Characterization of Groundwater Transport Parameters in Regional Fractured-Rock Aquifers Using Multiple Environmental Tracers and a Dual-Domain Modeling Approach

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Model of Upper Potomac River Basin

- MODFLOW-2000 Steady State Flow
- Grid resolution=500 ft   1000 cols, 2000 rows
- Seven Layers 10, 20, 40, 80, 150, 300, 600 ft
- Just over one million active cells per layer
- Anisotropy along strike of valleys 14:1
- Permeability Decreases with depth
- 1. Recharge calibrated against 12 base flows
- 2. Permeability calibrated against 200 heads
- 3. Porosity calibrated against tracers

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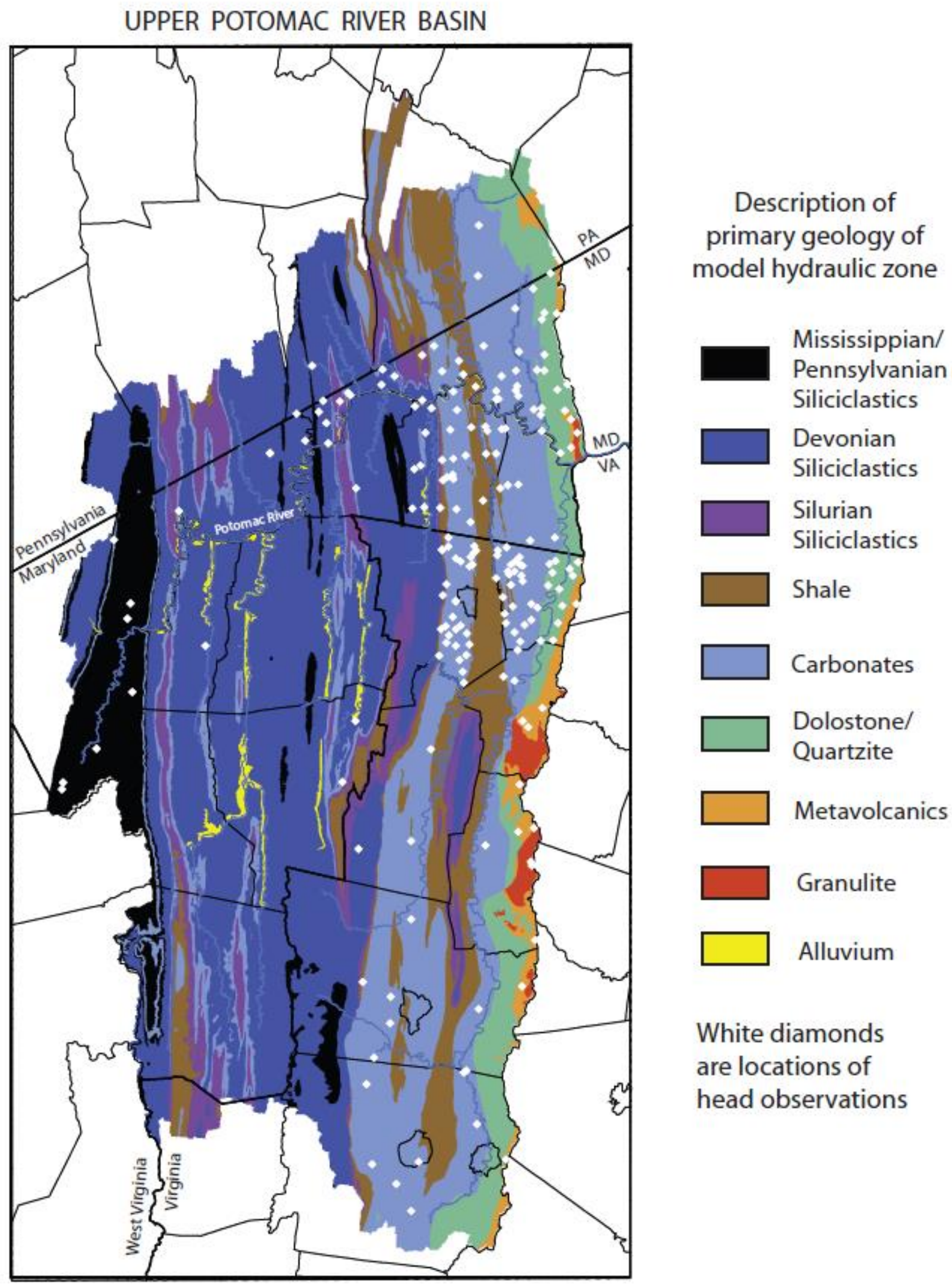
- **200 mean water levels from wells (each with several measurements) were used for calibration**

- **Nearly all wells are open holes in fractured rock, but the well depth and the depth to the water table allow for model layer assignment, and thus provide information on vertical head distribution**



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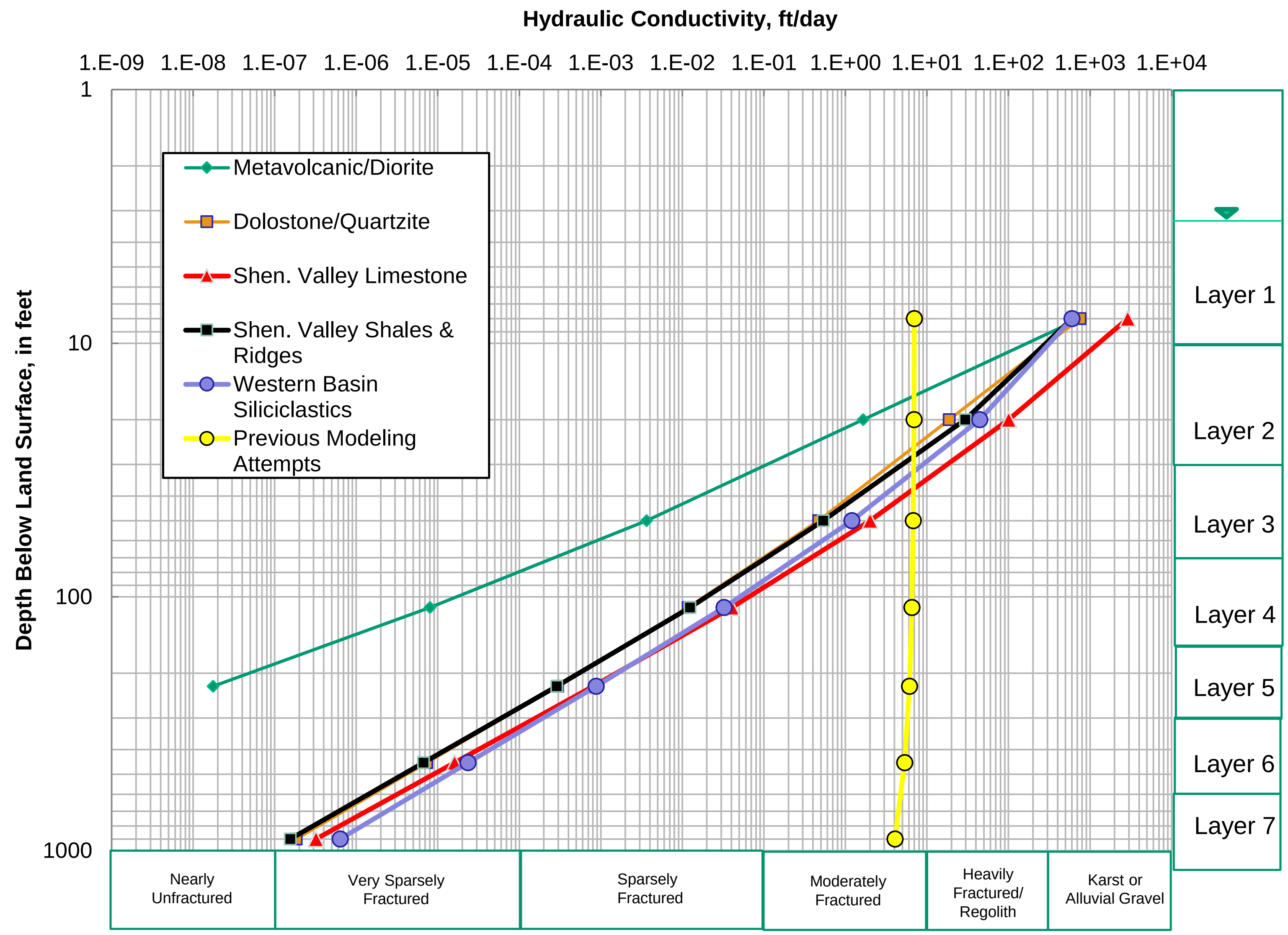


