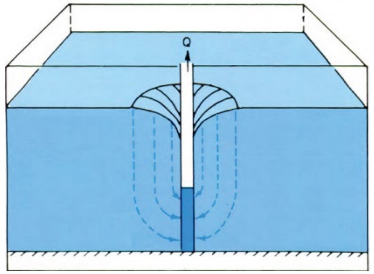

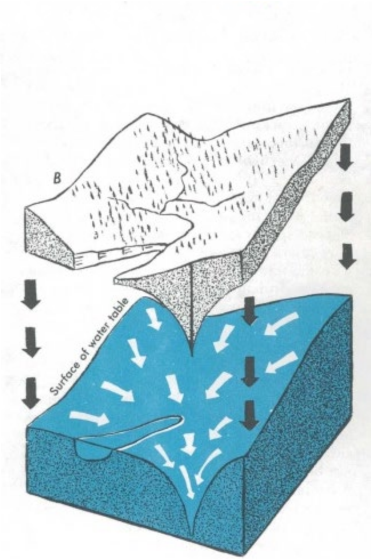

Groundwater Availability Screening Tool Project: Update

Michael Thompson, P.E.

June 18, 2025

Water Management Advisory Committee (WMAC)

Delaware River Basin Commission

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Outline

1. Groundwater availability (concepts)
2. Sloto & Buxton, 2006
3. DRBC, 2022
4. Scope of Work (for this project)
   - Seasonality highlight
5. Progress Updates:
   - **Spatial scale:** (modified HUC-12)
   - **Adding data:** How +20 years of data changes the results of Sloto & Buxton 2006
   - **Baseflow recurrence:** Moving from empirical estimates of baseflow to theoretical distributions
   - **Drought of Record:** estimates in terms of baseflow recurrence intervals

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1. Groundwater availability (concepts)

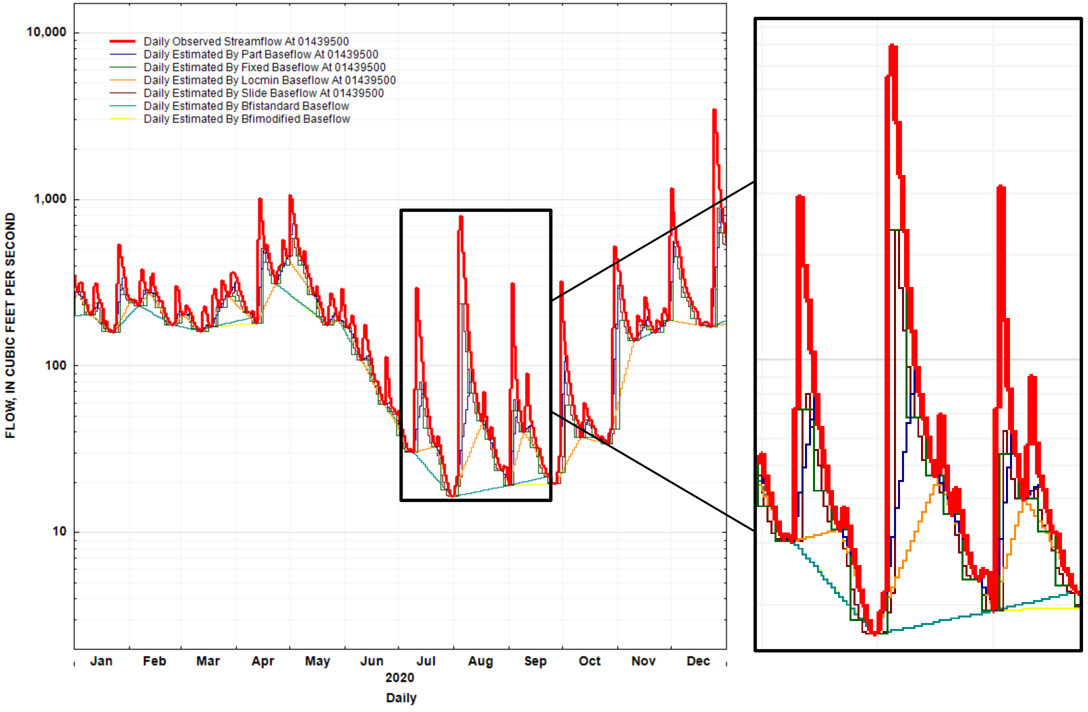
Groundwater baseflow

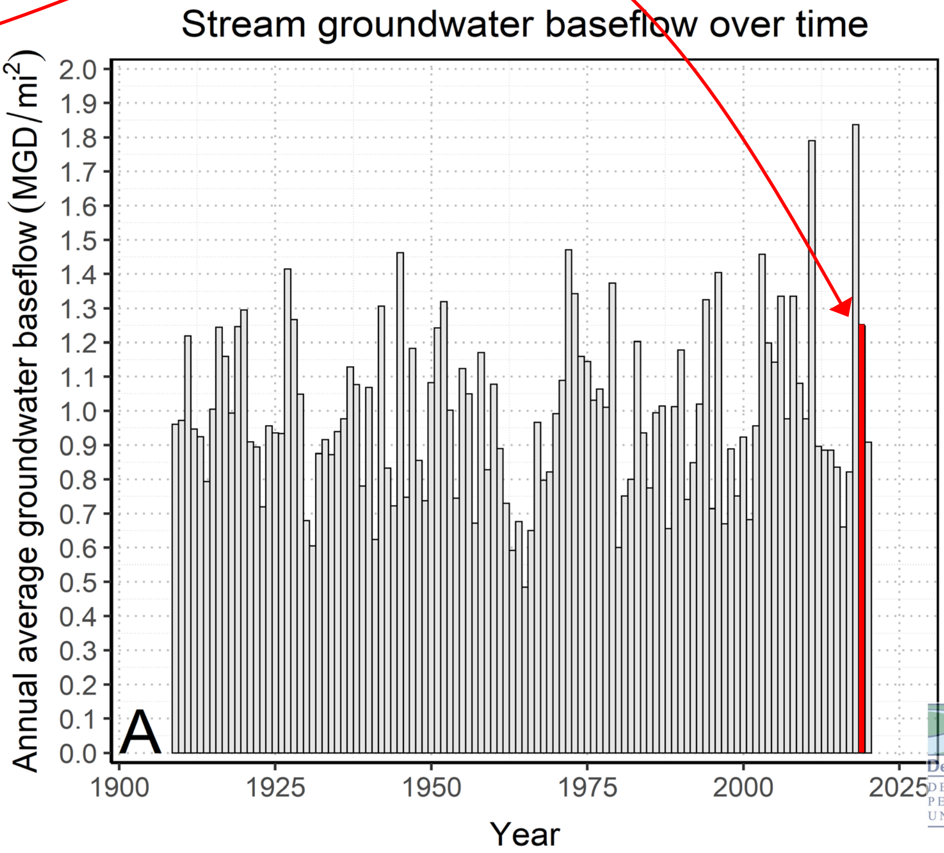
Baseflow Separation

Bush Kill at Shoemakers, PA

CY2020

Average = 0.909 MGD/mi^2





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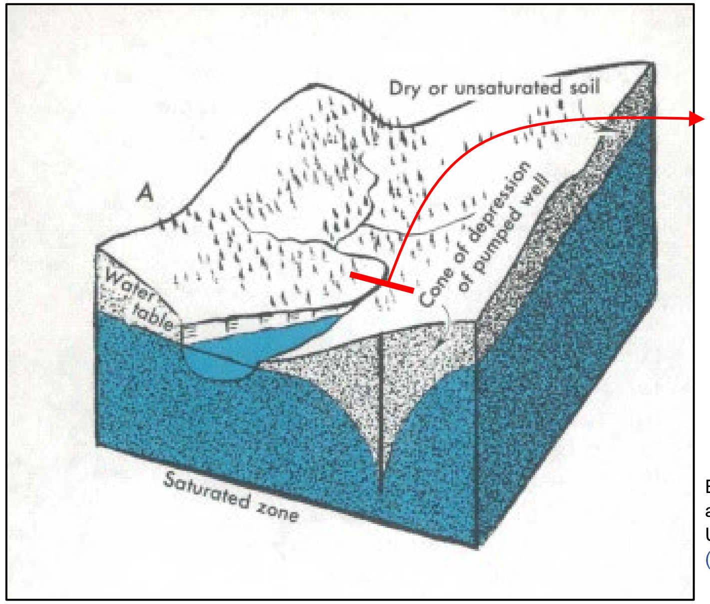
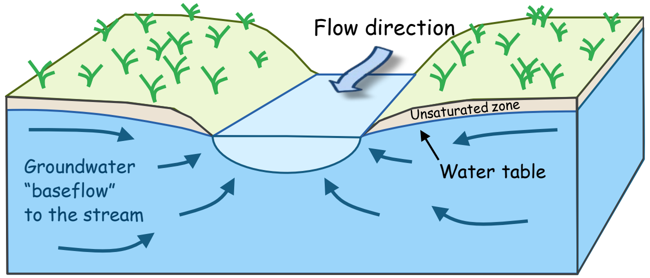
Groundwater availability

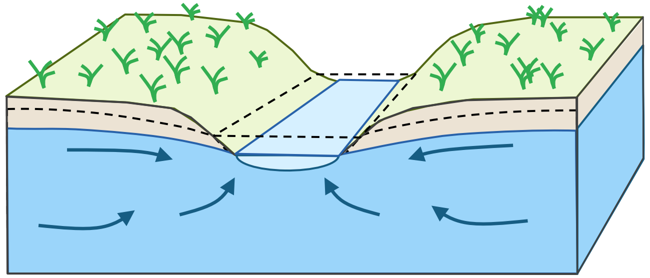


Look at a cross-section

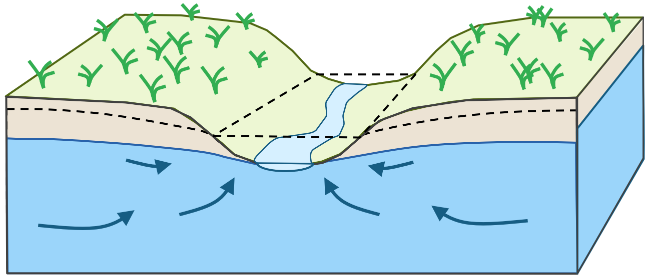
Effect on local water table of pumping a well. Adopted from the 1960 USGS report "*A Primer on Water*". (Leopold & Langbein, 1960)



"Regular" groundwater flow
(e.g. every other year)
"Normal" groundwater levels
2-year recurrence interval



"Dry" conditions
(e.g. once every 25 years)
Lower groundwater
25-year recurrence interval



"Very Dry" conditions
(e.g. once every 50 years)
Even lower groundwater
50-year recurrence interval

Annual Groundwater availability = Annual net GW withdrawal (MG) / Annual baseflow (MG)
(at 25-year and 50-year RI)

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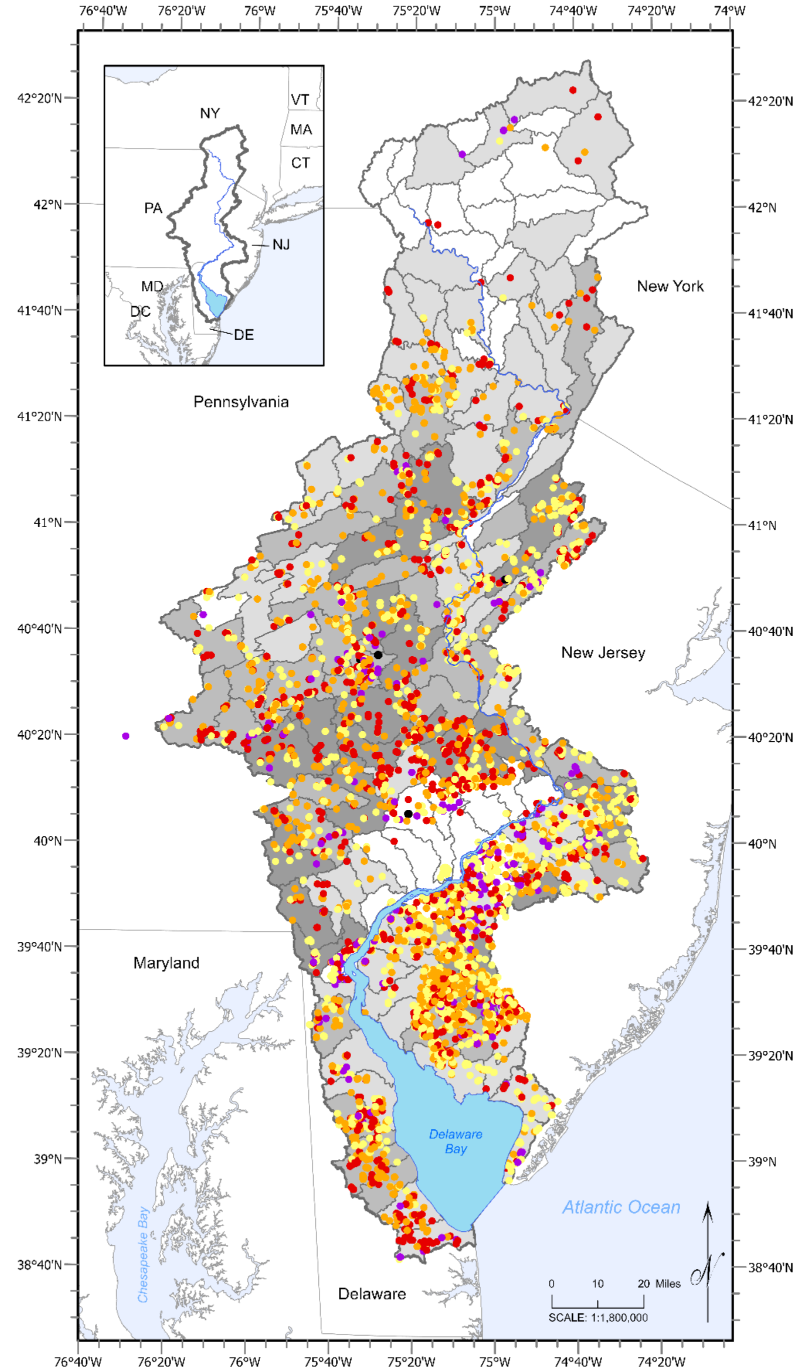
$$\text{Annual Groundwater availability} = \frac{\text{Annual net GW withdrawal (MG)}}{\text{Annual baseflow (MG)}}$$

