Linking altered flow regimes to stream biological condition in the Chesapeake Bay watershed

16 October 2020

Chesapeake Bay Program Stream Health Working Group

Kelly O. Maloney, Daren M. Carlisle, Claire Buchanan (ICPRB), Jennifer L. Rapp, Samuel H. Austin, Matthew J. Cashman, John A. Young

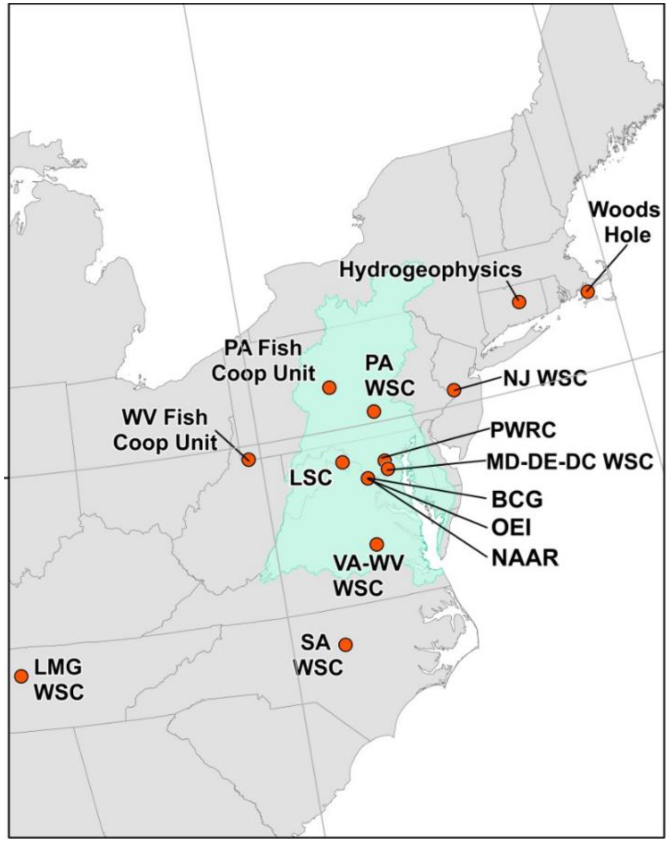
USGS Chesapeake Studies 2020-2025

USGS Role:

- Primary science agency
- Integrated science to inform restoration and conservation decisions

<u>2020:</u>

- New science plan, 2020-25
  - CBP Watershed Agreement
  - Evolving USGS and DOI priorities
- Multiple Mission Areas
  - PES is foundation
- 150 projects
- 13 Science Centers



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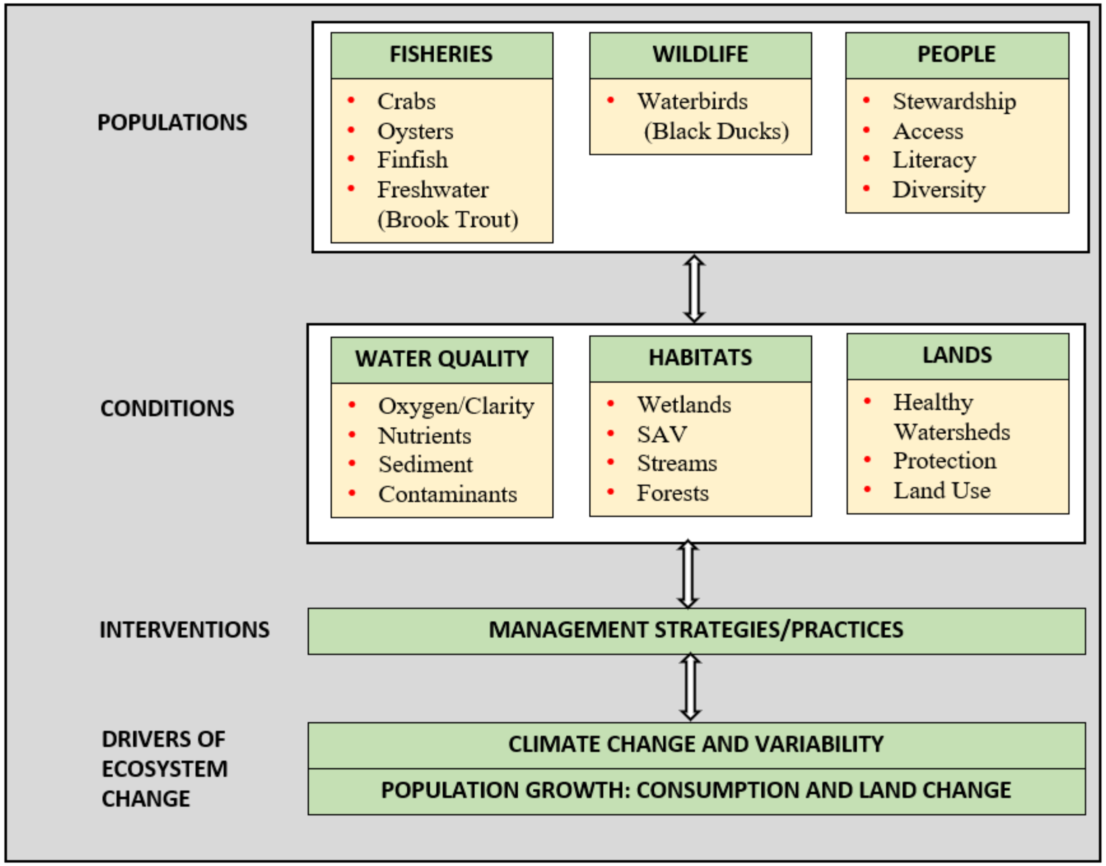
USGS Chesapeake Science Themes

