Appendix 1. Seasonal and low flow statistics from index gages

Table 1. Long-term median monthly streamflows for index gages across stream types

Type		Stream name	Drainage area	December	January	February	March	April	May	June	July	August	September	October	November
			sq mi	Q50	Q50	Q50	Q50	Q50	Q50	Q50	Q50	Q50	Q50	Q50	Q50
Headwaters	01422738	Wolf Creek at Mundale, NY	0.7	1	0.9	1	1.3	1.3	0.6	0.3	0.2	0.1	0.1	0.6	0.8
	01434021	West Br Neversink at Winnisook	0.9	1.4	1.2	0.8	0.5	3.2	2	1.2	0.7	0.6	0.8	1.8	1.8
	01422389	Coulter Brook near Bovina Center, NY	1.2	1.2	1	0.9	1.5	2.5	1.1	0.9	0.3	0.3	0.3	0.9	1.2
	01448500	Dilldown Creek near Long Pond, PA	2.39	4	3.4	3.7	6.1	6	4.5	2.9	1.7	1.3	1.1	1.8	3.1
	01434025	Biscuit Brook, NY	3.72	7.8	5.8	4.7	3.9	13	8	4.8	3.1	2.3	2.6	6	8.9
	01472174	Pickering Creek near Chester Springs, PA	5.98	6.5	8.1	9.5	11	11	8.6	6.4	4.7	3.8	3.5	4	5.1
	01440485	Swiftwater Creek at Swiftwater, PA	6.9	24	19	14	17	21	17	12.0	8.8	8.0	11.0	17	16
	01480675	Marsh Creek near Glenmoore, PA	8.57	8	9.5	11	14	13	9.6	5.6	3.3	3.0	2.7	3.7	6.4
	014340068	E Branch Neversink Northeast of Denning, NY	9	24	20	14	26	40	26	18.0	11.0	9.0	11.0	21	26
Creeks	01475850	Crum Creek near Newtown Square, PA	15.8	16	18	21	26	26	20	15.0	11.0	9.2	8.6	10	13
	0142400103	Trout Creek near Trout Creek, NY	20.2	25	20	20	42	54	22	12.0	4.4	1.9	2.3	8.4	21
	01472199	West Branch Perkiomen Creek at Hillegass, PA	23	30	33	36	46	42	29	19.0	13.0	11.0	10.0	14	21
	01464907	Little Neshaminy Creek at Valley Rd, PA	26.8	29	34	40	55	46	29	18.0	12.0	10.0	8.7	12	19
	01472198	Perkiomen Creek at East Greenville, PA	38	48	53	60	75	69	50	34.0	24.0	21.0	18	25	34
Small Rivers	01428750	West Branch Lackawaxen River near Aldenville, PA	41	62	48	50	99	97	64	29	17	14.0	14	25	53
	01449360	Pohopoco Creek at Kresgeville, PA	50	92	82	95	129	121	92	62	43	36	32	43	69
	01451800	Jordan Creek near Schnecksville, PA	53	71	66	74	110	82	49	30	19	18	16	27	48
	01473120	Skippack Creek near Collegeville, PA	54	48	56	61	88	65	38	21	12	11	9	16	27
	01472157	French Creek near Phoenixville, PA	59	58	71	87	101	96	70	46	33	27	24	28	44
	01419500	WILLOWEMOC CREEK NR LIVINGSTON MANOR NY	63	120	78	90	138	266	138	64	33	26	29	33	102
	01440000	Flat Brook near Flatbrookville NJ	64	96	91	105	156	149	105	58	33	24	21	32	65
	01440400	Brodhead Creek near Analomink, PA	66	121	100	105	189	171	128	69	36	26	24	43	93
	01435000	NEVERSINK RIVER NEAR CLARYVILLE NY	67	148	110	110	174	292	184	101	60	44	49	87	153
	01426000	Oquaga Creek at Deposit, NY	68	113	86	88	157	236	147	68	35	21	18	83	94
	01450500	Aquashicola Creek at PAlmerton, PA	77	131	116	127	187	167	124	79	58	50	46	63	103
	01418500	BEAVER KILL AT CRAIGIE CLAIR NY	82	165	105	120	185	367	192	87	42	28	34	40.5	159
	01447500	Lehigh River at Stoddartsville, PA	92	166	140	140	240	250	179	106	66	49	44	83	140
	01439500	Bush Kill at Shoemakers, PA	117	216	176	190	330	305	230	130	70	48	38	76	160
	01447720	Tobyhanna Creek near Blakeslee, PA	118	246	207	211	230	340	254	163	108	83	83	138	221
	01468500	Schuylkill River at Landingville, PA	133	235	210	234	353	316	250	171	127	108	95	117	171
	01413500	EAST BR DELAWARE R AT MARGARETVILLE NY	163	252	190	195	370	523	297	137	69	40	37	78	228
Medium Tributaries	01471000	Tulpehocken Creek near Reading, PA	211	94	97	114	135	122	94	78	67	58	54	94	68
	01442500	Brodhead Creek at Minisink Hills, PA	259	476	400	454	733	662	497	290	170	134	125	187	367
	01481000	Brandywine Creek at Chadds Ford, PA	287	339	405	455	547	534	416	292	221	185	165	182	244
	01423000	WBr Delaware River at Walton, NY	332	500	350	370	785	882	302	482	226	89	75	175	428
Large Rivers	01472000	Schuylkill River at Pottstown, PA	1147	1650	1541	1756	2570	2215	1651	1110	778	683	618	745	1130

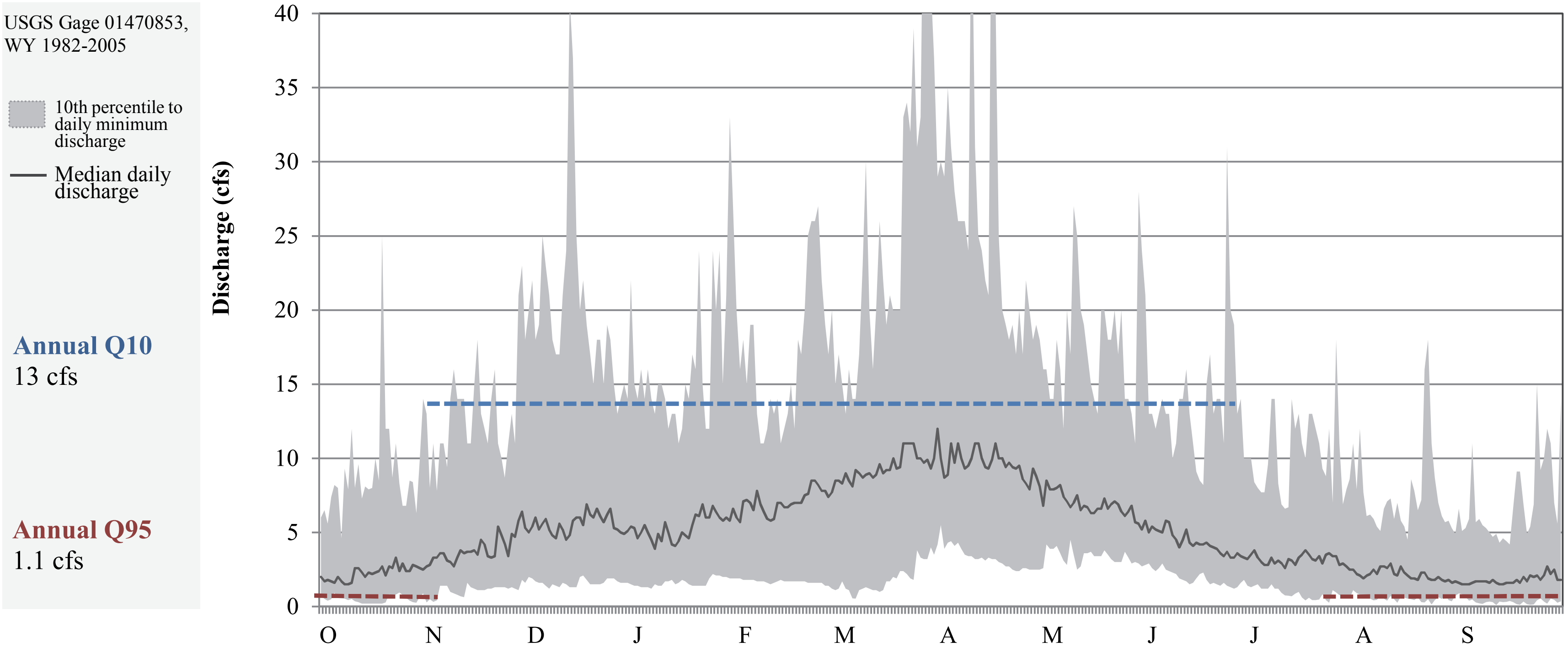
Table 2. Long-term monthly Q75 values at index gages across stream types

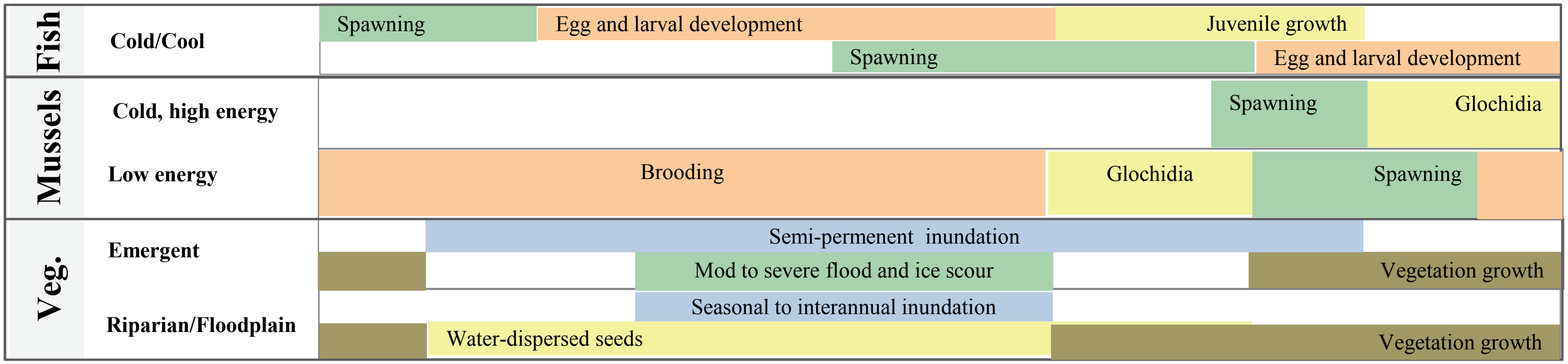
Type		Stream name	Drainage area	December	January	February	March	April	May	June	July	August	September	October	November
			sq mi	Q75	Q75	Q75	Q75	Q75	Q75	Q75	Q75	Q75	Q75	Q75	Q75
Headwaters	01422738	Wolf Creek at Mundale, NY	0.7	0.5	0.6	0.4	0.9	1	0.4	0.2	0.1	0	0.1	0.2	0.4
	01434021	West Br Neversink at Winnisook	0.9	0.9	0.8	0.6	0.8	2	1.3	0.8	0.4	0.3	0.5	1	1.2
	01422389	Coulter Brook near Bovina Center, NY	1.2	0.7	0.6	0.4	0.8	1.6	0.8	0.4	0.2	0.1	0.1	0.3	0.8
	01448500	Dilldown Creek near Long Pond, PA	2.39	2.4	2.2	2.3	3.9	3.2	3.4	1.9	1.2	0.9	0.7	0.95	1.8
	01434025	Biscuit Brook, NY	3.72	5.4	3.5	5.1	5.6	9.1	3.1	3.1	1.7	1.2	1.2	2.6	5.2
	01472174	Pickering Creek near Chester Springs, PA	5.98	4.4	5.2	6.6	8.3	7.7	6.2	4.5	3.4	2.9	2.6	2.8	3.5
	01440485	Swiftwater Creek at Swiftwater, PA	6.9	18	14	11	13	15	14	10.0	7.4	6.2	5.6	8.1	13
	01480675	Marsh Creek near Glenmoore, PA	8.57	5.2	5.7	7.1	10	9	6.5	3.3	2.2	1.7	1.6	2.1	3.7
	014340068	E Branch Neversink Northeast of Denning, NY	9.0	17	13	10	14	27	19	12.0	6.7	4.6	5.5	11	17
Creeks	01475850	Crum Creek near Newtown Square, PA	15.8	11	12	15	18	18	15	10.0	7.4	6.0	5.7	7.2	9.7
	0142400103	Trout Creek near Trout Creek, NY	20.2	13	11	10	27	38	14	5.2	2.0	0.9	1.0	2	6.8
	01472199	West Branch Perkiomen Creek at Hillegass, PA	23	18	19	23	33	29	22	13.0	8.7	6.1	6.3	8.3	12
	01464907	Little Neshaminy Creek at Valley Rd, PA	26.8	15	17	21	31	45	17	9.9	6.2	5.3	4.3	6.1	10
	01472198	Perkiomen Creek at East Greenville, PA	38	30	31	39	54	48	37	24.0	17.0	14.0	13.0	16	21
Small Rivers	01428750	West Branch Lackawaxen River near Aldenville, PA	41	38	28	32	56	66	40	18.0	11	8.2	7.9	12	25
	01449360	Pohopoco Creek at Kresgeville, PA	50	57	55	58	90	86	70	44	30	24	21	28	40
	01451800	Jordan Creek near Schnecksville, PA	53	35	35	40	64	51	33	17	10	8.1	7	12	23
	01419500	WILLOWEMOC CREEK NR LIVINGSTON MANOR NY	63	77	54	58	82	184	100	43	21	16	18	19	50
	01440000	Flat Brook near Flatbrookville NJ	64	54	60	68	104	102	76	38	22	14	13	16	30
	01440400	Brodhead Creek near Analomink, PA	66	77	65	72	115	119	89	42	22	15	13	20	48
	01435000	NEVERSINK RIVER NEAR CLARYVILLE NY	67	105	77	76	107	216	130	66	38	26	27	38	92
	01426000	Oquaga Creek at Deposit, NY	68	72	52	54	82	157	95	42	20	12	11	35	46
	01450500	Aquashicola Creek at PAlmerton, PA	77	78	77	81	125	113	90	56	39	33	28	40	60
	01418500	BEAVER KILL AT CRAIGIE CLAIR NY	82	110	68	74	102	256	138	56	28	17	19	19	82
	01447500	Lehigh River at Stoddartsville, PA	92	109	95	102	**156**	176	126	65	37	27	24	40	77
	01439500	Bush Kill at Shoemakers, PA	117	129	120	130	200	209	160	79	34	19	15	29	78
	01447720	Tobyhanna Creek near Blakeslee, PA	118	155	213	158	197	257	191	106	85	52	48	73	129
	01468500	Schuylkill River at Landingville, PA	133	146	145	157	237	223	182	121	87	76	68	80	97
	01413500	EAST BR DELAWARE R AT MARGARETVILLE NY	163	166	110	118	216	359	209	80	38	23	21	31	113
Medium	01471000	Tulpehocken Creek near Reading, PA	211	67	67	82	105	90	73	59	50	43	41	45	49
	01442500	Brodhead Creek at Minisink Hills, PA	259	289	260	280	473	449	353	193	119	88	80	107	220
	01481000	Brandywine Creek at Chadds Ford, PA	287	227	270	329	450	415	380	204	164	135	120	135	177
	01423000	WBr Delaware River at Walton, NY	332	310	230	210	418	584	250	134	72	47	44	56	201
Large Rivers	01472000	Schuylkill River at Pottstown, PA	1147	994	1040	1080	1740	1580	1180	776	547	464	437	530	709

Table 3. Long-term monthly Q90 values at index gages across stream typese

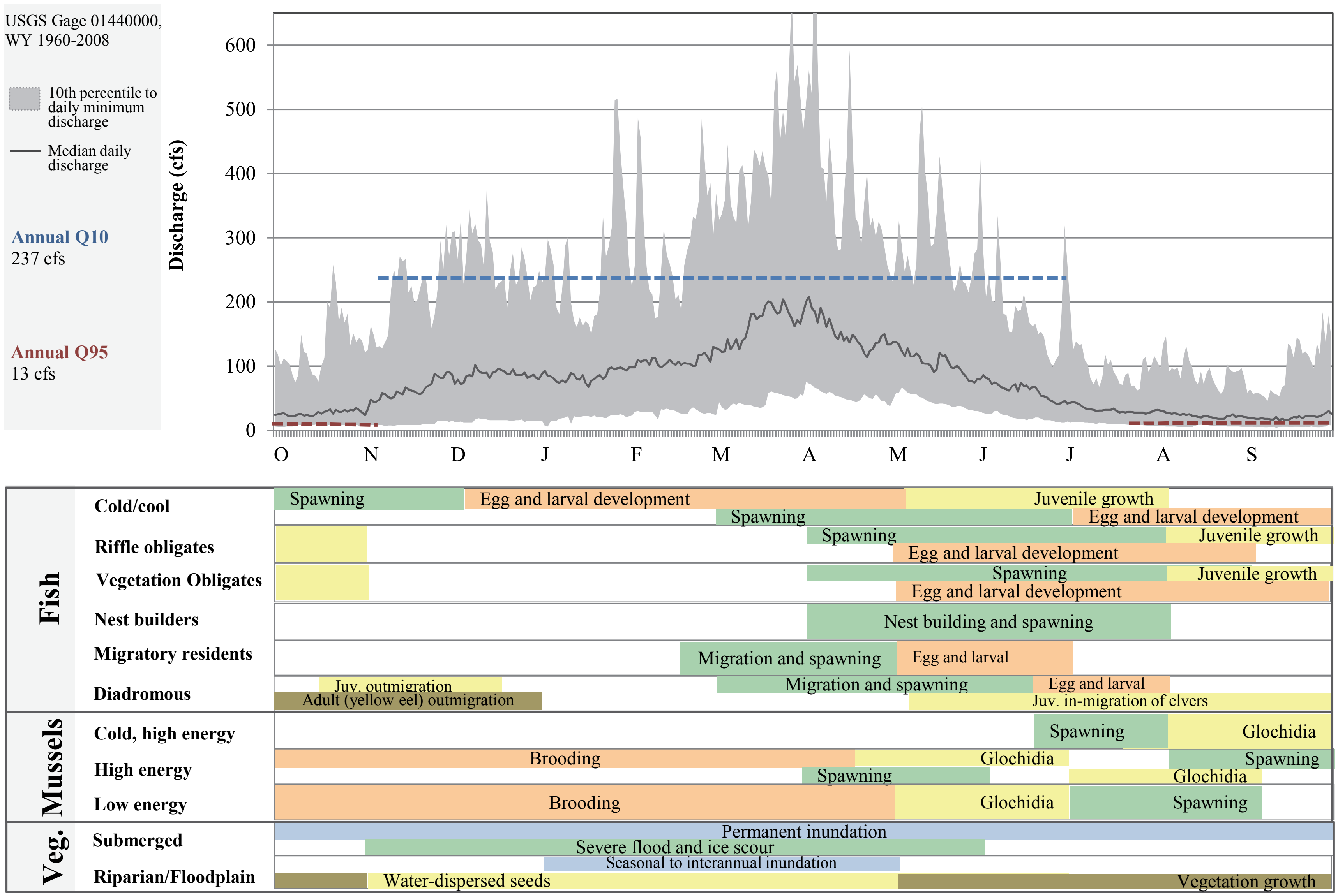
Type		Stream name	Drainage area	December	January	February	March	April	May	June	July	August	September	October	November
			sq mi	Q90	Q90	Q90	Q90	Q90	Q90	Q90	Q90	Q90	Q90	Q90	Q90
Headwaters	01422738	Wolf Creek at Mundale, NY	0.7	0.2	0.3	0.2	0.5	0.7	0.3	0.1	0.1	0	0	0.1	0.1
	01434021	West Br Neversink at Winnisook	0.9	0.7	0.5	0.4	0.6	1.3	1	0.6	0.3	0.2	0.2	0.6	0.6
	01422389	Coulter Brook near Bovina Center, NY	1.2	0.5	0.3	0.2	0.6	1.1	0.5	0.2	0.1	0	0	0	0.2
	01448500	Dilldown Creek near Long Pond, PA	2.39	1.6	1.5	3.3	2.7	3.3	2.6	1.5	0.9	0.6	0.5	0.66	0.77
	01434025	Biscuit Brook, NY	3.72	2.7	2.3	2.3	3.6	5.5	4.2	2.2	1.1	0.6	0.6	1.5	2.2
	01472174	Pickering Creek near Chester Springs, PA	5.98	2.9	3.3	4.2	5.8	5.5	4.7	3.4	2.4	1.9	2.1	2.2	2.5
	01440485	Swiftwater Creek at Swiftwater, PA	6.9	14	10	9.8	12	11	13	8.7	6.7	5.6	4.9	5.7	11
	01480675	Marsh Creek near Glenmoore, PA	8.57	3.1	3.6	4.6	8	6.8	4.5	2.3	1.4	1.1	0.9	1.4	2.3
	014340068	E Branch Neversink Northeast of Denning, NY	9.0	13	10	8	9.8	19	15	8.1	4.8	3.5	3.6	7	9
Creeks	01475850	Crum Creek near Newtown Square, PA	15.8	7.5	8.9	10	14	13	14	7.3	0.0	4.2	4.4	5.4	6.8
	0142400103	Trout Creek near Trout Creek, NY	20.2	7	6.8	7.4	18	28	8.2	2.5	1.0	0.6	0.6	0.8	1.9
	01472199	West Branch Perkiomen Creek at Hillegass, PA	23	11	11	17	24	21	16	9.5	5.6	4.0	4.1	6.2	7.8
	01464907	Little Neshaminy Creek at Valley Rd, PA	26.8	9.9	10	13	21	17	11	6.0	2.9	2.2	2.6	3.9	5.9
	01472198	Perkiomen Creek at East Greenville, PA	38	19	22	28	39	35	28	17.0	10.0	7.8	8.6	12	14
Small Rivers	01428750	West Branch Lackawaxen River near Aldenville, PA	41	22	20	23	35	47	27	12.0	8	6.0	5.5	6	11
	01449360	Pohopoco Creek at Kresgeville, PA	50	37	42	43	62	69	57	35	24	19	17	19	25
	01451800	Jordan Creek near Schnecksville, PA	53	21	23	34	26	34	24	11	5	3.6	3.6	6.9	12
	01473120	Skippack Creek near Collegeville, PA	54	14	15	18	28	22	14	6.3	3.1	2.5	2.6	4.6	7.9
	01472157	French Creek near Phoenixville, PA	59	25	32	39	54	47	37	23	15	13	12	15	20
	01419500	WILLOWEMOC CREEK NR LIVINGSTON MANOR NY	63	45	40	44	58	146	68	31	17	12	11	13	22
	01440000	Flat Brook near Flatbrookville NJ	64	34	41	48	69	75	59	27	15	10	8.9	11	16
	01440400	Brodhead Creek near Analomink, PA	66	41	50	50	72	82	6	29	28	10	8.9	13	17
	01435000	NEVERSINK RIVER NEAR CLARYVILLE NY	67	78	60	58	78	152	99	49	25	19	18	24	39
	01426000	Oquaga Creek at Deposit, NY	68	54	35	35	51	113	68	28	13	8.4	8	22	15
	01450500	Aquashicola Creek at PAlmerton, PA	77	57	57	58	86	89	70	44	30	24	21	27	33
	01418500	BEAVER KILL AT CRAIGIE CLAIR NY	82	60	47	56	64	198	89	40	21	14	11	14	32
	01447500	Lehigh River at Stoddartsville, PA	92	68	70	74	**75**	105	94	45	25	18	16	22	35
	01439500	Bush Kill at Shoemakers, PA	117	70	80	82	130	155	112	47	19	11	9.2	16	28
	01447720	Tobyhanna Creek near Blakeslee, PA	118	111	108	110	163	199	148	81	50	38	33	44	60
	01468500	Schuylkill River at Landingville, PA	133	100	101	117	162	171	145	95	68	61	58	62	66
	01413500	EAST BR DELAWARE R AT MARGARETVILLE NY	163	105	80	76	124	265	125	53	24	16	15	19	45
Medium	01471000	Tulpehocken Creek near Reading, PA	211	41	49	58	74	70	60	47	36	31	30	34	36
	01442500	Brodhead Creek at Minisink Hills, PA	259	170	191	203	323	342	267	131	89	66	62	60	92
	01481000	Brandywine Creek at Chadds Ford, PA	287	158	185	231	303	303	238	162	116	95	92	104	133
	01423000	WBr Delaware River at Walton, NY	332	190	150	150	235	438	200	91	48	32	30	36	79
Large Rivers	01472000	Schuylkill River at Pottstown, PA	1147	627	743	827	1180	1150	920	610	414	349	335	391	449