(at 25-year and 50-year RI)

Net groundwater withdrawals (by watershed)



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Groundwater sources net withdrawal for CY2017 (MGY)
- ≤1
- (1, 10]
- (10, 100]
- (100, 1,000]
- ≥ 1,000

Estimated net groundwater withdrawal for self-supplied domestic (MGY)
- ≤5
- (5, 25]
- (25, 50]
- ≥ 50

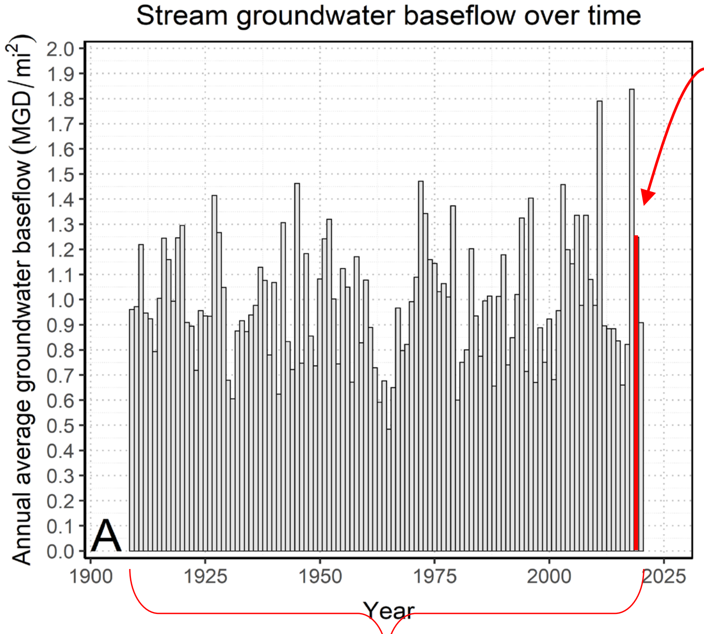
5,416 points reported data.

Num.	Withdrawal (MGY)
2,111	(< 1)
1,702	(1, 10]
1,313	(10, 100]
286	(100, 1,000]
4	(> 1,000)

Agriculture, **Mining** and **self-supplied domestic** (i.e. septic systems) have immediate localized GW returns.

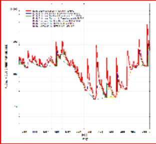
Annual Groundwater availability	=	Annual net GW withdrawal (MG) / Annual baseflow (MG) (at 25-year and 50-year RI)

Baseflow recurrence Intervals (*empirical*)



n = 112 data points

Recall



Baseflow Separation
Bush Kill at Shoemakers, PA
CY2020
Average = 0.909 MGD/mi²

0.909 MGD/mi² is the 44th lowest

Weibull plotting position: $P_i = \frac{i}{n+1}$ Where is P_i is the calculated probability for the i^{th} ranked observation, given n total observations.

$$P_i = \frac{44}{112+1} = 0.389$$

Recurrence interval: $T = \frac{1}{P}$ Where T is the recurrence interval (in years) for a specific baseflow, and P is the probability that this baseflow value will not be exceeded in a given year.

$$T = \frac{1}{0.389} = 2.57\ years$$

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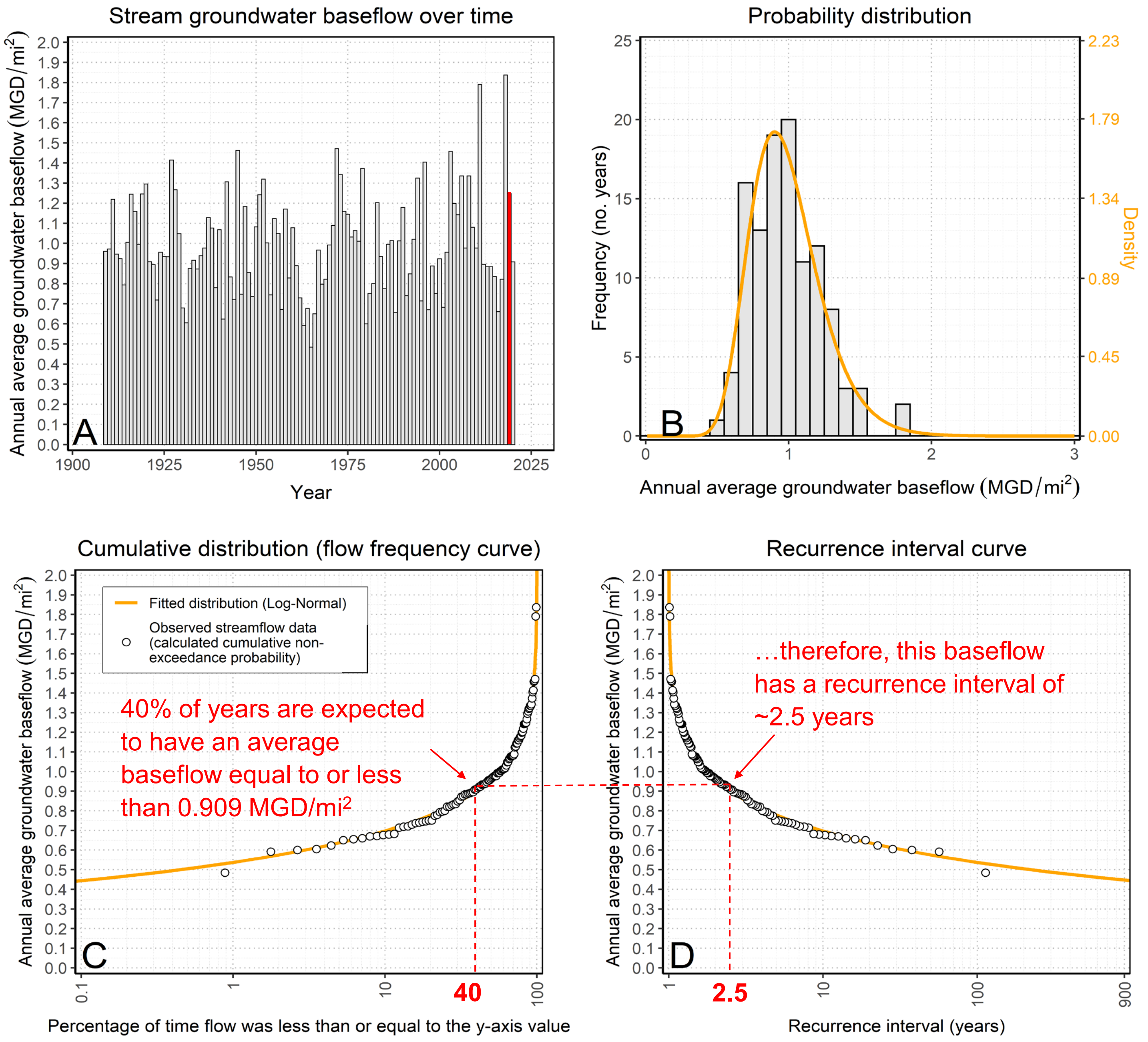
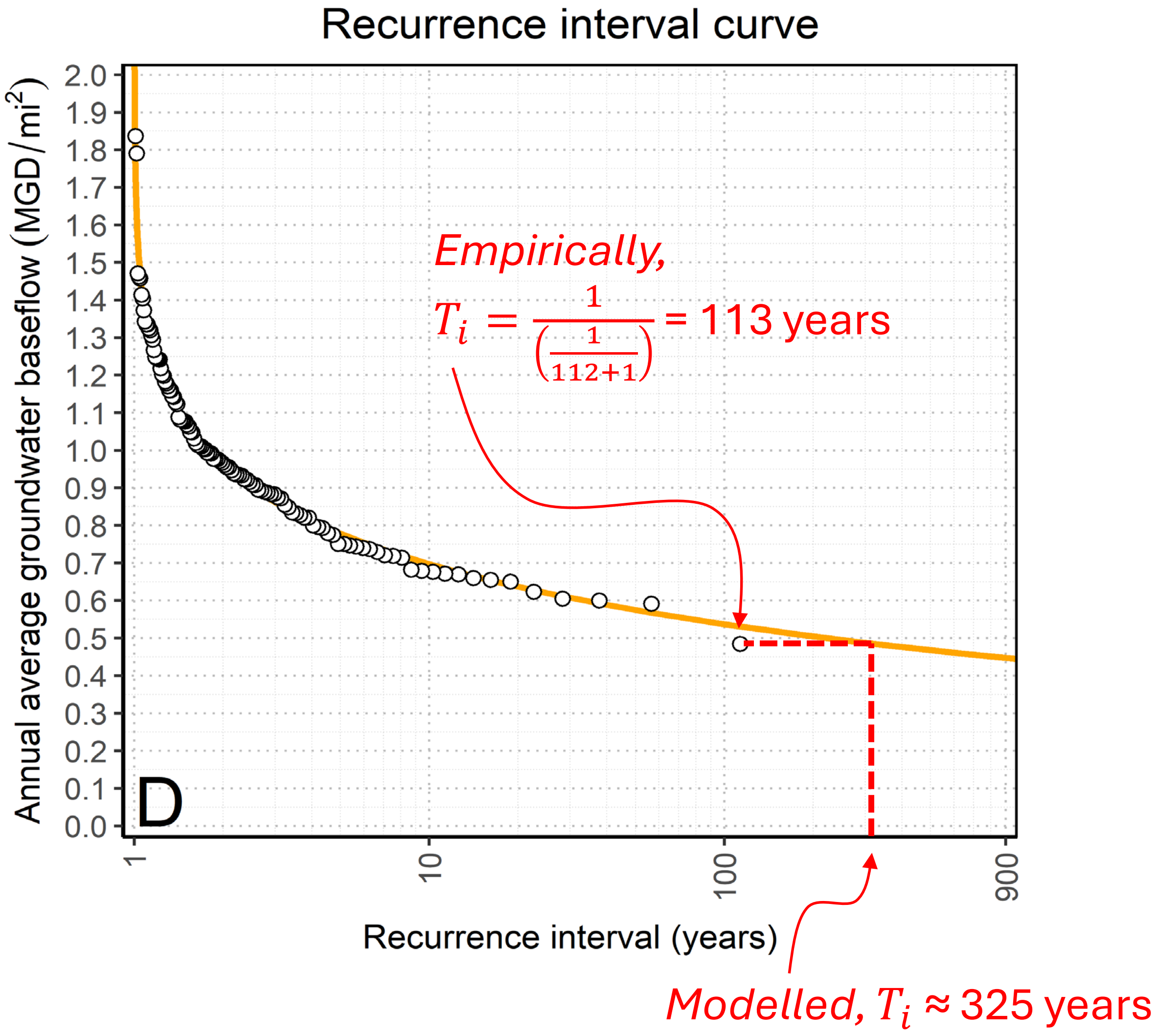
Annual Groundwater availability = $\frac{\text{Annual net GW withdrawal (MG)}}{\text{Annual baseflow (MG) (at 25-year and 50-year RI)}}$

Baseflow recurrence Intervals (*modelled*)



$$\text{Annual Groundwater availability} = \frac{\text{Annual net GW withdrawal (MG)}}{\text{Annual baseflow (MG) (at 25-year and 50-year RI)}}$$

Empirical vs Model



*A theoretical distribution may show where an empirical calculation is underestimated, due to the limited number of observations.

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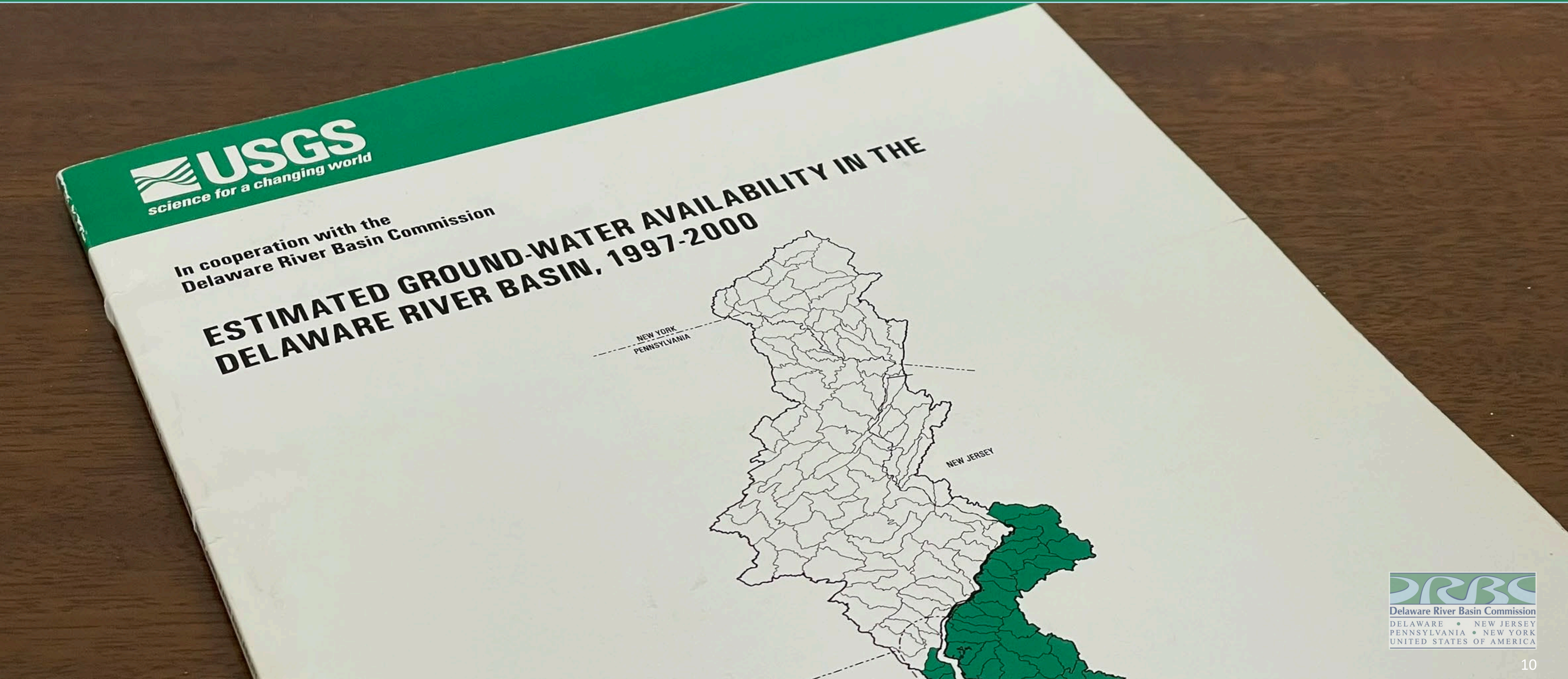
2. Sloto & Buxton, 2006