Hydraulic Conductivity, ft/day
1.E-09
1.E-08
1.E-07
1.E-06
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
Depth Below Land Surface, in feet
1
10
100
1000
Metavolcanic/Diorite
Dolostone/Quartzite
Shen. Valley Limestone
Shen. Valley Shales & Ridges
Western Basin Siliciclastics
Previous Modeling Attempts
Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
Layer 6
Layer 7
Nearly Unfractured
Very Sparsely Fractured
Sparsely Fractured
Moderately Fractured
Heavily Fractured/ Regolith
Karst or Alluvial Gravel

What determines how fast tritium or any tracer moves through the subsurface?

- Velocity = discharge / n

n = effective porosity

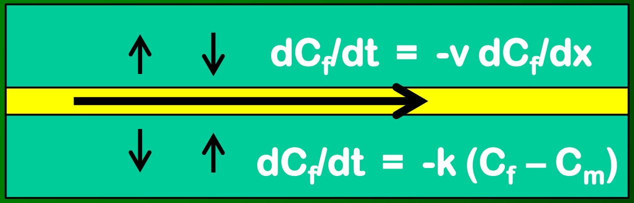
n = 0.30 sediments

n = 0.03 fractured rock

Single Porosity Model

Fractured Rock transport is more complicated

Chemical exchange occurs between the “mobile” fracture water and the “immobile” rock-matrix water



Dual Porosity or Dual Domain Model

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Using Dual-Domain MODPATH with Spring Data

- **CFC-113, SF_6, Tritium, Helium-3 collected at >40 springs 2003-2006**
- **>8000 MODPATH particles tracked forward to 28 springs**
- **Dual Domain calculations were added to each pathline from distance and velocity**
- **Dual-domain parameters are (1) mobile fracture porosity, (2) immobile fracture and matrix porosity, and (3) exponential exchange rate constant function of concentration difference**

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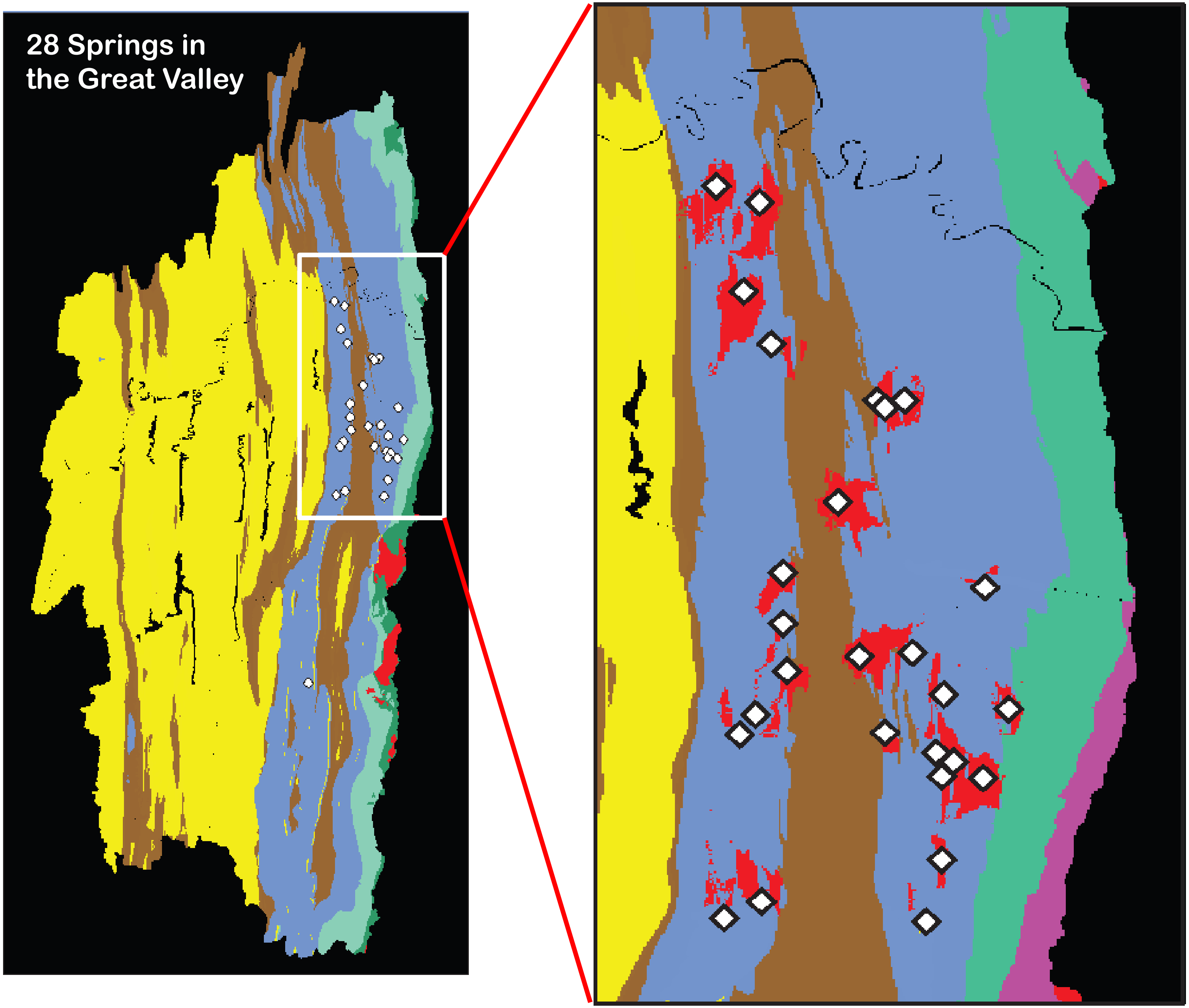
28 Springs in
the Great Valley

No.	Name	CFC-113					SF6					Tritium				Helium-3			
	Year -->	2003	2004	2005	2006	2009	2003	2004	2005	2006	2009	2003	2004	2005	2006	2003	2004	2005	2006
1	Balch Spring		71.0		62.6			4.65		5.84			7.70		6.93		1.30		
2	Bell Spring												7.10		6.11		0.56		
3	Borden Spring			65.4										7.02				4.78	
4	Branson Spring		83.9										7.20				1.66		
5	Buffalo Marsh Spring		81.9					4.17					7.20				0.91		
6	Carter Hall Spring	65.9										7.52				3.57			
7	Clifton Farm Spring		76.7					5.20					6.58				0.42		
8	Dennis Farm Spring												7.10		6.71		1.57		
9	Fay Spring											7.83				3.92			
10	Harlan Spring												5.90		6.65		1.22		
11	Horsepen Spring		75.1					5.88	2.12				6.89				2.64		
12	Huntingdon Spring			60.9										7.11					
13	Gray Spring							6.09					7.20				0.88		
14	Kilmer Spring												7.10				3.50		
15	Lockes Mill Spring		75.8										7.52				0.86		
16	Marsh Run Spring			39.0					2.17					8.33					
17	O.L. Payne Spring		71.6					4.20					8.14					17.25	
18	Old Town Spring	78.1										7.52				2.68			
19	Perry Spring	67.6					4.25					7.52				0.93			
20	Plains Mill Spring		46.0		46.3	32.5		4.24		4.10	3.84		5.60		4.90		3.37		
21	Priest Spring		72.2		58.3			6.01		5.45			5.60		6.98		2.27		
22	Prospect Hill Spring	71.2					5.95					8.14				1.43			
23	Robinson Spring		71.9										1.86						
24	Salem Church Spring		72.8					4.00					8.14				1.52		
25	Saratoga Spring	79.7					5.67					7.20				1.35			
26	Snodgrass Spring		73.1		57.9			5.82					6.30		7.10		3.61		
27	Vaucluse Spring	58.4										7.52				4.25			
28	Weddle Spring	76.4					5.41					7.52				1.05			
	Average Values	**66.4**					**4.45**					**6.9**				**2.7**			