Align CBP needs and USGS capabilities

USGS Themes:

1. Stream health, fish habitat and aquatic conditions
2. Coastal habitats and waterbirds
3. Land change and watershed health
4. Integrate science and inform decisions

CONCEPTUAL DIAGRAM OF CHESAPEAKE BAY ECOSYSTEM



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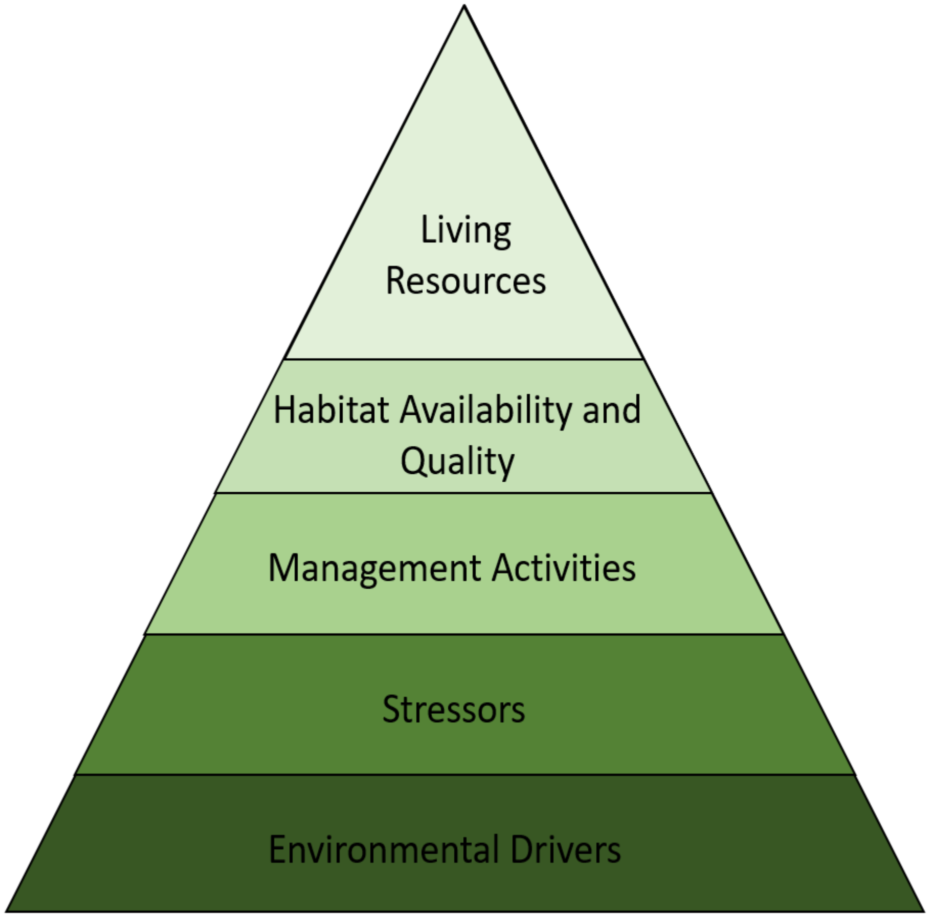
Theme 1: Stream Health, Fish Habitat, and Aquatic Conditions



Focused studies of habitat settings

- Cold Headwaters
- Streams
- Rivers
- Tidal response to watershed inputs

Regional assessments and forecasting

- Stream health
- Fish habitat
- Invasive blue catfish

Status and Trends

- Fish populations and benthic organisms
- Aquatic conditions

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Theme 1A: Focal Studies, *Explain factors and changes in stream health, fish habitats, and aquatic conditions.*

Greg Noe (gnoe@usgs.gov), Kelly Smalling (ksmall@usgs.gov), Jennifer Keisman (jkeisman@usgs.gov)

- **Streams**
  - Summarize what is known about the stressors and drivers affecting stream health in the Watershed
  - Determine effects of BMPs on instream conditions at a variety of settings, scales and temporal resolutions.
- **Cold headwaters**
  - Understanding effects of non-native removal on brook trout and synthesis of findings for the 2025 Brook Trout Outcome
  - Improve prediction of stream temperature in Karst streams
- **Rivers**
  - Identification of factors driving fish populations
  - BMPs effects on fish health and water quality
  - Ecosystem services and economic support
- **Watersheds & Estuaries**
  - Explaining Water-quality trends and response to BMP
  - Understanding tidal-system response to changing watershed conditions

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Theme 1B: Regional Assessments, *Quantitative Stream Condition, Fish Habitat and Fish Health Assessments.*

Stephen Faulkner (faulkners@usgs.gov), Christine Densmore (cdensmore@usgs.gov)

- **Assess relationships, identify stressors affecting stream health and freshwater fish habitats at 1:100K**
  - Regional stream health (Chessie BIBI) and fish habitat assessments with BMPs; evaluate and incorporate additional predictors and biological metrics.
  - Forecasting future climate and land-use scenarios.
  - Incorporate metrics into Healthy Watersheds Assessment (HWA).