(Estimated Groundwater Availability in the Delaware River Basin, 1997-2000)



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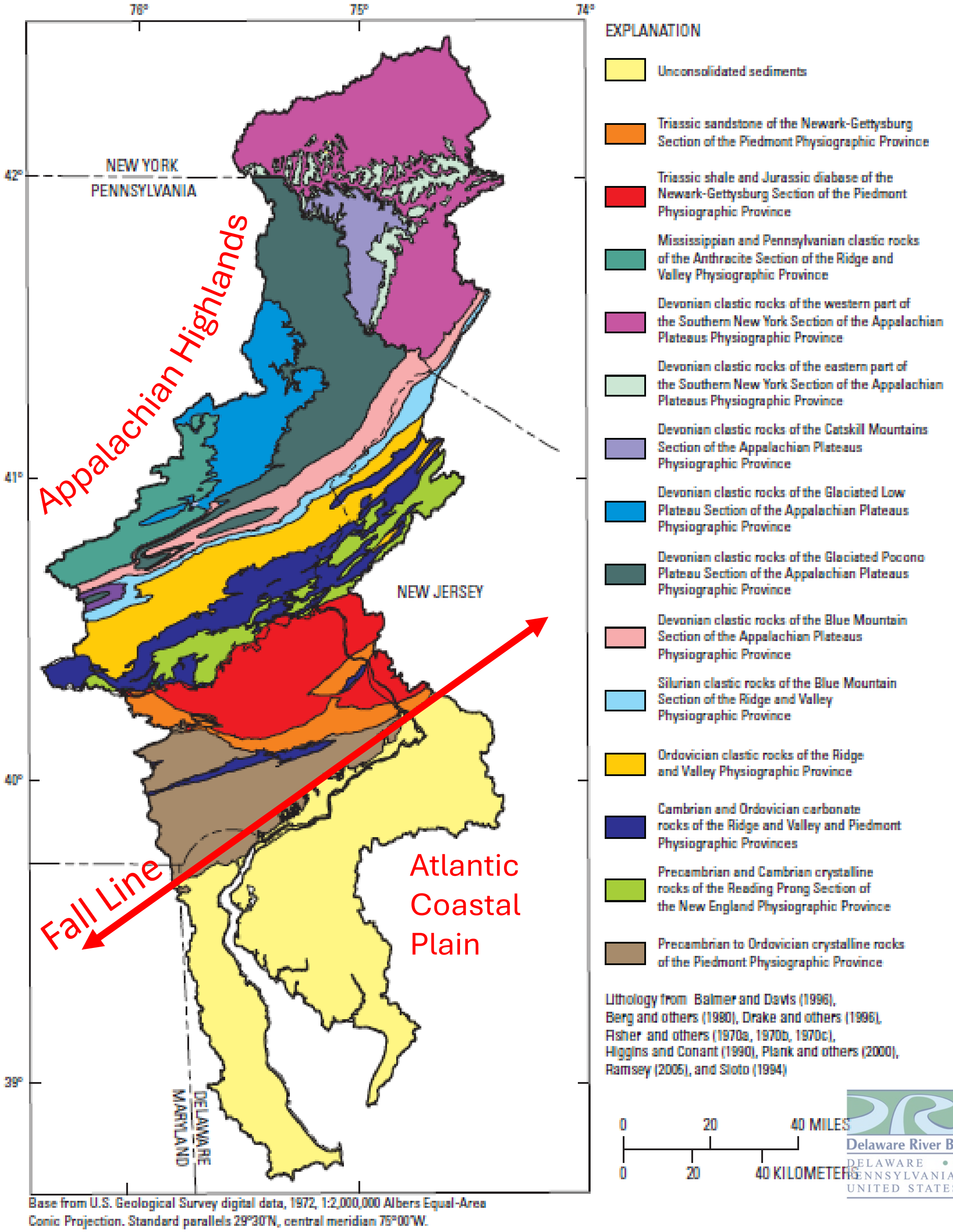
Estimation Methods

- **<u>APPALACHIAN HIGHLANDS</u>** (method #1)
  - Sloto & Buxton, 2006 grouped fractured rock into 14 generalized groups
  - Empirically calculate baseflow recurrence intervals for <u>each rock type</u>
  - Estimate baseflow recurrence intervals for watersheds based on "weighted geologic index"

- **<u>ATLANTIC COASTAL PLAIN</u>** (method #2)
  - Reference <u>surficial geology</u> & <u>land use</u>
  - Empirically calculate baseflow recurrence intervals for each combination
  - Estimate baseflow recurrence intervals for watersheds based on weighted average of classification



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Example baseflow estimation

Table 3. Potential index streamflow-gaging stations draining fractured rocks in the Delaware River Basin.

[USGS, U.S. Geological Survey]

USGS station number	Station name	Drainage area (square miles)	Period of record
01479000	White Clay Creek near Newark, Del.	89.1	1932-35, 1944-56, 1960-2001
01480000	Red Clay Creek at Wooddale, Del.	47.0	1944-2001
01480300	West Branch Brandywine Creek near Honey Brook, Pa.	18.7	1961-2001

Streamflow data through 2001

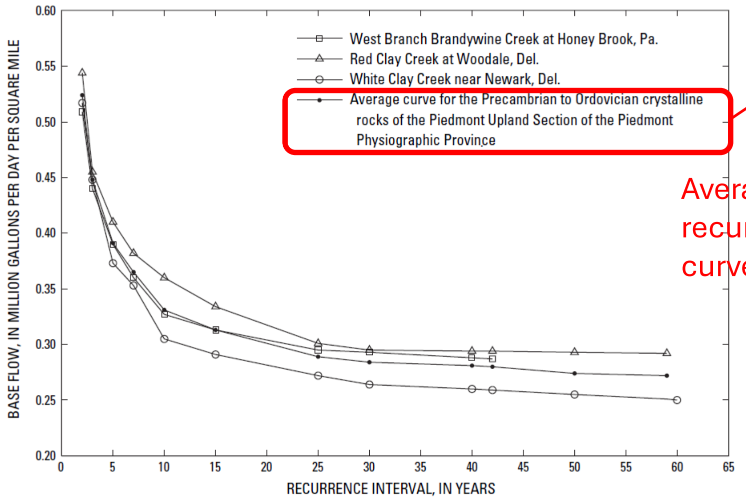
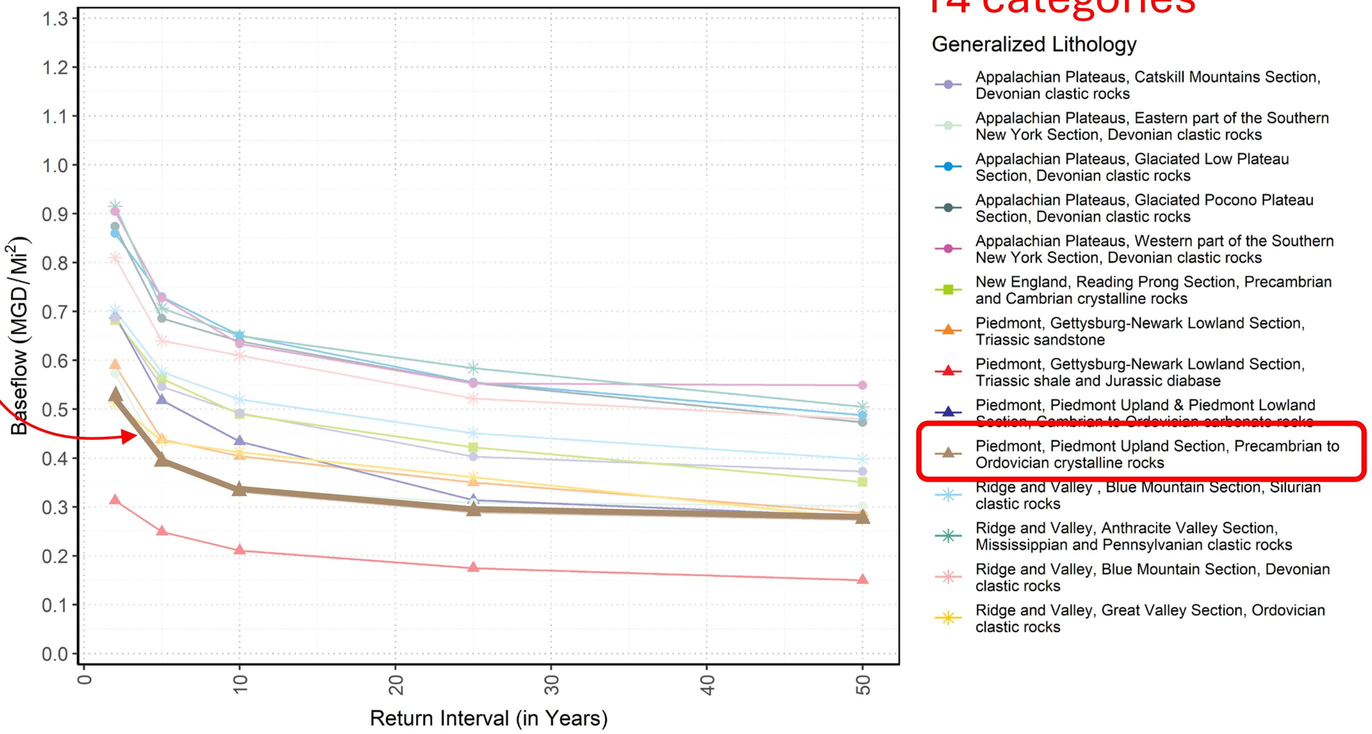


Figure 7. Base-flow-frequency curves for streamflow-gaging stations in the Precambrian to Ordovician crystalline rocks of the Piedmont Upland Section of the Piedmont Physiographic Province.

Average becomes recurrence interval curve

Average annual baseflow-recurrence values for generalized fractured rock types in the Delaware River Basin

14 categories



1. Use streamflow data from these gages
2. Separate baseflow (HYSEP Loc-min method)
3. calculate recurrence intervals to represent this rock type

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Results

- Calculated 2-, 5-, 10-, 25-, and 50-year recurrence interval baseflow values for 147 sub-watersheds in the Basin
- Quarry dewatering was tricky in terms of “net” withdrawal, as much goes back into stream
- Withdrawal from confined aquifers should not be considered in availability screening tool

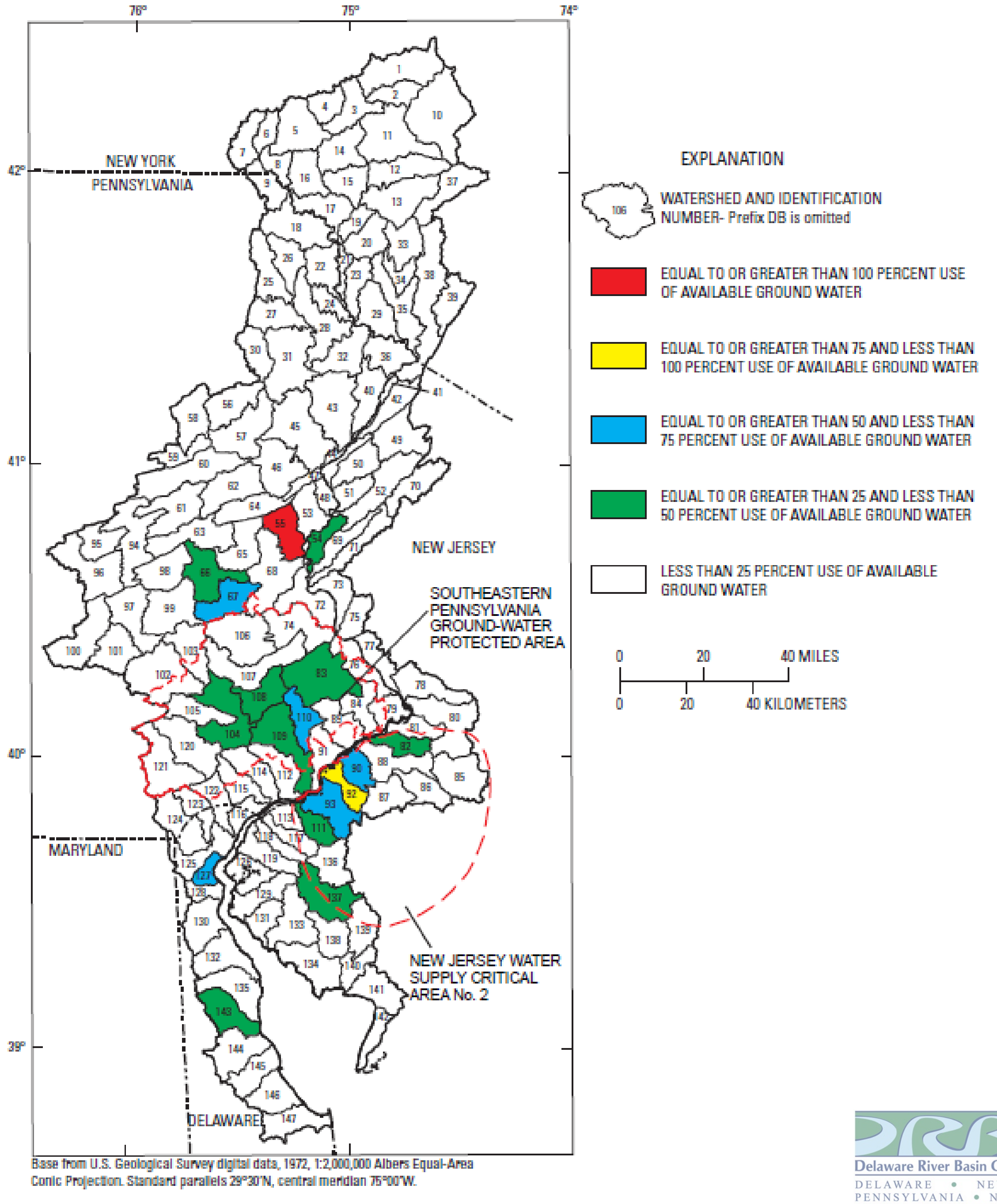

Figure 37. Percent of ground-water use for 50-year annual base-flow recurrence.