↑ 15 years ↑ 5 years ↑ 3 years

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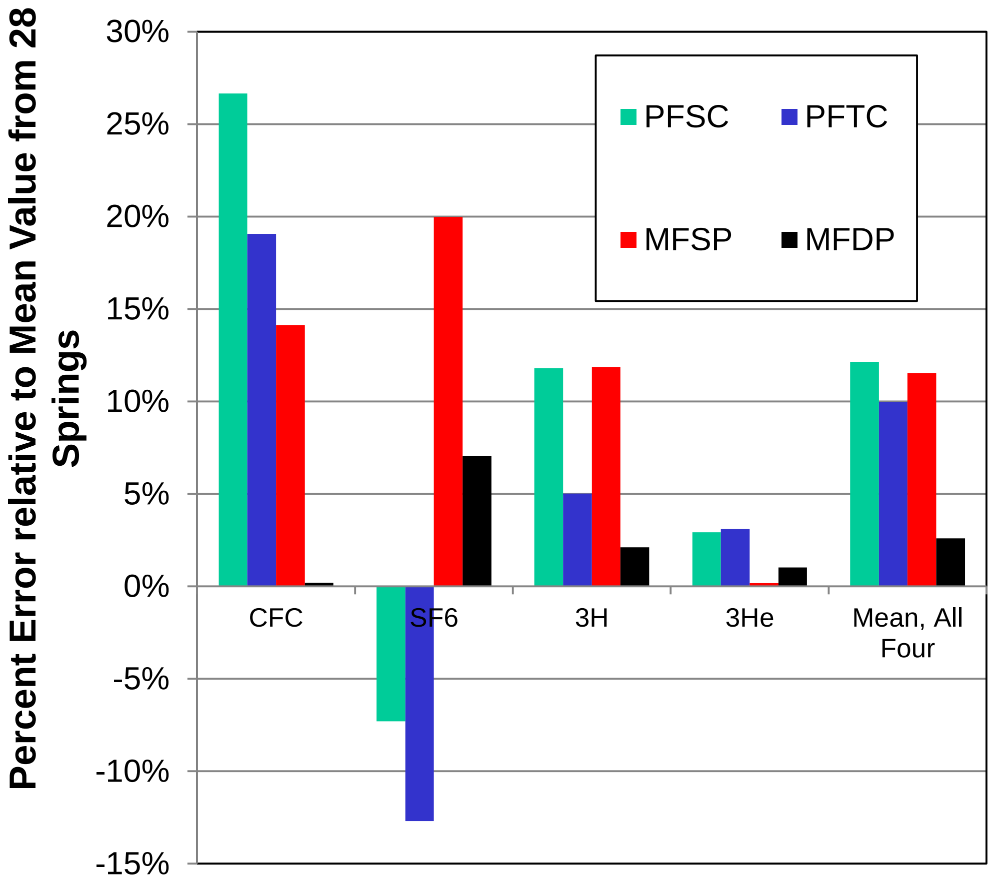

Best Fit Parameters: 1% Mobile, 18% Immobile, K=0.092 (7.5 years)

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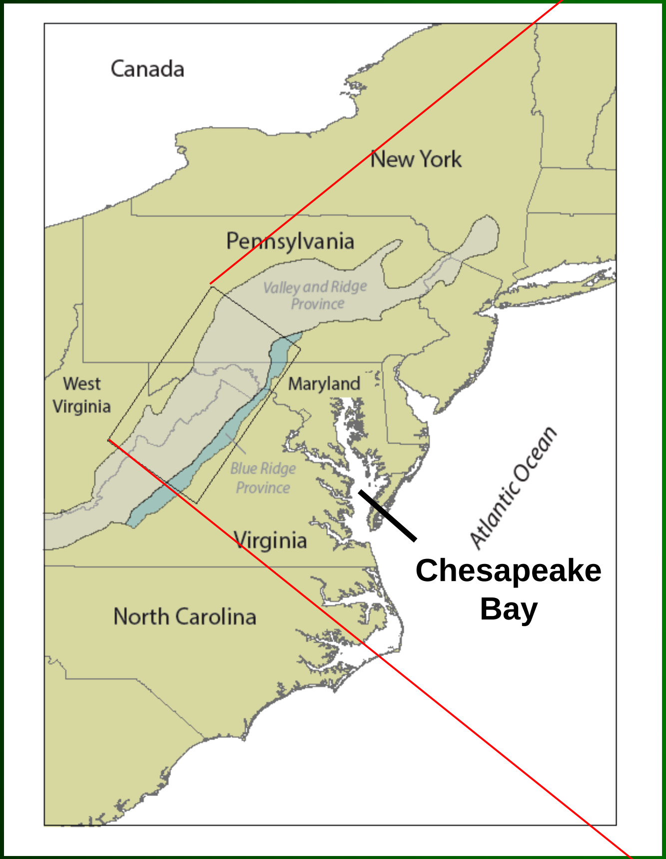
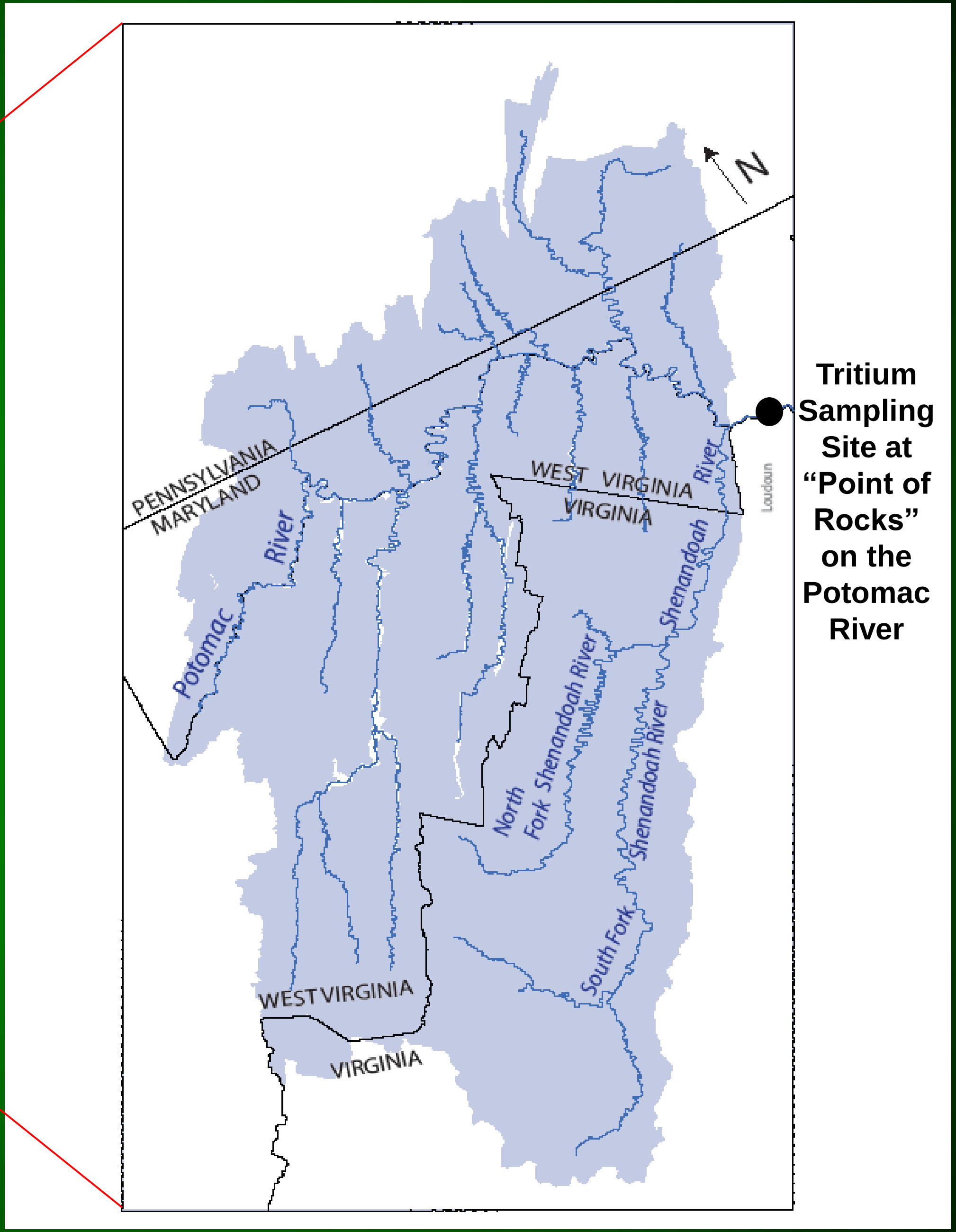
Upper Potomac River Basin Study Area