- **Refine Assessment Methodology**
  - Evaluate technical approaches and refine assessment methodology in test areas
  - Develop and evaluate high-resolution data for benthic and fish habitat assessments
  - Joint Planning with NOAA

- **Collaborate with partners and stakeholders to better understand science needs related to aquatic invasive species (AIS) and pre-listing/species of listing concern in the Chesapeake Bay and surrounding watershed.**

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Theme 1C: Status and Trends, *Data compilation, integrated monitoring networks and monitoring and computation of status and trends for relevant topics.*

Doug Moyer (dlmoyer@usgs.gov), Kelly Maloney (kmaloney@usgs.gov), Tammy Zimmerman (tmzimmer@usgs.gov)

Domains:

1. Aquatic communities
2. Flow
3. Water temperature
4. Water quality – nutrients and suspended sediment
5. Toxic contaminants
6. Conductivity and associated ions
7. Hydromorphology

Analyses:

1. An evaluation and test of USGS national study of hydrologic alteration
2. Predictive models for Cond. and geomorphic variables at the 1:100,000 scale.
3. Identify variables suited to a S&T analysis and of interest/need to stakeholders.
4. Develop S&T methodology for each variable.
5. Initiate preliminary S&T analyses for variables appropriate to do so.
6. Data sharing and visualization activities.

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Overall Objectives

1) Develop a model to predict flow status (altered or non-altered) for all reaches in the Chesapeake Bay watershed.

2) Link these predictions to a biological endpoint to evaluate if degraded biological stream conditions are more likely in a flow-altered reach.

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USGS National Effort (Eng et al. 2019)

- Quantitative and categorical estimates of hydrologic alteration for twelve HMs for 3,355 USGS gages across contiguous US.
- Observed (O_{hm}) metric values were calculated from daily flow data (1980–2014) from each gage.
- Predicted expected natural value of each HM (E_{hm}) using natural landscape variables and climatic conditions at 848 USGS gaging stations in hydrologically least disturbed watersheds.
- For each of the 3,355 gages, the ratio O_{hm} / E_{hm} was used to categorize hydrologic alteration as “indeterminant” (O_{hm} / E_{hm} within range of site-specific model error), “inflated” (O_{hm} / E_{hm} >1 and outside of model error), or “diminished” (O_{hm} / E_{hm} <1 and outside of model error).

Table 1. The 12 hydrologic metrics assessed in this study.

[P01 is the 1st-percentile non-exceedance flow (PNF); that is, 1 percent of daily flows do not exceed this threshold value. Skew is calculated as the third moment of the daily flows. + indicates the hydrologic metric was found to be associated with ecological impairment by Carlisle and others (2017). * indicates the hydrologic metric was not assessed for biological relevance by Carlisle and others (2017). DA, drainage area; CV, coefficient of variation; <, less than; P10, 10th PNF; P99, 99th PNF; >, greater than; P90, 90th PNF]

Hydrologic metric	Description
	Low flows
Magnitude	P01/DA+
Variability	CV of annual minimum daily flows
Frequency	Average annual number of flow pulses < P10+
Duration	Average annual duration of flow pulses < P10
Timing/seasonality	Seasonal distribution of flows < P10*
	High flows
Magnitude	P99/DA+
Variability	CV of annual maximum daily flows+
Frequency	Average annual number of flow pulses > P90
Duration	Average annual duration of flow pulses > P90
Timing/seasonality	Seasonal distribution of flows > P90*
	Flow symmetry and stochasticity
Skew	Average annual skew of daily flows+
Daily rises	Number of days where flow > previous day/ total number of days+

Eng et al. 2019

USGS

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Methods

- We used a subset of 1,235 gages that were located in four aggregated Level III ecoregions within the Chesapeake Bay watershed.
- We built random forest models for each HM that predict the hydrologic alteration category using drainage area and previously summarized upstream catchment accumulated values (NHDPlus v2.1, 1:100,000 scale) for 15 landscape variables that describe anthropogenic stress related to urban development, agriculture, water usage and augmentation.
- We then used these models to predict hydrologic alteration category for all Chesapeake Bay watershed stream reaches in the NHDPlus v2.1 data set.

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Calculating a Flow Alteration Intensity Score

Methods

- For every reach, each HMs was classified as altered (1) if the model predicted a diminished or inflated flow class, else non-altered (0).
- Flow alteration intensity (FAI) was the sum of these 12 classification and ranged from 0 (no altered HMs) to 12 (all altered HMs).

$$FAI = \sum_{1}^{12} HM\_class$$

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Results - Flow alteration intensity

All but one model were moderately accurate (Kappa > 0.40)

Hydrologic metric	Out of Bag Error Rate	AUC	Accuracy	Kappa
High flow duration	27.75	0.86	0.74	0.60
High flow frequency	31.53	0.83	0.69	0.52
High flow magnitude	29.81	0.81	0.67	0.45
High flow timing/seasonality	34.67	0.82	0.63	0.44
High flow variability	35.64	0.73	0.58	***0.33***
Low flow duration	33.88	0.82	0.66	0.46
Low flow frequency	34.56	0.78	0.64	0.43
Low flow magnitude	33.48	0.80	0.65	0.46
Low flow timing/seasonality	37.04	0.81	0.66	0.48
Low flow variability	36.11	0.78	0.68	0.47
Skew	30.67	0.81	0.67	0.46
Daily rises	31.43	0.79	0.70	0.46