Headwaters: Furnace Creek at Robesonia, PA (4 sq mi)

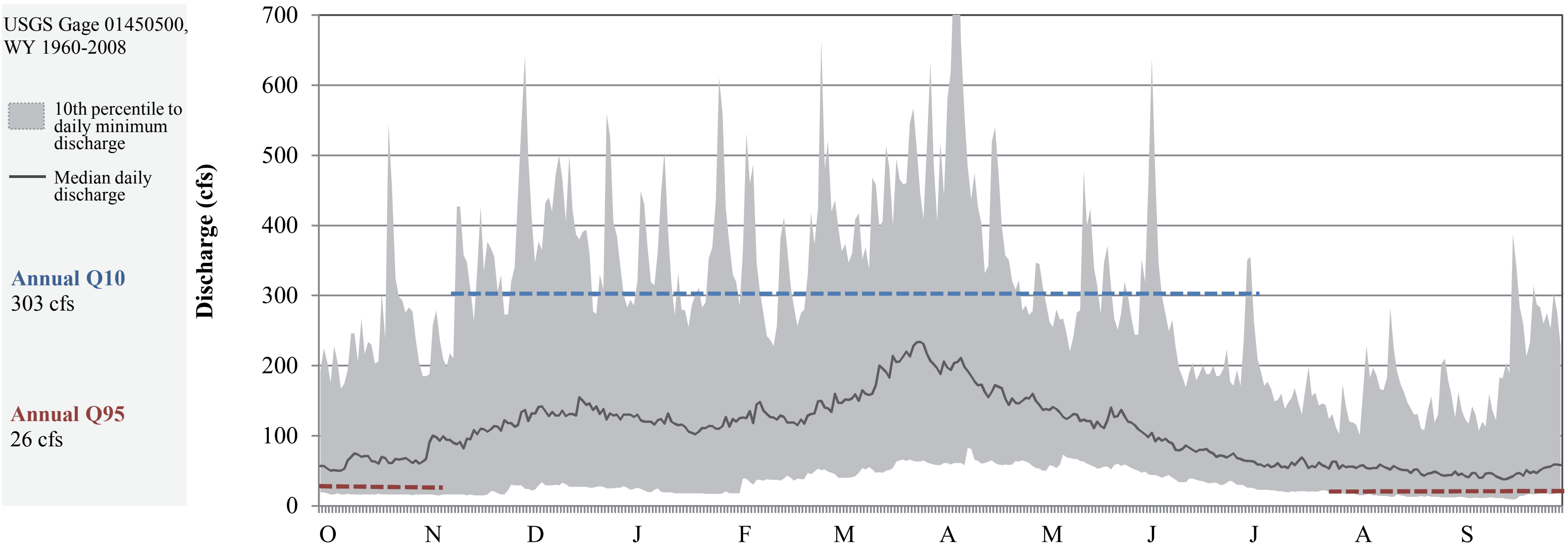


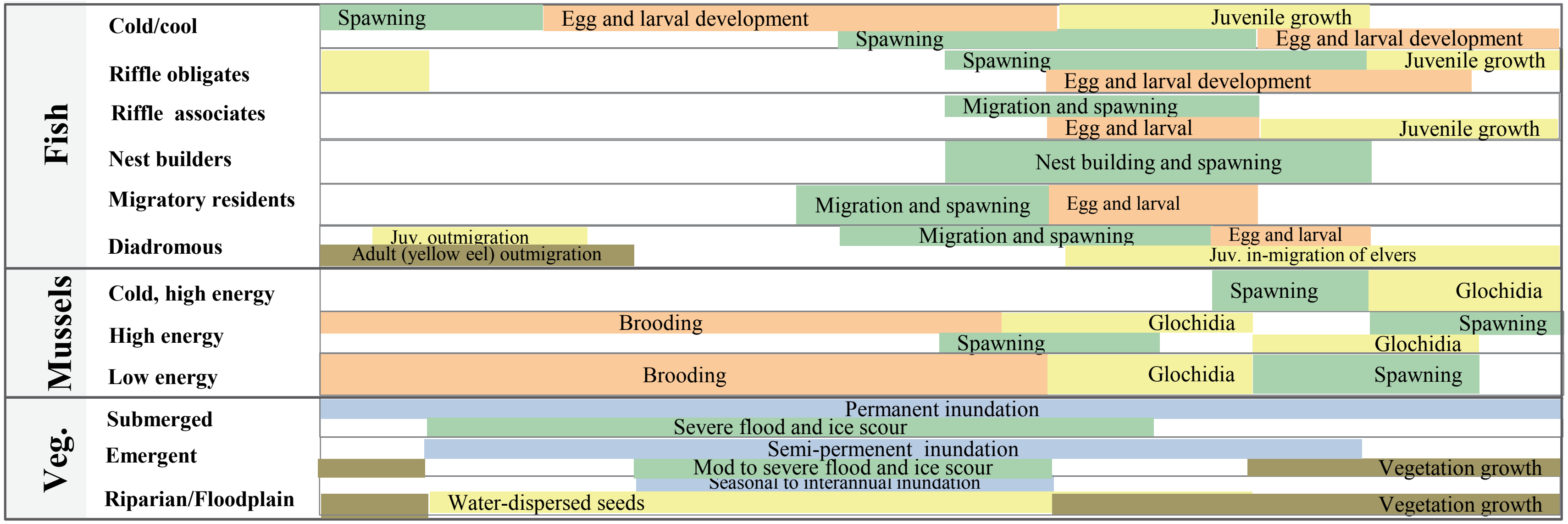


Cool-cold, Small Rivers: Flat Brook near Flatbrookville, NJ (64 sq mi)

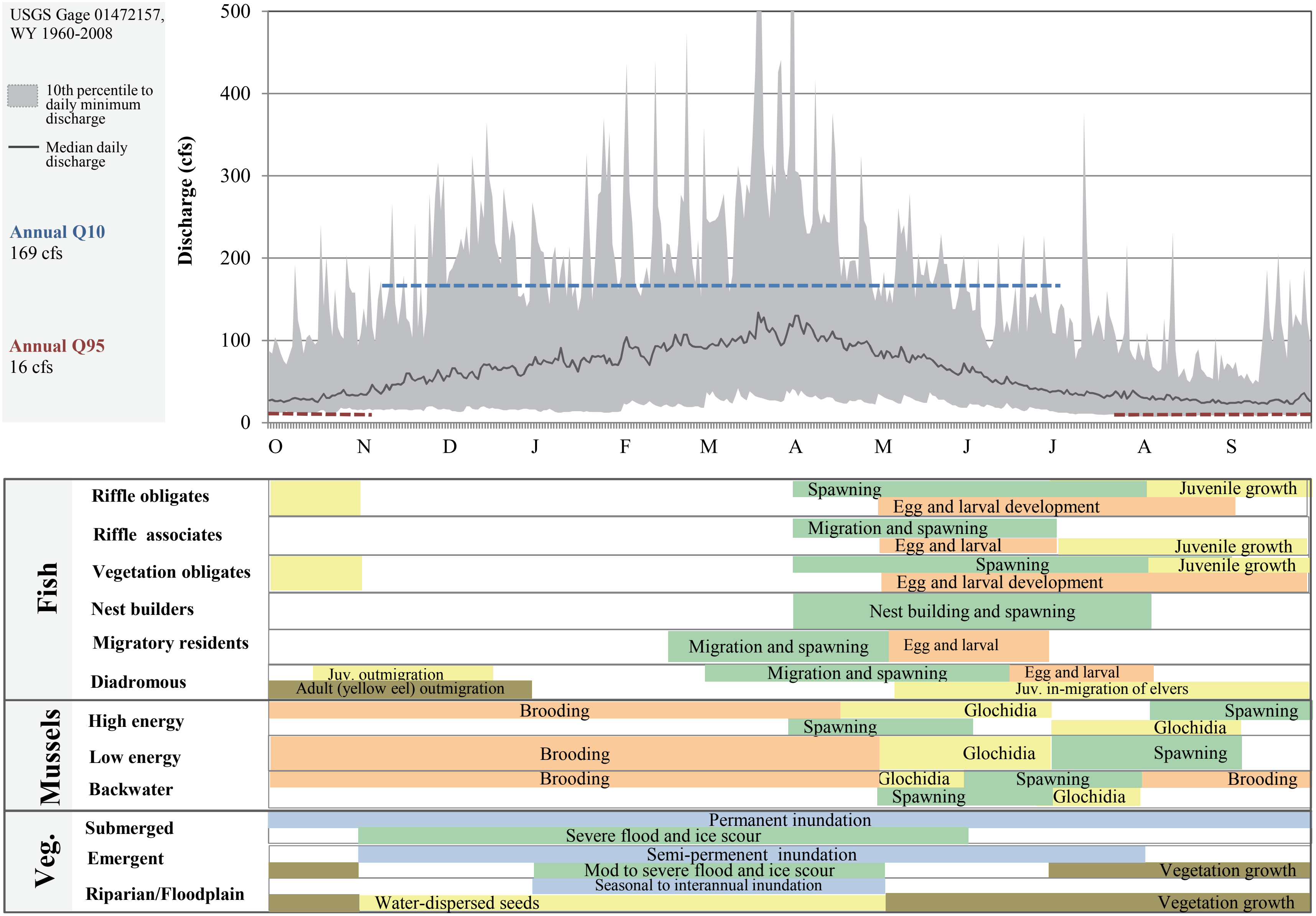


Spring-fed high baseflow, Small Rivers: Aquashicola Creek, PA (77 sq mi)

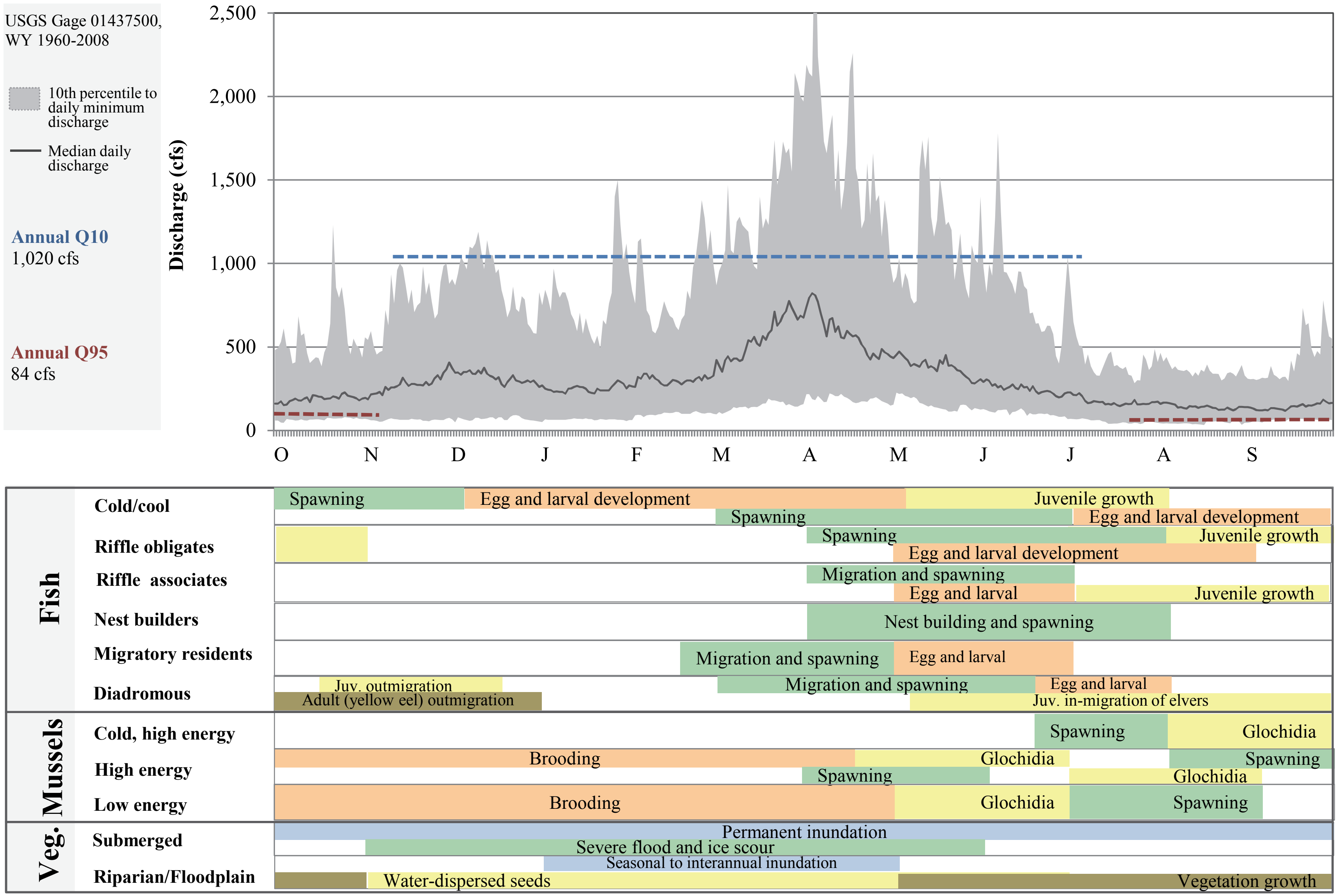




Warm, Small Rivers: French Creek near Phoenixville, PA (59 sq mi)



Cool Medium Tributaries: Neversink River at Godfroy, NY(307 sq mi)



Large/Great Rivers: Delaware River near Delaware Water Gap (3,850 sq mi)

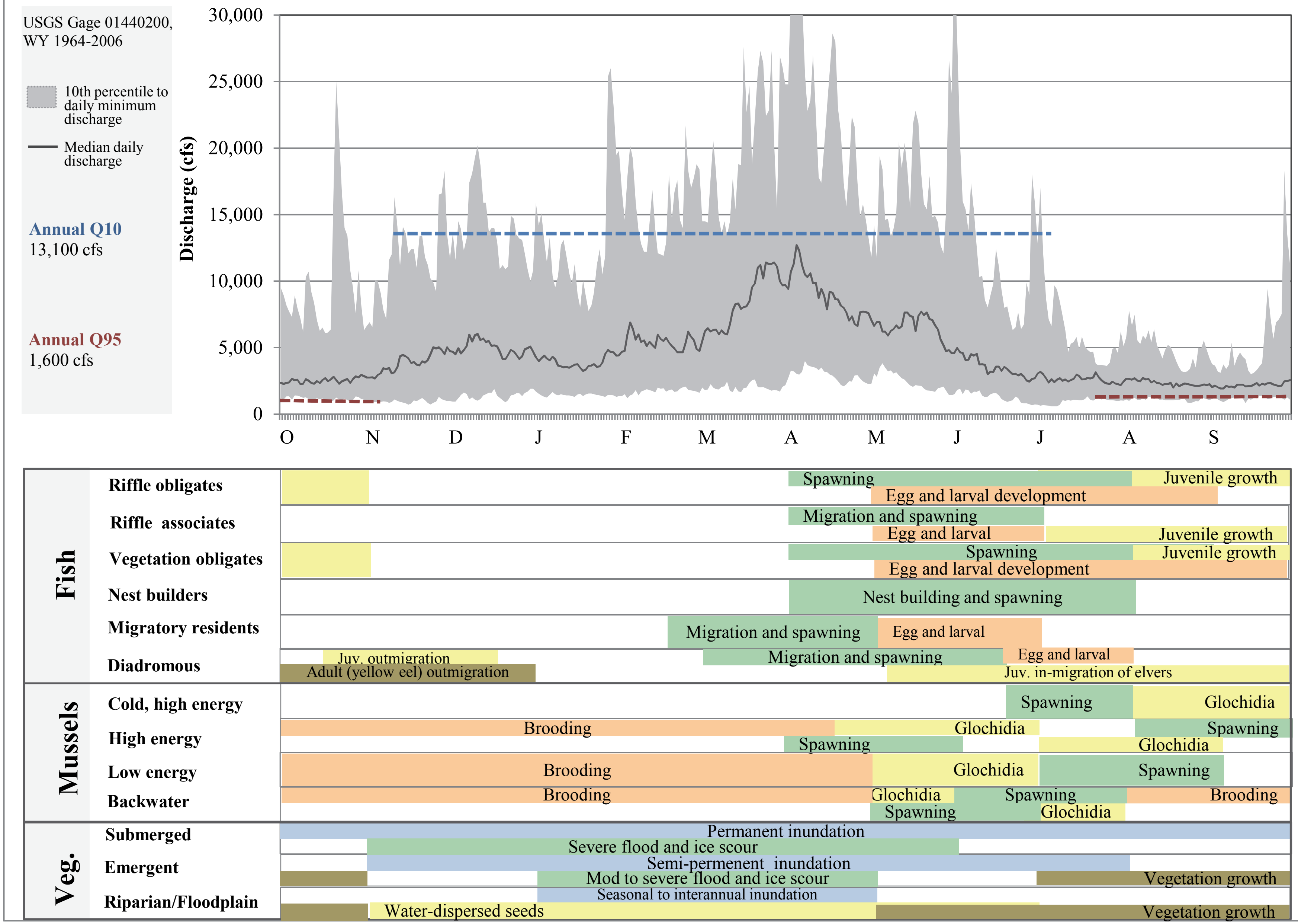


Table 1. Fish groups and associated habitats types for the Delaware River Basin.

Species Groups	Common Name	Scientific Name	Headwaters (< 4 sq mi)	Creeks (4 to 40 sq mi)				Small Rivers (40 to 200 sq mi)				Medium Tributaries (200 to 1000 sq mi)		Large Rivers (> 1,000 sq mi)
				Cool - cold	Wetland-dependent	Spring-fed, high baseflow	Warm	Cool - cold	Wetland-dependent	Spring-fed, high baseflow	Warm	Cool	Warm	Large, Great River
cold/coolwater fish	Mottled sculpin	*Cottus bairdii*		x	x	x		x	x	x		x		
	Slimy sculpin	*Cottus cognatus*		x	x	x		x	x	x		x		
	Brown trout	*Salmo trutta*		x	x	x		x	x	x		x		
	Brook trout	*Salvelinus fontinalis*	x	x	x	x		x	x	x				
	Pearl dace	*Margariscus margarita*	x	x	x	x		x	x	x				
vegetation obligate fish	Bridle shiner	*Notropis bifrenatus*							x		x		x	x
	Ironcolor shiner	*Notropis chalybaeus*							x		x		x	
	Golden shiner	*Notemigonus crysoleucas*									x		x	x
	Eastern mudminnow	*Umbra pygmaea*			x		x		x		x		x	x
	Redfin pickerel	*Esox americanus americanus*			x		x		x		x			
	Blackbanded sunfish	*Enneacanthus chaetodon*					x				x		x	x
	Bluespotted sunfish	*Enneacanthus gloriosus*			x		x		x		x		x	x
riffle obligate fish	Longnose dace	*Rhinichthys cataractae*		x		x		x				x		
	Eastern blacknose dace	*Rhinichthys atratulus*		x		x		x				x		
	Central stoneroller	*Campostoma anomalum*		x	x	x	x	x	x	x	x	x	x	
	Margined madtom	*Noturus insignis*					x				x		x	x
riffle associate fish	White sucker	*Catosomus commersonii*					x				x	x	x	x
	Northern hogsucker	*Hypentelium nigricans*		x		x	x	x		x		x		
nest building fish	River chub	*Nocomis micropogon*						x				x		
	Creek chub	*Semotilus atromaculatus*						x	x	x		x		
	Smallmouth bass	*Micropterus dolomieui*							x	x	x	x	x	x
	Fallfish	*Semotilus corporalis*									x		x	x
	Redbreast sunfish	*Lepomis auritus*					x		x	x	x	x	x	x
	Bluespotted sunfish	*Enneacanthus gloriosus*					x		x		x		x	
migratory resident fish	Walleye	*Sander vitreus*						x	x	x	x	x	x	x
diadromous fish	American shad	*Alosa sapidissima*						x	x	x	x	x	x	x
	Hickory Shad	*Alosa mediocris*						x	x	x	x	x	x	x
	Blueback herring	*Alosa aestivalis*										x	x	x
	Alewife	*Alosa pseudoharengus*										x	x	x
	Striped bass	*Morone saxatilis*										x	x	x
	Shortnose sturgeon	*Acipenser brevirostrum*										x	x	x
	Atlantic sturgeon	*Acipenser oxyrhynchus*										x	x	x
	Sea lamprey	*Petromyzon marinus*						x		x	x	x	x	x
	American eel	*Anguilla rostrata*		x	x	x	x	x	x	x	x	x	x	x

Table 2. Mussel groups, example species and associated habitats types for the Delaware River Basin.