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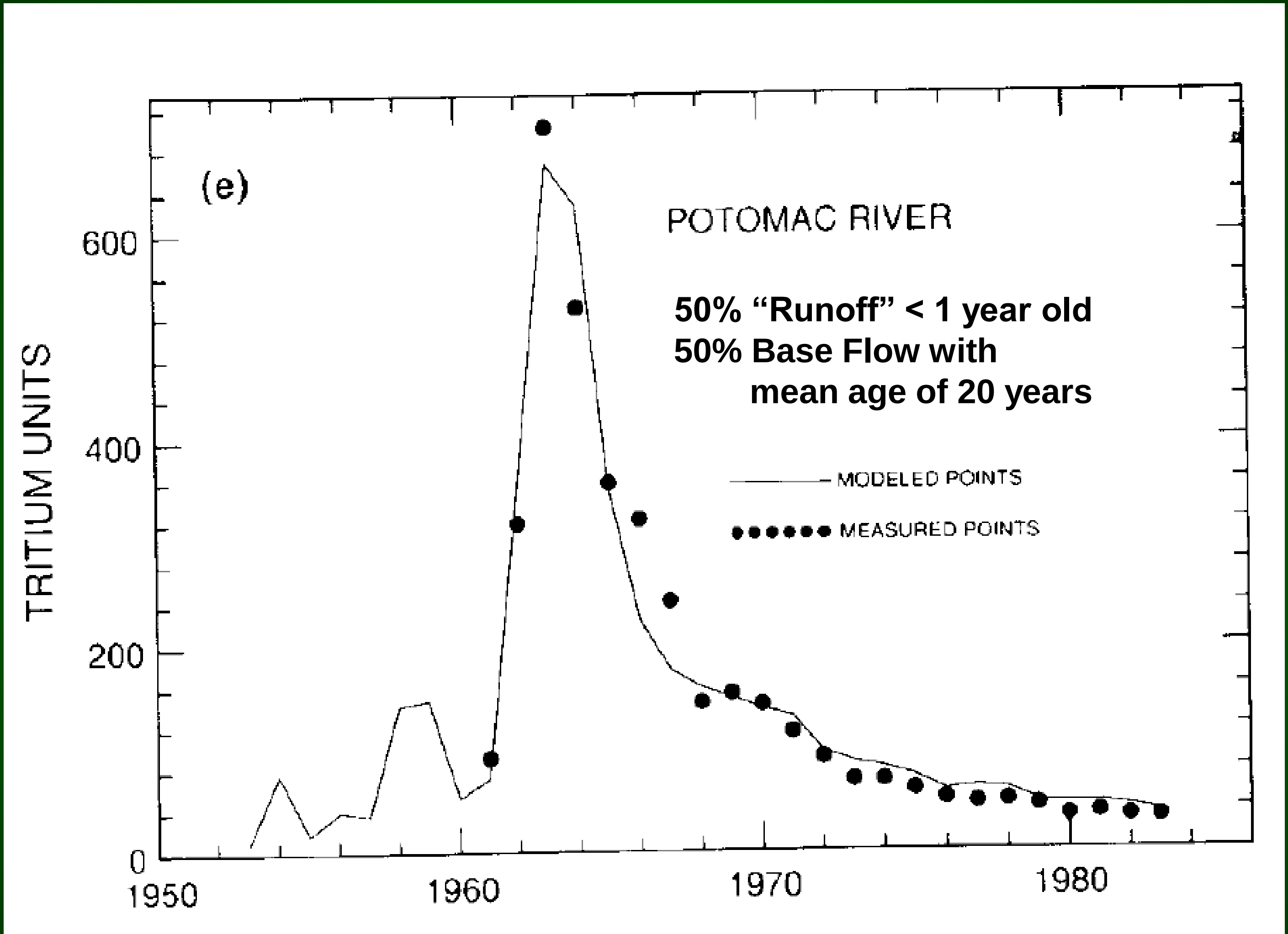
Residence Time Analysis by Bob Michel (USGS)



Journal of Hydrology (1992), Fig. 2e

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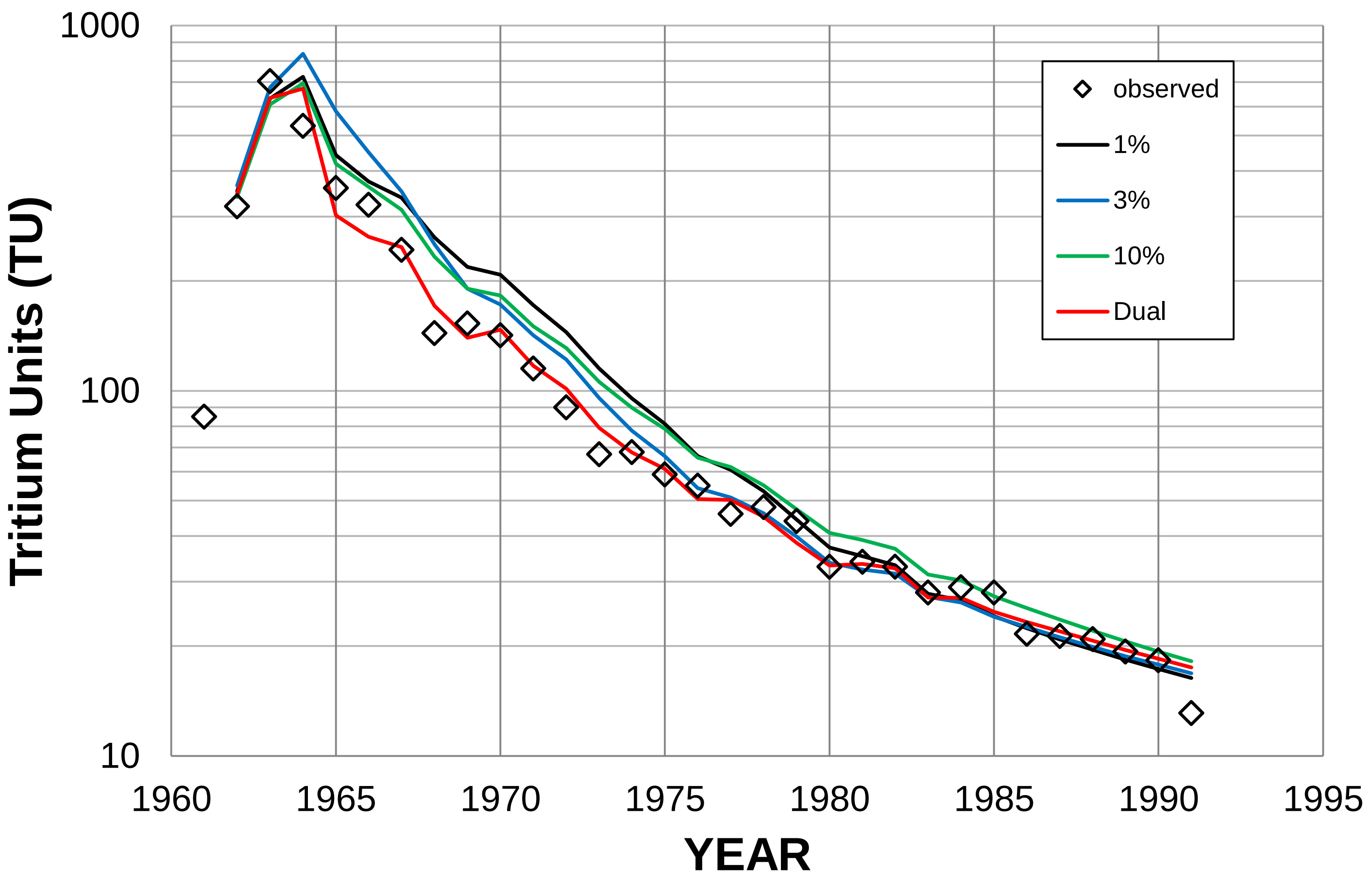