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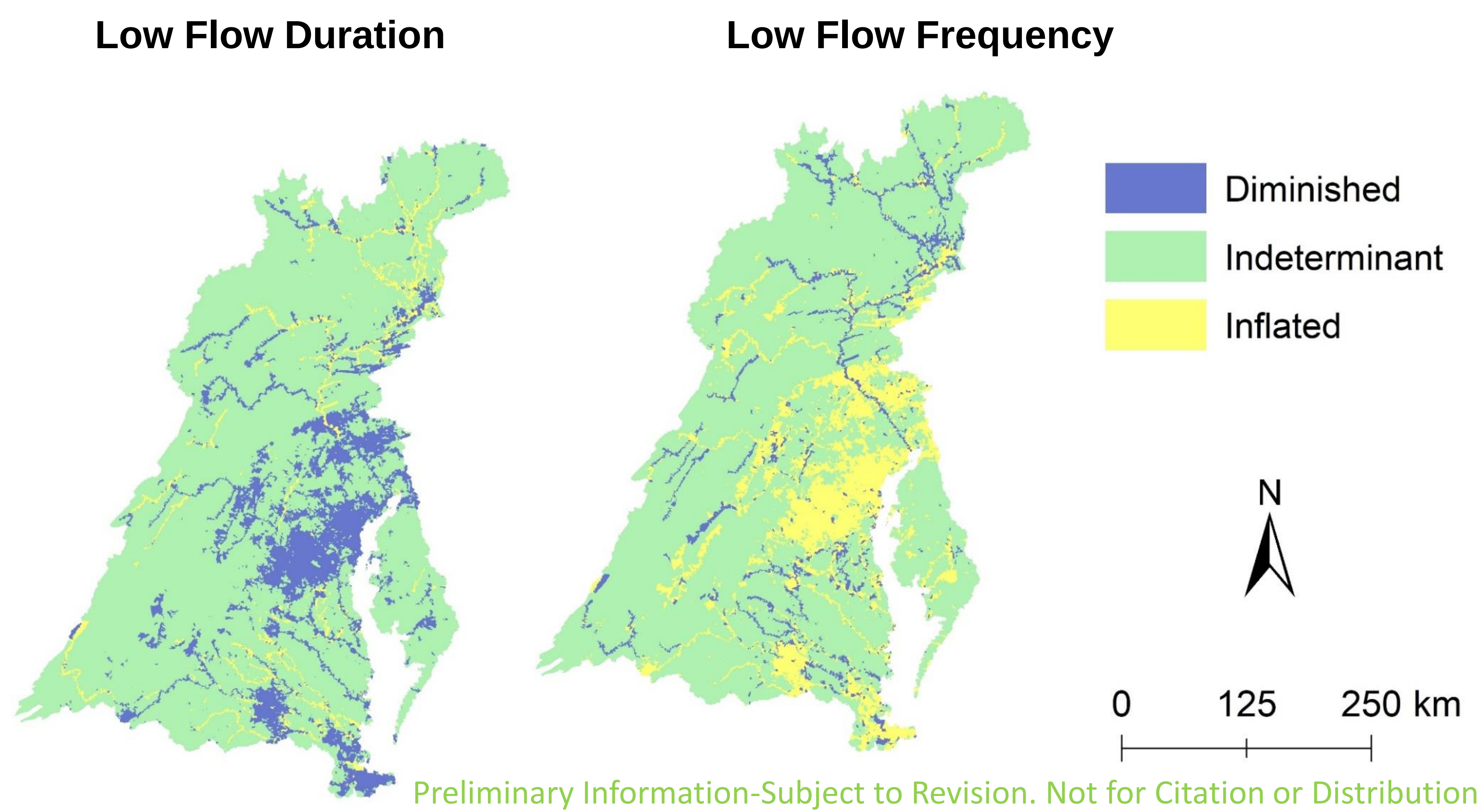
Results - Flow alteration intensity Predictions



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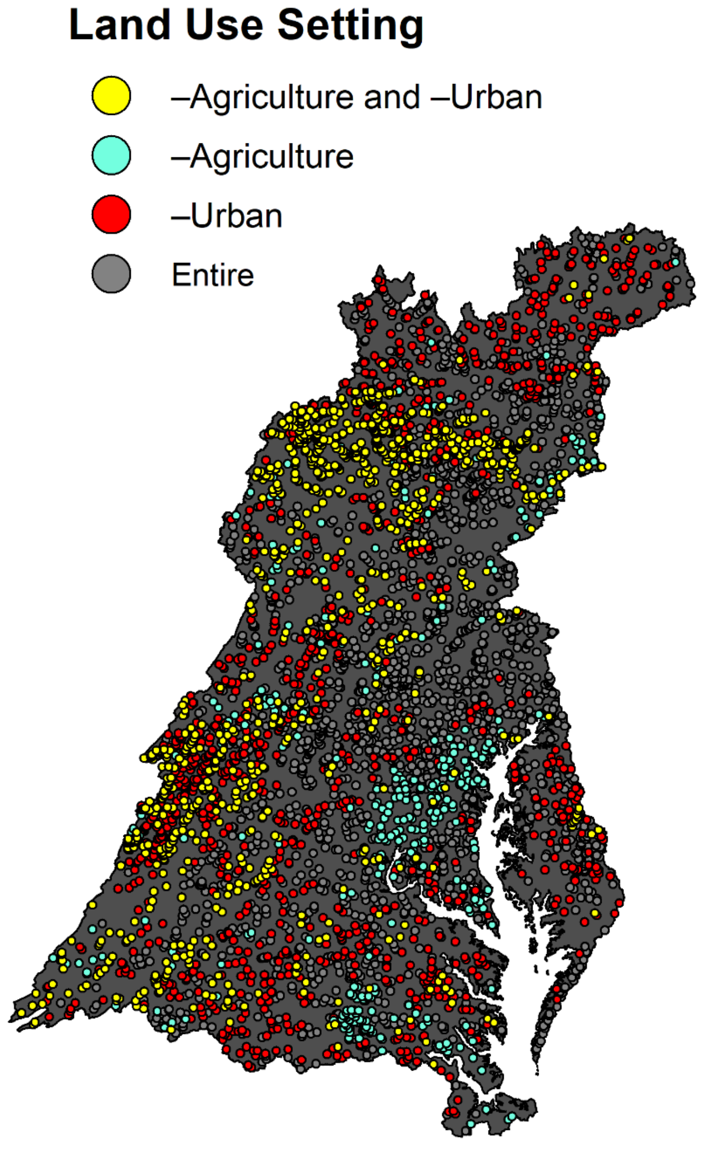
Biology - Methods