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3. DRBC, 2022

(Estimated Groundwater Availability in the Delaware River Basin 2020-2060)

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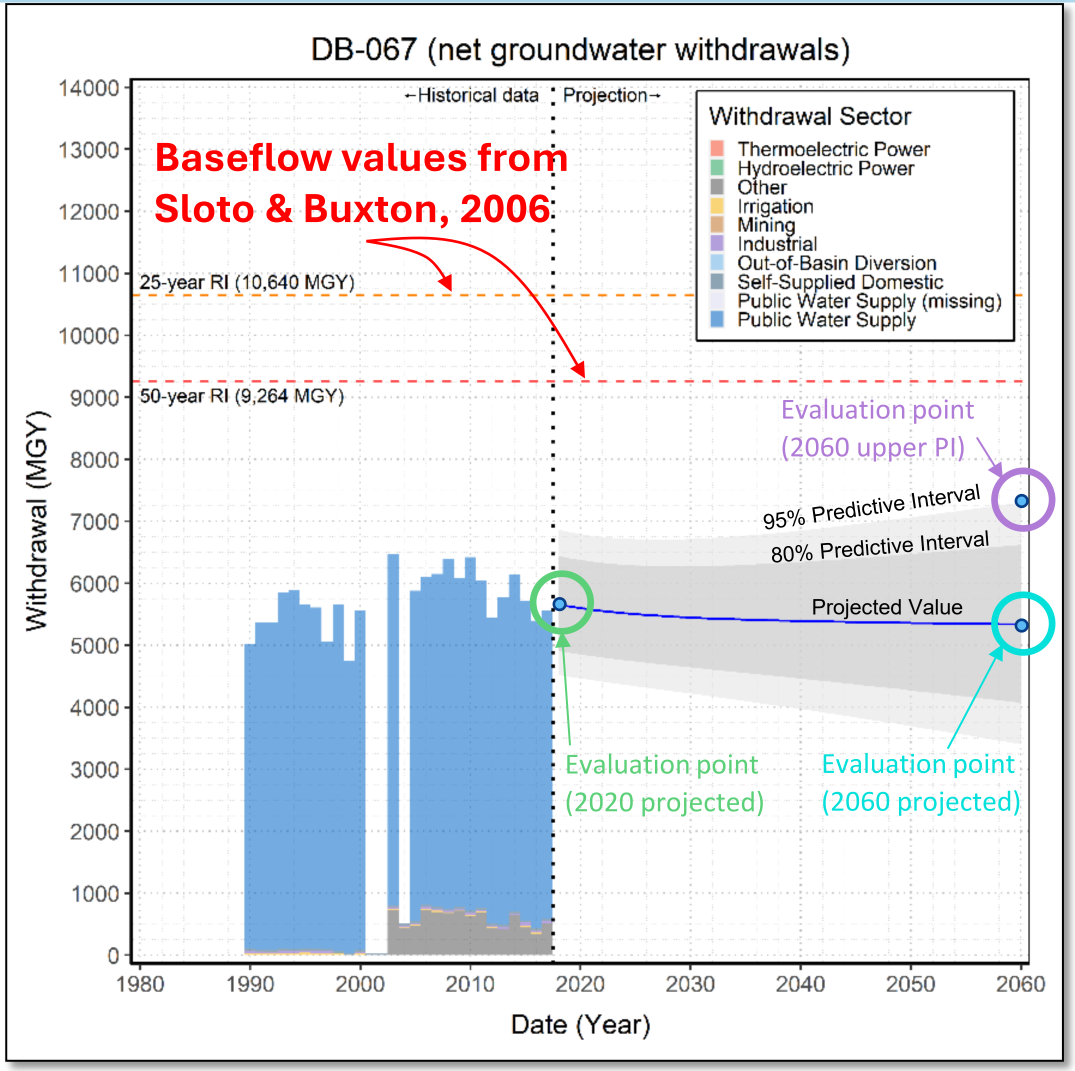
DRBC used this tool…



** This is a <u>screening tool</u>

2020 Projected: / 25-year RI Baseflow:	5,558 MGD/mi² / 10,640 MGD/mi²	= 51% use
2060 Projected: / 25-year RI Baseflow:	5,373 MGD/mi² / 10,640 MGD/mi²	= 50% use
2060 Upper PI: / 25-year RI Baseflow:	7,319 MGD/mi² / 10,640 MGD/mi²	= 69% use

2020 Projected: / 50-year RI Baseflow:	5,558 MGD/mi² / 9,264 MGD/mi²	= 60% use
2060 Projected: / 50-year RI Baseflow:	5,373 MGD/mi² / 9,264 MGD/mi²	= 58% use
2060 Upper PI: / 50-year RI Baseflow:	7,319 MGD/mi² / 9,264 MGD/mi²	= 79% use

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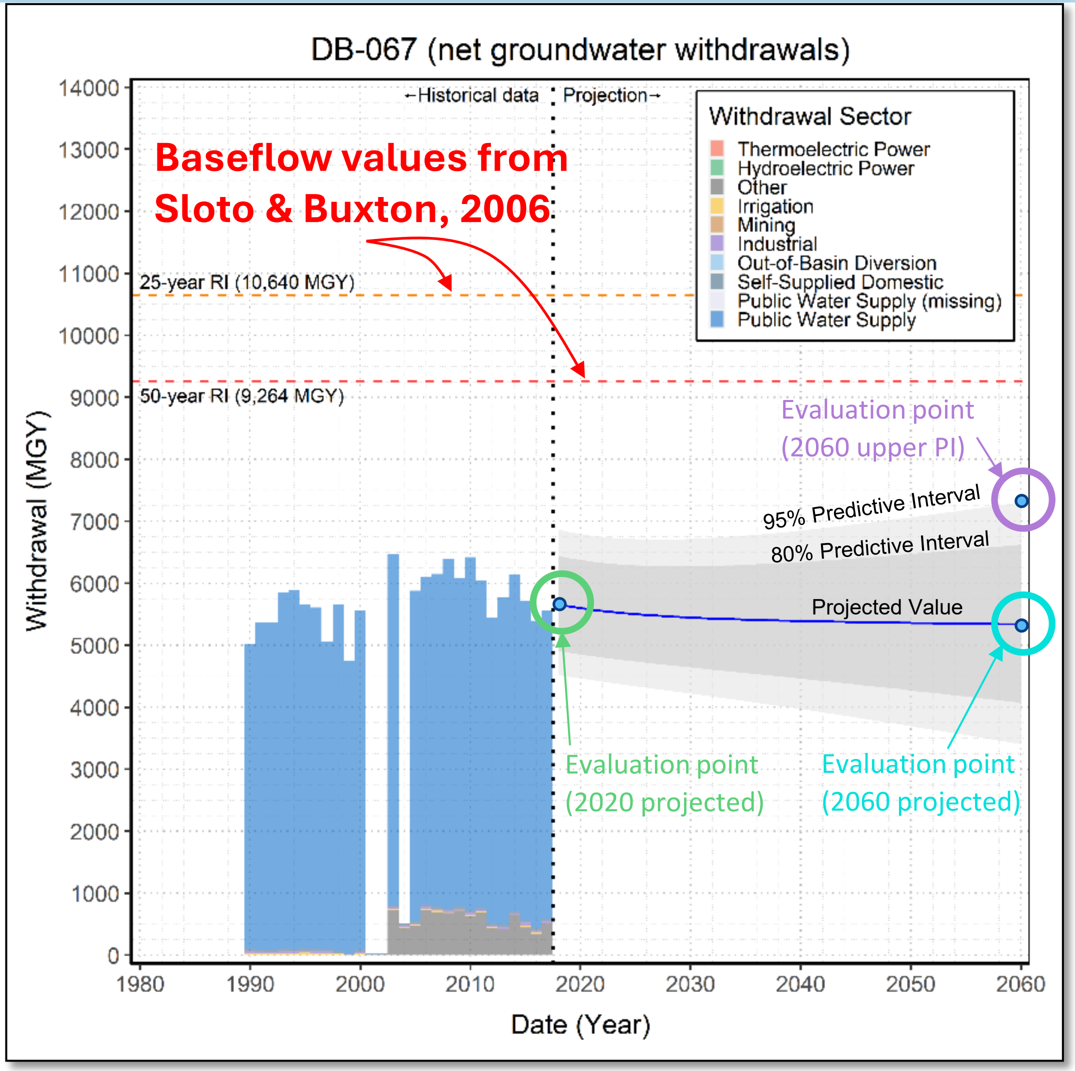
… but also came up with some questions.



** This is a screening tool

2020 Projected: 5,558 MGD/mi^2
25-year RI Baseflow: 10,640 MGD/mi^2
= 51% use

2060 Projected: 5,373 MGD/mi^2
25-year RI Baseflow: 10,640 MGD/mi^2
= 50% use

2060 Upper PI: 7,319 MGD/mi^2
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50-year RI Baseflow: 9,264 MGD/mi^2
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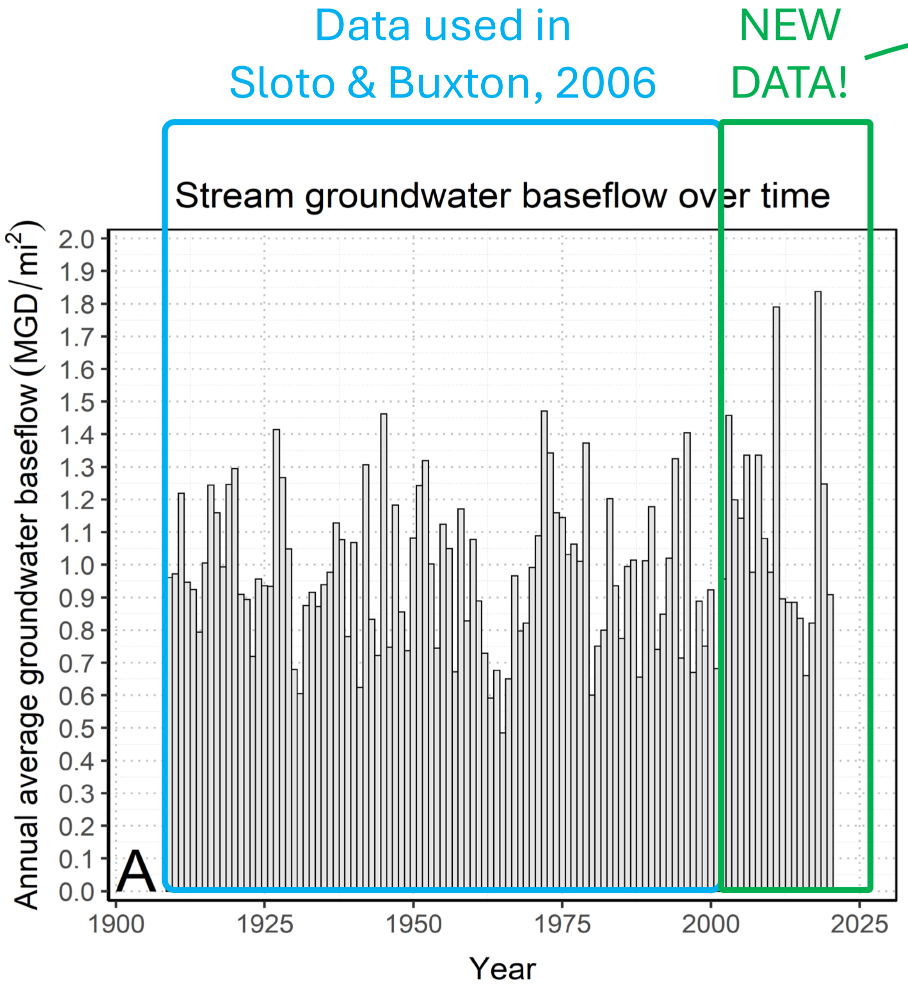
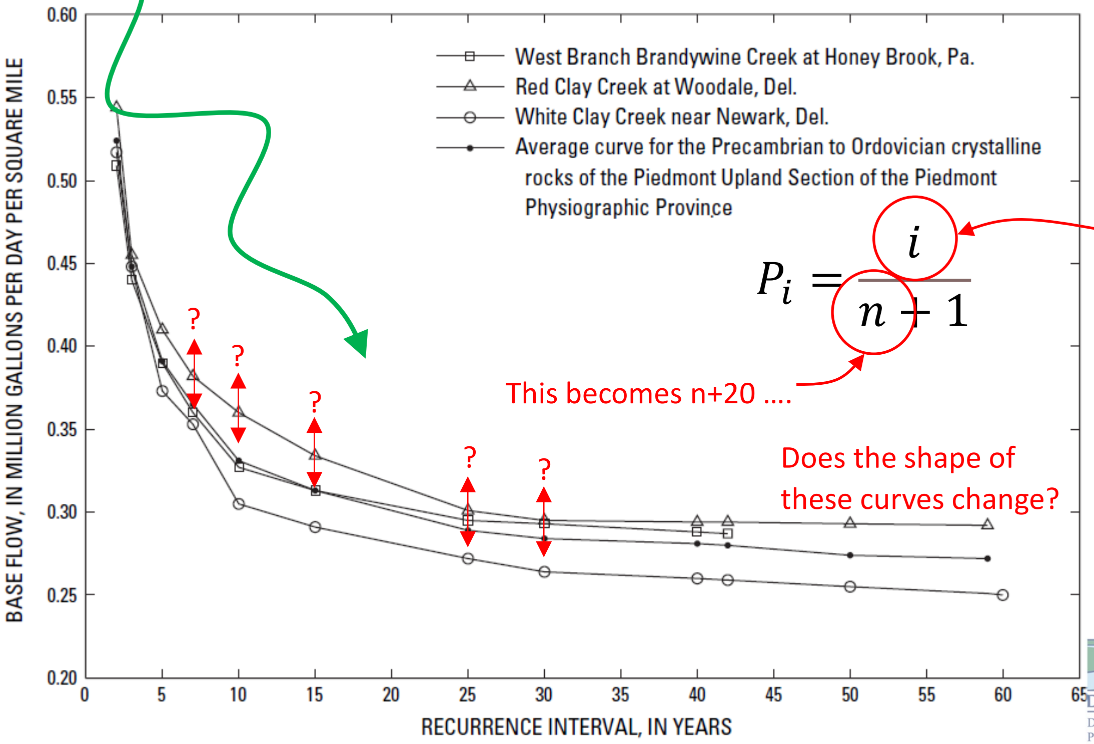
50-year RI Baseflow: 9,264 MGD/mi^2
= 58% use

2060 Upper PI: 7,319 MGD/mi^2
50-year RI Baseflow: 9,264 MGD/mi^2
= 79% use

1. Would adding new data change the tool?

Would adding 20+ years of data change the results of Sloto & Buxton, 2006 – using the same empirical methods?