Tritium Units (TU)
1000
100
10
1960
1965
1970
1975
1980
1985
1990
1995
YEAR
observed
1%
3%
10%
Dual

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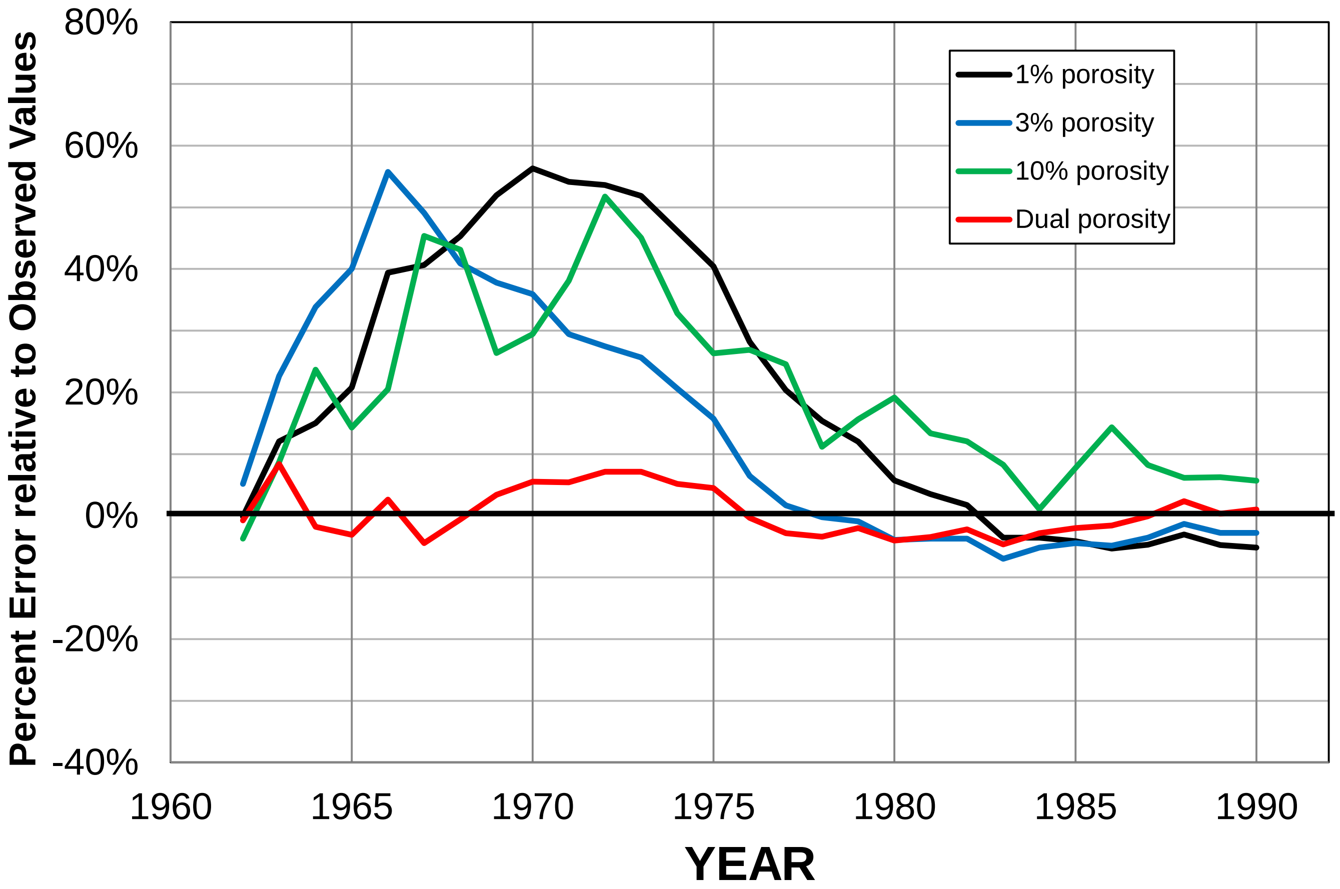

Best Fit Parameters: 6% Mobile, 12% Immobile, K=0.23 (3 years)
53% of total stream flow is base flow

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Weibull Equation for Fitting Base-Flow Age Distributions

$$CF = 1 - \exp(-K(t - t_o)^n)$$

CF = the cumulative fraction of the base flow

K = the time constant [t^{-1}] = 1/(median travel time)

t_o = 1 year = the minimum travel time in the distribution

n = exponent that controls the slope of the distribution

n = 1 (exponential)

n < 1 (flatter than exponential)

n > 1 (steeper than exponential)

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Weighted Weibull Equation

subscripts E and L stand for early and late time

$$CF_E = 1 – \exp(- K_E (t – t_o)^{n_E})$$

$$CF_L = 1 – \exp(- K_L (t – t_o)^{n_L})$$

the two are weighted linear by early and late flows

$$\text{so } CF = (1\text{-}CF)*CF_E + CF*CF_L$$

$$\text{or } CF = CF_E/(1+CF_E-CF_L)$$

note that if $K_E = K_L$ and $n_E = n_L$ then $CF_E = CF_L$ and the equations collapse to one unweighted Weibull equation

