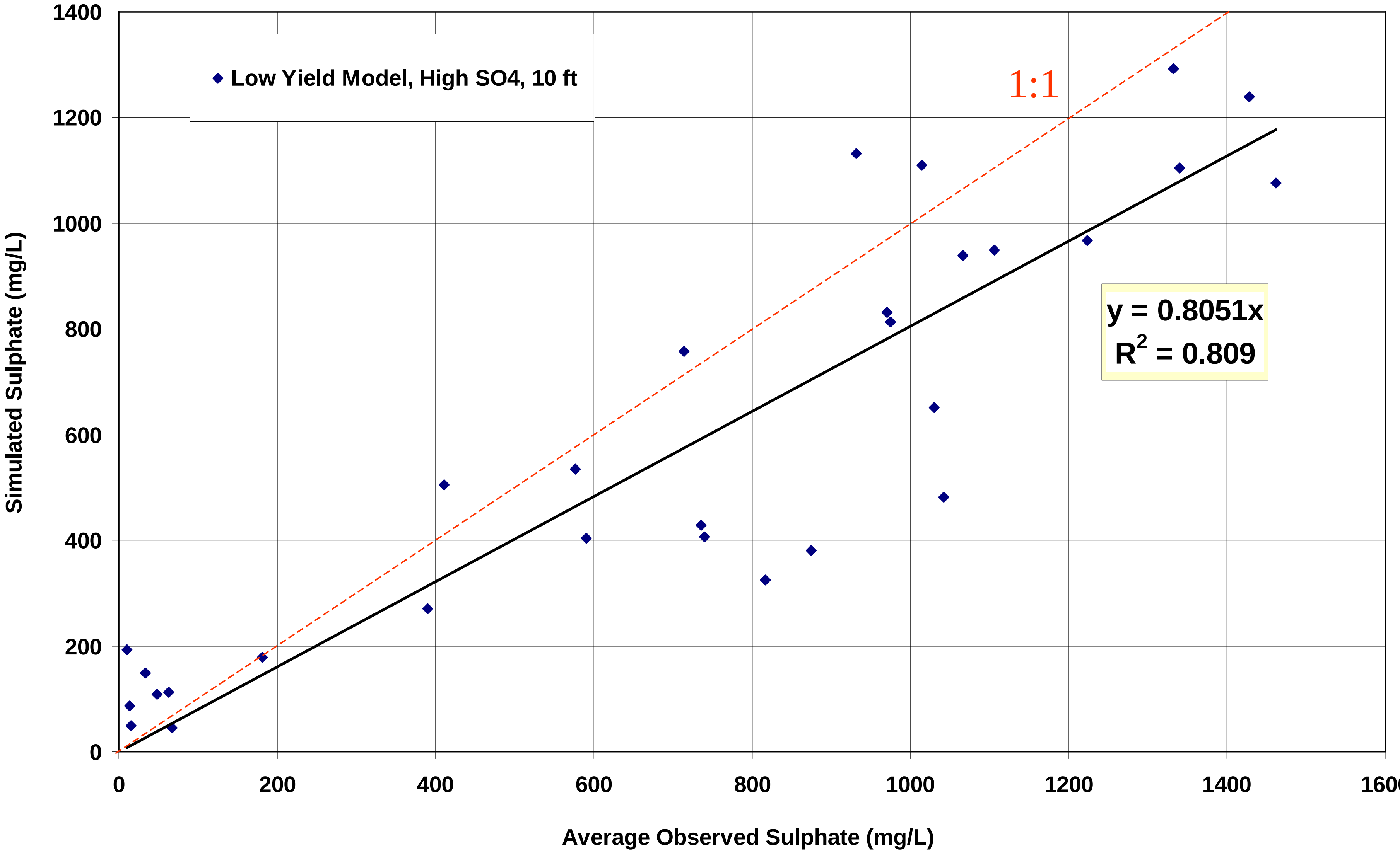


Calibration Results – Current Conditions

Model[1]	Run ID	Current SO4 on Mine Site	α_L (ft)	Current Load to Red River (lbs/day)	Regression on Observed SO4	
					Slope	R^2
"High Yield" Model	RRT19_3	Intermediate	10	22,511	1.0321	0.8631
	RRT19_1	Low	10	21,503	0.9027	0.8542
	RRT19_2	High	10	29,143	1.4139	0.8263
	RRT19_5	Intermediate	20	22,563	0.8119	0.7596
"Low Yield" Model	RRT24_1	High	10	15,243	0.8051	0.809
	RRT24_5	Low	10	12,260	0.5406	0.8176
	RRT24_6	Intermediate	10	12,613	0.5759	0.8201
	RRT24_4	High	20	16,194	0.5838	0.6704

[1]Sensitivities for both yield models carried out using "High Source" model.

(highlighted) Best calibration for each yield model.