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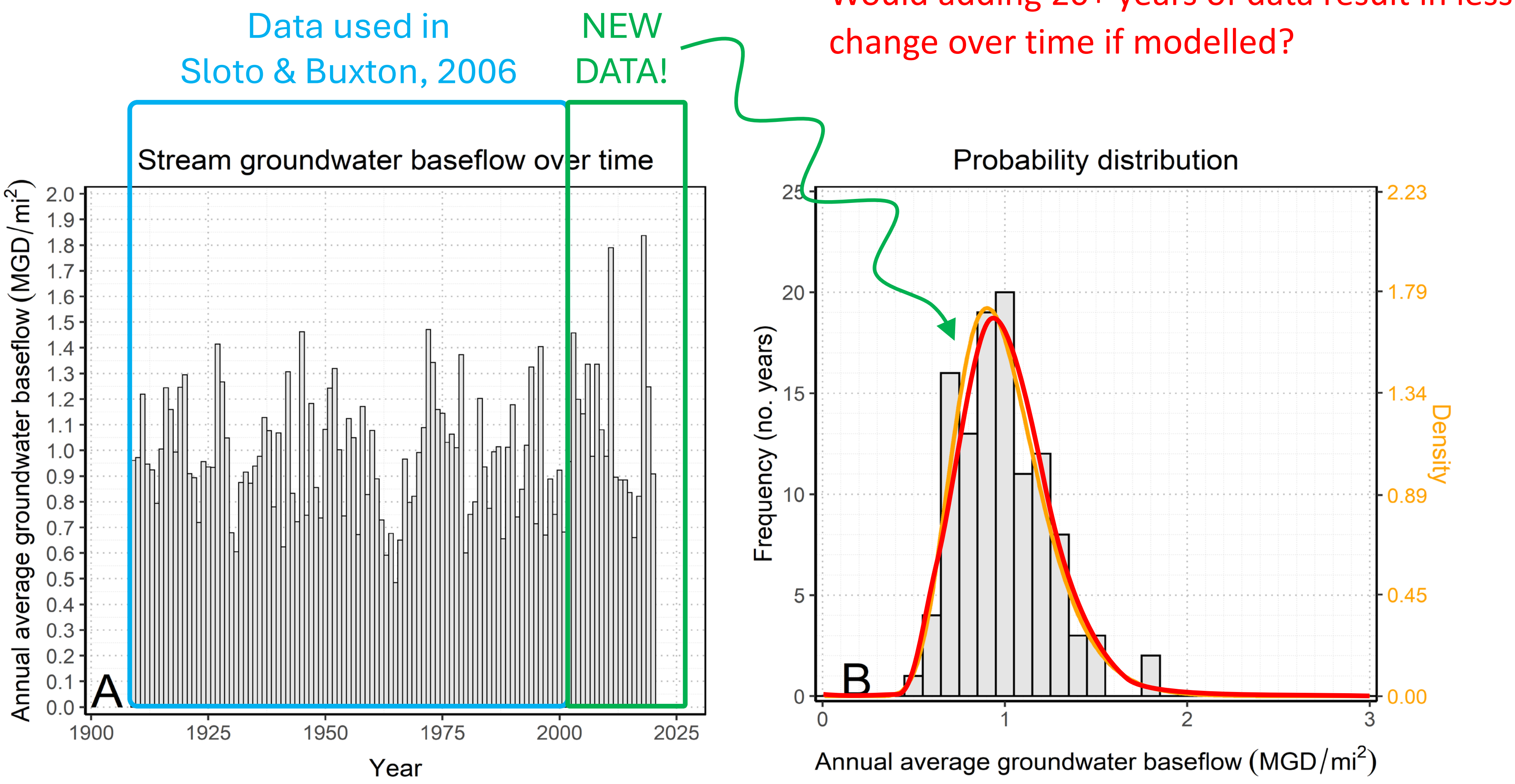
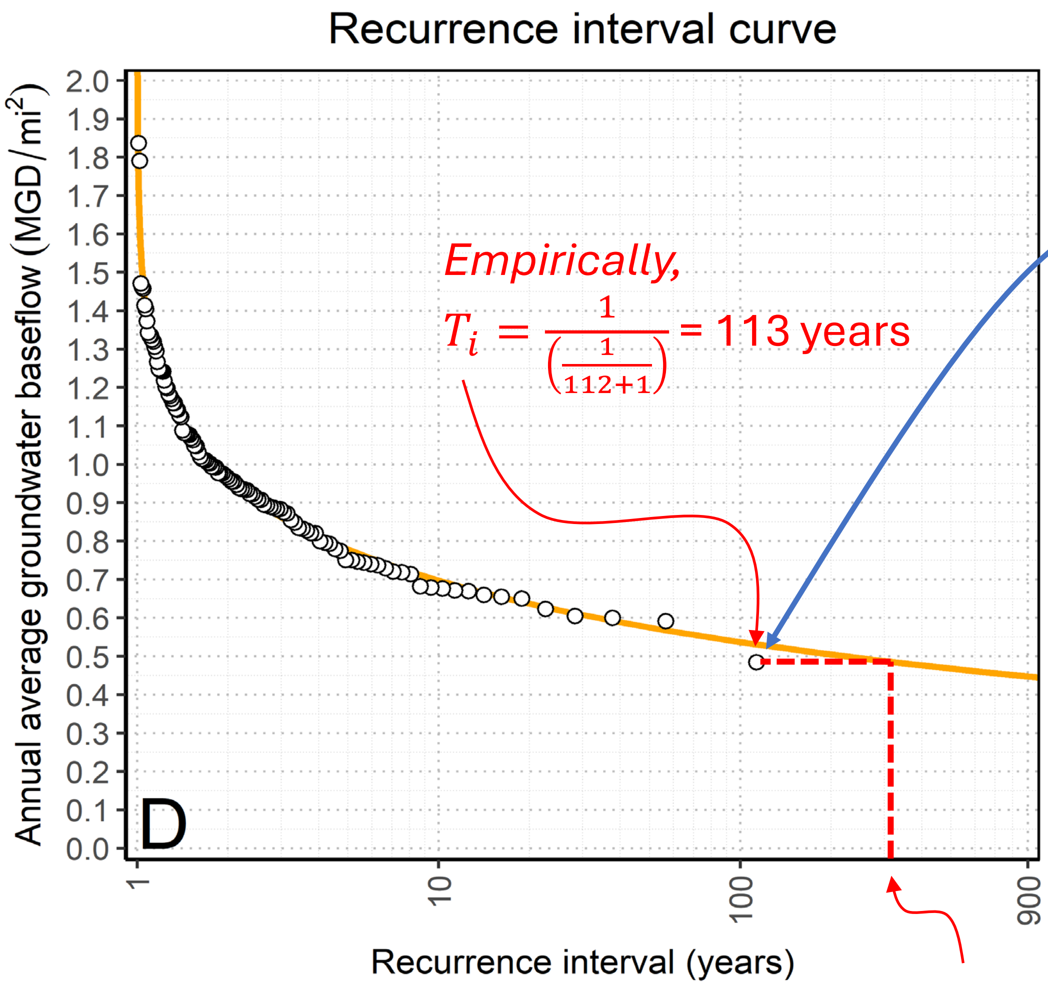
2. Would modelling probability change results? Would the results have more longevity?

Would adding 20+ years of data result in less change over time if modelled?



3. Does a 50-year baseflow recurrence interval represent the Drought of Record?



Empirically,

$$T_i = \frac{1}{\left(\frac{1}{112+1}\right)} = 113 \text{ years}$$

Modelled, $T_i \approx 325$ *years*

This point is the baseflow during the year 1965!

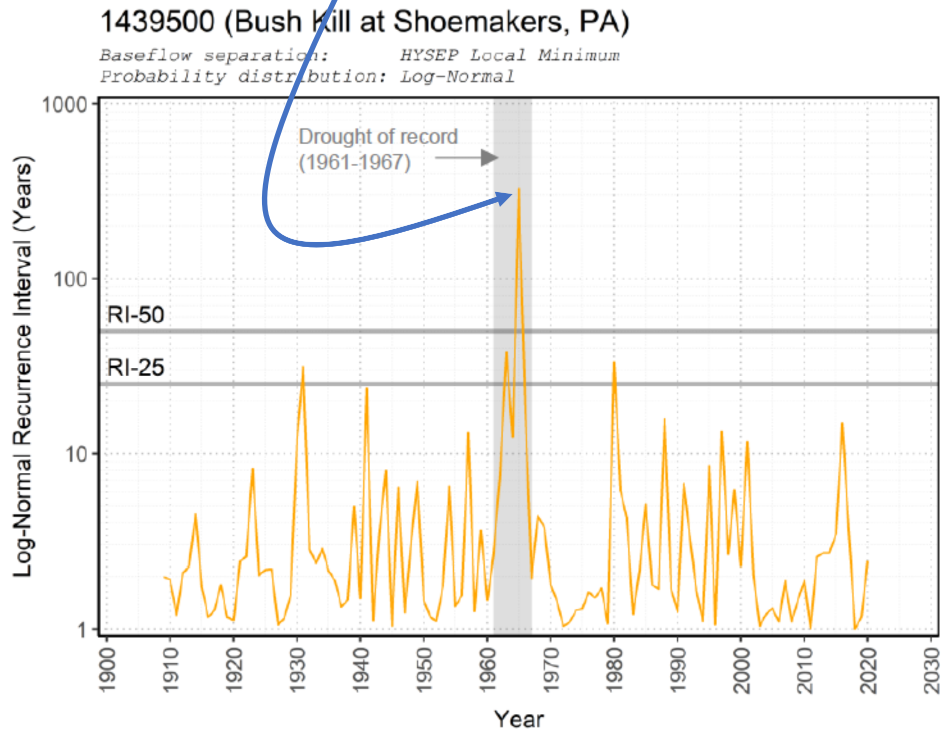


Figure 5: *The recurrence intervals associated with the annual average baseflows calculated using HYSEP-LocMin for USGS Site Number 01439500 (Bush Kill at Shoemakers, PA), based on the fitted Log-Normal distribution in Figure 4.*

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4. Would considering the season provide a more conservative screening tool?

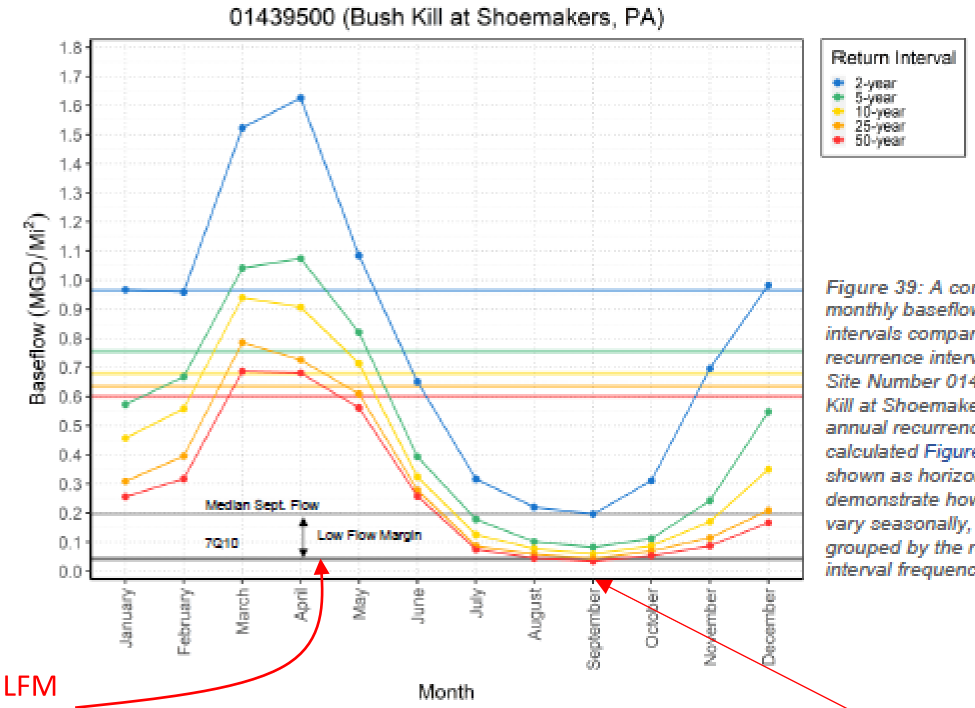

Figure 39: A comparison of monthly baseflow recurrence intervals compared to annual recurrence intervals for USGS Site Number 01439500 (Bush Kill at Shoemakers, PA). The annual recurrence intervals calculated Figure 4B are shown as horizontal lines. To demonstrate how baseflows vary seasonally, data are grouped by the recurrence interval frequency.