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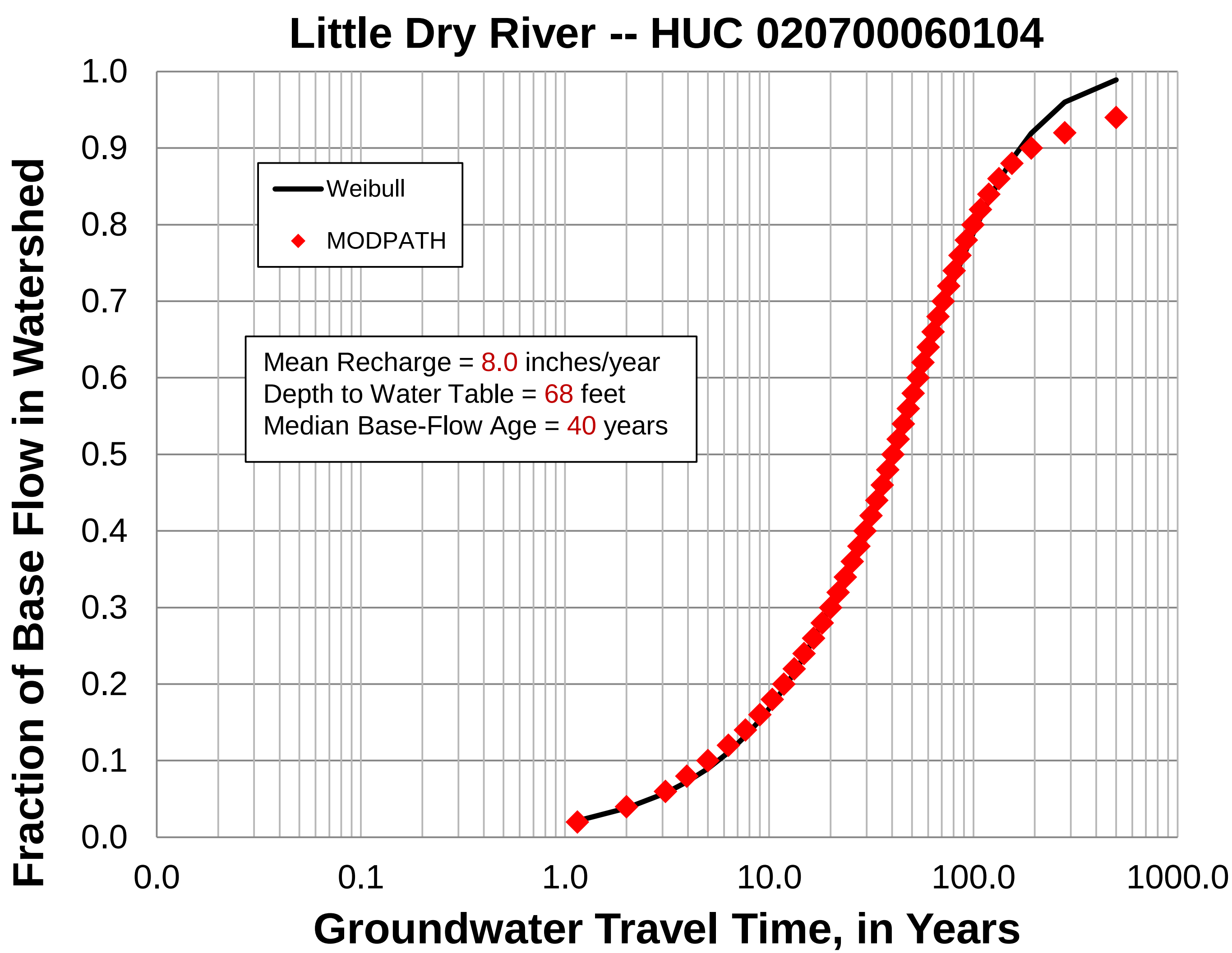
Little Dry River -- HUC 020700060104
Weibull
MODPATH
Mean Recharge = 8.0 inches/year
Depth to Water Table = 68 feet
Median Base-Flow Age = 40 years
Fraction of Base Flow in Watershed
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.1
1.0
10.0
100.0
1000.0
Groundwater Travel Time, in Years