- We paired the FAI score to a measure of stream health as defined by benthic macroinvertebrates (Chessie-BIBI).

- We examined if stream reaches with predicted altered flows are more likely to have degraded biological condition in four data sets:

  1. Entire,
  2. Subset w/o urban sites,
  3. Subset w/o agriculture sites,
  4. Subset w/o both urban and agr. sites.



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Analyses

- Contingency tables with odds ratios (Fisher's Exact Test for Count Data) stream condition (Poor or Fair/Good) and FAI score (altered or not-altered) separately for each of the 12 levels for each data set.

- Logistic regression using the entire data set with the 12 Level FAI score, 15 predictor variables used in HM models, bioregion where the Chessie BIBI site resided, and 11 geospatial indicators of natural factors that characterized topography, climate, soil and lithology.

  - Coefficients expressed in terms of odds ratios.

    Odds ratios for categorical predictors indicate how much more likely a degraded condition is in each category relative to a baseline category, and for continuous predictors they infer the number of times more likely a degraded condition is given a unit increase each predictor variable

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Results – FAI, BIBI Contingency Tables

		Entire				–Agriculture				–Urban				–Agriculture and Urban			
		Stream Condition		Fisher's Exact Test		Stream Condition		Fisher's Exact Test		Stream Condition		Fisher's Exact Test		Stream Condition		Fisher's Exact Test	
HM Cutoff	Flow	Not Degr	Degr	p-value	Odds Ratio (95% CI)	Not Degr	Degr	p-value	Odds Ratio (95% CI)	Not Degr	Degr	p-value	Odds Ratio (95% CI)	Not Degr	Degr	p-value	Odds Ratio (95% CI)
1	Not Altered	2252	924	< 2.2e-16	3.8	862	239	< 2.2e-16	8.0	1532	549	0.042	1.7	738	196	0.002	3.0
	Altered	528	818		(3.3-4.3)	83	185		(5.9-10.9)	45	27		(1.0-2.8)	21	17		(1.5-6.2)
2	Not Altered	2390	1067	< 2.2e-16	3.9	878	246	< 2.2e-16	9.5	1556	558	0.01	2.4	748	199	2E-04	4.8
	Altered	390	675		(3.3-4.5)	67	178		(6.9-13.2)	21	18		(1.2-4.7)	11	14		(2.0-11.8)
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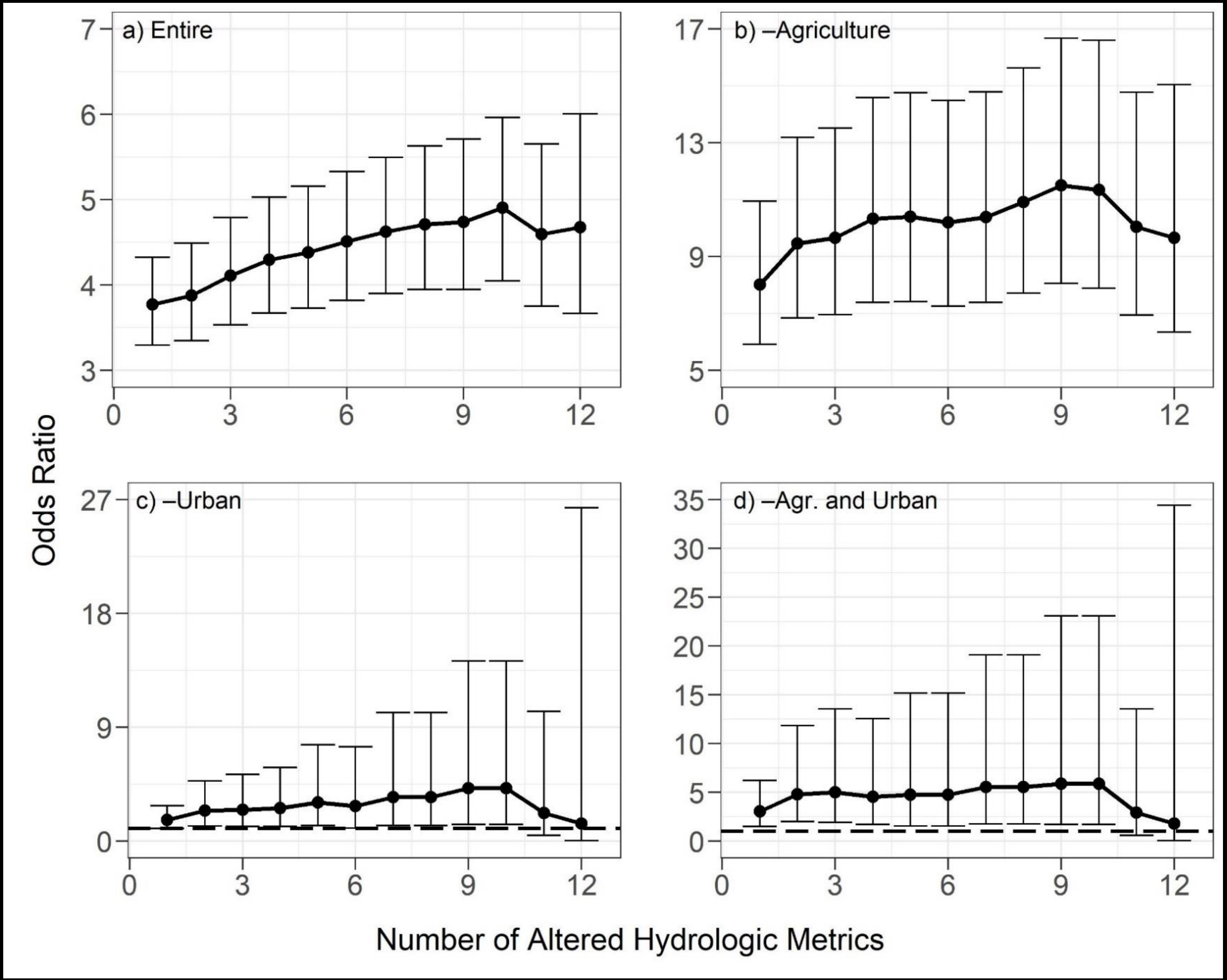
12	Not Altered	2680	1483	< 2.2e-16	4.7	912	314	< 2.2e-16	9.7	1575	575	1	1.4	757	212	0.524	1.8
	Altered	100	259		(3.7-6.0)	33	110		(6.3-15.0)	2	1		(0.02-26.3)	2	1		(0.03-34.4)