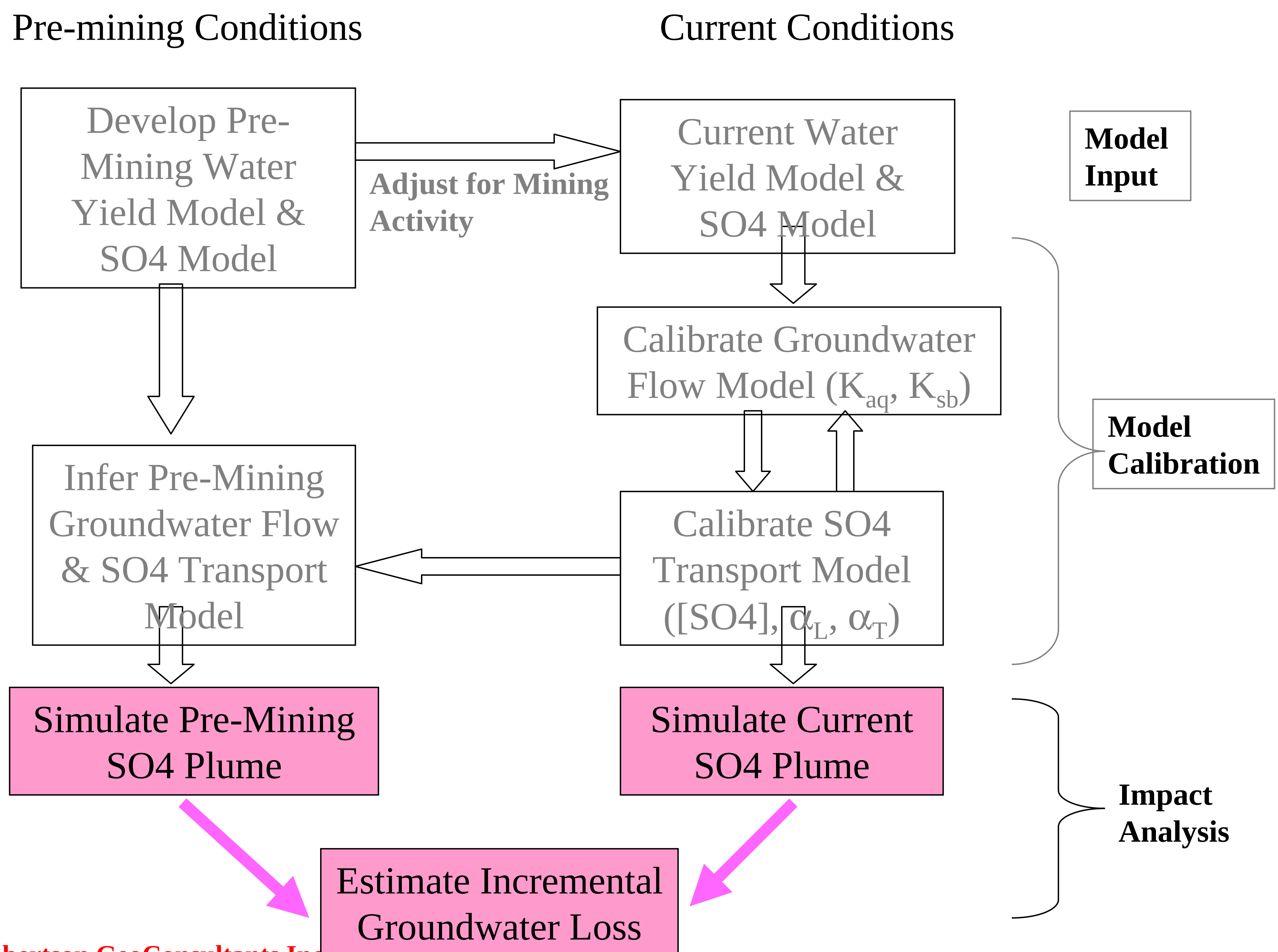
SO4 Loading to Red River

- simulated SO4 loading with "calibrated" model
  - ~ 15,000 lbs/day (low yield model)
  - ~ 23,000 lbs/day (high yield model)
- "observed" incremental loading along mine reach:
  - ➢ Vail model: 8,400 lbs/day
  - ➢ URS surveys: 6,200 to 13,100 lbs/day
  - ➢ USGS survey: 4,800 to 12,500 lbs/day
- potential reasons for discrepancy:
  - ➢ low flow stream surveys versus "average yields"
  - ➢ SO4 non-conservative
  - ➢ stream surveys underestimate total load (i.e. potential underflow at gauging station)

Conclusions
Transport Model Calibration

• Calibrated “high yield” model provides better match to observed [SO4] in aquifer
• Calibrated “low yield” model provides better match to observed net loading to Red River