New Jersey's LFM method

Lower flows, but higher demand!

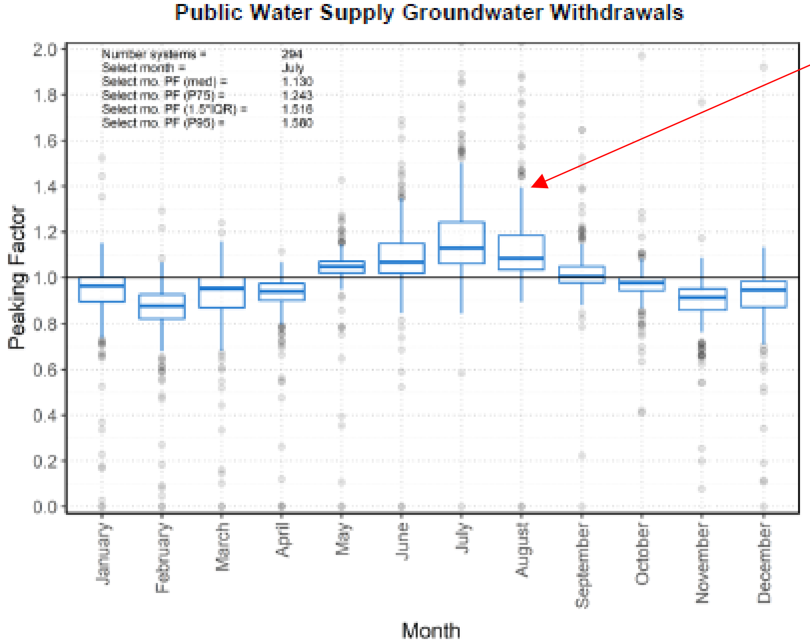

Figure 40: Monthly peaking factors for public water supply systems in the Delaware River Basin. This data considers 294 systems that withdrawal groundwater, based on data used in developing the projections provided in Thompson & Pindar, 2021.

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4. Scope of Work (for this project)

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Scope of work

- re-assess the groundwater baseflow recurrence intervals with up to 20 years of additional hydrologic data;
- use an ensemble of baseflow separation algorithms for hydrograph analysis (e.g., USGS GW-Toolbox);
- estimate recurrence intervals based on modelled distributions, assess estimates during the Drought of Record;
- use an alternative method to correlate groundwater baseflow recurrence intervals to un-gaged subwatersheds;
- assess additional geographic scales;
- assess temporal resolution (i.e. seasonality).

5. Progress Updates

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use an ensemble of baseflow separation algorithms for hydrograph analysis (e.g., USGS GW-Toolbox);

Record No.	USGS station number	Station name	2-year recurrence average annual base flow (million gallons per day per square mile)			5-year recurrence average annual base flow (million gallons per day per square mile)		
			Hydrograph separation	Spatial Data Analysis	Difference (percent)	Hydrograph separation	Spatial Data Analysis	Difference (percent)
1	01413500	East Branch Delaware River at Margaretville, N.Y.	0.746	0.694	-7.2	0.589	0.551	-6.7
2	01414000	Platte Kill at Dunraven, N.Y.	.681	.689	1.2	.530	.547	3.2
3	01414500	Mill Brook near Dunraven, N.Y.	.896	.724	-21.2	.741	.574	-25.4
4	01415000	Tremper Kill near Andes, N.Y.	.654	.688	5.1	.539	.547	1.5
5	01415500	Terry Clove Kill near Pepacton, N.Y.	.770	.687	-11.4	.624	.546	-13.3
6	01418500	Beaver Kill at Craigie Clair, N.Y.	.962	.753	-24.4	.716	.594	-18.6
7	01419500	Willowemoc Creek near Livingston Manor, N.Y.	.929	.760	-20.0	.704	.603	-15.5
8	01420000	Little Beaver Kill near Livingston Manor, N.Y.	.838	.802	-4.4	.674	.639	-5.3
9	01420500	Beaver Kill at Cooks Falls, N.Y.	.905	.748	-19.0	.729	.588	-21.4
10	01421900	West Branch Delaware River upstream From Delhi, N.Y	.672	.687	2.2	.503	.545	8.0
11	01422000	West Branch Delaware River at Delhi, N.Y.	.555	.687	21.3	.413	.545	27.6
12	01422500	Little Delaware River near Delhi, N.Y.	.660	.687	4.0	.532	.546	2.6
13	0142400103	Trout Creek near Trout Creek, N.Y.	.588	.687	15.5	.442	.546	21.1
14	01424500	Trout Creek at Cannonsville, N.Y.	.632	.687	8.3	.524	.545	3.9
15	01426000	Oquaga Creek at Deposit, N.Y.	.517	.705	30.8	.426	.560	27.2
16	01427500	Callicoon Creek at Callicoon, N.Y.	0.573	0.659	14.0	0.401	0.487	19.4
17	01428000	Tenmile River at Tusten, N.Y.	.539	.577	6.8	.409	.405	-1.0
18	01437500	Neversink River at Godeffroy, N.Y.	.583	.708	19.4	.472	.563	17.6
19	01439500	Bush Kill at Shoemakers, Pa.	.875	.869	-0.7	.686	.684	-0.3
20	01440000	Flat Brook near Flatbrookville, N.J.	.702	.715	1.8	.576	.584	1.4
21	01440400	Brodhead Creek near Analomink, Pa.	.790	.872	9.9	.677	.694	2.5
22	01441000	McMichaels Creek at Stroudsburg, Pa.	.805	.832	3.3	.611	.660	7.7
23	01442500	Brodhead Creek at Minisink Hills, Pa.	.829	.853	2.9	.648	.677	4.4
24	01445500	Pequest River at Pequest, N.J.	.674	.667	-1.0	.559	.524	-6.5
25	01446000	Beaver Brook near Belvidere, N.J.	.625	.602	-3.7	.479	.481	0.4
26	01447500	Lehigh River at Stoddartsville, Pa.	.861	.864	0.3	.730	.729	-0.1
27	01447720	Tobyhanna Creek near Blakeslee, Pa.	.876	.860	-1.8	.720	.729	1.2
28	01448000	Lehigh River at Tannery, Pa.	.847	.873	3.0	.708	.725	2.4
29	01449360	Pohopoco Creek at Kresgeville, Pa.	.896	.848	-5.5	.761	.673	-12.3
30	01450000	Pohopoco Creek near Parryville, Pa.	.722	.846	15.8	.565	.675	17.7
31	01450500	Aquashicola Creek at Palmerton, Pa.	0.810	0.794	-2.0	0.640	0.633	-1.1
32	01451500	Little Lehigh Creek near Allentown, Pa.	.625	.673	7.4	.468	.523	11.1
33	01451800	Jordan Creek near Schnecksville, Pa.	.514	.515	0.2	.435	.435	0.0
34	01452500	Monocacy Creek at Bethlehem, Pa.	.582	.628	7.6	.435	.490	11.9
35	01456000	Musconetcong River near Hackettstown, N.J.	.813	.683	-17.4	.625	.561	-10.8
36	01457000	Musconetcong River near Bloomsbury, N.J.	.810	.674	-18.3	.651	.546	-17.5
37	01459500	Tohickon Creek near Pipersville, Pa.	.259	.313	18.9	.211	.249	16.5
38	01460000	Tohickon Creek at Point Pleasant, Pa.	.335	.313	-6.8	.246	.249	1.2
39	01465000	Neshaminy Creek at Rushland, Pa.	.430	.430	0.0	.329	.328	-0.3
40	01467500	Schuylkill River at Pottsville, Pa.	.837	.915	8.9	.677	.707	4.3
41	01468500	Schuylkill River at Landingville, Pa.	.993	.901	-9.7	.736	.698	-5.3
42	01470756	Maiden Creek at Virginville, Pa.	.606	.548	-10.1	.457	.456	-0.2
43	01470779	Tulpehocken Creek near Bernville, Pa.	.786	.665	-16.7	.622	.508	-20.2
44	01471000	Tulpehocken Creek near Reading, Pa.	.682	.596	-13.5	.494	.478	-3.3
45	01471980	Manatawny Creek near Pottstown, Pa.	.567	.637	11.6	.480	.510	6.1
46	01472157	French Creek near Phoenixville, Pa.	0.566	0.523	-7.9	0.463	0.391	-16.9
47	01472198	Perkiomen Creek at East Greenville, Pa.	.576	.584	1.4	.486	.473	-2.7
48	01472199	West Branch Perkiomen Creek at Hillegass, Pa.	.620	.552	-11.6	.519	.447	-14.9
49	01472500	Perkiomen Creek near Frederick, Pa.	.434	.429	-1.2	.322	.343	6.3
50	01473000	Perkiomen Creek at Graterford, Pa.	.334	.388	15.0	.280	.310	10.2
51	01473120	Skippack Creek near Collegeville, Pa.	.313	.313	0.0	.249	.249	0.0
52	01475850	Crum Creek near Newtown Square, Pa.	.567	.523	-8.1	.477	.390	-20.1
53	01479000	White Clay Creek near Newark, Del.	.517	.534	3.2	.373	.398	6.5
54	01480000	Red Clay Creek at Wooddale, Del.	.544	.535	-1.7	.410	.399	-2.7
55	01480300	West Branch Brandywine Creek near Honey Brook, Pa	.509	.529	3.9	.390	.395	1.3
56	01481000	Brandywine Creek at Chadds Ford, Pa.	.565	.682	18.8	.407	.560	31.6
57	01481500	Brandywine Creek at Wilmington, Del.	.606	.538	-11.9	.393	.403	2.5

Record No.	10-year recurrence average annual base flow (million gallons per day per square mile)			25-year recurrence average annual base flow (million gallons per day per square mile)			50-year recurrence average annual base flow (million gallons per day per square mile)			Drainage Area
	Hydrograph separation	Spatial Data Analysis	Difference (percent)	Hydrograph separation	Spatial Data Analysis	Difference (percent)	Hydrograph separation	Spatial Data Analysis	Difference (percent)	
1	0.507	0.496	-2.2	0.475	0.408	-15.2	0.457	0.379	-18.7	163
2	.497	.493	-0.8	.376	.404	7.2	--	.375	--	34.9
3	.691	.511	-30.0	.579	.427	-30.2	.554	.404	-31.3	25.2
4	.457	.493	7.6	.419	.404	-3.6	.373	.374	0.3	33.2
5	.566	.492	-14.0	.428	.403	-6.0	--	.373	--	13.6
6	.677	.523	-25.7	.607	.446	-30.6	--	.429	--	81.9
47	.462	.412	-11.4	--	.351	--	--	.294	--	38
48	.473	.388	-19.7	--	.329	--	--	.276	--	23
49	.303	.296	-2.3	.278	.250	-10.6	--	.211	--	152
50	.224	.266	17.1	.210	.224	6.5	--	.190	--	279
51	.211	.211	0.0	.175	.175	0.0	--	.150	--	53.7
52	.421	.330	-24.2	--	.289	--	--	.274	--	15.8
53	.305	.337	10.0	.272	.291	6.7	.255	.275	7.5	89.1
54	.360	.337	-6.6	.301	.291	-3.4	.293	.275	-6.3	47
55	.327	.334	2.1	.295	.290	-1.7	.274	--	--	18.7
56	.357	.486	30.6	.319	.415	26.2	.310	.346	11.0	287
57	.362	.341	-6.0	.325	.294	-10.0	--	.276	--	314

Record No.	USGS station number	Station name	2-year recurre base flow (millio squ	
			Hydrograph separation	Spa Dat Ana
1	01413500	East Branch Delaware River at Margaretville, N.Y.	0.746	0.69
2	01414000	Platte Kill at Dunraven, N.Y.	.681	.68
3	01414500	Mill Brook near Dunraven, N.Y.	.896	.72
4	01415000	Tremper Kill near Andes, N.Y.	.654	.68
5	01415500	Terry Clove Kill near Pepacton, N.Y.	.770	.68
6	01418500	Beaver Kill at Craigie Clair, N.Y.	.962	.75
7	01419500	Willowemoc Creek near Livingston Manor, N.Y.	.929	.76