Results – FAI, BIBI Contingency Tables



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Results – Logistic regression

The best logistic regression model consisted of 15 predictors, a Nagelkerke R^2 of 0.35, and non-significant Hosmer and Lemshow GOF (p = 0.60) indicating a good fit of the model.

			95% Confidence Interval			Odds Ratio			
Variable	Estimate	Std. Error	Lower	Upper	z value	Estimate	Lower CI	Upper CI	p-value
Intercept	2.0710	0.3725	1.3403	2.8024	5.559	-----	-----	-----	2.71E-08
Flow alteration intensity	0.0420	0.0177	0.0073	0.0766	2.379	1.043	1.007	1.080	0.01737
Bioregion: Central Appalachians	-0.1365	0.3389	-0.7973	0.5334	-0.403	0.872	0.451	1.705	0.687051
Bioregion: Lower-Northern Piedmont	-0.5069	0.3171	-1.1262	0.1189	-1.599	0.602	0.324	1.126	0.109863
Bioregion: Middle Atlantic Coastal Plain	-2.8117	0.4031	-3.6038	-2.0222	-6.976	0.060	0.027	0.132	3.05E-12
Bioregion: Northern Appalachian Plateau and Uplands	-2.0018	0.2902	-2.5679	-1.4278	-6.898	0.135	0.077	0.240	5.26E-12
Bioregion: North Central Appalachians	-0.8195	0.2780	-1.3601	-0.2674	-2.948	0.441	0.257	0.765	0.003202
Bioregion: Northern Ridge and Valley	-1.4928	0.2834	-2.0452	-0.9317	-5.268	0.225	0.129	0.394	1.38E-07
Bioregion: Piedmont	-0.4500	0.3227	-1.0805	0.1866	-1.395	0.638	0.339	1.205	0.16312
Bioregion: Southeastern Plains	-2.6732	0.3392	-3.3383	-2.0065	-7.88	0.069	0.035	0.134	3.27E-15
Bioregion: Southern Great Valley	-0.6595	0.3557	-1.3542	0.0424	-1.854	0.517	0.258	1.043	0.063761
Bioregion: Southern Ridge and Valley	-1.2489	0.2775	-1.7880	-0.6976	-4.501	0.287	0.167	0.498	6.76E-06
Bioregion: Upper-Northern Piedmont	-1.4209	0.3215	-2.0496	-0.7872	-4.419	0.241	0.129	0.455	9.90E-06
Drainage area (km2)	-0.0017	0.0011	-0.0038	0.0004	-1.602	0.998	0.996	1.000	0.109102
Average elevation (m)	-0.0014	0.0004	-0.0022	-0.0007	-3.598	0.999	0.998	0.999	0.00032
Estimated mean depth to water table (m)	0.0189	0.0038	0.0116	0.0264	5.034	1.019	1.012	1.027	4.80E-07
Percent Calcium Oxide in lithology	0.0586	0.0083	0.0424	0.0749	7.08	1.060	1.043	1.078	1.44E-12
Total freshwater withdrawal (megaliters y-1 km-2)	-0.0013	0.0005	-0.0023	-0.0002	-2.397	0.999	0.998	1.000	0.016519
Density of NPDES "major" point locations (No. per 100km-2)	0.0621	0.0404	-0.0002	0.1739	1.537	1.064	1.000	1.190	0.124241
NHD "canal" or "ditch" or "pipeline" segments (%)	-0.0209	0.0142	-0.0528	0.0042	-1.464	0.979	0.949	1.004	0.143311
Percent open water	0.1190	0.0542	0.0264	0.2317	2.195	1.126	1.027	1.261	0.028177
Percent barren land	0.1345	0.0412	0.0559	0.2185	3.265	1.144	1.057	1.244	0.001097
Percent grassland/herbaceous	0.0339	0.0193	-0.0036	0.0720	1.758	1.034	0.996	1.075	0.078695
Percent development	0.0165	0.0046	0.0076	0.0258	3.565	1.017	1.008	1.026	0.000364
Percent wetlands	0.0169	0.0072	0.0028	0.0313	2.339	1.017	1.003	1.032	0.019347
Percent forest	-0.0168	0.0027	-0.0221	-0.0115	-6.239	0.983	0.978	0.989	4.42E-10