Species Groups	Common Name	Scientific Name	Headwaters (0 to 4 sq mi)	Creeks (4 to 40 sq mi) and Small Rivers (40 to 200 sq mi)				Medium Tributaries		Large Rivers (> 1,000 sq mi)
				Cool - cold	Wetland-dependent	Spring-fed, high baseflow	Warm	Cool	Warm	Large, Great River
Freshwater mussel associated with very high energy, cold, clear, flowing waters	Eastern Pearlshell	*Margaritifera margaritifera*	x	x	x	x		x		x
Freshwater mussels associated with high energy, dynamic substraits, flowing waters	Alewife Floater	*Anodonata implicata*						x	x	x
	Eastern Elliptio	*Elliptio complanata*		x	x	x	x	x	x	x
	Eastern Lampmussel	*Lampsilis radiata*					x	x	x	x
	Yellow Lampmussel	*Lampsilis cariosa*					x	x	x	x
Freshwater mussels associated with moderate to low energy, stable substrate, flowing waters	Brook Floater	*Alasmidonta varicosa*		x	x	x		x		x
	Creeper	*Strophitus undulatus*		x	x	x	x	x	x	x
	Dwarf Wedgemussel	*Alasmidonta heterodon*	x	x	x	x		x		x
	Green Floater	*Lasmigona subviridis*		x	x	x		x	x	
	Triangle Floater	*Alasmidonta undulata*		x	x	x		x		x
Freshwater mussel associated with stagnant, vegetated backwaters	Eastern Floater	*Pyganodon cataracta*					x		x	x

Table 3. Vegetation groups, communities and associated habitats types for the Delaware River Basin.

Species Groups	Dominant Species or Community Types	Dominant species	Headwaters (0 to 4 sq mi)	Creeks (4 to 40 sq mi) and Small Rivers (40 to 200 sq mi)				Medium Tributaries (200 to 1000 sq mi)		Large Rivers (> 1,000 sq mi)
				Cool - cold	Wetland-dependent	Spring-fed, high baseflow	Warm	Cool	Warm	
Submerged Aquatic Vegetation (these are not communities but represent groupings of species occurring in similar riverine habitats)	submerged aquatic vegetation associated with riffles	threadfoot, *Podostemum ceratophyllum*		x	x	x		x		x
	submerged aquatic vegetation associated with runs	illinois pondweed, *Potamogeton illinoisis, c* lasping-leaved pondweed, *P. perfoliatum,* water-crowfoot, *Ranunculus trichophyllus,* water-stargrass, *Heteranthera dubia*						x		x
	submerged aquatic vegetation associated with pools	waterweed, *Elodea nuttallii, Elodea canadensis* , eel-grass, *Vallisneria american*					x	x	x	x
Emergent Vegetation	Spadderdock - Water-lily Emergent Wetland	Dominated by rooted, floating-leaved aquatic species, with both submergent and emergent aquatics including spatterdock, *Nuphar advena/ N. variegata,* water-lily, *Nymphaea oderatoa,* common bladderwort, *Utricularia vulgaris*	x	x		x	x		x	x
	Pickerel-weed – Arrow-arum – Arrowhead Emergent Wetland	Dominated by broad-leaved, aerenchymatous plants including pickerel-weed, *Pontederia cordata* , arrow-arum, *Peltandra virginica* , common bladderwort, *Utriculariamacrohiza,* duckweed, *lemna minor*	x	x		x	x		x	x
Floodplain and Riparian Vegetation	Floodplain Scour Community	Sparse to dense varied vegetation including various warm season grasses, ferns, and herbaceous species with scattered, often battered shrubs and trees. Trees, including sycamore (Platanus occidentalis), silver maple (Acer saccharinum), and river birch (Betula nigra) are often battered and contorted. Forbes include St. John's-Wort, *Hypericum spp., Osmunda regalis* , Joe-Pye weed, *Eutrochium spp* ., etc.. Rare species such as Chamissoi's miners-lettuce, *Montia chamissoi*						x	x	x
Shoreline and Scour Vegetation	Periodically Exposed Shoreline Community	Sparsely to densely vegetated, comprised of weedy, opportunistic natives and exotic plants including water-pepper, *Persicaria punctata,* smartweed, *P. pensylvanicum* , water smartweed, *P. amphibia* , straw-colored nutsedge, *Cyperus strigosus* , blue vervain (Verbena hastata), and other annuals	x	x	x	x	x	x	x	x
	Twisted Sedge Floodplain Margin	Dominated by twisted sedge, *Carex torta* , Joe-Pye-weed, *Eutrochium fistulosum* , pale St. John's-wort, *Hypericum ellipticum*	x	x	x	x	x			
	Water-Willow - Smartweed Riverbed Community	Dominated by water-willow, *Justicia americana,* often in large, monotypic colonies	x	x	x	x	x	x	x	x

Table 3. Vegetation groups, communities and associated habitats types for the Delaware River Basin.

Species Groups	**Dominant Species or Community Types**	**Dominant species**	**Headwaters (0 to 4 sq mi)**	**Creeks (4 to 40 sq mi) and Small Rivers (40 to 200 sq mi)**				**Medium Tributaries (200 to 1000 sq mi)**		**Large Rivers (> 1,000 sq mi)**
				Cool - cold	Wetland-dependent	Spring-fed, high baseflow	Warm	Cool	Warm	
Low Floodplain Vegetation	Alder - Dogwood Floodplain Thicket	Dominated by alders and/or silky dogwood including speckled alder, *Alnus incana ssp. rugosa,* smooth alder, *Alnus serrulata,* black willow, *Salix nigra,* silky dogwood, *Cornus amomum*	x	x	x	x	x			
	Big Bluestem - Indian-grass Floodplain Grassland	Predominantly composed of warm season grasses including big bluestem, *Andropogon gerardii,* switchgrass, *Panicum virgatum,* Indian-grass, *Sorghastrum nutans,* rare species include sand cherry, *prunus pumila*						x	x	x
	Floodplain Meadow	Vegetation is characteristically "meadow-like," composed of a dense herbaceous layer of tall forbs and graminoids. Representative species include goldenrods, *Solidago rugosa, S. canadensis, S. gigantea, Euthamia graminifolia* , wingstem, *Verbesina alternifolia* , jewelweed, *Impatiens capensis* , Joe-Pye-weed, *Eutrochium fistulosum* , spotted Joe-Pye-weed, *E. maculatum,* etc.		x	x	x	x	x	x	
	Hairy-fruited Sedge (Carex trichocarpa) Floodplain Wetland	In some areas there are nearly pure stands of hairy-fruited sedge, in other areas, this type may include a more diverse plant composition. Hairy-fruited sedge, *Carex trichocarpa*						x	x	x
	Japanese Knotweed Floodplain Thicket	Dominated by the invasive species, japanese knotweed, *Fallopia japonica*	x	x	x	x	x	x	x	x
	Mixed Hardwood Floodplain Thicket	Characterized by an open to dense layer of tall shrubs, dominated by sycamore, *Platanus occidentali* , silver maple, *Acer saccharinum* , river birch, *Betula nigra* , black willow, *Salix nigra.*		x	x	x	x	x	x	x
	Reed Canary-grass Floodplain Grassland	Dominated by the invasive species, reed canary-grass , *Phalaris arundinacea*						x	x	x
	Willow-Indian Grass Shrub Wetland	Species composition is mixed and varied, with no one one species consistently dominating. Stunted individuals of black willow, *Salix migra* , other willows, *Salix eriocephata, Salix sericea* , and sycamore, *Platanus occidentalis*	x	x	x	x	x	x	x	x
Mid-Floodplain Vegetation	Bitternut Hickory Floodplain Forest	Canopy dominated or co-dominated by bitternut hickory *Carya cordiformis.* Co-dominants include northern red oak, *Quercus rubra,* butternut, *Juglans cinerea,* black cherry, *Prunus serotina,* American elm, *Ulmus americana,* white ash, *Fraxinus americana,* silver maple, *Acer saccharinum*						x	x	x
	Buttonbush Wetland	Buttonbush, *Cephalanthus occidentalis* is usually the clear dominant.	x	x	x	x	x	x	x	x
	Silver Maple Floodplain Forest	Canopy dominated by silver maple, *Acer saccharinum*		x	x	x	x	x	x	x
	Sycamore Floodplain Forest	Canopy dominated by american syacamore, *Plantanus occidentalis*		x	x	x	x	x	x	x

Table 3. Vegetation groups, communities and associated habitats types for the Delaware River Basin.

Species Groups	**Dominant Species or Community Types**	**Dominant species**	**Headwaters (0 to 4 sq mi)**	**Creeks (4 to 40 sq mi) and Small Rivers (40 to 200 sq mi)**				**Medium Tributaries (200 to 1000 sq mi)**		**Large Rivers (> 1,000 sq mi)**
				Cool - cold	Wetland-dependent	Spring-fed, high baseflow	Warm	Cool	Warm	
High Floodplain Vegetation	Sugar Maple - Mixed Hardwood Floodplain Forest	Dominated by sugar maple, *Acer saccharum.* Other associated canopy species include basswood, *Tilia americana,* white ash, *Fraxinus americana,* green ash, *Fraxinus pennsylvanica,* bitternut hickory, *Carya cordiformis,* American beech, *Fagus grandifolia*		x	x	x	x	x	x	x
	Sycamore - Mixed Hardwood Floodplain Forest	Canopy clearly dominated by sycamore, *Platanus occidentalis,* in the forest canopy, but usually has significant cover of one or more other hardwood species, usually river birch *betula nigra*		x	x	x	x	x	x	X
Backchannel Vegetation	Green Ash - Mixed Hardwood Floodplain Forest	Canopy dominated by green ash, *Fraxinus pennsylvanica* and co-dominated by black walnut, *Juglans nigra,* sycamore, *Platanus occidentalis*		x	x	x	x	x	x	x
	Red Maple - Elm - Willow Floodplain Forest	Canopy dominated by red maple, *Acer rubrum,* with green ash *Fraxinus pennsylvanica* , American elm, *Ulmus americana* , willows, *Salix spp* . as co-dominants.						x	x	x
Palustrine Forest and Wetland Vegetation	Circumneutral Mixed Shrub Swamp	Shrub layer may be dominated by a single species or consists of a mix of shrub species that may form clonal patches within the community including smooth and speckled alder, *Alnus serrulata, A. incana ssp. rugosa*), ninebark, *Physocarpus opulifolius* , willows, *Salix spp.*), etc.	x	x	x	x	x			
	Hemlock - Mixed Hardwood Palustrine Forest	Co-dominance of Eastern hemlock, *Tsuga canadensis,* in the canopy with eastern white pine, *Pinus strobus* , red spruce, *Picea rubens* , yellow birch, *Betula alleghaniensis,* red maple, *Acer rubrum* , black ash, *Fraxinus nigra* , black-gum, *Nyssa sylvatica,* gray birch, *Betula populifolia*	x	x	x	x	x	x	x	
	Highbush Blueberry - Meadow-sweet Wetland	Highbush blueberry , *Vacinium corymbosum,* meadow-sweet, *Spiraea latifolia* or *Spirea alba* are usually both present and dominant in the shrub layer	x	x	x	x	x			
	Oak - Mixed Hardwood Palustrine Forest	Canopy dominated by pin oak, *Quercus palustris,* swamp white oak, *Quercus bicolor*		x	x	x	x			
	Red Spruce - Mixed Hardwood Palustrine Forest	Dominated by red spruce, *Picea rubens, Eastern hemlock, Tsuga canadensis,* eastern white pine, *Pinus strobus,* tamarack, *Larix laricina,* yellow birch, *betula alleghaniensis, red maple, Acer rubrum, black ash, Fraxinus nigra, black-gum, Nyssa sylvatica*	x	x	x	x	x	x	x	

Table 1. Working Hypotheses developed for fishes in Delaware River basin habitats

🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Flow Component and Timing												River Types
		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	
	Support resident fish spawning													
1	During the spring and summer, increase in frequency or magnitude of high flows may **flush nest builders** from guarding nests, scour eggs or destroy nests, resulting in reduced recruitment							🟦	🟦	🟦	🟦	🟦		All types where present
2	During winter and early spring, a reduction in high flow frequency or magnitude may reduce availability of **suitable spawning and nest building substrate** for riffle associates, riffle obligates, and nest building fishes.				🟦	🟦	🟦	🟦						All types where present
3	During spring, a reduction in flow magnitude may shift seasonality of the hydrograph, reducing reproductive success of spring spawning fishes by **limiting habitat conditions for successful egg and larval development** (riffle obligates, riffle associates, migratory, vegetation obligates, diadromous).							🟧	🟧	🟧	🟧			All types where present
4	During spring, a reduction in low flow magnitude may **reduce persistent riffle spawning habitats** for riffle obligates and associates, resulting in reduced reproductive success.							🟥	🟥	🟥	🟥			All types where present
5	During spring and summer, after spawning, nest building fishes need relatively stable flows during the incubation and swim up period. An increase in flashiness may **expose or scour developing eggs**.							🟪	🟪	🟪	🟪	🟪		All types where present
	Cue spawning migration and maintain access to spawning habitat													
6	During spring, a reduction in seasonal to high flow magnitude and duration may reduce **extent of upstream migration by shortnose sturgeon** and restrict access to suitable gravel spawning beds (upstream from Trenton)							🟦 🟧	🟦 🟧					Large River
7	During the spring, a change in the timing or magnitude of seasonal to high flows may result in **loss of spawning cue synchrony (temperature, flow, light availability) for diadromous and migratory fishes** and reduction in spawning success including the extent of spawning runs.							🟧	🟧	🟧				All types where present
8	During the spring, a change in the timing or magnitude of seasonal to high flows may result in **delayed migration** of diadromous and migratory fishes **increasing bioenergetic costs** and reducing spawning success.							🟧	🟧	🟧	🟧			All types where present
9	From March through June, a decrease in the magnitude of seasonal or high flows may **reduce tributary access for migrating fish** (diadromous, migratory residents, riffle associates)							🟧	🟧	🟧	🟧			All types where present
10	From April through June, a decrease in low flow magnitude or duration, may **reduce reproductive success of riffle associates (endemics -white sucker)** adapted to spring spawning conditions.							🟥	🟥	🟥	🟥			All types where present
11	From March through June, diadromous fish use the decending limb as triggers for movement, and increase in the rate of recession **may limit the extent of upstream spawning migration**							🟪	🟪	🟪				All types where present

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	Working Hypotheses	Flow Component and Timing												River Types
		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	
	Maintain access to and quality of shallow-slow margin and backwater spawning and nursery habitats													
12	From May through June, a reduction in seasonal flow magnitude and duration may **reduce access to backwater and sidechannel spawning habitats.** These are particularly critical for **vegetation obligates** (bluespotted sunfish and mudminnow).							🟧	🟧	🟧	🟧			All types where present
13	From late spring through early fall, juvenile American shad need access to refugia provided by SAV beds. A reduction in low flow magnitude may **reduce extent and depth of SAV bed refugia, increasing predation of juvenile fishes** (American shad).	🟥						🟥	🟥	🟥	🟥	🟥	🟥	All types where present
14	From late spring through early fall, an increase in flashiness may **reduce persistence of and access to shallow-slow habitat** for juvenile fishes and vegetation obligates	🟪						🟪	🟪	🟪	🟪	🟪	🟪	All River types
	Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes													
15	During late spring, early summer, if the timing of baseflows decreases (earlier Julian date), may exacerbate chronic conditions in the late summer and result in a **fish** community **shift toward one that is more tolerant**								🟧	🟧	🟧	🟧		All river types
16	During summer and fall, because of their **limited mobility and narrow velcocity niche breadth, small-bodied fishes** (riffle obligates and juveniles) would be most susceptible to hydraulic changes to seasonal flow conditions	🟧	🟧								🟧	🟧	🟧	All types where present
17	During summer, **a decrease in groundwater contribution** may contract range of suitable habitat and increase degree of overlap between cold and cool species, **increasing competition and predation**.	🟥									🟥	🟥	🟥	Headwaters, Cold-cool creeks and small rivers, High Baseflow creeks and small rivers
18	During summer, a decrease in magnitude and duration of low flows may **increase temperature outside of thermal ranges for cool/cold fishes (sculpin and salmonids)**, leading to stress, reduced body mass and possibly mortality (sublethal and lethal effects)	🟥									🟥	🟥	🟥	Headwaters, Cold-cool creeks and High Baseflow Creeks and Small rivers
19	In summer, if flows are lower, temperature is warmer and can increase growth /productivity of vegetation and may **increase food availability for warm tolerant fishes like suckers.**										🟥	🟥	🟥	All river types
20	During summer and early fall, in headwater and cold-cool streams, a reduction in low flow magnitude may **increase temperature, reducing quality of habitat for female eels** and potentially favoring male differentiation (skew sex ratios).	🟥									🟥	🟥	🟥	Headwaters, Cold-cool, High base flow Creeks and Small rivers
21	During summer and early fall, a reduction in low flow magnitude may **limit longitudnal connectivity and access to thermal refugia** (tributaries, groundwater seeps).	🟥	🟥								🟥	🟥	🟥	All river types

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	Working Hypotheses	Flow Component and Timing												River Types
		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	
22	During Summer and early fall, a reduction in low flow magnitude will increase temperature and decrease **dissolved oxygen**, leading to a loss of suitable habitat for **fish eggs and larvae** (all groups)	🟥	🟥								🟥	🟥	🟥	All river types
23	During summer and fall, under low flow conditions, below reservoirs, maintenance of low flows can **lower temperatures impeding the growth and development of warm water fishes.**	🟥	🟥										🟥	All types where present
24	During summer and fall, a decrease in flow magnitude **may reduce access to and abundance of shallow slow margin and backwater habitats**, reducing abundance of associated fishes (**vegetation obligates**) (increased predation).	🟥	🟥								🟥	🟥	🟥	All types where present
25	In summer, a reduction in low flow magntidued may **reduce available cover** and extent of habitat (e.g. concentrating fish in shrinking pools) and **increase predation and competition.**	🟥									🟥	🟥	🟥	All river types
26	In summer if low flows decrease, it **may increase the amount of riffle habitat** which could be good for riffle species like longnose dace (in settings with developed channel features, where runs and glides turn to riffles).	🟥	🟥									🟥	🟥	Small streams, Medium tributaries and Large river
27	During summer and fall, a decrease in flow magnitude may expose stream margins **, reducing shallow-slow habitat for juvenile fishes**	🟥	🟥									🟥	🟥	All river types
28	During summer and fall, an increase in daily streamflow fluctuations may lead to **stranding for juvenile and small fishes** using stream margin habitat.	🟪	🟪	🟪								🟪	🟪	All river types
29	Anytime of year, loss of the natural variability of flow can **shift composition to favor generalist species (green sunfish)**	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All river types
30	Anytime of year, loss of the natural variability of flow can **shift composition to favor generalist species (green sunfish)**	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	All river types
	Cue outmigration of diadromous fishes													
31	During fall and early winter, a loss of high flow events could impede **out migration of American eels.**	🟦	🟦	🟦	🟦									All types where present
	Maintain fall salmonid spawning habitat and promote egg, larval, and juvenile development (brook and brown trout)													
32	During spawning, an increase in high flow frequency or magnitude may **inhibit spawning, or scour eggs**.	🟦	🟦	🟦										All types where present
33	During spawning and egg development, prolonged low flow events can **reduce quality of, access to or expose spawning redds** and decrease reproductive success.	🟥	🟥	🟥										All types where present

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	Working Hypotheses	Flow Component and Timing												River Types
		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	
	Maintain overwinter habitats for resident fish													
33	During fall and winter, and increase in the frequency or magnitude of high flows may result in scour and failure of **trout redds** (post spawning), decreased reproductive success.	🟦	🟦	🟦	🟦	🟦	🟦							All types where present
34	During winter, fish have low energy reserves, an increase in high flow frequency, magnitude or rate of change, may require **significant movement to flow refugia, increasing bioenergetic costs.**				🟦 🟪	🟦 🟪	🟦 🟪							All river types
35	From late summer through winter, a decrease in low flows may reduce habitat conditions and food availability, **reducing gonadal production and reproductive fitness.**	🟥	🟥	🟥	🟥	🟥	🟥					🟥	🟥	All river types
36	During winter, a decrease in in groundwater contribution may decrease water temperature and **increase bioenergetic cost for cool/cold fishes.**				🟥	🟥	🟥							All types where present
37	During winter, a decrease in low flow magnitude may decrease groundwater contribution and **survival of brook trout eggs/larvae.**				🟥	🟥	🟥							All types where present
38	During winter, a reduction in low flow magnitude may **reduce vegetated thermal refugia (in roots system) for vegetative/cover obligates** (specifically bridle and ironcolor shiner) which are intolerant of cold temperatures				🟥	🟥	🟥							All types where present
39	During winter, a reduction in low flow magnitude may lead to reduced temperature and **decreased survival of YOY migratory fish (e.g. striped bass)**				🟥	🟥	🟥							Large river
40	During winter, a reduction in low flow magnitude may **increase concentrations of salts, impacting osmoregulation** and known to have sub-lethal and lethal impacts to fishes (American eel dosing studies).				🟥	🟥	🟥							

Table 2. Working Hypotheses developed for aquatic insects in Delaware River basin habitats

🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	River Types
	Support spring emergence for aquatic insects and maintain habitats for mating and egg laying													
1	During spring and early summer, if high flow frequency or magnitude increases, associated increased velocity may **scour aquatic insects from benthic habitats prior to emergence**.							🟦	🟦	🟦	🟦			All river types
2	During spring, a reduction of seasonal flows may cause **gravel substrates to be armored with fines, reducing the quality of benthic habitat** and abundance of sensitive (EPT) aquatic insects.							🟧	🟧	🟧				All river types
3	During spring and early summer, a shift in the onset of baseflow conditions (timing and magnitude) may result in exacerbated chronic conditions characteristic of late summer (depressed flows and higher temperatures), resulting in a **shift to a macroinvertebrate community that is more tolerant.**							🟧	🟧	🟧	🟧	🟧		All river types
	Promote macroinvertebrate diversity, growth and emergence													
4	During summer low flow period, decreased low flows can result in network contraction (toward downstream) and **compression of species and thermal gradients**.	🟥									🟥	🟥	🟥	Headwaters, Creeks and Small streams
5	During summer, a reduction in low flow magnitude and duration may reduce riffle habitats, eventually leading to **decreased abundance of erosional taxa (riffle -adapted)** and increase in depositional taxa (pool - adapted).										🟥	🟥	🟥	All river types
6	During summer and fall, a reduction in groundwater contribution may increase temperatures, resulting in a **community shift from cold-cool (stenothermal, stoneflies) specialists** to thermal generalists (eurythermal).	🟥	🟥	🟥							🟥	🟥	🟥	Headwaters, All Creeks and Small streams (except Warm)
7	During the summer and fall, a decrease in low flow magnitude may decrease extent and persistence of riffle habitats, **decreasing the abundance of macroinvertebrates with low mobility** (fixed case caddisflies).	🟥	🟥	🟥							🟥	🟥	🟥	All river types
8	During the summer low flow period, a decrease in low flow magnitude may reduce available refugia resulting in a **community transition toward one that is predator-dominated.**	🟥									🟥	🟥	🟥	All headwater and small stream types
9	Anytime of year, increased occurrence of intermittent conditions (decrease in extreme low flow magnitude) may shift assemblage, **reducing abundance of long-lived species (Odonates)** and increasing short-lived species.	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	Headwaters and creeks most sensitive

Table 2. Working Hypotheses developed for aquatic insects in Delaware River basin habitats

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	Working Hypotheses	Flow Component and Timing												River Types
		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	
10	Anytime of year, an increase in flashiness may **reduce abundance (survival) of macroinvertebrates with > 1 year aquatic larval stage** and may also **reduce abundance of sensitive taxa (preferring erosional habitats)**	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	All river types
11	From summer through winter, a decrease in extreme low flow magnitude or duration (intermittency) may **cue exit of shredders from headwater systems**, resulting in a reduction of energy transformation and downstream export (CPOM to FPOM).	🟥	🟥	🟥	🟥	🟥	🟥					🟥	🟥	Headwaters and Creeks
12	During fall and winter, an increase in the magnitude or frequency of high flows may **flush CPOM or shredders before energy conversion** occurs, reducing the downstream contribution of FPOM.	🟦	🟦	🟦	🟦	🟦	🟦							Headwaters and Creeks
	Support winter emergence and maintain overwinter habitat for macroinvertebrates													
13	During winter, a decrease in the magnitude of low flows may **alter emergence cues and reduce egg laying habitats** for winter emerging insects (winter stoneflies).				🟥	🟥	🟥							All river types except Large river
14	During winter, a decrease in the magnitude of low flows may i**ncrease concentration of pollutants, particularly road salts** which may have sublethal or lethal impacts to macroinvertebrates.				🟥	🟥	🟥							All River types, Headwaters and Creeks most senstive
15	During the winter, under low flow conditions, hypolimnetic reservoir releases may increase temperatures, reducing surface ice (thermal buffer) and **increasing anchor ice, reducing abundance of macroinvertebrates**				🟥	🟥	🟥							Cool medium tributaries and Large river

Table 3. Working Hypotheses developed for mussels in Delaware River basin habitats

🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Flow Component and Timing												River Types
		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	
	Support mussel spawning, glochidia transfer, juvenile colonization and growth													
1	During spawning and glochidia transfer, an increase in high flows may **decouple mussels from host-fish (turbidity or increased velocities) or reduce spawning efficiency**. Species with intricate lures or those requiring direct contact for transfer of glochidia, would be especially sensitive.	🟦							🟦	🟦	🟦	🟦	🟦	All types where present
2	During spring, a decrease in high flow magnitude may result **loss or dampened migration cue for diadromous host-fish**, reducing potential for interaction with gravid mussels (*Anodonata implicata*).								🟦	🟦				All types where present
3	During spring, a decrease in low flow magnitude or an increase in low flow duration may restrict suitable hydraulic habitat across the channel, **limiting interaction between diadromous host-fish and mussels** (*Anodonata implicata*).							🟥	🟥	🟥				All types where present
4	During spawning and glochidia transfer, decrease in low flow magnitude may **restrict depth over mussel beds for host-fish access**. Species with intricate lures and requiring direct contact for transfer of glochidia, would be especially sensitive.	🟥							🟥	🟥	🟥	🟥	🟥	All types where present
5	During summer, a decrease in low flows may **concentrate fish in pools and increase potential for interaction with mussels** that are found in pools.	🟥	🟥									🟥	🟥	All types where present
6	During summer and early fall, a decrease in low flow magnitude may **increase water temperature and sublethal stress for thermally sensitive mussels** (*Margaritifera margaritifera*).	🟥	🟥									🟥	🟥	All types where present
7	During summer, a decrease in low flow magnitude may **decrease dissolved oxygen and increase ammonia concentrations outside of mussel tolerance**. Juvenile mussels may be more sensitive to this increase than adults.	🟥	🟥									🟥	🟥	All types where present
8	During late summer and early fall, brooding mussels are susceptible to low flows, a decrease in flow magnitude can decrease dissolved oxygen, **increase stress and result in glochidial abortion**.	🟥	🟥									🟥	🟥	All river types
9	During later summer and early fall, a decrease in low flows may **expose mussels in stream margin habitats.**	🟥	🟥									🟥	🟥	All types where present
10	Any time of year, especially summer and early fall, a decrease in low flow magnitude **may increase algal production** and shift DO concentrations outside of the range of mussel tolerance, leading to reduced growth or mortality. Backchannels and settings ith high surface water exposure would be particularly susceptible.	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	All types where present

Table 3. Working Hypotheses developed for mussels in Delaware River basin habitats

🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Flow Component and Timing												River Types
		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	
11	Anytime of year, while some species have the ability to slowly migrate on the surface (*Strophitus undulatus* and *Alasmodanta varicosa*), **a high rate of decrease to a low flow condition may strand mussels**, particularly in margin and riffle habitats.	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	All types where present
	Maintain overwinter thermal regime and habitat for mussels													
12	During late fall and winter, a decrease in low flow magnitude and duration may reduce water depth and temperature at a time when mussels have limited ability to move to refugia, resulting in **physical stress and potential freezing**. This would apply to all mussel groups with *Alasmidonta heterodon* being most sensitive.			🟥	🟥	🟥	🟥							All types where present
13	Anytime of year, especially winter and early spring, an increase in flood frequency or magnitude may **bury or physically scour (particularly thin-shelled) freshwater mussels**. **Loss of long-term brooders from fall to spring (while gravid) would also result in a missing year class.**	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All types where present

Table 4. Working Hypotheses developed for aquatic, riparian and floodplain vegetation in Delaware River basin habitats

🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Flow Component and Timing												River Types
		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	
	Support establishment and growth of floodplain, riparian and aquatic vegetation													
1	During the growing season, if high flow magnitude, duration or frequency are reduced, **water availability (indundation days and soil saturation) may be reduced, causing a shift in riparian community assemblage**.	🟦						🟦	🟦	🟦	🟦	🟦	🟦	All types where present
2	During the growing season, if high flow magnitude, duration or frequency are increased, **scour and /or inundation may retard growth of herbaceous and woody vegetation** and may encourage establishment of invasive species.	🟦						🟦	🟦	🟦	🟦	🟦	🟦	All types where present
3	During fall and winter, an increase in the frequency and magnitude of high flows may **scour SAV and emergent seed beds (at a time when roots are dormant)** resulting in a local loss of seedbank (may redistribute elsewhere).			🟦	🟦	🟦	🟦							All types where present
4	During late winter and early spring, a reduction of high flow magnitude, and duration will **reduce extent of water-dispersed seeds and scour and preparation of seed beds reducing availability and moisture of bare mineral soil.**				🟦	🟦	🟦	🟦						All types where present
5	During winter, a reduction in high flow magnitude may **reduce ice scour and maintence of shoreline scour communities**				🟦	🟦	🟦							All types where present
6	Year-round, a decrease of high flow frequency and duration may reduce intermediate disturbances necessary to **prevent terrestrialization of floodplain and riparian habitats.**	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All types where present
7	During late spring, early summer, if the timing of baseflows decreases (earlier Julian date), may exacerbate chronic conditions in the late summer and result in **reduced abundance and extent of submerged and emergent aquatic vegetation**, particularly *Justicia americana* and *Podostemum.*								🟧	🟧	🟧			All types where present
8	Some of the vegetation dynamics may not happen as often in high baseflow streams as in other stream types. High baseflow streams often have very narrow zones for vegetation. There may be species adapted to this flow regime and water chemistry (limestone).	🟧	🟧								🟧	🟧	🟧	High baseflow Creeks and Small streams
9	During the growing season, if low flow magnitude is decreased, groundwater storage may decrease, **lowering the water table and resulting in stress to riparian plant and forest communities.**	🟥						🟥	🟥	🟥	🟥	🟥	🟥	Headwaters, Creeks, Small Streams

Table 4. Working Hypotheses developed for aquatic, riparian and floodplain vegetation in Delaware River basin habitats

🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Flow Component and Timing												River Types
		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	
10	During the growing season, if low flow magnitude is decreased, **habitat conditions supportive of native plants will decrease** and invasive species (e.g. knotweed and Didymo) abundance and composition will increase.	🟥						🟥	🟥	🟥	🟥	🟥	🟥	All types where present
11	During the summer and fall, a decrease in low flow magnitude and increase in duration may **increase exposure of SAV beds (ie Podostemum) and lead to reduced bed extent and individual condition (loss of leaves, exposed root bases)**.	🟥	🟥								🟥	🟥	🟥	Creeks, Small rivers, Medium tributaries, Large river
12	During summer and fall, increased duration of low flows may reduce water availability in the margins, leading to a **decrease in extent and condition of** the **shoreline scour vegetation** community	🟥	🟥								🟥	🟥	🟥	All types where present
13	During summer and fall, increased duration of low flows may increase water temperatures and lead to **increased emergent, submerged and algal growth.**	🟥	🟥								🟥	🟥	🟥	Warm medium tributaries and Large River
14	During summer and fall, under low flow conditions, below reservoirs, maintenance of low flows can lower summer water temperatures **impeding the growth and development of submerged and emergent aquatic vegetation**	🟥	🟥								🟥	🟥	🟥	Cool medium tributaries
15	Prolonged or repeated low flows in fall and winter might **freeze aquatic tubers (e.g., spadderdock) and increase mortality.**		🟥	🟥	🟥	🟥	🟥							All types where present

Table 5. Working Hypotheses developed for reptiles, amphibians, birds and mammals in Delaware River basin habitats

🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	River Types
	Promote/support development and growth of reptiles and amphibians													
1	During summer and early fall, a decrease in groundwater contribution may **increase stream temperatures, resulting in stress (respiration and thermoregulation) of streamside salamanders**.	🟥	🟥	🟥							🟥	🟥	🟥	All types where present, Headwaters most sensitive
2	October through April, many species hibernate in stream beds and banks. A decrease in low flow magnitude may **decrease water temperatures or dewater hibernacula increasing risk of mortality.**	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥					All types where present, Headwaters most sensitive
3	Any time of year (predominantly late summer/early fall), a shift or increase frequency of intermittent periods would **reduce successful reproduction and growth (food availability) for amphibians and reptiles in headwater settings.**	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	Headwaters
4	Anytime of year, in the active channel of the uppermost reaches , if flows are too high, **streamside salamander larvae could be scoured**. Species with > 1 year larval development stage would be particularly sensitive.	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All types where present
5	Anytime of year, in the active channel of the uppermost reaches, if flashiness increases, **streamside salamander larvae could be scoured**. Species with a > 1 year larval development stage would be particularly sensitive.	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	All types where present
	Provide abundant food sources and maintain feeding and nesting habitat for birds and mammals													
6	An increase in the frequency or magnitude of high flow events may **destabilize beaver dens** (and dens of other semi-aquatic mammals). This species is common in high baseflow and tannic streams				🟦	🟦	🟦	🟦	🟦	🟦				All types where present
7	A decrease in seasonal flows during the late winter and spring may **limit availability of early vegetation (blueberries, sphagnum headwater seep community) and open water used by terrestrial fauna** (bears).						🟧	🟧	🟧	🟧				Headwaters, Creeks and small streams

Table 6. Working Hypotheses developed for water quality and geomorphology and unique habitats in Delaware River basin

🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Flow Component and Timing												River Types
		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	
	Maintain valley and island formation, channel morphology and sediment distribution													
1	Anytime of year, a reduced frequency, duration or magnitude of large floods (> 20 year) may **reduce floodplain and valley inundation and island formation.**	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All river types
2	An increase in the frequency of bankfull flows (1 in 2 year) may **increase scour, change dominant substrate type and result in altered channel shape and capacity.**	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All river types
3	Loss of variability and loss of channel maintenance flows can create more of a fixed niche, **reducing diversity of habitat and species** (Intermediate disturbance hypothesis).	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All river types
		🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	
4	From winter through spring, a decrease in high flows may reduce **maintenance of spawning substrates** for nest building and riffle spawning fishes.				🟦	🟦	🟦	🟦	🟦	🟦				All river types
5	High flows in winter can **destabilize stream banks** (saturation, freezing, and collapse), resulting in **increased erosion and sediment loads**.				🟦	🟦	🟦							All river types
6	Anytime of year (mostly winter and spring), reduced frequency of high flow events could **alter substrate distribution and composition**.	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All river types
7	Anytime of year (mostly winter and spring), reduced frequency of high flow events could decrease the **recruitment of large woody debris.**	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	All river types
	Maintain temperature and water quality													
8	Anytime of year, a loss of headwater contribution to downstream habitats decreases habitat suitability by increasing temperatures and decreasing wetted habitat—cumulative contribution	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	Headwaters and Creeks
9	During the late summer and early fall, a reduction of high flow pulses may result in **increased temperatures, algal growth and a drop in DO**	🟦	🟦									🟦	🟦	All river types
10	Decreased baseflow in summer and fall impacts temperature, quality and availability of habitat along stream margins, loss of thermal buffering capacity, especially where the channel is exposed (no canopy closure).	🟥	🟥	🟥								🟥	🟥	All river types
11	During winter, a decrease in groundwater contribution may **decrease instream temperatures and decrease temperature of downstream creeks**.				🟥	🟥	🟥							Headwaters and Creeks
12	During summer, a decrease in groundwater contribution may **increase instream temperatures and increase temperature of downstream creeks**.	🟥										🟥	🟥	Headwaters and Creeks

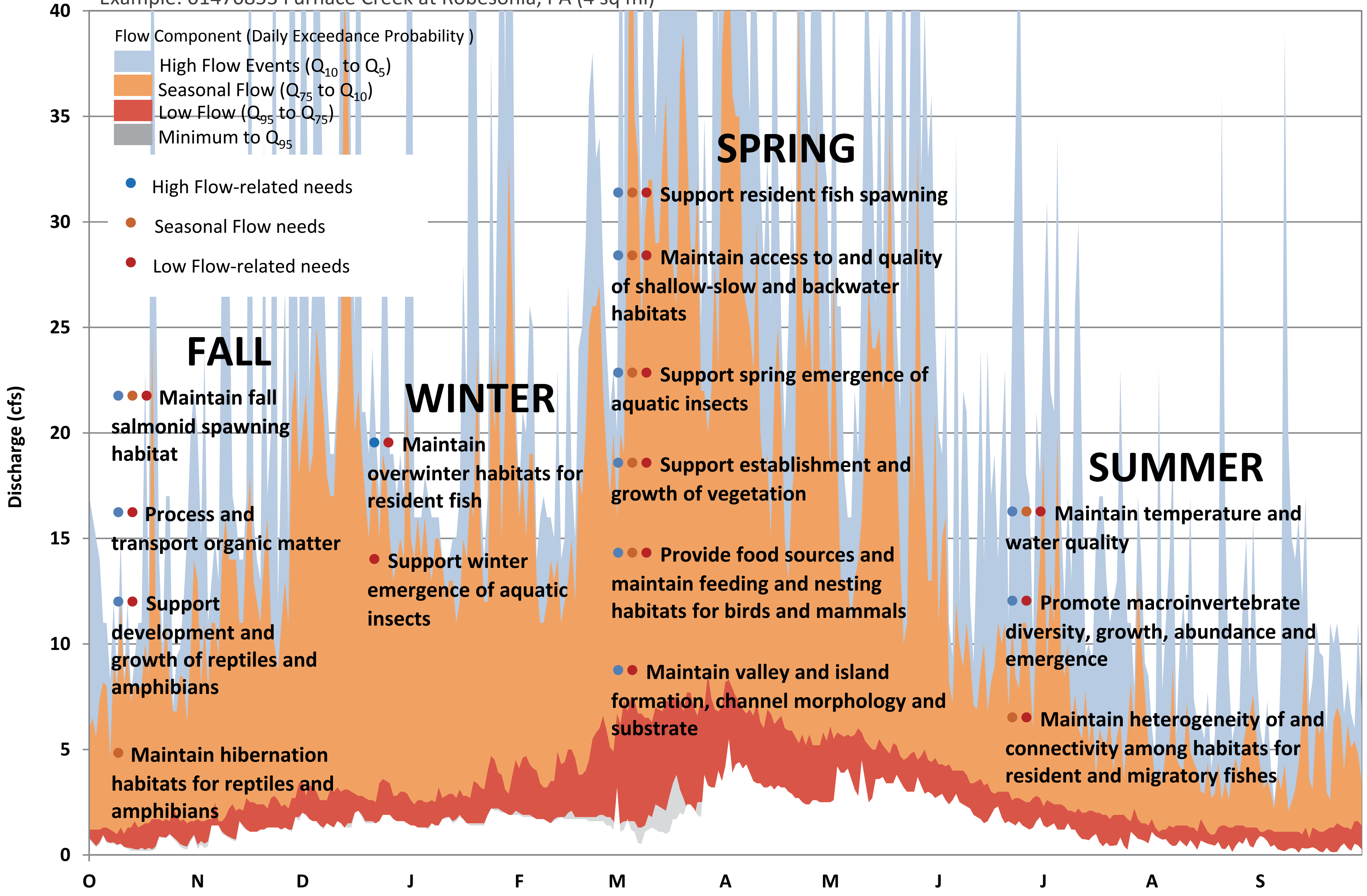
Table 6. Working Hypotheses developed for water quality and geomorphology and unique habitats in Delaware River basin

🟥 Low flow component
🟧 Seasonal flow component
🟦 High flow component
🟪 Rate of change

	Working Hypotheses	Flow Component and Timing												River Types
		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	
	Transport organic matter and fine sediment													
13	An increase in the frequency of high flow events may flushing LWD and leaf packs				🟦	🟦	🟦	🟦	🟦	🟦				Headwaters and Creeks
14	During fall and winter, an increase in the magnitude or frequency of high flow events **may flush CPOM resources before they can be processed (shredders)**, decreasing downstream allochthonous inputs.		🟦	🟦	🟦	🟦	🟦							All river types
15	During the late summer and early fall, a **reduction of high flow pulses may result in accumulation of fine sediment**	🟦	🟦	🟦								🟦	🟦	All river types
16	From fall through spring, low flows that reduce riffle habitat ultimately affect leaf breakdown and other processes (some discussion of how important riffles are for lots of processes).		🟥	🟥	🟥	🟥	🟥							Headwaters, Creeks and Small streams
	Maintain ice scour events and floodplain connectivity													
17	During winter, decreased magnitude and increased duration of low flow magnitude may lead to **development of anchor ice**.				🟥	🟥	🟥							All river types
18	In fall and winter, decreased high flows could **decrease ice scour**. The function may be replaced by high flows and floods – in other words, the disturbance still happens but it is the ice scour and not the flood that causes the disturbance.				🟦	🟦	🟦							All river types

Flow Components and Needs: Headwater

Example: 01470853 Furnace Creek at Robesonia, PA (4 sq mi)



FALL

●●● Maintain fall salmonid spawning habitat

●● Process and transport organic matter

●● Support development and growth of reptiles and amphibians

● Maintain hibernation habitats for reptiles and amphibians

WINTER

●● Maintain overwinter habitats for resident fish

● Support winter emergence of aquatic insects

SPRING

●●● Support resident fish spawning

●●● Maintain access to and quality of shallow-slow and backwater habitats

●●● Support spring emergence of aquatic insects

●●● Support establishment and growth of vegetation

●●● Provide food sources and maintain feeding and nesting habitats for birds and mammals