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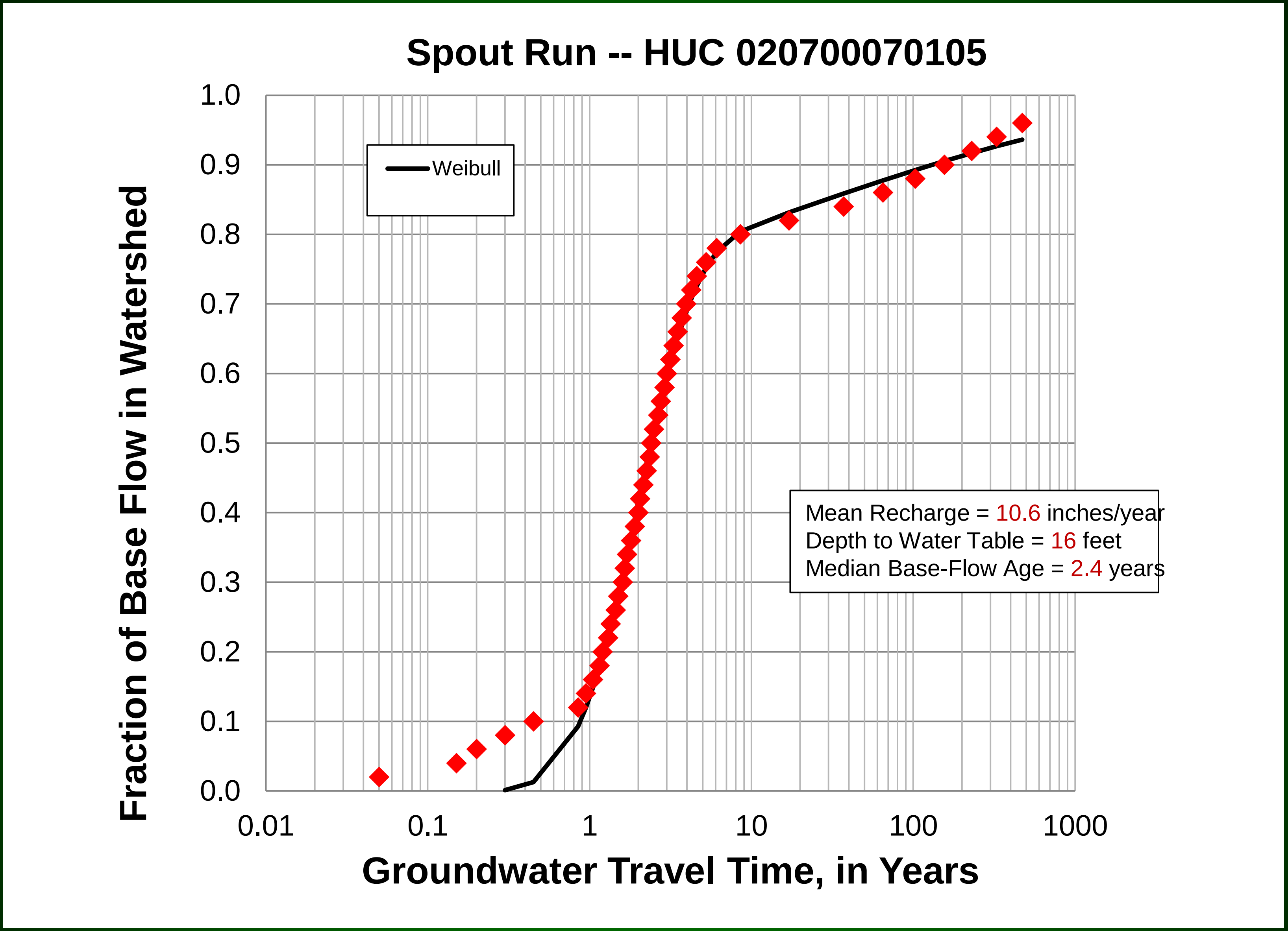
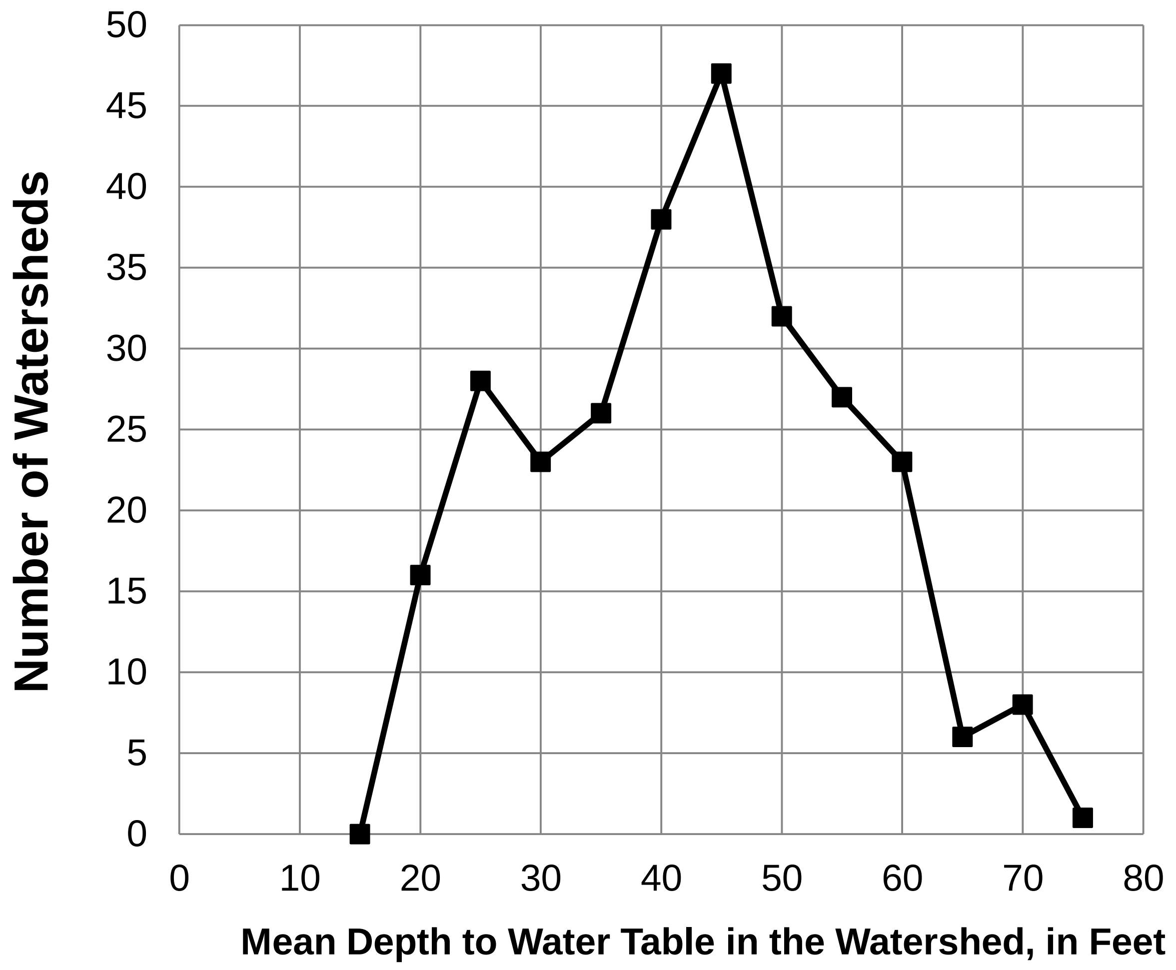
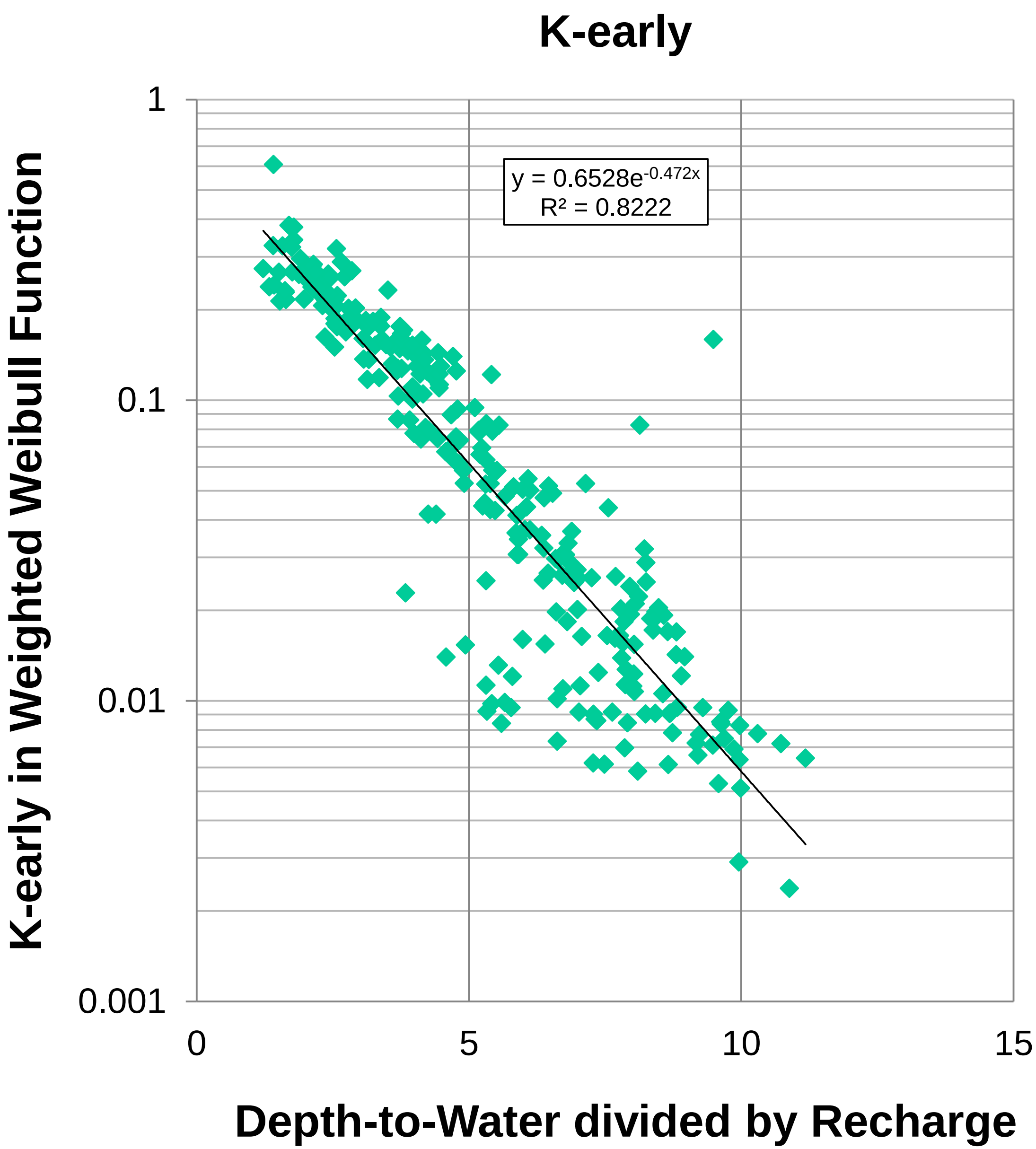