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Results – Logistic regression The best logistic regression model consisted of 15 predictors, a Nagelkerke R^2 of 0.35, and non-significant Hosmer and Lemshow GOF ($p = 0.60$) indicating a good fit of the model.

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The flow alteration intensity score had a significant coefficient of 0.0420 and an odds ratio of 1.043 which indicates, controlling for all other predictors, the odds of a degraded macroinvertebrate condition increased 4.3% for every increase in the flow alteration intensity score.

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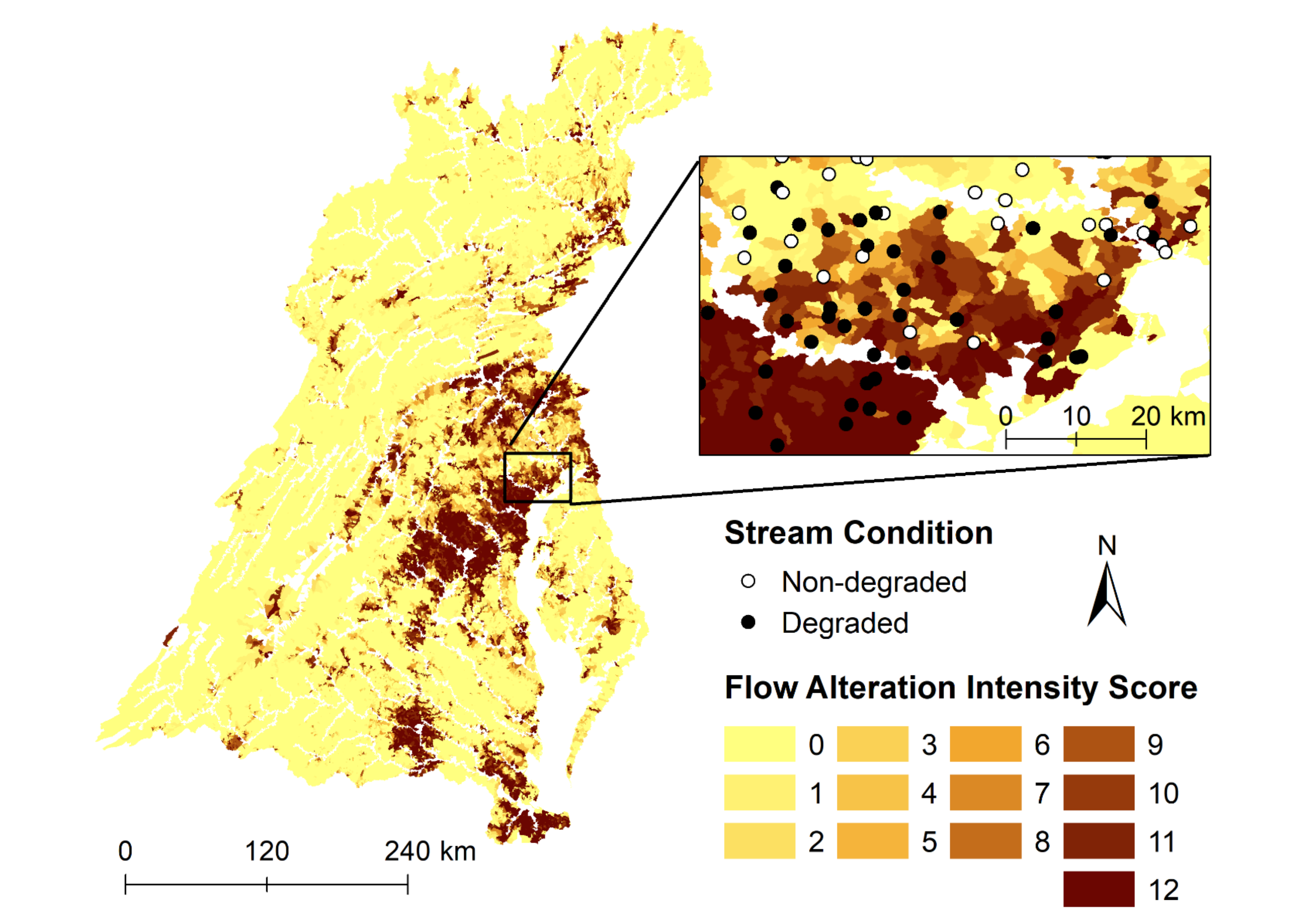
Where are the flow altered sites?