●● Maintain valley and island formation, channel morphology and substrate

SUMMER

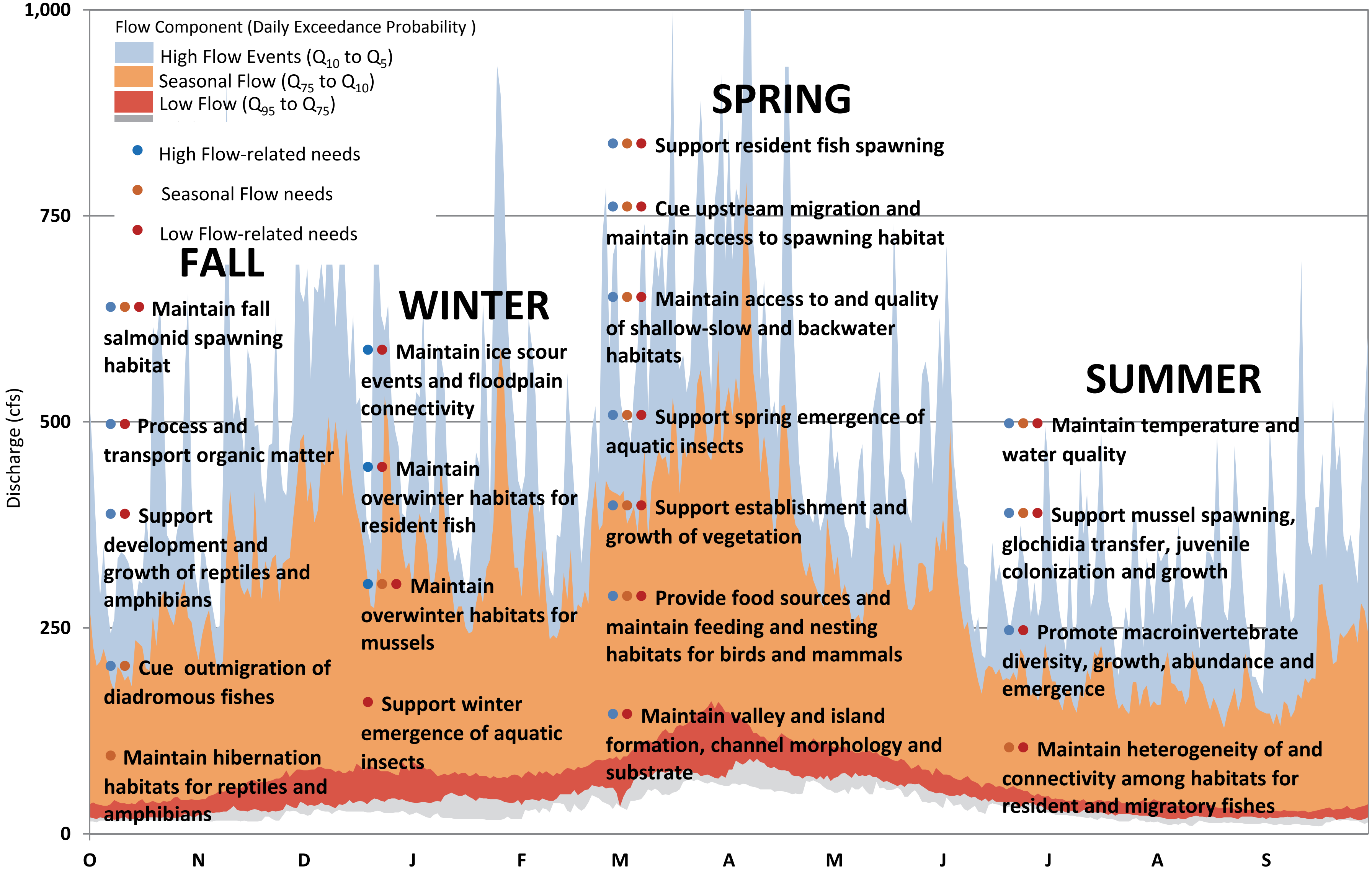
●●● Maintain temperature and water quality

●● Promote macroinvertebrate diversity, growth, abundance and emergence

●● Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes

Flow Components and Needs: Spring-fed high baseflow small river

Example: 01450500 Aquashicola Creek at Palmerton, PA (77 sq mi)



FALL

- 🔵🟠🔴 Maintain fall salmonid spawning habitat
- 🔵🔴 Process and transport organic matter
- 🔵🔴 Support development and growth of reptiles and amphibians
- 🔵🟠 Cue outmigration of diadromous fishes
- 🟠 Maintain hibernation habitats for reptiles and amphibians

WINTER

- 🔵🔴 Maintain ice scour events and floodplain connectivity
- 🔵🔴 Maintain overwinter habitats for resident fish
- 🔵🟠🔴 Maintain overwinter habitats for mussels
- 🔴 Support winter emergence of aquatic insects

SPRING

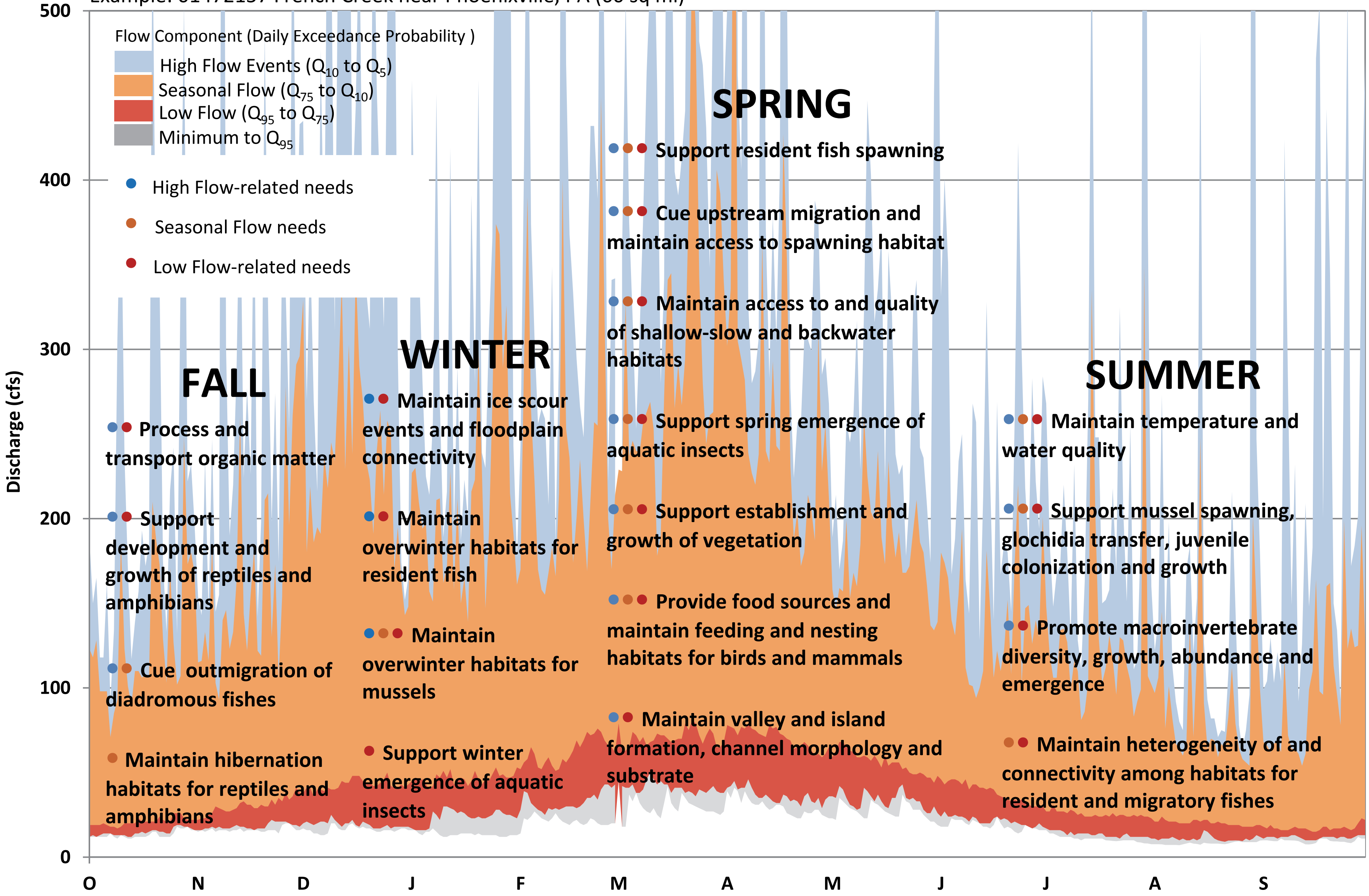
- 🔵🟠🔴 Support resident fish spawning
- 🔵🟠🔴 Cue upstream migration and maintain access to spawning habitat
- 🔵🟠🔴 Maintain access to and quality of shallow-slow and backwater habitats
- 🔵🟠🔴 Support spring emergence of aquatic insects
- 🔵🟠🔴 Support establishment and growth of vegetation
- 🔵🟠🔴 Provide food sources and maintain feeding and nesting habitats for birds and mammals
- 🔵🔴 Maintain valley and island formation, channel morphology and substrate

SUMMER

- 🔵🟠🔴 Maintain temperature and water quality
- 🔵🟠🔴 Support mussel spawning, glochidia transfer, juvenile colonization and growth
- 🔵🔴 Promote macroinvertebrate diversity, growth, abundance and emergence
- 🟠🔴 Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes

Flow Components and Needs: Warm Small River

Example: 01472157 French Creek near Phoenixville, PA (60 sq mi)



FALL

🔵🔴 Process and transport organic matter

🔵🔴 Support development and growth of reptiles and amphibians

🔵🟠 Cue outmigration of diadromous fishes

🟠 Maintain hibernation habitats for reptiles and amphibians

WINTER

🔵🔴 Maintain ice scour events and floodplain connectivity

🔵🔴 Maintain overwinter habitats for resident fish

🔵🟠🔴 Maintain overwinter habitats for mussels

🔴 Support winter emergence of aquatic insects

SPRING

🔵🟠🔴 Support resident fish spawning

🔵🟠🔴 Cue upstream migration and maintain access to spawning habitat

🔵🟠🔴 Maintain access to and quality of shallow-slow and backwater habitats

🔵🟠🔴 Support spring emergence of aquatic insects

🔵🟠🔴 Support establishment and growth of vegetation

🔵🟠🔴 Provide food sources and maintain feeding and nesting habitats for birds and mammals

🔵🔴 Maintain valley and island formation, channel morphology and substrate

SUMMER

🔵🟠🔴 Maintain temperature and water quality

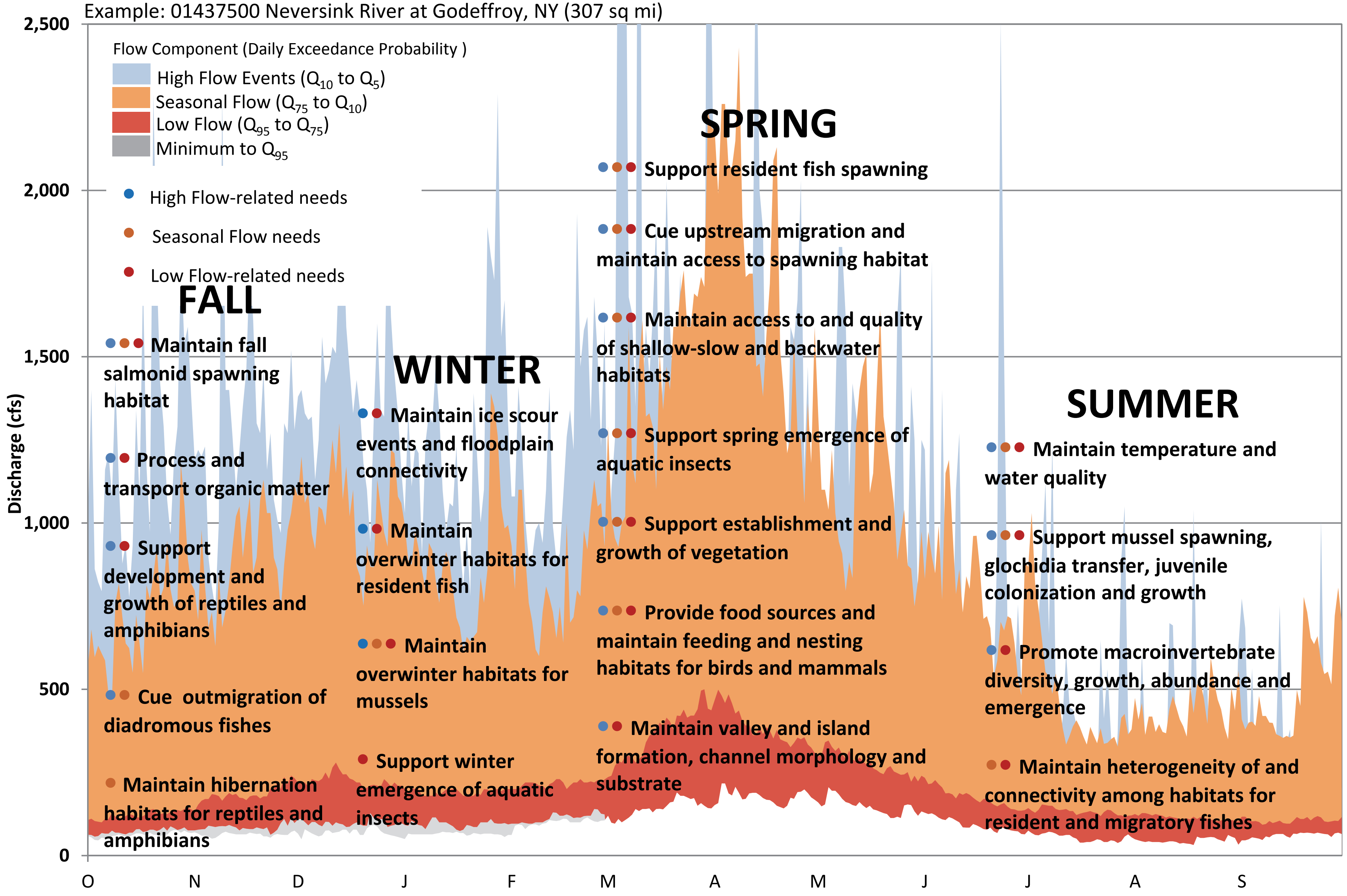
🔵🟠🔴 Support mussel spawning, glochidia transfer, juvenile colonization and growth

🔵🔴 Promote macroinvertebrate diversity, growth, abundance and emergence

🟠🔴 Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes

Flow Components and Needs: Cool Medium Tributary

Example: 01437500 Neversink River at Godeffroy, NY (307 sq mi)



FALL

🔵🟠🔴 Maintain fall salmonid spawning habitat

🔵🔴 Process and transport organic matter

🔵🔴 Support development and growth of reptiles and amphibians

🔵🟠 Cue outmigration of diadromous fishes

🟠 Maintain hibernation habitats for reptiles and amphibians

WINTER

🔵🔴 Maintain ice scour events and floodplain connectivity

🔵🔴 Maintain overwinter habitats for resident fish

🔵🟠🔴 Maintain overwinter habitats for mussels

🔴 Support winter emergence of aquatic insects

SPRING

🔵🟠🔴 Support resident fish spawning

🔵🟠🔴 Cue upstream migration and maintain access to spawning habitat

🔵🟠🔴 Maintain access to and quality of shallow-slow and backwater habitats

🔵🟠🔴 Support spring emergence of aquatic insects

🔵🟠🔴 Support establishment and growth of vegetation

🔵🟠🔴 Provide food sources and maintain feeding and nesting habitats for birds and mammals

🔵🔴 Maintain valley and island formation, channel morphology and substrate

SUMMER

🔵🟠🔴 Maintain temperature and water quality

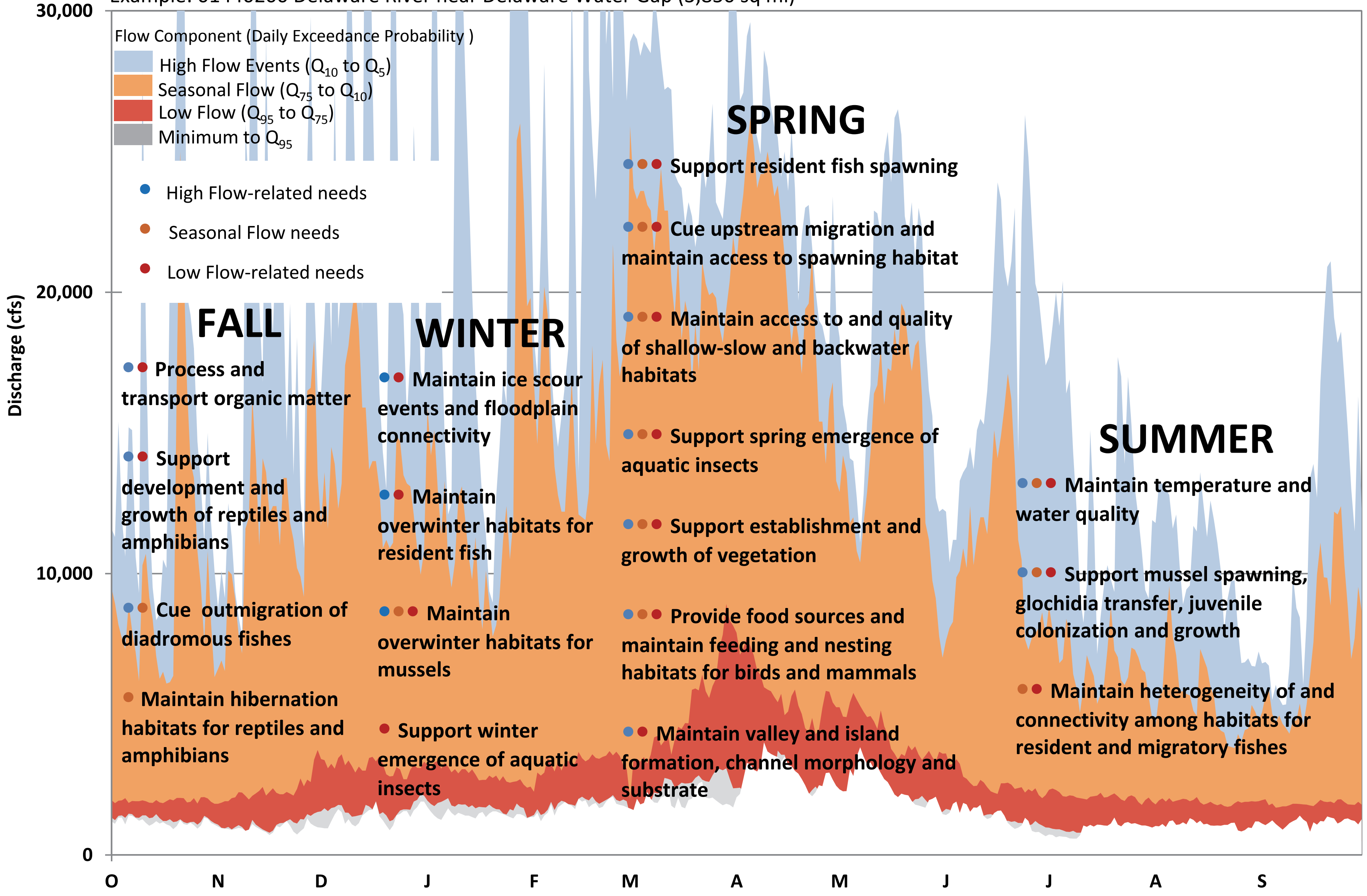
🔵🟠🔴 Support mussel spawning, glochidia transfer, juvenile colonization and growth

🔵🔴 Promote macroinvertebrate diversity, growth, abundance and emergence

🟠🔴 Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes

Flow Components and Needs: Large/Great River

Example: 01440200 Delaware River near Delaware Water Gap (3,850 sq mi)



FALL

●● Process and transport organic matter

●● Support development and growth of reptiles and amphibians

●● Cue outmigration of diadromous fishes

● Maintain hibernation habitats for reptiles and amphibians

WINTER

●● Maintain ice scour events and floodplain connectivity

●● Maintain overwinter habitats for resident fish

●●● Maintain overwinter habitats for mussels

● Support winter emergence of aquatic insects

SPRING

●●● Support resident fish spawning

●●● Cue upstream migration and maintain access to spawning habitat

●●● Maintain access to and quality of shallow-slow and backwater habitats

●●● Support spring emergence of aquatic insects

●●● Support establishment and growth of vegetation

●●● Provide food sources and maintain feeding and nesting habitats for birds and mammals

●● Maintain valley and island formation, channel morphology and substrate

SUMMER

●●● Maintain temperature and water quality

●●● Support mussel spawning, glochidia transfer, juvenile colonization and growth

●● Maintain heterogeneity of and connectivity among habitats for resident and migratory fishes

Appendix 6. Summary of Supporting Literature

This document is organized by

TAXA

SEASON

Flow Need – a statement summarizing why a range of flows is important to a taxa group

● **Hypothesis – states an anticipated ecological response to a change in high ●, seasonal ● or low ● flow conditions. [**Brackets include a **code** and indicate **degree of support** based on literature and existing studies**]**

- Summary of findings relevant to the hypothesis followed by the citation. Any quantitative thresholds in the paper are in **bold text.**

FISH

Summer

Maintain heterogeneity of and connectivity between habitats for resident and migratory fishes

● **During spring and summer, if the long-term timing (earlier Julian date) or magnitude of base flows decreases, suitable hydraulic habitat may decrease particularly during chronic conditions in the late summer, resulting in a shift in species abundance or assemblage [DF15, Supported]**

- On headwaters, creeks and small streams (1st to 4th order), a regional assessment of the influence of water withdrawal magnitude on fish assemblage found that streams with high withdrawal rates were generally characterized by lower proportions of fluvial dependent fishes and benthic invertevores (many riffle obligates). Benthic invertevores decreased by an estimated 10% when withdrawals were 50% of 7Q10 (**> 5% of August median**) and by an estimated 15% when withdrawals were 100% of 7Q10 (**>10% of August median**) (Kanno and Vokoun 2010).
- On creeks and small streams, fish assemblage characteristics were related to percent alteration of August median flow. **A 10% to 20% reduction in August Q50 flows reduced fluvial fish relative abundance by 9% and 17% respectively** (Armstrong et al. 2011).
- Estimated species richness and fish density were greatest under **median seasonal discharge** and lowest at 7Q10 discharge across all channel types and sizes (McCargo and Peterson 2010).
- On headwater and small streams, a simulated removal of **8% to 15% of the August median** predicted a 10% shift in fish assemblage; on large rivers, removal of **10 to 25 % of the August median** predicted a 10% shift in fish assemblage (Zorn et al. 2008).
- A comparison of large warmwater streams along a withdrawal index gradient finds a shift in fish assemblages from fluvial specialists to habitat generalists as withdrawals increase from 50 to 100% of 7Q10 or (**>10% of August median**). Vulnerable species included cyprinids, catostomids and

percids, ictalurids and stream-dwelling centrarchids. Altered flow regimes affected biota in relation to the degree of alteration and increased the odds that a site's IBI score fell below the regulatory threshold (Freeman and Marcinek 2006).