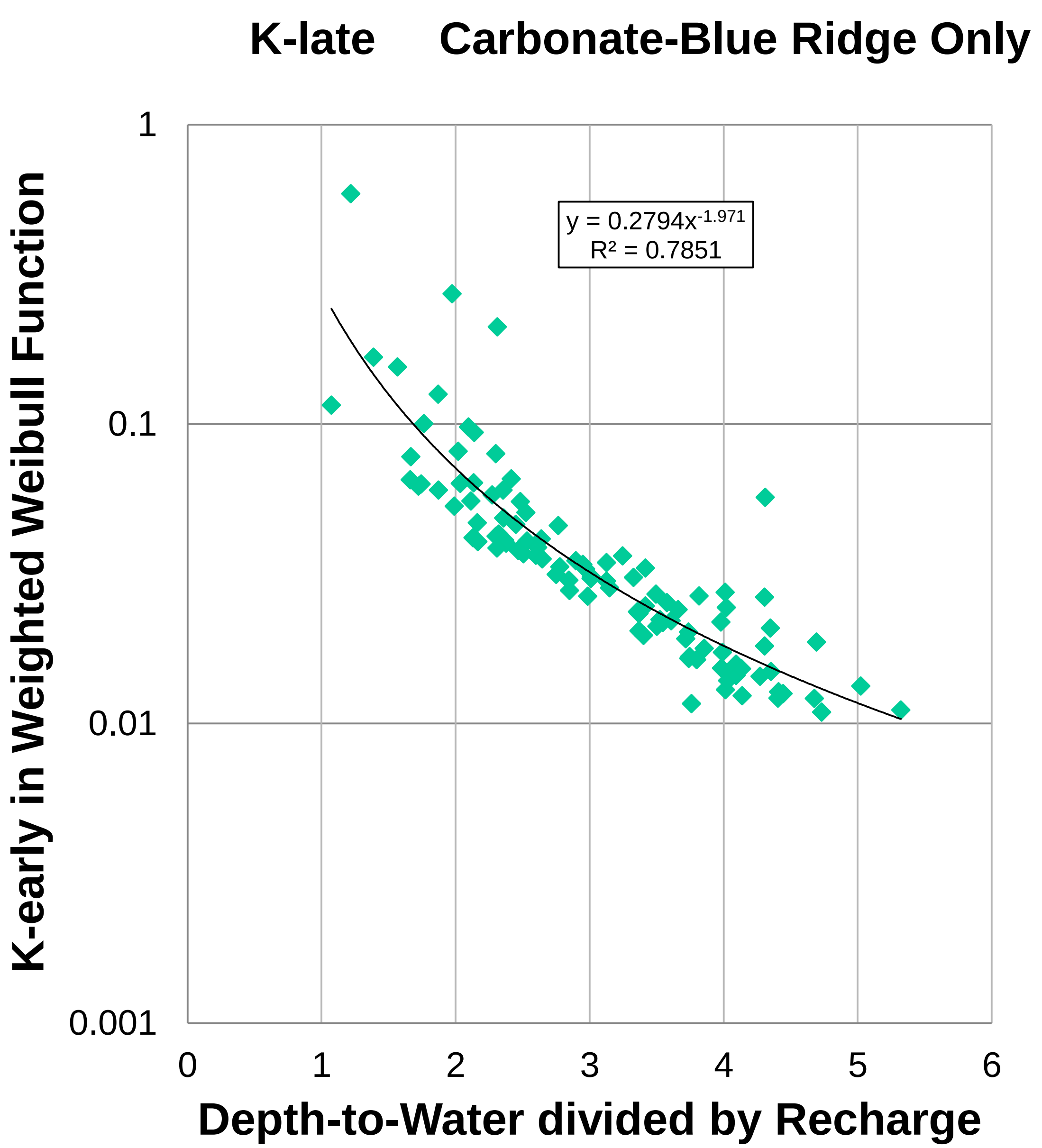
Spout Run -- HUC 020700070105
Weibull
Mean Recharge = 10.6 inches/year
Depth to Water Table = 16 feet
Median Base-Flow Age = 2.4 years
Fraction of Base Flow in Watershed
Groundwater Travel Time, in Years
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.01
0.1
1
10
100
1000

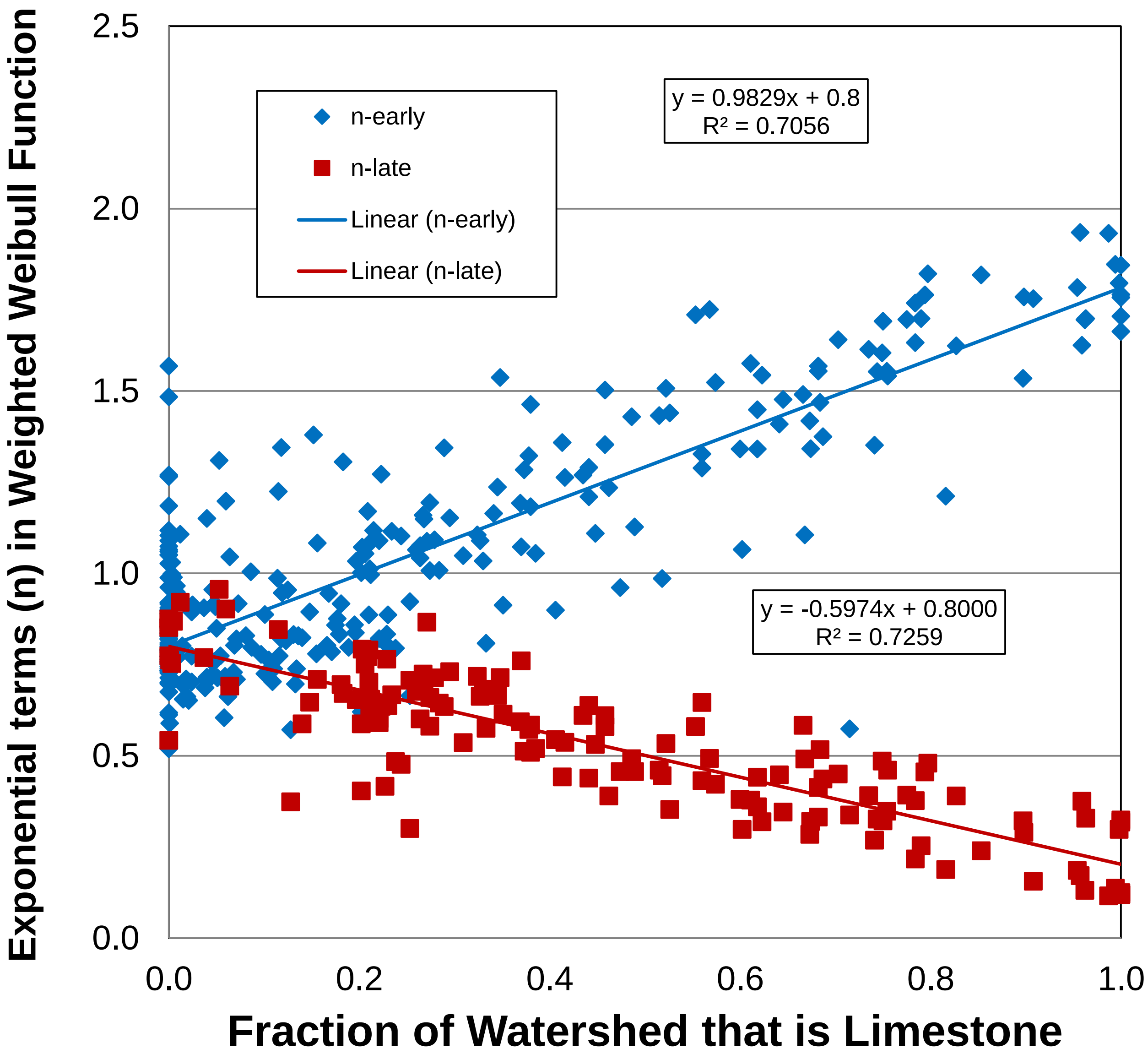


Number of Watersheds
50
45
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
Mean Depth to Water Table in the Watershed, in Feet



K-early
y = 0.6528e^-0.472x
R² = 0.8222
1
0.1
0.01
0.001
0
5
10
15
K-early in Weighted Weibull Function
Depth-to-Water divided by Recharge


K-late Carbonate-Blue Ridge Only
y = 0.2794x^-1.971
R² = 0.7851
1
0.1
0.01
0.001
0
1
2
3
4
5
6
K-early in Weighted Weibull Function
Depth-to-Water divided by Recharge


Exponential terms (n) in Weighted Weibull Function
Fraction of Watershed that is Limestone
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
n-early
n-late
Linear (n-early)
Linear (n-late)
y = 0.9829x + 0.8
R² = 0.7056
y = -0.5974x + 0.8000
R² = 0.7259

DISCUSSION?

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