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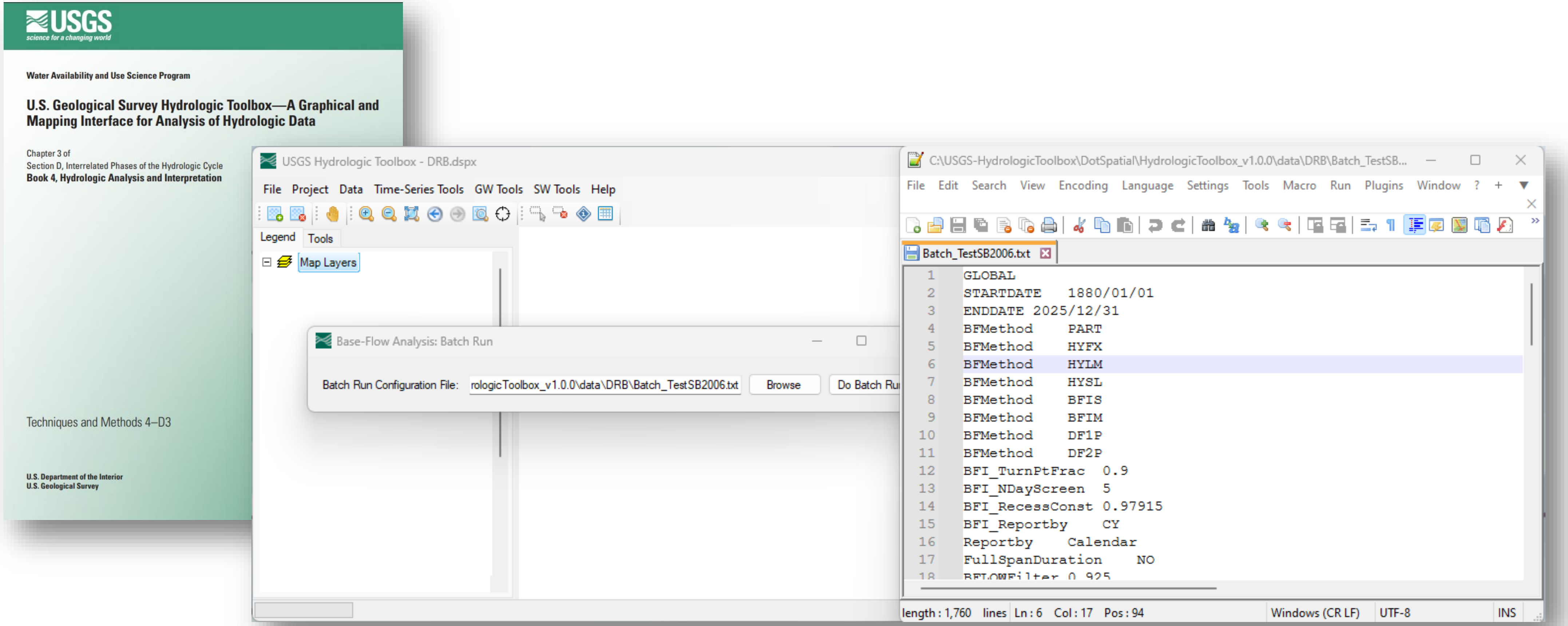
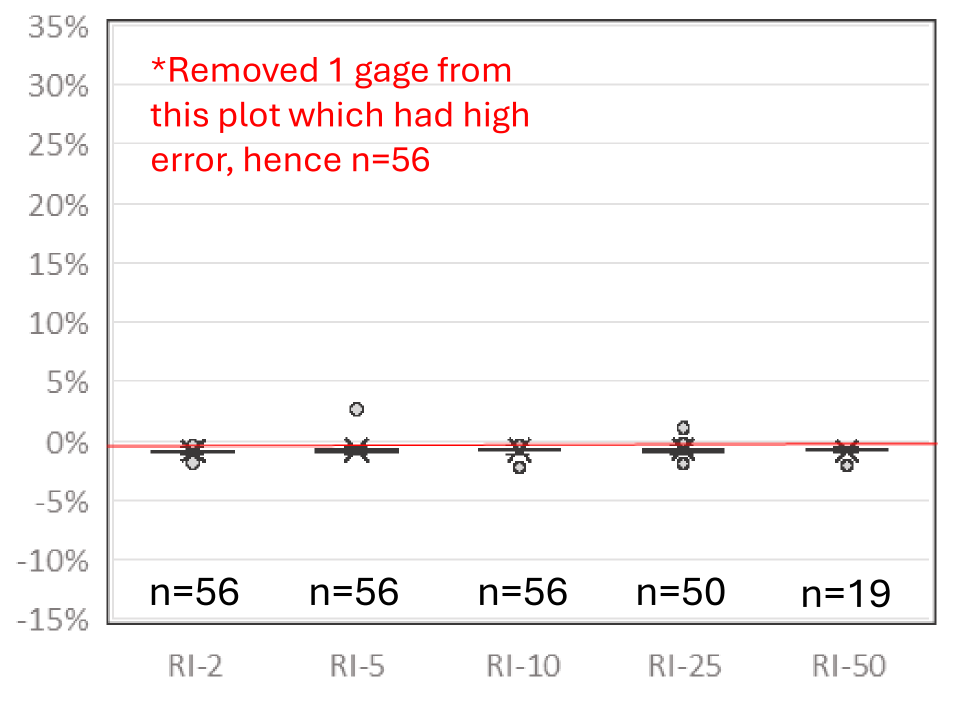
use an ensemble of baseflow separation algorithms for hydrograph analysis (e.g., USGS GW-Toolbox);



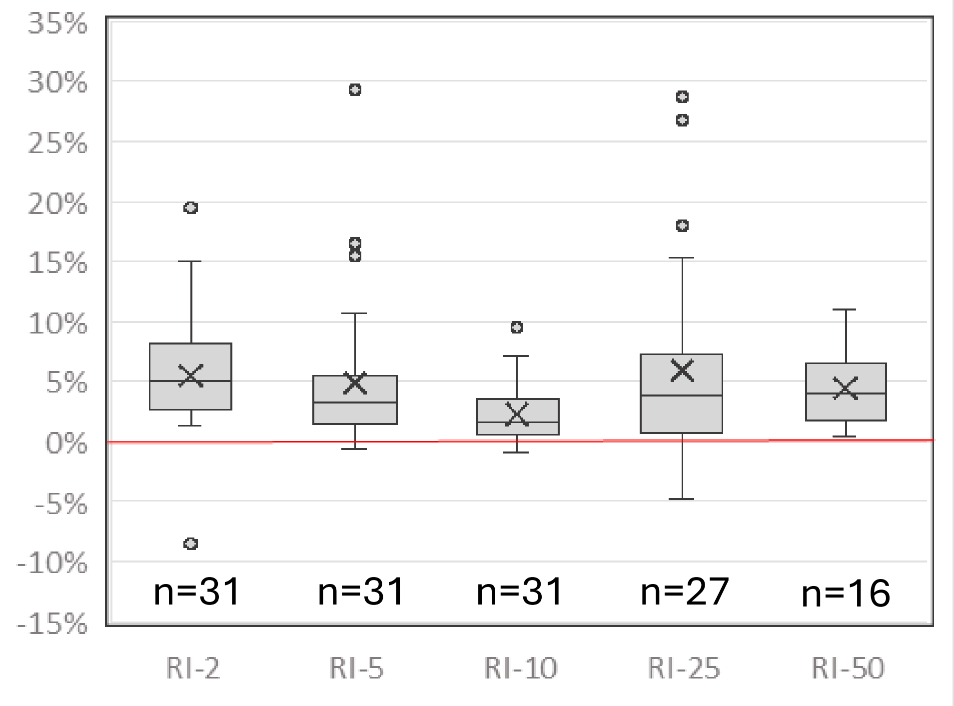
- **USGS Hydrologic Toolbox > GW Tools > Baseflow Separation**
- Ran all 57 gages used in Sloto & Buxton, 2006 using multiple separation methods

re-assess the groundwater baseflow recurrence intervals with up to 20 years of additional hydrologic data;

BF Sep. Method:	HYSEP Loc-Min
RI Calculation:	Empirical
Data Start:	Sloto & Buxton, 2006
Data End:	Sloto & Buxton, 2006



BF Sep. Method:	HYSEP Loc-Min
RI Calculation:	Empirical
Data Start:	Sloto & Buxton, 2006
Data End:	2024



Conclusions:

1. Adding new data results in significant change in baseflow estimates at all recurrence intervals

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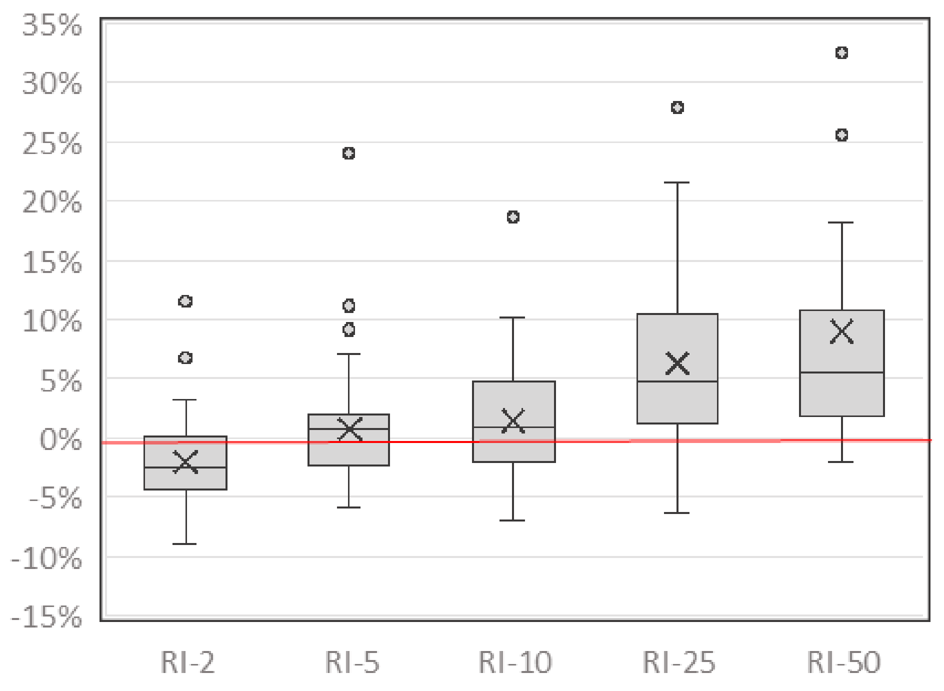
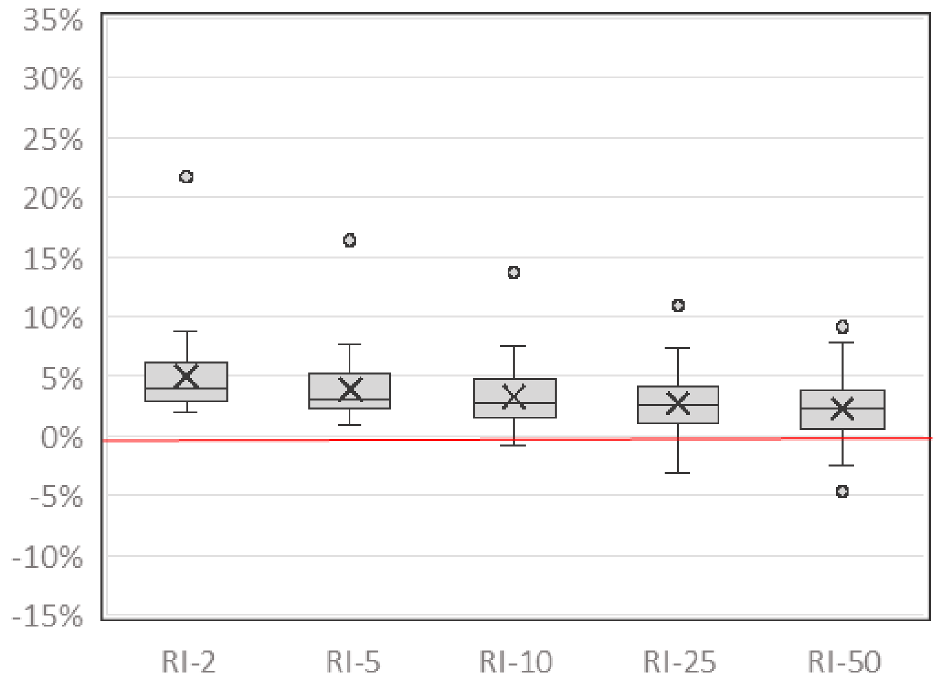
estimate recurrence intervals based on modelled distributions,
assess estimates during the Drought of Record;

BF Sep. Method:	HYSEP Loc-Min
RI Calculation:	Log-Normal
Data Start:	Sloto & Buxton, 2006
Data End:	Sloto & Buxton, 2006



BF Sep. Method:	HYSEP Loc-Min
RI Calculation:	Log-Normal
Data Start:	Sloto & Buxton, 2006
Data End:	2024



Conclusions:

1. Using same data at Sloto & Buxton: Calculating the return interval baseflow using modelled Log-Normal distribution shows significant changes, especially at the extremes of the distribution
2. Adding new data to log-normal distributions dampens the change in calculated baseflows

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estimate recurrence intervals based on modelled distributions,

assess estimates during the Drought of Record;

Record No.	Site No.	Name	Drainage Area (mi^2)	Period of Record	Years of data	Baseflow Separation Method	Log-Normal Distribution Method						
							1961	1962	1963	1964	1965	1966	1967
19	01439500	Bush Kill at Shoemakers, Pa.	117	1909-2024	116	PART	114	164	438	201	2,994	307	117
						HySEP-Fixed	104	152	430	178	2,328	235	105
						HySEP-LocMin	94	120	589	166	3,659	191	99
						HySEP-Slide	105	154	468	212	2,639	259	108
						BFIStandard	77	84	189	234	669	123	75
						BFIModified	79	84	181	225	1,072	127	76
						BFLOW	106	157	551	209	2,603	257	105

Conclusions:

1. It is likely that the DRBC specified “Drought of Record” is characterized by flows less-frequent than a 1-in-50 year flow
2. Assessing GW availability using a 1-in-50 year flow may not be conservative enough for planning purposes
3. Baseflow separation methods fed into a modelled distribution yield a range of values
4. The distribution “tail” may result in very high recurrence intervals (e.g. thousands of years) – likely needs to be dealt with in a more realistic manner

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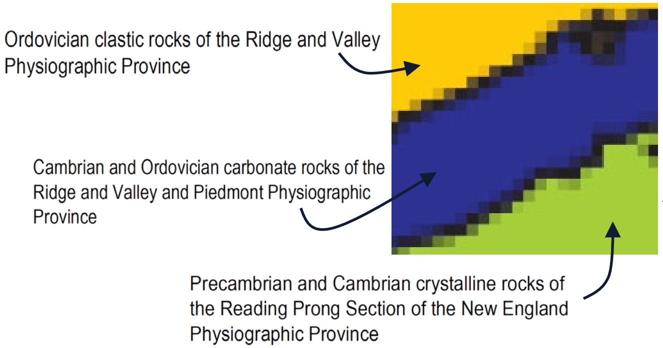
use an alternative method to correlate groundwater baseflow recurrence intervals to un-gaged subwatersheds;

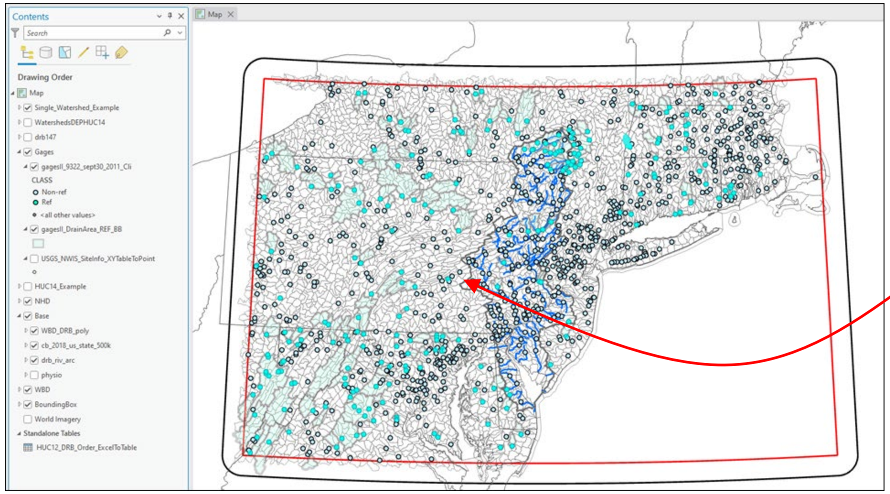
Instead of....



$$\frac{0.3\,RI_{25} + 0.4\,RI_{25} + 0.3\,RI_{25}}{\text{Watershed } RI_{25}}$$

A “geologic index” approach with discrete estimates for each return interval

We will try...