- A national study (coterminous US) of flow alteration and biological response found that diminished flow magnitudes were the primary predictors of biological integrity for fish and macroinvertebrate communities (~250 sites). The likelihood of biological impairment doubled with increasing severity of diminished streamflows. Fish assemblages transitioned to those with increasing lotic species, preferring slow-moving currents and fine-grained substrates as well as high mobility (some aquatic insects able to temporarily leave the aquatic environment) (Carlisle et al 2011).

● **During summer and fall, because of their limited mobility and narrow velocity niche breadth, small-bodied fishes (riffle obligates and juveniles) would be susceptible to hydraulic changes to seasonal flow conditions [DF16, Supported].**

- In a small Massachusetts river (Ipswich), overallocation of groundwater reduced baseflow. Communities shifted from fluvial dependent or fluvial-specialist species to macrohabitat generalists (Armstrong et al 2001).
- Using an IFIM model, weighted usable area for riffle obligates **increased with increasing flow up to summer median flow values** and then decreased due to velocity preferences (Leonard and Orth 1988).
- Resource depression and the competition for food between darter species was highest during summer months (low prey densities and high metabolic demands). Darters reduced consumption as opposed to partitioning food resources (Schlosser and Toth 1984; Stauffer et al. 1986).
- In a tributary to the Upper Ohio (Elk River), ten darters were observed during the summer to find patterns of partitioning were significant between genera. Etheostoma occurred in riffles and were associated with benthic habitats (under, between and on top of rocks) whereas Percina were more common in riffle/run habitat within the water column (Welsh and Perry 1998).
- Low stream discharge tends to reduce riffle area habitats to a greater extent than pool area habitats (Hakala and Hartman 2004, Armstrong et al. 2001).
- Mullen and Burton 1998, Freeman and Stouder 1989.

● **During summer and fall, a decrease in seasonal flow magnitude may expose stream margins and side-channel habitats reducing shallow-slow habitat for small-bodied and juvenile fishes, resulting in reduced abundance and assemblage shifts [DF27, Supported]**

- In an unregulated system, the distribution, location and size of shallow-slow habitat followed an annual pattern **tied to the seasonal hydrograph**: small, dispersed patches in side channels and tributary backwaters remained connected, migrating to the main channel during recession and forming large, contiguous patches and benefiting egg and larvae with poor swimming capabilities and reliance on zooplankton, small insects and detritus as primary food sources (Bowen et al. 2003).
- A decrease in the **magnitude of median daily flows** resulted in an assemblage shift and a reduction in available shallow-slow habitat in summer. Young-of-year abundance was most correlated with shallow-slow habitat size and persistence. Suitable conditions were predicted by conditions including the seasonal median daily flow (Freeman et al. 2001).

- Growth rates and survival of brassy minnows in backwaters were significantly lower in dry years than wet years. Survival was higher in backwaters that were larger and dried more slowly (Falke et al.2010).
- Hydrologic models indicate shallow-slow backwaters dry with greater frequency and duration compared to similar in-channel habitat. Fish communities had a higher richness of rheophilic species where habitats remained connected (Flinn et al. 2008).
- Gibbons and Gee 1972; Dauwalter and Fisher 2007

● **During summer and early fall, a decrease in surface or groundwater contribution may limit access to suitable habitat and increase degree of overlap between cold and cool species (compressing the species and thermal gradient), increasing competition and predation.[DF21, Alternative Hypothesis]**

- The PFBC documented increased brook trout abundance following a drought year. They hypothesize that increased abundance was a result of reduced connectivity to creeks and headwater streams, reducing stresses including competition and predation (brown trout) (Greene and Weber 1993).

● **During summer, a decrease in magnitude and duration of low flows may increase temperature outside of thermal ranges for cool/cold fishes (sculpin and salmonids), leading to increased competition, stress, reduced body mass and possibly mortality (sublethal and lethal effects) [DF 17,DF18, Moderate]**

- Extreme low flow conditions resulted in individual fish (brook trout) having significant lower body condition during the drought relative to the post-drought period. Proportionally larger decreases in riffles and reduced flow velocity combined to limit food availability. Restricted habitat availability increased competition for limited food resources. (Hakala and Hartman 2004).
- In an **experimental diversion (to an estimated summer Q90 and 95**), fish body length was 30 to 40% smaller for larger bodied fishes and 10% smaller for small bodied fishes (Walters and Post 2008).
- Body temperatures of brook and brown trout were monitored during the summer and early fall. Access to and use of areas of groundwater discharge and tributary confluences were critical for thermoregulation, particularly for brook trout (Baird and Krueger 2003).
- Alonso-Gonzalez et al. (2008) observed a negative correlation between age 1 trout mean fork length and the **number of days flow was below the Q75** discharge during the late spring and early summer.
- Brook and brown trout will move considerable distances to access coldwater refugia (Petty et. al 2012)
- Cowx et al. (1984) observed salmonid year class failure during a summer with low flows that led to extreme temperatures (26° C). Similarly, trout survival was negatively related to time that water temperature exceeded 20 C and was more sensitive to higher water temperatures.
- Waco and Taylor (2010) did not observe temperature changes > 1C in response to modeled increasing withdrawals for high baseflow streams, but impacts might be greater in lower baseflow streams.
- Knight (2008); Powers and Matthew 1983; Kraft 1972

- For cold water fish, declining year class strength and adult biomass in relation to decreased wetted stream area and loss of pool habitat was observed (Elliot 2006; James et al 2010)

● **During summer and fall, if flows are lower, temperatures may be warmer and can increase growth /productivity of vegetation and may increase food availability for warm tolerant fishes like suckers [DF19]**

● **During summer and early fall, in headwater and cold-cool streams, a reduction in low flow magnitude may increase temperature, reducing quality of habitat for female eels and potentially favoring male differentiation (skew sex ratios) [DF20]**

● **During summer and fall, maintenance of adequate low flow magnitude may provide access to and abundance of shallow slow margin habitats, supporting abundance of associated fishes (vegetation obligates) (increased predation) [DF24, Some]**

- Implementation of a minimum release program **increased flows during the summer from extreme low flow conditions to low flows** and increase diversity of the shallow shoreline fish assemblage to more closely resemble unaltered reaches. Several fluvial-specialist species in the genera Cottus, Percina, Etheostoma, Lepomis, Hypentelium, Notropis returned (Travnicek et al. 1995).

● **During summer and early fall, a reduction in low flow magnitude will increase temperature and decrease dissolved oxygen, leading to a loss of suitable habitat for fish eggs and larvae (all groups)[DF22] See Water Quality for support**

● **During summer and fall, under low flow conditions, below reservoirs, maintenance of low flows can lower temperatures impeding the growth and development of warm water fishes [DF23] No evidence**

● **In summer, a reduction in low flow magnitude may reduce available cover and extent of habitat (e.g. concentrating fish in shrinking pools) and increase predation and competition, reducing species richness and abundance [DF25].**

- **During the drought of 1999,** the relative abundance of the single most-common species (dominance) was higher during a drought year than during normal-flow years (Fischer et al. 2004).
- During the same drought, northern mid-atlantic IBI scores were lower than in normal-flow years (Daniels et al. 2002).

● **During summer and fall, if low flows decrease, it may decrease the amount of riffle habitat for riffle-obligate species like longnose dace, increasing competition and eventually shifting assemblages [DF26, Alternative Hypothesis Supported]**

- **Riffle habitat is maintained by the August Q77**. Overallocation of water led to a reduction in baseflow, loss of riffle habitat and disconnected reaches. In response, fish communities shifted from fluvial dependent/specialist species to macrohabitat generalists (Armstrong et al. 2001).
- Habitat partitioning among several species of darters occurred along depth, velocity and substrate during base flow conditions. Habitat heterogeneity increased as did partitioning among species,

reducing competition above the July Q80 flows (Stauffer et al. 1996, USGS Unpublished data, IHA Analysis).

- Negative effects of drought induced low flows (**low flow range**) were greatest on species with large adult body sizes, low tolerance, or species that used fast-flowing and deepwater habitats (McCargo and Peterson 2010)
- Using a habitat model, demonstrated that stonecats were susceptible to habitat limitation when discharge was below 10 cfs in the summer (**low flow range**). In reference to long term variation, find that stonecats may be naturally limited by flow in some years but low flow alteration can make it worse (Brewer and Rabeni 2008)
- In an experimental test of depth selection by mottled sculpin in a southern Appalachian stream, researchers find that shallow-fast habitats were preferred and influenced by pressures of predation and instra-specific competition (Freeman et al. 1989).
- Observed increases in habitat diversity and high velocity habitats after increasing **extreme low flows** due to power generation. A mesohabsim models predicts a benefit to rheophilic species (Harvey et al. 2005)
- Spatial habitat and habitat breadth among riffle obligates decreased with decreasing discharge (**low flow range**) (Kessler et al. 1995)
- Increased duration of low flow during late summer and early autumn and was correlated to decreased rheophilic species and increased richness of lentic tolerant species (Roy et al. 2005).

● **During summer and fall, an increase in daily streamflow fluctuations may lead to stranding for juvenile and small fishes using stream margin habitat.[DF28, Supported]**

- Observed that over 50% of nests were dewatered or in near 0 flow conditions for several days on two separate occasions due to rapid flow fluctuations (Grabowski and Isley 2007)
- Found that juvenile brown trout yoy stranding increased with dewatering rate through several repeated experiments in an experimental channel (Halleraker et al. 2003)
- Regulated river reach experienced 3 hr elevation changes of 2 m regularly during power generation periods, and these effects were dampened downstream. Overall, this provides evidence that nursery function of nearshore waters can be impaired by artificial flow fluctuations (Scheidegger and Bain 1995)
- Travnicheck 1995; Raiblet et al. 1997; Kinsolving and Bain 1993

Fall

Maintain fall salmonid spawning habitat and promote egg, larval and juvenile development (brook and brown trout)

● **From fall through spring, an increase in high flow frequency or magnitude may inhibit spawning, or scour eggs or redds [DF32, DF34 Moderate].**

- Observed a negative relationship between age-0 brown trout and the **total number of days discharge exceeded the 25th percentile** during incubation period (Alonzo-Gonzoles et al. 2008)
- A pre-post flood survey on 14 headwater streams revealed a flood event (during the incubation period) reduced age-0 trout by 98% and age 1+ trout by 84% (Carline and McCullough 2003).
- Observed a significant negative relationship between brown trout YOY densities and peak discharge during incubation (Spina 2001).

🟠 **During spawning and egg development, a decrease in seasonal groundwater or surface water flows can reduce quality of, or access to spawning redds, decreasing reproductive success [DF33, Supported]**

- On headwaters to small streams in the unglaciated plateau, a regional IFIM study predicted a 10% brook trout habitat loss for **withdrawals of 11 to 14%** of average daily flow (Figure 6.10) (roughly equivalent to the **November Q50**) (Denslinger et al. 1998).
- In a Pennsylvania stream median discharge during spawning period, in addition to density dependent factors, was positively associated with age 0 brown trout density (recruitment) over 19 years of sampling (Carline 2006).
- Hazzard 1932, Petty et al. 2005

🟠 **During summer and fall, a decrease in suitable conditions for feeding and growth may reduce overwinter survival [DF33, Supported]**

🔴 **During spawning and egg development, a decrease in low flows may decrease connectivity or increase exposure of spawning redds, decreasing reproductive success [DF39, Supported]**

- (Raleigh 1982, Jensen and Aas 1995, Arnekleiv and Kraabol 1996, Curry et al. 1995, Alonzo-Gonzalez et al. 2008).

Cue outmigration of diadromous fish

🔵 **During fall and early winter, a change to the timing or magnitude of high flow events could decouple cues for American eel outmigration, delaying or impedeing [DF31, Moderate].**

- Cues for silver eel emigration include precipitation and high flow pulses, temperature decreases of > 1-4 C, and the lunar cycle (Hildebrand and Welsh 2005, Greene et al. 2009)
- Without fall high flow cues, eels delayed outmigration from fall to winter on the Shenandoah River (Eyler et al. 2010).
- The fall downstream migrations of juvenile American shad began when water temperatures declined to 19C and peaked at 9 to 14 C. Found that decreasing water temperature, not increasing flow, determined the beginning and ending of the migration period (O’Leary and Kynard 1986).

● **During fall and early winter, a reduction in seasonal flows may increase bioenergetic costs during outmigration [DF].**

- #1 In a Massachusetts River, emigration of juvenile river herring migration was inhibited due to low water levels. #2 Juveniles in this system were an average of 25 mm smaller than those in the higher baseflow systems (Yako et al. 2001)
- Adequate flow during outmigration – not too high, not too low, velocities between .5 and 3 feet per second (Stier and Crance 1985)
- In the Susquehanna River, higher in river flow from October through November may help push juvenile shad downstream (Greene et al. 2009).
- Juveniles begin emigrating from streams and rivers when water temperatures drop below 15 C. Water temperature is an important factor affecting growth and survival of juvenile American shad. Sublethal effects occur at temperatures between 4 and 6C. Interaction between temperature and flow (Chittenden 1972).

Winter

Maintain overwinter habitats for resident fish

● **During winter, fish have low energy reserves, an increase in high flow frequency, magnitude or rate of change, may require significant movement to flow refugia, increasing bioenergetic costs [DF35, Supported].**

- During winter, frazil ice poses direct physiological effects (attaching to gills) in addition to restricting available physical habitat. In the fall, trout began to aggregate in deep pools with high cover and low velocity. Trout aggregations were found in areas where groundwater buffered temperatures by 2-6 degrees C (Brown et al. 1993).
- Found evidence for decreased swimming ability at higher velocities for two water column species (rainbow trout, rosyside dace) during winter. Also observed an increase in metabolic activity with increasing velocity in winter for rainbow trout. (Facey and Grossman 1990)
- Compared habitat use of musky in a regulated river in winter and summer. Fish movements occurred in response to high flow events and were stronger in winter. This suggests that fish may use more energy to move in response to increased discharge in winter when energy reserves are lower (Brenden et al. 2006).
- Simpkins et al. 2000

● **From late summer through winter, a decrease in low flows may reduce habitat conditions and food availability, reducing gonadal production and reproductive fitness [DF36].**

● **During winter, a decrease in groundwater contribution may decrease water temperature and increase bioenergetic cost for cool/cold fishes [DF37, Moderate].**

- Population size for mottled sculpin is regulated by overwinter habitat availability. Juveniles and adults directly compete for refuge (Rashleigh and Grossman 2005).
- Winter growth of juvenile salmonids increased with lower discharge. Higher temperatures and stream discharge led to lower growth rates in winter (Davidson et al. 2010).
- Compared growth and condition of salmonid YOY over two winters (cold/warm) in one stream and compared to a second stream (warmer). Found that degree of mass loss was related to temperature and flow in early winter. The stream that got cold and stayed cold with ice cover and lower flow had smaller negative growth rates (Murpy et al. 2006).
- Cunjak and Power 1986: a (brook trout) and b (blacknose dace)

● **During winter, a decrease in low flow magnitude may decrease groundwater contribution and survival of brook trout eggs/larvae [DF 38, Some].**

- An observational study found that persistent groundwater upwelling (from spawning through incubation) was critical in protecting redds from infiltrating surface water and ice and maintaining dissolved oxygen levels. Survival was lowest (6%) in the redd with the lowest proportion of groundwater contribution and lowest temperatures (Curry et al 1995b).

● **During winter, a reduction in low flow magnitude may reduce vegetated thermal refugia (in roots system) for vegetative/cover obligates (specifically bridle and ironcolor shiner) which are intolerant of cold temperatures [DF39]**

● **During winter, a reduction in low flow magnitude may lead to reduced temperature and decreased survival of YOY migratory fish (e.g. striped bass) [DF40]**

Spring

Support resident fish spawning

● **During the spring and summer, increase in frequency or magnitude of high flows may flush nest builders from guarding nests or scour eggs and developing larvae, limiting recruitment of nest builders, riffle obligates and riffle associates [DF1, Supported]**

- For smallmouth bass, years when mean June flow was more than 40% above the mean resulted in near year class failures (Smith et al. 2005). Several studies noted the relationship between high flows, nest scour and smallmouth bass recruitment (Graham and Orth 1986, Peterson and Kwak 1999).
- After a successful spawning event, all centrarchid nests were scoured by a high flow event (Lukas and Orth 1993).
- A high flow event (> 10m/s) was responsible for 85% of smallmouth bass nest failures in a Virginia stream (Lukas and Orth 1995)
- Larger males that nested earlier and more often had more reproductive success by avoiding floods or having more opportunities to renest after floods (Noltie and Keenleyside 1986)

- Survival of walleye larvae were directly related to the frequency of high flow events with low survival during years with multiple events during the spring (Mion et al. 1998).
- Observed that maximum discharge was the strongest predictor of slimy sculpin survival (Keeler et al. 2007)
- Relationship between high flows and success for brook trout and brown trout redds (Letcher 1998, Smith 1999, Roghair 2002 brook trout, Lobón-Cerviá 2004, 2007 and 2009)

● **From winter through early summer, a reduction in high flow frequency or magnitude may reduce availability of suitable spawning and nest building substrate, by increasing deposits of fines and decreasing recruitment success [DF2, Supported] See Geomorphic Need for relationship between high flows and substrate**

- Increased sand bed load (4 to 5 times baseline) resulted in decreased survival of eggs and juveniles and a 50% decline in overall population. (Alexander and Hansen 1986).
- Substrate dominated by fine sediments reduced intragravel permeability, dissolved oxygen and survival of brook trout eggs and larvae (Argent and Flebbe 1999).
- Fine organic sediment decreased salmonid embryo survival. Fish in the high-sediment treatment did not postpone emergence in response to predator odour and had reducing swimming ability (Louhi and Ovaska 2011).

● **During spring, a reduction in flow magnitude may shift seasonality of the hydrograph, limiting suitable habitat for successful egg and larval development and reducing reproductive success of spring spawning fishes (riffle obligates, riffle associates, migratory, vegetation obligates, diadromous).** [**DF3, Supported]**

- Built simulation model based on previous work that suggests walleye larval drift survival is more a function of velocity than temperature at distances less than 80 km. High velocities (>0.6 m/sec-Sandusky river) or low velocities with high temps lead to increased mortality. (Jone 2003)
- Found positive association between YCS of sturgeon and June. Hypothesize that higher flows decreased predation and increased dispersal. (Nilo 2007)
- Measured larval drift across 3 years in one river. Larval drift was associated with mean daily water temperatures, with the highest CPUE values of drifting larvae observed after peak water flows (Smith 2009)

● **During spring and summer, a reduction in low flow magnitude may reduce persistent riffle spawning habitats for riffle obligates and associates, resulting in reduced reproductive success [DF4, Some**]

● **During spring and summer, after spawning, nest building fishes need relatively stable flows during the incubation and swim up period. An increase in flashiness may expose or scour developing eggs** [**DF5**]

Cue upstream migration and maintain access to spawning habitat

● ● **During spring, a reduction in seasonal or high flow magnitude and duration may reduce extent of upstream migration by shortnose sturgeon and restrict access to suitable gravel spawning beds (upstream from Trenton)** [**DF6**, **Supported]**

- O'Herron et al. 1993; Brundage and Meadows 1986; ERC 2006 a, ERC 2008 (Delaware)
- Kieffer et al. 1993 and Kieffer et al. 1996 (Merrimack); Smith et al. 1991 (Savannah)
- Monitoring experimental discharges on a regulated reach, find that shovelnose sturgeon spawned in under high flow conditions in conjunction with the ascending, peak and decending limb and water temperatures from 11 °C to 23 °C. **No evidence of shovelnose sturgeon spawning was documented during two low flow years (2007 and 2008)** despite optimal water temperatures.
- Evaluated external cues to spawning, study suggests that stream temperature, discharge period and lunar cycle were significantly associated with the initiation of migration, and timing of arrival at spawning sites. Overall study reveals importance of lagged declining flow rates and increasing temperatures as important spawning cues. In a subsequent study found that these factors may vary among subpopulations (Forsythe et al. 2012a and b).
- Sturgeon migration and spawning occurred in association with increasing temperatures, and the receding limb of a spring high flow event (Heise et al. 2004, LaHaye et al. 1992, Paragamian and Kruse 200, Paragamian and Wakkinen 2011, Auer and Baker 2002).

● **During the spring, a change in the frequency, timing or magnitude of seasonal to high flows may result in loss of spawning cue synchrony (temperature, flow, light availability) for diadromous and migratory fishes, this may reduce the extent of spawning runs [DF7, Supported]**

- White sucker, creek chub, northern hogsucker, and black redhorse partition spawning timing and longitudinal position. Stream alterations that affect temperature, flow regimes, substrate or connectivity may reduce niche diversity impacting catostomid species composition Descriptive study over 3 years that noted **interaction between temp and discharge peaks on the timing of sucker runs** (Curry and Spacie 1984).
- A decrease in the **magnitude of median daily flows** in spring results in an assemblage shift, reducing the number of spring spawners and increasing the number of summer spawners (Freeman et al. 2001).
- Observed movement of walleye upstream during peaking discharges downstream of a dam (DiStefano and Hebert 2000).
- Sucker spawning migrations were delayed by a flood event in spring. Spawning was initiated on the receding limb of this flood event in conjunction with rising temperatures. (Reid 2006).
- Greene et al. 2009

● **From March through June, a decrease in the magnitude of seasonal or high flows may reduce tributary and headwater access for migrating fish and suitable spawning habitat, may reduce reproductive success of riffle associates, diadromous, migratory residents, riffle associates (white sucker) adapted to spring spawning conditions [DF9, DF10, Moderate Support]**

- Meta-analysis of three studies found a positive relationship between YOY density and 10-day maximum discharge during spawning period (Craven et al. 2010).
- Illustrates a relationship between the spring pulse followed by increased white sucker spawning activity (Doherty et al 2010).
- Observed that after a second high flow pulse, there was a second walleye run (live eggs were suspended in drift (Dust 2003, Koel and Sparks 2002).
- In the Delaware River, Hendricks et al. (2002) found that hatchery-reared American shad homed to a specific tributary within the Delaware river system several years after stocking. They showed preference for migrating on the side of the tributary influenced by the plume of their natal river.