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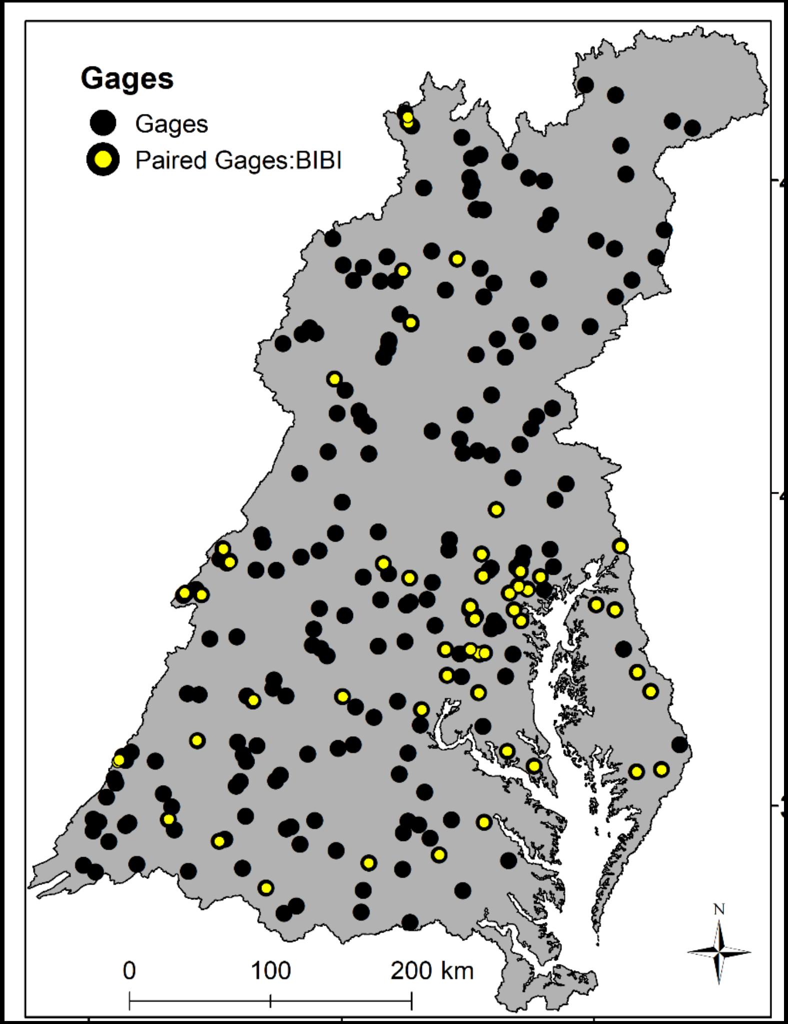
Why not just use paired gage-BIBI sites?

- Of the 247 gages used in Eng et al. 2019, 50 were in small streams and confidently matched with a BIBI point.
- Spatially clustering was apparent (27 within Maryland).
- Limited sample size resulted in weak contingency tables and lack of samples in each bioregion precluded use of logistic regression.



Conclusions

- We built separate random forest models to predict flow status (inclined, diminished, or indeterminant) for 12 published hydrologic metrics (HMs) that characterize main components of flow regimes (duration, frequency, magnitude, timing, and rate of change).

- We used these models to predict each HM status for each stream reach in the watershed, and linked predictions to macroinvertebrate condition samples collected from small streams (<200 km^2 drainage).

- Flow alteration was calculated as the number of HMs with inclined or diminished status and ranged from 0 (no HM with inclined or diminished) to 12 (all 12 HMs with inclined or diminished).

Conclusions

- When focused solely on the stream condition and flow alteration relationship, degraded macroinvertebrate condition was more likely in a flow-altered site for four datasets but depended on number of HMs used (entire: 3.8–4.9, agriculture-removed: 8.0–11.5, urban-removed: 1.7–4.2, and both agriculture and urban removed: 3.0–5.9).

- Logistic regression analysis using the entire dataset showed for every unit increase in flow alteration intensity the odds of a degraded condition increased 4.3%.

- Our results support the importance of flow alteration in small streams and could aid managers challenged with conserving and restoring the multitude of streams without observed flow data.

- Few paired gage and biological samples.

Acknowledgements

- **R: A Language and Environment for Statistical Computing**
- **Andrea Nagel, ICPRB**

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- Anne Arundel County Maryland - Department of Public Works
- City of Baltimore - Department of Public Works
- Baltimore County Department of Environmental Protection
- District of Columbia Department of Energy and Environment
- Delaware Department of Natural Resources and Environmental Control
- Frederick County Department of Public Works
- Fairfax County Department of Public Works and Environmental Services
- Howard County Department of Public Works
- Loudoun County Department of Building and Development
- Montgomery County Department of Environmental Protection
- Maryland Department of Natural Resources
- New York Department of Environmental Conservation
- Pennsylvania Department of Environmental Protection
- Prince George's County Department of the Environment
- Susquehanna River Basin Commission
- United States Environmental Protection Agency
- USDA Forest Service
- United States Geological Survey
- Virginia Department of Environmental Quality
- Virginia Commonwealth University
- West Virginia Department of Environmental Protection