Working on data gathering. Focus on GAGES-II reference sites.

Multi-variate regression to model the distribution parameters

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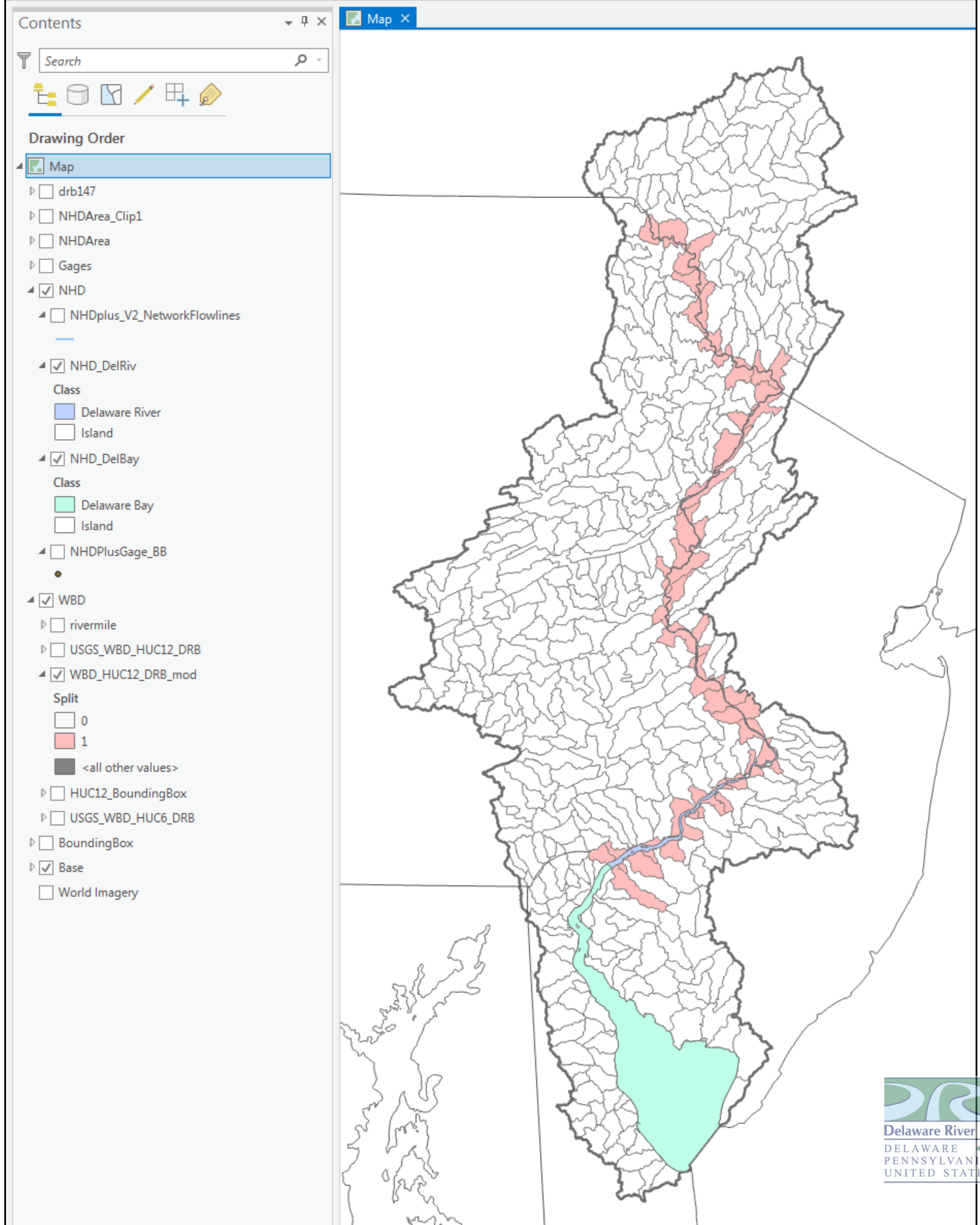
assess additional geographic scales;

<u>Basic steps:</u>

- Start by using USGS WBD HUC-12
- Add in River & Bay as polygons
- Split HUC-12 around river



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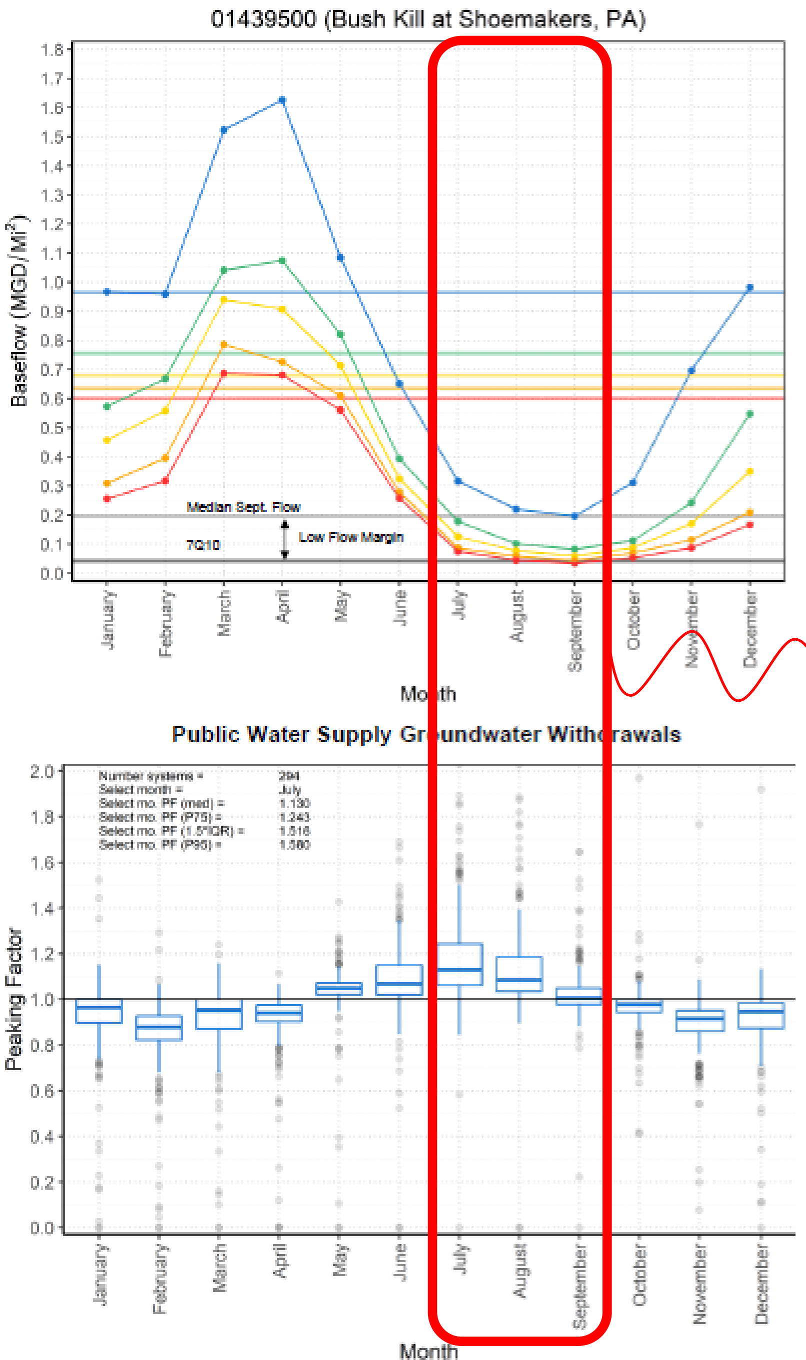
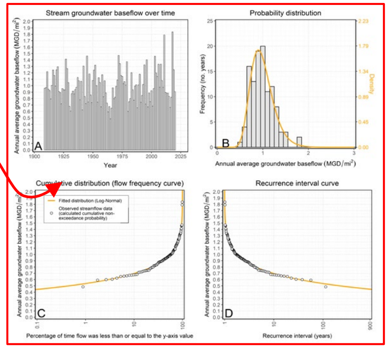
assess temporal resolution (i.e. seasonality).

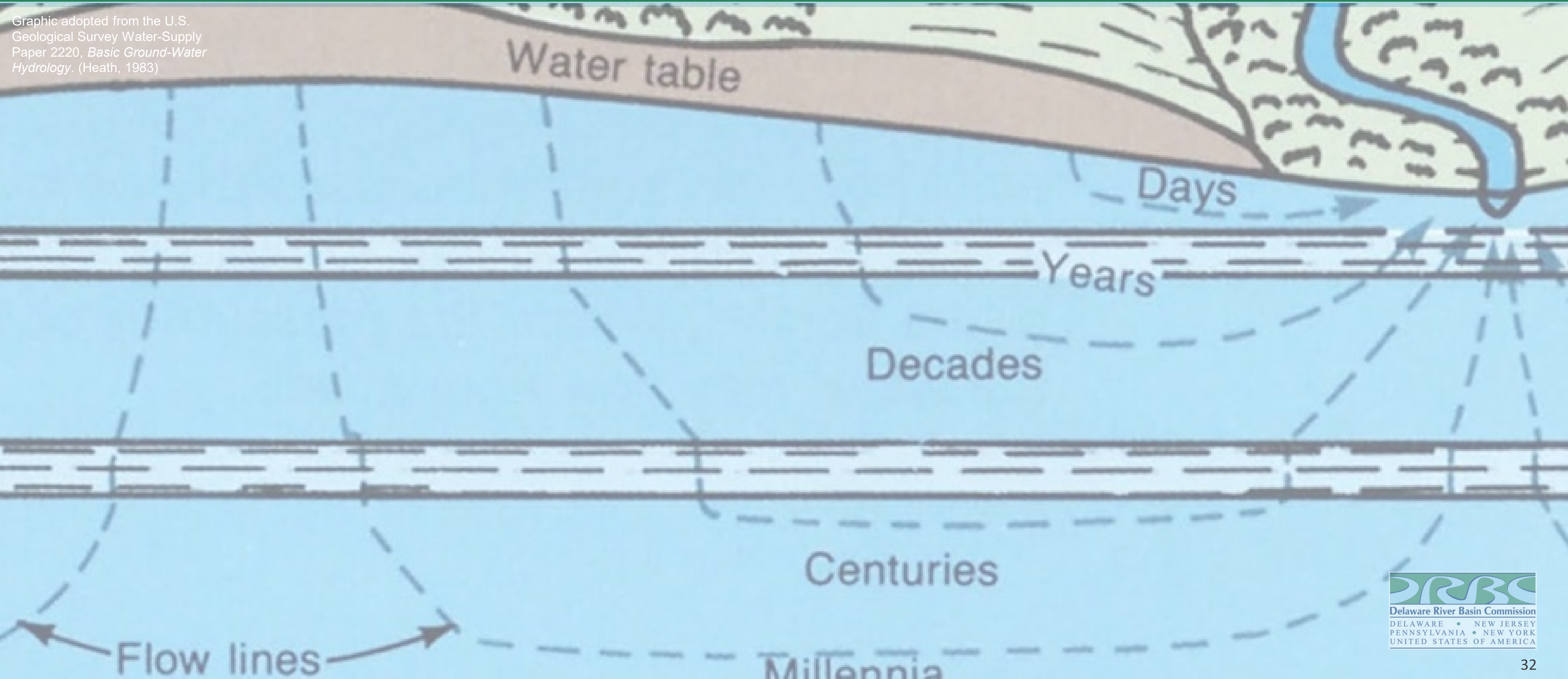
- Likely continue by defining a “season” to have “worst case” model.
- Not necessary to make a model for each month

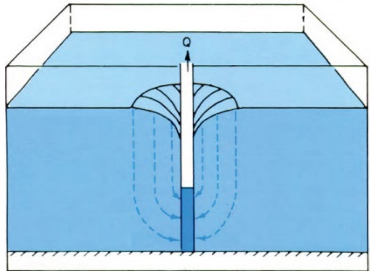


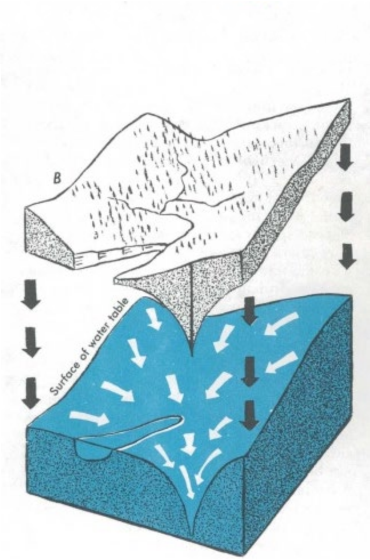


6. Why

Graphic adopted from the U.S. Geological Survey Water-Supply Paper 2220, *Basic Ground-Water Hydrology*. (Heath, 1983)







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