● **From March through June, diadromous fish use the descending limb as triggers for movement, and increase in the rate of recession may limit the extent of upstream spawning migration [DF11]**

● **During the spring, a change in the timing or magnitude of seasonal to high flows may result in delayed migration of diadromous and migratory fishes increasing bioenergetic costs and reducing spawning success [DF8]**

● **From March through June, a decrease in the magnitude of low flows may delay upstream migration [DFX]**

Maintain access to and quality of shallow-slow margin and backwater habitats

● **During spring and early summer, a reduction in high flow magnitude (> monthly Q10) may reduce maintenance of side channel and backwater habitats [Geomorph]**

●● **During spring and early summer, a reduction in high or seasonal flow magnitude and duration may reduce access to backwater and sidechannel spawning habitats, reducing successful larval development. These are particularly critical for vegetation obligates (bluespotted sunfish and mudminnow) [DF12, Supported]**

- Reported positive linear relationship between phytophilic juvenile species (vegetation obligates) abundance and duration of flooded vegetation in floodplain backwaters over 5 years (Janac et al. 2010)
- In the absence of shallow emergent spawning/rearing habitats, pike were found to use deeper habitats less conducive to egg and larval development (colder temperatures). Their size at swim-up was smaller than when shallow backwater habitats were available (Farrell 2001).
- Created a spatial-temporal model of pike spawning habitat demonstrates that discharge magnitude and duration have a direct and positive effect on both abundance and quality of pike spawning habitats. Maintaining high water levels for 4 weeks until swimout is important (Mingelbier et al. 2008).

- Developed early life history pike model which supports the hypothesis that pike need flooded marshes along tributaries for reproductive success, a habitat that has been lost due to flow alteration (Farrell 2006).
- Extensive flooding of long duration was particularly favorable for periodic strategists (large body size, delayed maturation, high fecundity, low parental investment) (Gorski et al. 2011).
- Year class strength was correlated to years with both warmer temperatures and higher water levels in spring and summer (Smith et al. 2005, Hudon et al. 2010).
- From spring to summer, in an unregulated system, the distribution, location and size of shallow-slow habitat **followed an annual pattern tied to the seasonal hydrograph**: patches in side channels and tributary backwaters remained connected, migrating to the main channel during recession and benefitting larvae with poor swimming abilities and reliance on zooplankton and detritus as primary food sources (Bowen et al. 2003).
- Within oxbow habitats, fish assemblage structure was associated with both macrohabitat features (depth, temperature, conductivity) and the **frequency of floods** that connected backwater habitats to the channel. Six species that were collected in oxbow lakes were never collected in river channel surveys and several species that were rare in river channel surveys were abundant in oxbows (Zeug et al. 2005).

● **From late spring through early fall, juvenile fish, like American shad, need access to refugia provided by SAV beds. A reduction in low flow magnitude may reduce extent and depth of SAV bed refugia, increasing predation of juvenile fishes. [DF13]**

● **From late spring through early fall, suitable low flow magnitudes are needed to maintain temperature and dissolved oxygen in backwater habitats. [See Water Quality Section]**

● **From late spring through early fall, an increase in flashiness may reduce persistence of and access to shallow-slow habitat for juvenile fishes and vegetation obligates [DF14]**

MUSSELS

Summer

Support mussel spawning, glochidia transfer, juvenile colonization and growth

● **During spawning and glochidia transfer, an increase in high flows may decouple mussels from host-fish (turbidity or increased velocities), reduce spawning efficiency or inhibit successful colonization of juveniles. [DM1, Supported]**

- During glochidia release and excystment, high flows and associated shear forces may be the primary factors in determining suitability of juvenile settlement locations. High flow releases from Green River dam (above median) in the spring and summer likely limit recruitment (Hardison and Layzer 2001).
- Using a particle distribution model, authors find that suitable habitats for juvenile colonization occur where shear stress ratio <1 and hypothesize that annual peak flows limit the availability of colonization habitats (Morales et al. 2006).
- High flows increase water column velocity inhibiting juvenile settlement after excystment from fish-host. Once reaching the substrate, velocity and shear forces can displace juveniles before they burrow or for some species, attach to substrate with their byssal thread (Holland-Bartels 1990; Layzer and Madison 1995).

● **During spring, a decrease in high flow magnitude may result loss or dampened migration cue for diadromous host-fish, reducing potential for interaction with gravid mussels (Anodonata implicata).[DM2, Supported through fish needs]**

- See Spring Need: Cue spawning and Migration

● **During spawning and glochidia transfer, change to seasonal flows may flows may decouple mussels from host-fish and reduce spawning efficiency. [DM, Some]**

● **From spring to fall, an increase in seasonal flow magnitude may increase velocity and associated shear stress, reducing abundance, richness, or individual growth [DM15, Moderate].**

- In an analysis correlating unionid growth rings with long-term hydrology, growth for some species was negatively correlated with increasing **May and June medians** and **high pulse count** (events > 75th percentile) (Rypel et al. 2009).
- A mussel extinction gradient was observed downstream from an impoundment. In increase in high flow frequency and magnitude and increased shear stress was considered one factor in the reduced diversity and abundance (Vaughn and Taylor 1999).

● **During spring and summer, a decrease in low flow magnitude or an increase in low flow duration may restrict suitable hydraulic habitat across the channel, limiting interaction between diadromous host-fish and mussels (*Anodonata implicata*) (spring), or species requiring direct contact for transfer of glochidia.[DM3, DM4, Supported]**

- Maintenance of host fish habitat is critical in streams where mussels use hosts that exhibit upstream spawning migrations. If migrations occur during glochidial release periods, the movements of infested host fish may be crucial for mussel dispersal and maintenance of upstream populations. Maintenance of hydrology for host-fish interaction may be most critical for highly mobile fish species (riffle associates and migratory fishes) that are not obligated to a specific hydraulic condition (Layzer and Madison 1995)
- On the Green River, below the Green River dam, researchers found relationship between reservoir conservation flow releases and mussel recruitment. Before low flow releases began, only 4% of the mucket population was <100 mm long. After the releases, 28% of the muckets were <100 mm long. **Find that *Lampsilinae* recruitment is related to low flow releases made in the late spring and early summer, and *Ambleminae* recruitment is related to low flow releases made during summer months**. Quantification: Daily stream gage data is available below the dam. It may be possible to translate hydraulic conditions preceding successful recruitment years (Layzer 2009).
- Gravidity, fecundity and fertilization success of *Actinonaias ligamentina* were examined at 4 sites below the Green River dam, Kentucky. Find that females are not necessarily dependent on nearby males for fertilization and factors necessary for species recovery include presence of host-fish and suitable conditions for juvenile survival and growth (Moles and Layzer 2008).
- At the regional scale, authors found that rare mussels relied on host fish with short movement distances, where mussels with a more secure conservation status had host fish with 2 to 3 orders of magnitude movement distances. This suggests limited dispersal by host-fish affects the abundance and distribution of unionid mussels, and supports the need to consider host-fish mobility to ensure connectivity between and maintenance of metapopulations (Schwalb et al. 2011).

● **During summer, a decrease in low flows may concentrate fish in pools and increase potential for interaction with mussels that are found in pools. [DM5]**

● **During summer and early fall, a decrease in low flow magnitude may increase water temperature and sublethal stress for thermally sensitive mussels (*Margaritifera margaritifera*).[DM6, DM8, Supported]**

- For a study conducted in the southeast, **above 30 C, thermally sensitive species, such as mucket** *(Actinonaias ligamentina)* **experience sublethal stress** in respiration patterns, the catabolization of glycogen stores, and reduce nutrient processing. They find a seasonal pattern to glycogen stores increasing from summer to winter and declining in the spring, likely due to seasonal energetic investment in reproduction. Therefore **stressful conditions that cause mussels to catabolyze glycogen, will be magnified during the reproduction period**. (Spooner et al. 2005, Spooner and Vaughn 2008).
- Low flow events resulted in decreased velocity, disconnected habitats and increased water temperatures. Mortality rates of thermally sensitive species (including *Actinosis ligamenta* (mucket) and species in the *Truncilla, Quadrula* and *Lampsilis* genera). Authors believe that thermal stress

associated with low water levels was one of the proximate causes of decline in species density, abundance and diversity (Galbraith et al. 2010, Galbraith et al. 2012).

- Thermal tolerances for glochidia and juvenile life stages for eight species of mussels ranged from 21.4 to 42.7 C. Find that freshwater mussels generally have a slightly greater thermal tolerance then their host fish, therefore the effective thermal tolerance is reduced by the obligate relationship with the host fish (Pandlofo 2010, Pandolfo 2012).
- Cole et al. 2008; Krueger and Heise 2005

- **During summer, a decrease in low flow magnitude may decrease dissolved oxygen and increase ammonia concentrations outside of mussel tolerance. Juvenile mussels may be more sensitive to this increase than adults. [DM7, Moderate]**

- Strayer and Malcom 2012; Newton 2003; Augspurger et al. 2003; Wang et al. 2007;

- **During later summer and early fall, a decrease in low flows may reduce depth or dewater shallow riffle or margin habitats exposing mussels to increased predation or desiccation [DM9, Supported]**

- On a glaciated stream in Pennsylvania **dewatered margin habitats exposing mussels**. During this period, the minimum flow was the **August Q90**, and the median flow was the **August Q85** (Pers Comm, Charles Bier 2012, USGS Unpublished data, IHA Analysis).
- During record droughts, **reduced flows resulted in mussel emersion and increased predation**. Emersion did not result in mortality in all mussels. Small-bodied mussels incurred higher mortality than large-bodied mussels (Johnson et al. 2001, Peterson et al. 2011).
- During a summer low flow event, researchers found a significant negative relationship between water depth and mussel mortality (Galbraith et al. 2010, Gough et al. 2012).
- During a drought, discharge was 50% less than median conditions and, in small streams resulted in disconnected pools. On large river reaches, stream margins dried, but the stream remained hydrologically connected (Haag and Warren 2008).

- **Any time of year, especially summer and early fall, a decrease in low flow magnitude may increase algal production and decrease DO concentrations outside of the range of mussel tolerance, leading to glochidial abortion, reduced growth or mortality. Brooding mussels and mussels in backchannels or settings with high surface water exposure would be particularly susceptible. [DM8, DM10, Moderate]**

- Thermal stress associated with low water levels was one of the proximate causes of reduction in species density, abundance and richness. Once the mussels began dying, tissue decay led to nutrient pulses and algal blooms which lowered DO, resulting in further mortality (Galbraith et al. 2010).
- During a drought, mortality increased when DO fell below 5 mg/L and velocity below .01 m/s (Johnson et al. 2001).
- Stream reaches that ceased surface and ground water connectivity under drought conditions (exacerbated by groundwater withdrawals) had significant declines in taxa richness and abundance (Golladay et al. 2004).

● **In summer and fall, during the baseflow months, a decrease in low flow magnitude may have more significant impacts on mussel populations in creeks and small streams than on large rivers [DM14, Moderate]**

- A record drought resulted in disconnected pools resulting in a loss of species in small stream habitats (4 to 105 square miles). Tributary and large river habitats maintained connectivity and flow refuges and mussel assemblages survived the drought. **A > 50% reduction of median monthly flows in summer months** resulted in a 60-85% decrease in mussel abundance (number/m2) (Haag and Warren 2008).
- Under drought conditions, higher habitat impairments (hydrologic connectivity, temperature and DO stress) occurred in small streams than larger tributaries) (Johnson et al. 2001).

● **In summer and fall, during larval transfer, development and juvenile establishment (between two weeks and a month after glochidia release), a decrease in low flows may increase TDS concentrations, causing glochidia to close before attaching to host fish gills or may reduce suitable habitat for juvenile establishment [DM15]**

● **Anytime of year, while some species have the ability to slowly migrate on the surface (*Strophitus undulatus* and *Alasmodanta varicosa*), a high rate of decrease to a low flow condition may strand mussels, particularly in margin and riffle habitats. [DM11, Moderate]**

- While mussels have been documented to move under extreme high and low flow conditions, movements are slow, limited by substrate, and do not occur over long distances. They are not adapted to follow receding water levels when low flows quickly change (Layzer and Madison 1995, Anniet and Downing 1997).
- Instream flow conditions supportive of mussel habitat need to consider persistent suitable habitat that combine the limiting factors of high flow (shear stress) and low flow (low velocity and restricted depth (Cole et al. 2008, Maloney et al. 2012).

Winter

Maintain overwinter thermal regime and habitat for mussels

● **Any time of year, an increase in the frequency or magnitude of small or large flood events may eliminate flow refuges, bury or physically scour (particularly thin-shelled) mussels. Recovery time would be reduced, resulting in reduced abundance and shifts in assemblage. [DM13, Supported]**

- A small flood event (5 to 7 year return interval) redistributed bedload and unionids. Post-flood, individuals were 5 to 15 times more likely to occur within flow refuges than outside of them. Species were abundant in areas where shear stresses during the 3 to 30 year floods are too low to displace them (Strayer 1999).

- A large flood event (> 100 year return interval) resulted in loss of 4 to 8% of the regional mussel population (>50,000 individuals). Increased frequency of this magnitude of flood puts many mussel species at risk (Hastie et al. 2001).
- A large flood event (> 50 year return interval) resulted in significant decreases in the abundance and distribution of unionids, especially those in narrow, high gradient reaches lacking flow refuges (Fraley and Simmons 2006).

● **From winter through summer, during gametogenisis, a decrease in seasonal flow magnitude may reduce temperatures, shifting thermal regimes that cue gamete development and release. Long-term brooders may be particularly sensitive [DM14]**.

- Reproductive success of long-term brooders may be influenced by overwinter flow magnitude (R. Villella, personal communication, 2010).
- Temperatures less than 10 C (and greater than 30 C) limit individual growth (Spooner and Vaughn 2008).
- Both field and lab studies suggest that thermal regimes are important cues for the timing of gamete development and potentially for gamete release. For all species, timing of reproduction was correlated with the number of accumulated degree days (Galbraith and Vaughn 2009).

● **During late fall and winter, a decrease in low flow magnitude and duration may reduce water depth and temperature at a time when mussels have limited ability to move to refugia, resulting in physical stress and potential freezing. This would apply to all mussel groups with *Alasmidonta heterodon* being most sensitive [DM12].**

AQUATIC INSECTS AND CRAYFISH

Summer

Promote macroinvertebrate growth and emergence, abundance and diversity

🔵 **During fall and summer, a change to the magnitude or frequency of flows could cue exit of shredders from headwater systems, resulting in a reduction of energy transformation and export (from CPOM to FPOM) [DA12, Some]**

- Export of fine particulate organic matter from headwater streams was measured during a 5 year period in three catchments. Annual export of FPOM was strongly related to annual discharge. Macroinvertebrate populations were experimentally eliminated in one catchment (insecticides). In this catchment, FPOM concentrations were reduced by an estimated 170 to 200 kg. Macroinvertebrate reduction altered the magnitude of FPOM export during summer and fall storms, the seasonal pattern of export and the total annual export (Wallace et al. 1991).

🔴 **During summer low flow period, decreased low flows can result in network contraction (toward downstream) or contraction of the hyporheic zone, compressing species and thermal gradients [DA4, Moderate]**

- The hyporheic zone acts as refuge for early instars and stream invertebrates during extreme conditions including drought. Exchange between surface water and the hyporheic zone occurs in response to variations in discharge and bed topography (Boulton et al. 1998, Feminella 1996).
- In an Appalachian headwater stream, abundance and taxa richness varied more with depth into the hyporheic zone than among seasons or sites. However, epibenthic and hyporheic community structure varied most among season. Abundance and taxa richness were positively correlated with interstitial flow, especially during the late summer/fall when stream flow was lowest (Angradi et al. 2001).
- Crayfish were found in the hyporheic zone during seasonal summer drying; they did not migrate downstream to avoid desiccation. Hyporheic burrows served as refuge for other invertebrates (DiStefano 2009).

🔴 **During summer and fall, a reduction in low flow magnitude and duration may shift species assemblage (e.g. stenothermal to warm, rheophilic and erosional to depositional, shifts in trophic dominance, dominant trophic habit) [DA5-DA9, Supported]**

- **During the drought of 1999** in the Delaware Basin, noninsect invertebrates (higher tolerance) exhibited a higher relative richness (percentage of the total number of invertebrate species) during the drought year than during low flow years. Insect communities in urbanized settings were less sensitive to change (Fischer et al. 2004).
- A comparison of streams along a withdrawal gradient, **finds direct effects were proportional to the amount of water withdrawn**. Indirect effects were more closely related to change in the

macroinvertebrate community. Changes included decreased relative abundance and shifts from collector-gatherer and filterer to predatory insects, non-insect taxa and scraping beetles (Miller et al. 2007, Brooks et al. 2011).

- In headwaters and creeks, an experimental withdrawal quantifies response between summer flow and macroinvertebrate density, community composition and available habitat. **A threshold seems to occur between summer Q75 and 85** (Walters and Post 2011).
- An experimental **summer flow reduction of 90% of baseflow** resulted in a decrease in EPT taxa (-50%), filter feeding insects (-90%), and grazing insects (-48%) (Wills et al. 2006).
- An experimental **summer flow reduction of 90%** resulted in a decrease in macroinvertebrate density (-57%) and density of EPT taxa (-26%) (Dewson et al. 2007b).
- **Following a drought event**, taxa groups including free-living caddisflies and stoneflies were eliminated. Once rewetted, taxa with limited desiccation tolerance were the last and fewest to recolonize (Boulton 2003)
- In response to decreased low flow magnitudes, there was an increase in the abundance of species with small-body size at maturity (Richards et al. 1997, Apse et al. 2008, Walters and Post 2011).
- A decrease in low flow magnitude resulted in an increase in eurythermal taxa and a decrease in stenothermal taxa (Lake 2003).
- A decrease in low flow magnitude resulted in a decrease in taxonomic richness (Boulton and Suter 1986, Englund and Malmqvist 1996, Wood and Armitage 1999, Wood and Armitage 2004).
- A decrease in low flow magnitude resulted in increased predator densities (Miller et al. 2007, Walters and Post 2011).

Winter

Support winter emergence of aquatic insects and maintain overwinter habitat

- **During winter, a decrease in the magnitude of low flows may alter emergence cues and reduce egg laying habitats for winter emerging insects (winter stoneflies) [A13, Some].**
  - Decreased winter flows have been correlated with anchor ice formation and reduction or elimination of winter emerging stonefly taxa (Clifford 1969, Flannigan 1991).
- **During winter, a decrease in the magnitude of low flows may increase concentration of pollutants, particularly road salts which may have sublethal or lethal impacts to macroinvertebrates [DA14]**
- **During the winter, under low flow conditions, hypolimnetic reservoir releases may increase temperatures, reducing surface ice (thermal buffer) and increasing anchor ice, reducing abundance of macroinvertebrates [DA15]**

Spring

Support spring emergence for aquatic insects and maintain habitats for mating and egg laying

🔵 **During spring and early summer, if high flow frequency or magnitude increases, associated increased velocity may scour aquatic insects from benthic habitats prior to emergence [DA1, Moderate]**

- Gore et al 2001; Holomuzki 2000; Enclada and Peckarsky 2011
- Kennen et al 2009; Kennen et al. 2010; Konrad et al 2008

🟠 **During spring, a reduction of seasonal flows may cause gravel substrates to be armored with fines, reducing the quality of benthic habitat and abundance of sensitive (EPT) aquatic insects [DA2, Some]**

🟠 **During spring and early summer, if the long-term timing or magnitude of seasonal flows shift may result in lost cues for emergence (degree days) and exacerbated chronic conditions characteristic of late summer, resulting in an assemblage shift. Headwaters and creeks may be most sensitive [DA3, Some]**

🔴 **During spring and early summer, if the magnitude of low flows decreases, oviposition sites may decrease, decreasing successful egg development [DA, Some]**

WATER QUALITY, TEMPERATURE and GEOMORPHOLOGY

Summer

Maintain temperature and water quality

● **During summer and fall, a decrease in high flow events may result in cumulative thermal and water quality stress (dissolved oxygen) [W2, Moderate].**

- A regional study found high flow pulses during summer relieved chronic high temperatures and DO sags (Chaplin 2008).
- During summer and fall temperature and dissolved oxygen in surface and subsurface waters – headwater streams most sensitive (Angradi et al 2001).

● **Anytime of year, a loss of headwater contribution (surface and groundwater) to downstream habitats decreases habitat suitability by altering temperatures, potentially increasing temperatures in the summer and decreasing temperatures in the winter** [**W1, W4, W5**]

- Sloto and Buxton 2006; Walters et al. (2010); Dewson et al.(2007)

● **During summer and fall, a decrease in low flow magnitude in proximity to a point source discharge would reduce dilution capacity (effluent ratio) which may exacerbate existing water quality impairments or result in new impairments [W6, Some].**

- During the drought of 1999 (**July streamflows < daily 75th percentile**), total phosphorus concentrations at recurring sampling sites exceeded standards and were higher than in normal and wet years. This is likely due to point-source discharges from waste-water treatment plants which dominate the stream flow at these sites under low flow conditions (Fischer et al. 1994).
- Assimilative capacity for streams is calculated using the 7Q10. Using a set of index gages, the **7Q10 condition occurs between the summer (J, A, S) Q99 and Q93, with most relationships falling between the Q96 and Q98** (USGS 2012).

● **During the summer and fall, reduced magnitude and increased duration of low flows will increase temperature which can increase the presence of algae and diel dissolved oxygen swings outside the range of tolerance for sensitive species [W7, Supported].**

- During the drought of 1999 (July/August) algal growth rates increased as a result of decreased streamflow and increased water temperatures and nutrient concentrations. At seven of the eight streams, diatom species considered tolerant of environmental stress made up higher percentages of the drought samples than in higher flow years (Fischer et al. 2004).
- DRBC (2012); USGS (2004); Bartholow and Heasley (2005)
- Developed a hierarchical model to simulate oxygen dynamics in streams and finding a positive correlation between dissolved oxygen and discharge (Garvey et al. 2007).