$\Rightarrow$ both scenarios represent a plausible model of actual conditions
$\Rightarrow$ both scenarios carried forward for impact analysis to determine plausible range of net impact



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Impact Analysis

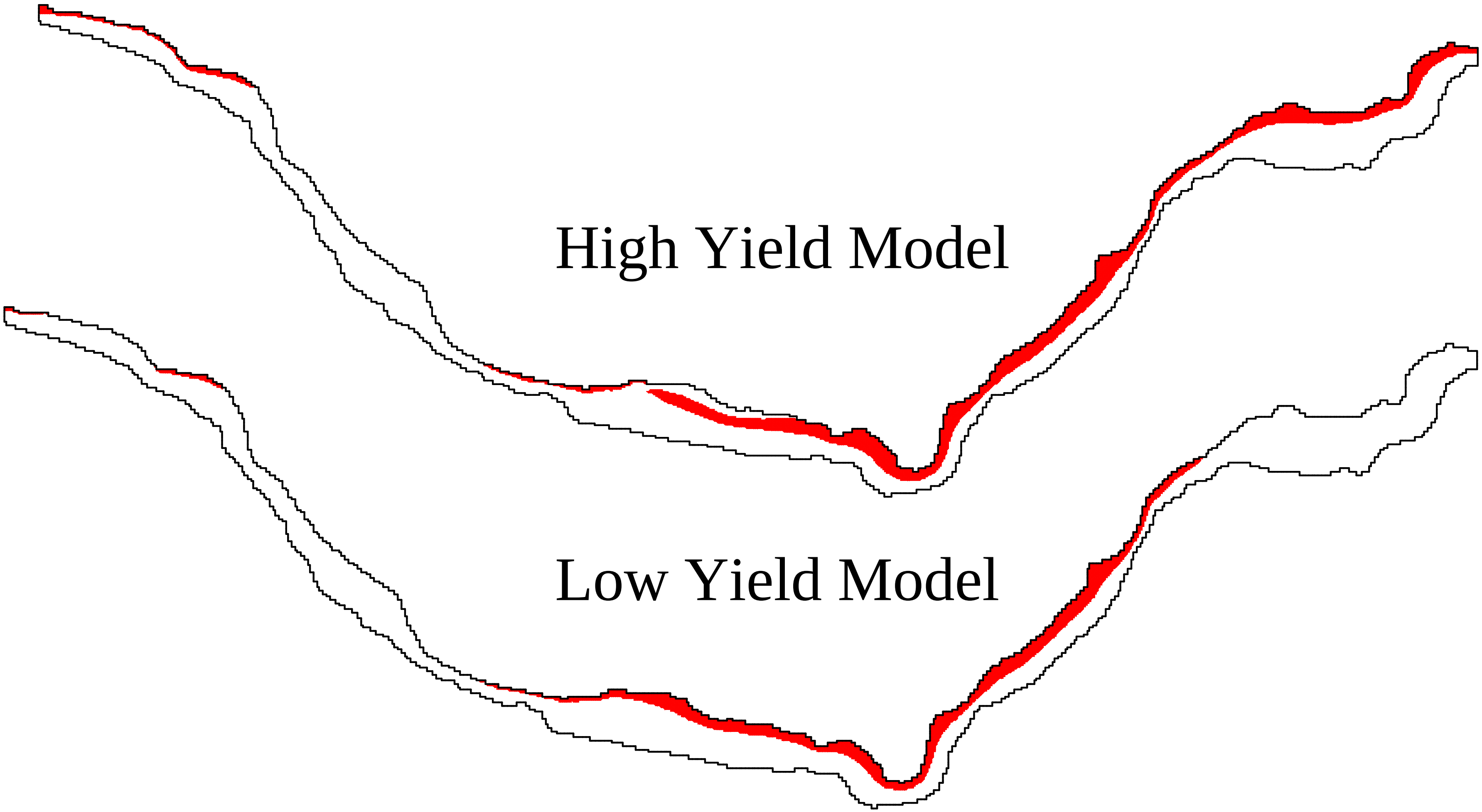
Scenarios

Water Yield Model	Pre-mining SO4 Model	Run ID
"High Yield" Model	High SO4	RRT19_3
	Low SO4	RRT20_2
"Low Yield" Model	High SO4	RRT24_1
	Low SO4	RRT24_3

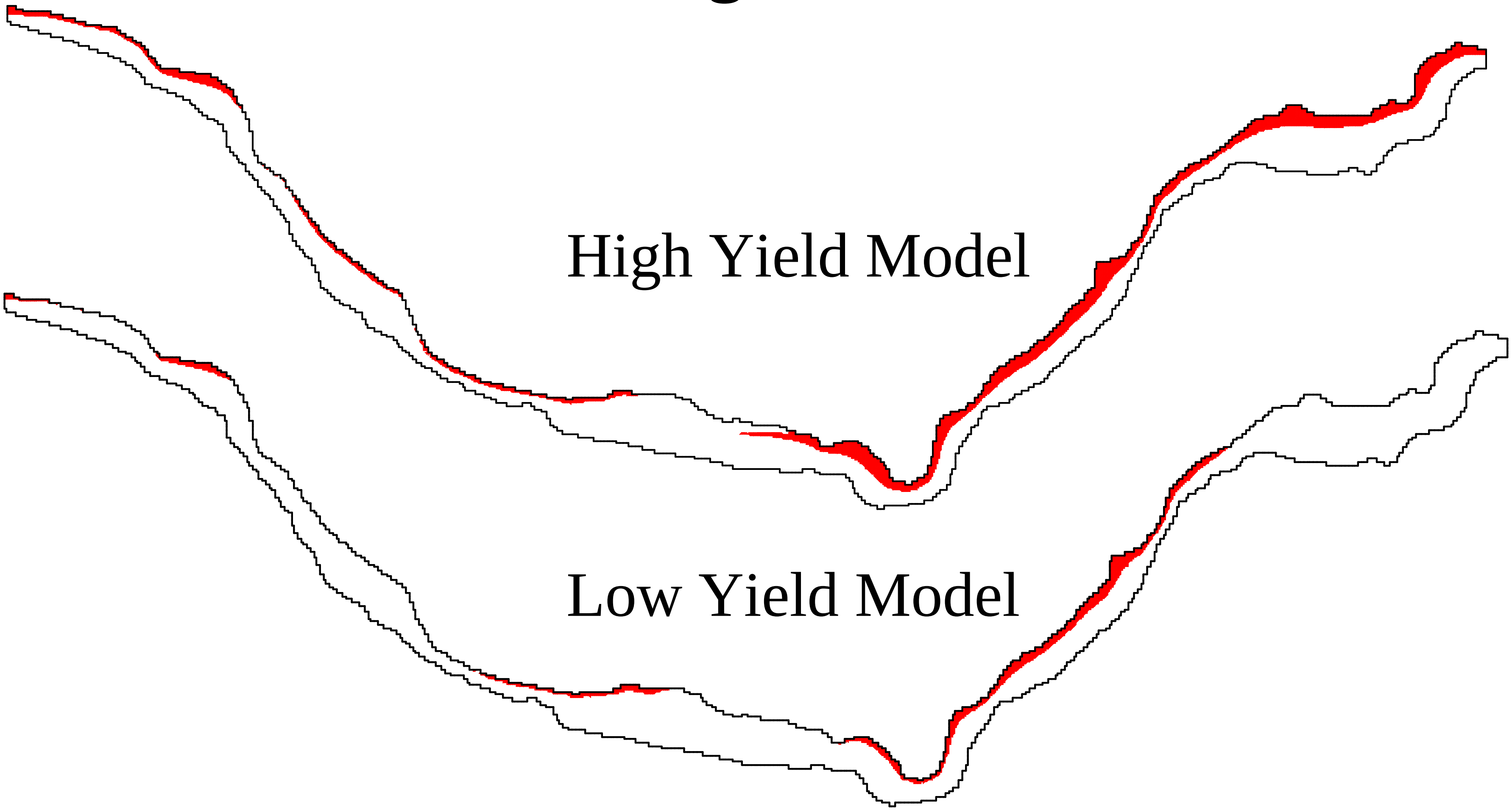
Assessment of GW Impact Methodology

=> calculate average "impacted" GW flux w/ (SO4 >600 mg/L)

Assessment of GW Impact (SO4 >600 mg/L) Current Conditions



Assessment of GW Impact (SO4 >600 mg/L)
Pre-mining Conditions



Impact Analysis
Groundwater Flux

Yield Model	Pre-mining SO4 Model	Run ID	GW Flow Impacted		
			Pre-mining (cfs[1])	Current (cfs[1])	Incremental Loss (cfs[1])
"High Yield" Model	High SO4	RRT19_3	1.20	1.36	0.16
	Low SO4	RRT20_2	0.75	1.33	0.58
"Low Yield" Model	High SO4	RRT24_1	0.47	0.88	0.41
	Low SO4	RRT24_3	0.07	0.83	0.76

[1] using average flux of "impacted" GW flow through 13 sections

Conclusions

• Estimated net impact on Red River aquifer assuming "High" SO4 pre-mine model ranges from 0.16 to 0.41 cfs

• Estimated net impact on Red River aquifer assuming "Low" SO4 pre-mine model ranges from 0.58-0.76 cfs

• "High" SO4 pre-mine model provides better fit to observed SO4 in analogue watershed (Straight Creek)

=> Best estimate of incremental loss of groundwater in alluvial aquifer: 0.16-0.41 cfs