Process and transport organic matter

🔵 **During fall and winter, an increase in the magnitude or frequency of high flow events may flush LWD and CPOM resources before they can be processed (shredders), decreasing downstream allochthonous inputs [T1, T2, Some]**

🔴 **From fall through spring, low flows that reduce riffle habitat may reduce leaf breakdown and energy and nutrient cycling [T4, Moderate]**

- Leaves in riffle packs decomposed to 98% within a two week interval. Leaves in depositional settings only decomposed to 75% in a two week interval (Clare 1994).
- Hydraulic habitat including velocity and discharge, were important factors in leaf break down rates (Benfield et al. 2000, Cummins et al. 1980, Meyer 1980).
- Lack of current, burial and reduced numbers of shredders were important factors explaining the difference in breakdown rates in riffles (faster breakdown) vs. pools (Webster and Benfield 1986).

Winter

Maintain ice scour events and floodplain connectivity

🔵 **In late fall and winter, decreased high flows could decrease ice cover, breakup and scour and associated communities with a high fidelity to ice-related scour [DG9, Moderate].**

- The riverine scour vegetation community is found throughout Pennsylvania’s major basins on all stream orders. They are dependent on flood and ice scour and high water velocities (Fike 1999, Eichelberger et al. 2009).
- Five high quality examples of the river scour community occur at the elevation that would be scoured above the February Q48 to the Q66. (Zimmerman et al. 2008, USGS 2012).

🔴 **During winter, decreased magnitude and increased duration of low flow magnitude may lead to development of anchor ice [DG8].**

Spring

Maintain valley and island formation, channel morphology and substrate

🔵 **Anytime of year, a reduced frequency, duration or magnitude of large floods (> 20 year) may reduce floodplain and valley inundation and island formation [DG1, Some]**

- On a regulated river, the number of river islands has been reduced from 14 to 6 in the last 50 years (-67% of island shoreline habitat) as a result of changes to river elevation, hydrology and dredging (Fortney et al. 2001).

🔵 **An increase in the frequency of inter-annual floods (overbank and bankfull flows) may increase bed scour, change dominant substrate type and result in altered channel shape and capacity [DG2]**

- Reports documenting recent flooding on the Delaware;

🔵 **An increase in the frequency or magnitude of high flows (Q10 and greater) in winter can destabilize stream banks (saturation, freezing, and collapse), resulting in increased erosion and sediment loads [DG5]**

🔵 **Anytime of year (mostly winter and spring), reduced frequency of high flow events could alter substrate composition, reducing abundance and distribution of suitable habitat for fish spawning, egg and larval development and macroinvertebrates [DG6, DG4, DG3, Moderate]**

- Regression equations to estimate bankfull discharge for streams in the Appalachian Plateau fall within the **1 in 2 year recurrence interval** (Chaplin et al. 2005).
- **1 in 5 year high flow events are associated with channel maintenance and overbank events** (Nanson and Croke 1992).

🔵 **Any time of year (mostly winter and spring), reduced frequency of high flow events could decrease the recruitment of large woody debris [DG7, Some]**

- **Flood events transport large woody debris**, specifically 'key member' logs which initiate formation of stable bar apex and meander jams that alter the local flow hydraulics leading to pool and bar formation. Individual jams provide interim stability, bank protection and refugia for local forest patches and influence pool intervals and depth (Abbe 1996).

🔴 **During the late summer and early fall, an increase in the duration of low flow conditions may result in accumulation of fine sediment [T3, Some]**

- Dewson et al. 2007, Hakala and Hartman 2004

REPTILES and AMPHIBIANS

Summer

Promote/support development and growth of reptiles and amphibians

- **Anytime of year, in the active channel of the uppermost reaches, if flows are too high, streamside salamander larvae could be scoured. Species with > 1 year larval development stage would be particularly sensitive [DH4, Some]**

- **From winter through early spring, if the frequency, duration or magnitude of high flow events decreases, inundation of vernal pools and intermittent stream beds will decrease, reducing the hydroperiod and success of egg and larval development for amphibians (streamside and mole salamanders) [DH6, Some].**

- **During summer and early fall, a decrease in groundwater contribution may increase stream temperatures, resulting in stress (respiration and thermoregulation) of streamside salamanders [DH1, Some]**

- **Any time of year (predominantly late summer/early fall), a shift or increase frequency of intermittent periods would reduce successful reproduction and growth (food availability) for amphibians and reptiles in headwater settings [DH3, Some]**

- Environmental conditions act as a cue for amphibian breeding. Under dry conditions, it was estimated that 90% of mole salamanders skipped a breeding year (Kinkead 2007).

- Nesting sites of *Desmognathus* are generally found in aquatic habitats including cascading waterfalls, streambeds, stream banks and seepage areas. During a drought (1980), nests were found in high elevation seepages. The clutches were likely laid during flowing water, but lacked flowing water in the brooding chambers when collected. The breadth of viable nesting habitat is greatly increased during average precipitation and hydrologic years (Trauth 1988).

- **During summer and early fall, a decrease in low flow magnitude may decrease suitability of mating and feeding habitats for aquatic reptiles and amphibians [DH7, Moderate]**

- A major drought in South Carolina provided opportunity to observe reproductive and emigration responses of freshwater turtle populations that had been studied for 15 years. Clutch numbers were significantly lower and emigrations were much higher than average in the years preceding the drought. *Sternotherus odoratus*, an aquatic turtle, did not emigrate and ceased reproduction (Gibbons et al. 1983).

Fall

Maintain stable hibernation habitat for reptiles and amphibians

- **From fall through spring, a decrease in seasonal flow magnitude may decrease water temperatures or dewater individual or communal hibernacula for aquatic and semi-aquatic reptiles in stream banks and beds (e.g. wood turtle) [DH2, Supported].**

- During the hibernation period, map and wood turtles need flowing waters (that generally do not freeze) and high DO concentrations (Crocker et al. 2000).
- Wood turtles are only capable of small and slow movements to avoid freezing or poor water quality conditions during the overwinter period (Graham and Forseberg 1991, Kaufmann 1995).
- Wood turtles were surveyed and radio-tracked to monitor location of hibernacula and describe movement during the hibernation period. Wood turtles hibernated on the riverbed at a depth of approximately 1 m and approximately 1m from the riverbank. While air temperatures fluctuated between 10.5 and -40C, thermal buffering provided by flowing water maintained turtle body temperatures near 0 from December through April (Greaves 2007 and 2008).
- Reptiles and amphibians have several behavioral and physiological adaptations to survive freezing temperatures during the hibernation period. Most species rely on hiberation sites capable of buffering winter air temperatures (aquatic) (Storey and Storey 1992).

VEGETATION

Spring

Support establishment and growth of floodplain, riparian and aquatic vegetation

● **During the growing season, if high flow magnitude, duration or frequency are reduced, water availability (inundation days and soil saturation) and disturbance intensity may be reduced, causing a shift in floodplain and riparian community assemblage [DV1, Supported]**

- Using a flood inundation model derived from radar imagery, researchers quantified relationships between forest composition and flooding gradients on the Roanoke River floodplain. They find that **spring high flows are important in driving competitive sorting** especially during the establishment/early succession by limiting competitive advantage of early-season seedlings. Annual hydroperiod affects relative dominance. The elimination of flooding events would promote a homogenization of community composition. Flooding throughout the year, including the dormant period has been demonstrated to affect the ability of plants to maintain the stored reserves that are crucial to survivorship (Townsend 2001).
- The flood regime of the Illinois river has shifted due to regulation, reducing the magnitude and frequency of flood events. This has resulted in a shift in plant communities, including reduced abundance and diversity of many moist-soil species. They use a non-steady state hydraulic model to simulate annual hydrographs of river under different management scenarios to predict moist-soil plant success (Ahn et al. 2004)
- Seasonal flood magnitude and frequency on a Pennsylvania River were reduced by construction and operation of a flood control dam. Researchers found that spring scour is now insufficient to open sites for colonization and later stages of succession are more widely represented. Light regime one of a closed canopy favoring species with life history characteristics atypical of the pre-dam environment (Cowell and Dyer 2002).
- Reservoir operations and irrigation diversion have reduce flood magnitude, frequency and duration, causing sharp declines in pioneer woodland species. Under new hydrologic regime, a model projects replacement communities will be dominated by later successional woodland or grassland species. **A 25 to 50% reduction in spring high flows and mean annual flows** results in riparian encroachment into former channels (Johnson et al. 1998, Johnson et al. 1994).
- Silver maple and Sycamore floodplain forest communities have a high scour disturbance fidelity. Streams with high quality examples of silver maple and sycamore floodplain forest communities occur at elevations **between the Annual .5 and the 62** (Zimmerman et al. 2008, USGS Unpublished data and IHA Analysis).
- Comparing freeflowing to regulated rivers, find that both vegetation community composition and structure changed in response to and altered hydrologic regime. Regulated reaches had increased leaf litter and grass thatch composition compared to naturally flowing reaches. There was also an increased woody species canopy coverage as distance from the stream increased altering light

conditions and reducing successful establishment of rare species in the floodplain (Eldered et al. 2003).

- Regulation of a large river (Salt River, AZ) decreased the frequency and magnitude of overbank floods and changed the seasonal timing of flows with high flows in the summer which reduced the quality of habitat available for Populus regeneration (Fremont cottonwood) (Fenner at al. 1985).
- Riparian assemblages in large rivers are particularly sensitive to changes to the minimum flow and high flow events (Auble et al. 1994).
- Regulation of a large river decreased the frequency and magnitude of overbank floods and changed the seasonal timing of flows with high flows in the summer which reduced the quality of habitat available for Populus regeneration (Fremont cottonwood) (Fenner et al. 1985).
- Plant communities were arrayed along a hydrologic gradient with the Salix community occurring on surfaces with a recurrence interval < 2.2 years and *Betula* and *Alnus* on sites between 2.2 and 4.6 (Friedman et al 2006).

● **During fall and winter, an increase in the frequency and magnitude of high flows may scour SAV and emergent seed beds (at a time when roots are dormant) resulting in a local loss of seedbank (may redistribute elsewhere) [DV3, Some]**

- Quantification of the effects of sediment mobilization and extended inundation on box elder saplings. Two stressor threshold functions from inundation and shear stress. Box elders were either killed by > 85 days of inundation or by shear stress that mobilizes the underlying sediment particles (Friedman and Auble 1999).

● **During late winter and early spring, a reduction of high flow magnitude and duration will reduce extent of water-dispersed seeds and scour and preparation of seed beds reducing availability and moisture of bare mineral soil. [DV4, Supported]**

- Regulated high flows on the Allegheny River have altered the flow regime and led to failure in recruitment of Silver Maple and American sycamore along that portion of the river (Walters and Williams 1999).
- Comparison of riparian and floodplain vegetation communities between a regulated and unregulated river in western Arizona. Recent seedling establishment (saplings established since the 1980's when the dam was constructed) occurred over a wider band along the unregulated stream than the regulated. The 1 in 10 year flood has decreased from 1397 to 148 m3/s (Shafroth et al. 2002).
- Comparing presence of vascular plants with different dispersal mechanisms between free-flowing and regulated river reaches. Find that regulated reaches had a higher proportion of wind-dispersed species and species with generalist dispersal mechanisms (Jansson et al. 2000).
- River bank and bed propagule samples were taken to determine whether species abundance of plant propagules varies in space and time (seasonally) and to what extent patterns of deposition can be attributed to fluvial processes. Highest deposited propagule species richness in late autumn and winter, followed by spring implicates the importance of winter high flows for remobilizing and transporting propagules (Gurnell et al. 2008)
- Seeds of riparian trees including American sycamore, river birch and silver maple, depend on high flows for dispersal (Burns and Honkala 1990).

- Fenner et al 1985; Andersson et al 2000

● **During winter, a reduction in high flow magnitude may reduce ice scour and maintenance of shoreline scour communities [DV5]** *See Ice Scour, High flow need*

● **Year-round, a decrease of high flow frequency and duration may reduce intermediate disturbances necessary to prevent terrestrialization of floodplain and riparian habitats [DV6]**

● **Year-round, a decrease of high flow frequency and duration may alter nutrient biogeochemistry and floodplain soils, mychorrhisal activity and decomposition rates [DV15]**

- Measured litterfall, leaf breakdowns and floodplain litter before and after a flood at twelve sites (inundated and non-inundated). The flood was characterized as a 1 in 5 year flood. Found the flood increased leaf breakdown of all species (families Acer, Plantanus, Juglans and Carpinus). Additionally it transported leaves from the floodplain to the river via entrainment (Netrour 2004).

● **During late spring, early summer, if the timing of baseflows decreases (earlier Julian date), may exacerbate chronic conditions in the late summer and result in reduced abundance and condition of submerged and emergent aquatic vegetation, particularly *Justicia americana* and *Podostemum* [DV7, Moderate]**

- Podostemum grows in fast riffles and runs of relatively undisturbed and unpolluted streams. Beds were reduced in extent and condition under low flow conditions (1991) on the Upper Delaware, Lehigh and Allegheny. Beds typically thrive under normal conditions (Munch 1993, Pers. Comm. Munch 2013).
- Pahl 2009; Davis and Brinson 1980; Wilcox 1995; Chambers et al. 1991

● **Some of the vegetation dynamics may not happen as often in high baseflow streams as in other stream types. High baseflow streams often have very narrow zones for vegetation. There may be species adapted to this flow regime and water chemistry (limestone) [DV8]**

● **During the growing season, if seasonal flow magnitude is decreased, groundwater storage may decrease, lowering the water table and resulting in stress to riparian plant and forest communities [DV9, Moderate]**

- In headwater and small stream settings in Pennsylvania, examined the influence of inundation potential (high, moderate or low probability of seasonal inundation) and forest overstory on species richness, biomass and cover of the summer groundlayer (vascular plants) at six riparian sites. Richness and biomass were significantly greater for high inundation sites. Obligate and facultative wetlands species occurred most often at high inundation sites. Facultative upland, and upland species occurred most often in moderate to low inundation sites. High inundation sites were subject to seasonal inundation (during March and May) and high flow pulses; moderate inundation periodic inundation during seasonal high flows; beyond the influence of normal high stream flows. Sites with high inundation potential support great ground-layer species richness, biomass and cover and a relatively distinct wetland flora compared to mesic floodplains (Williams et al. 1999).
- In a headwater setting, nineteen geomorphic site combinations were grouped according to inundation class (frequent, moderate and low inundation) to determine the influence of flood frequency on seedbank composition. Species composition by growth and form varied across

inundation classes. Forbs dominated seed bank composition for frequently inundated sites. Graminoids and forbs were codominant in the seed banks of moderately inundated sites. Low inundation sites were similar to moderate inundation sites with the addition of woody species. For the extant vegetation, there was a significant difference in occurrence of wetland and upland species across inundation classes with wetland species occurring most often at frequently inundated sites (Hanlon et al. 1998).

- Poiani et al. 1996; Wilcox 1995; Nilsson et al. 1997

● **During summer and fall, increased duration of low flows may reduce water availability in the margins, leading to a decrease in extent and condition of the shoreline scour vegetation community [DV12]**

- Riparian assemblages in large rivers are particularly sensitive to changes to the minimum flow and high flow events (Auble et al. 1994).

● **During summer and fall, increased duration of low flows may increase water temperatures and lead to increased emergent, submerged and algal growth [DV13]** *See Water Quality*

● **During summer and fall, under low flow conditions, below reservoirs, maintenance of low flows can lower summer water temperatures impeding the growth and development of submerged and emergent aquatic vegetation [DV14]**

● **Prolonged or repeated low flows in fall and winter might freeze aquatic tubers (e.g., spadderdock) and increase mortality [DV15]**

BIRDS and MAMMALS

Spring

Provide abundant food sources and maintain feeding and nesting habitat for birds and mammals

🔵 **An increase in the frequency or magnitude of high flow events may destabilize dens of semi-aquatic mammals (like beaver). This species is common in high baseflow and tannic streams [DB1].**

🟠 **A decrease in seasonal flows during the late winter and spring may limit availability of early vegetation (blueberries, sphagnum headwater seep community) and open water used by terrestrial fauna (bears) [DB2, Some].**

- Small mammals including the northern water shrew and many bat species require continuous localized access to an abundance of aquatic insects (Merritt 1987, PNHP 2009).

🔴 **From the later winter through summer, a decrease in low flows may reduce the abundance of aquatic prey and feeding habitats for birds and mammals [DB3, Some].**

- Low flows can reduce aquatic prey availability for birds of prey and wading birds (Brauning 1992).
- Low flows can create land bridges between mainland and island habitats, introducing predators which may threaten rookeries and breeding success (PGC and PFBC 2005).
- Small mammals including the northern water shrew and many bat species require continuous localized access to an abundance of aquatic insects (Merritt 1987, PNHP 2009).

Appendix 7: Using a Weight of Evidence Approach to Document Support for Regionally-Specific Flow Ecology Hypotheses, Needs and Recommendations

The weight-of-evidence approach is built on the idea that one can seldom infer cause and effect from individual ecological studies (Downes et al. 2002). Evidence to support a hypothesis may come from a wide range of ecological studies including observational studies, repeated studies of similar hypothesized relationships in different environments with different study designs and methods, or experimental results from small-scale manipulations in the laboratory or field. None of these types of evidence may be convincing by themselves, but using a causal-criteria analysis, together they can provide numerous lines of evidence that result in strong support for a hypothesis (Norris et al. 2012). Our approach differs slightly from Norris et al. (2012) in that our goals were not only to characterize support for causality for each specific hypotheses, but to characterize support for flow needs and associated flow components. Thus, our goals were to: 1) articulate flow needs through hypothesis generation; 2) use hypotheses to structure a systematic literature review that assessed support for flow needs; and 3) use results to draw conclusions about the relative weight-of-evidence for each flow need.

We used framework presented by Norris et al. 2012 which can grouped into three phases *Problem formulation*, *Literature review*, and *Weighting evidence and judging support*. This approach has been successfully applied to water resource question related to stream sediments and riparian flooding regimes (Greet et al. 2011, Norris et al. 2012).

Problem formulation

For this project, the overarching question is, "*what are the flows needed to protect stream ecosystems within the Delaware River basin?*" Our problem formulation involved using flow-ecology diagrams and life history information in an expert workshop setting to generate more than 100 flow ecology hypotheses that describe ***who*** (species or guild), is affected by ***what*** (flow component), ***when*** (month or season), ***where*** (habitat), and ***how*** (hypothesized ecological response). We then used these hypotheses to develop a conceptual model of general flow needs represented by different seasons and flow components.

Targeted Literature Review

The *Eco Evidence* framework requires that a systematic and documented method for retrieving literature be employed to reduce subjectivity and bias of the reviewer (Greet et al. 2011). Key words (*who, what, when, where, how*) from flow ecology hypotheses were used to develop the literature search and review to test hypotheses and support identified needs for the region. In general, justification for relevance can include a combination of geographic proximity, similar environmental characteristics (i.e. temperate river systems), and similar causal agents (flow component, target species groups). Most relevant publications related to temperate streams of North America that had similar target species or functional groups. Some publications documented responses outside of North America, yet were determined to be relevant were if the taxa or biogeochemical process was expected to have similar responses independent of hydrogeography. Additionally, because we were looking at questions related to variation in the natural flow regime and how organisms respond, we reviewed studies that documented responses to human impacts to flow regimes as well as observations of target species or species groups to natural variation in the flow regime (i.e. responses to drought or flood events). Only studies relevant to the hypotheses were weighted as described below.

Weighting Evidence and Judging Support

Following the *Eco Evidence* framework, we used a rule-based approach to weight individual studies based on the tenet that studies that better account for environmental variation or error should carry more weight in the overall analysis than studies with less robust designs (Norris et al. 2012). For example, inclusion of control or reference sampling units, or data collected before the hypothesized disturbance, as well as the use of gradient-response models, all improve a study's inferential power (Downes et al. 2002). Additional replication provides an estimate of variability around a normal condition, further adding weight to the findings of any difference between treatments or time periods caused by the hypothesized causal agent (Downes et al. 2002). For each relevant study, we evaluated the quality of the evidence based on three attributes:

1. Study design type
2. Number of independent sampling units used as controls
3. Number of potentially impacted independent sampling units

We assessed these three attributes using the scoring criteria presented in Table 1. The combined weights based on all attributes are summed to give an overall study weight for each piece of evidence identified from a study. For example, if a reference vs impact study had 1 reference site and 2 impact sites, the overall study weight would be 2 (design) + 2 (reference site) + 2 (impact site) = 6 (based on criteria in Table 1). In addition to the criteria presented in Table 1, we scored studies that published observational results confirming the relationship between and ecological response and a component of the flow regime. Observational studies were given a weight of 1 (similar to the after impact only score). The weights reflect previously elicited expert opinions about the number of consistent results from high and/or low quality studies that is needed to confidently support a hypothesis (Norris et al. 2012).

Table 1. Weights applied to study types and the number of sampling units (Nichols et al. 2011). B= before, A= after, C= control, R= reference, I= impact, M= multiple. Overall evidence weight is the sum of design weight and replication weight (Norris et al. 2012).

Study design component	Weight
Study design type	
After impact only	1
Reference/control vs impact with no before data	2
Before vs after with no reference/control location(s)	2
Gradient response model	3
BACI, BARI, MBACI, or beyond MBACI	4
Replication of factorial designs	
Number of reference/control sampling units	
0	0
1	2
>1	3
Number of impact/treatment sampling units	
1	0
2	2
>2	3
Replication of gradient-response models	
<4	0
4	2
5	4
>5	6

After assembling and weighting evidence from each relevant paper, we combined it to assess evidence of support for each hypothesis. The method of causal criteria analysis presented by Norris et al. (2012) relies on the causal criterion of the repeated observation of an association between cause and effect under different conditions and assessed using different methods or ‘consistency of association’ (Hill 1967). This is measured simply by comparing the sum of weights for supporting evidence for the hypothesis against the sum of weights against the hypothesis. A default threshold of 20 summed study weight points delineates the point at which sufficient evidence for (or against) the hypothesis. The default 20-point threshold means that ≥ 3 independent, high quality studies are sufficient to conclude that a hypothesis is supported. However, the same conclusions can be met with ≥ 7 low quality studies or a combination of high and low quality studies. The threshold is somewhat analogous to the use of a *p*-value of 0.05 to ascertain statistical significance, and while based on numerous trials and extensive consultation, should be considered more as a convenient division of a continuous score, rather than an unmovable threshold (Norris et al. 2012).