**Supplementary Material for Linking altered flow regimes to biological condition: an example using benthic macroinvertebrates in small streams of the Chesapeake Bay watershed**

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**Supplemental Materials**

Table S1. Summary statistics and description for predictors used in the HM (n =1,235) and Chessie BIBI (training n = 3,391) models and for all reaches in the Chesapeake Bay watershed (n = 82,234). Predictor values from Wieczorek et al. (2018), Bioregion was also included in the Chessie BIBI logistic regression models but is not included in the table. Min. = minimum, Max = maximum, PRISM = Parameter-elevation Regressions on Independent Slopes Model, NPDES = National Pollutant Discharge Elimination System, NHD = National Hydrography Dataset, NLCD = National Land Cover Database.

See separate csv file.

Table S2. Summary statistics for urban and agriculture land cover (2011 National Land Cover Database) by data set. Min = minimum, Max = maximum, Perc. = percentile.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | Urban Cover | | | | | |  | Agriculture Cover | | | | | |
| Data set | n | Mean | Median | Min | Max | 10th Perc. | 90th Perc. |  | Mean | Median | Min | Max | 10th Perc. | 90th Perc. |
| Entire | 4522 | 10.9 | 5.2 | 0.0 | 98.7 | 2.1 | 25.1 |  | 21.6 | 15.5 | 0.0 | 91.3 | 0.3 | 53.9 |
| Agriculture | 955 | 3.6 | 3.8 | 0.0 | 5.0 | 2.2 | 4.8 |  | 22.9 | 17.0 | 5.0 | 91.3 | 7.0 | 49.8 |
| Urban | 300 | 37.0 | 20.0 | 5.0 | 93.7 | 5.4 | 83.1 |  | 1.6 | 1.2 | 0.0 | 5.0 | 0.0 | 4.0 |

Table S3. Results of exploratory non-linear only logistic regression model analyses using the entire data set (n = 3,391 for training and 1,131 as test data set). Reduced models using stepAIC function in R package MASS. Confusion matrices and accuracy statistics for the test data set.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  | Linear Model | |  | Non-linear Model | |
| **Training data set accuracy** |  |  |  |  |  |  |
| Nagelkerke's pseudo R2\* |  | 0.36 | |  | 0.35 | |
| Hosmer and Lemeshow goodness of fit (GOF) test p-value |  | 0.73 | |  | 0.05 | |
|  |  |  |  |  |  |  |
| **Test data set accuracy** |  |  |  |  |  |  |
| Confusion Matrices |  | Observed | |  | Observed | |
|  | Degraded | Not Degraded |  | Degraded | Not Degraded |
| Degraded |  | 267 | 134 |  | 260 | 128 |
| Not Degraded |  | 172 | 558 |  | 179 | 564 |
|  |  |  |  |  |  |  |
| Model Fit and Accuracy Statistics |  |  |  |  |  |  |
| Optimized Threshold |  | 0.45 | |  | 0.45 | |
| Accuracy |  | 0.73 | |  | 0.73 | |
| Kappa |  | 0.42 | |  | 0.42 | |
| AUC |  | 0.77 | |  | 0.77 | |
| Sensitivity |  | 0.61 | |  | 0.59 | |
| Specificity |  | 0.81 | |  | 0.82 | |

Table S4. Number of paired gage and Chessie BIBI sites in each bioregion by flow alteration intensity score estimated using observed hydrologic metrics and modeled hydrologic metrics (in parentheses). For flow alteration intensity, scores of 2, 3, 4, and 6 are not displayed because no sites fell in these levels.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Flow Alteration Intensity | | | | | | | | |
| Bioregion | 0 | 1 | 5 | 7 | 8 | 9 | 10 | 11 | 12 |
| Blue Ridge | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) |
| Central Appalachians | 1 (2) | 0 (0) | 0 (0) | 1 (0) | 0 (0) | 0 (0) | 1 (1) | 0 (0) | 0 (0) |
| Lower-Northern Piedmont | 1 (1) | 0 (1) | 0 (0) | 0 (0) | 1 (1) | 1 (0) | 1 (0) | 0 (0) | 0 (1) |
| Middle Atlantic Coastal Plain | 4 (5) | 0 (1) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 2 (0) | 0 (0) | 0 (0) |
| Northern Appalachian Plateau and Uplands | 0 (0) | 0 (0) | 0 (1) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 2 (1) | 0 (0) |
| North Central Appalachians | 2 (2) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) |
| Northern Ridge and Valley | 2 (2) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) |
| Piedmont | 3 (3) | 0 (0) | 0 (0) | 1 (1) | 0 (0) | 0 (0) | 1 (1) | 0 (0) | 0 (0) |
| Southeastern Plains | 2 (2) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 2 (2) | 5 (4) | 2 (3) |
| Southern Great Valley | 0 (0) | 0 (0) | 0 (0) | 0 (1) | 0 (0) | 0 (0) | 1 (1) | 1 (1) | 1 (0) |
| Southern Ridge and Valley | 2 (2) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 1 (1) | 0 (0) |
| Upper-Northern Piedmont | 2 (2) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 1 (1) | 3 (1) | 3 (4) | 0 (1) |

Table S5. Accuracy statistics for each hydrologic metric for subset of gages with upstream drainage areas <200 km2. OOB = out of bag error rate from models, AUC = area under the receiver operation curve. Bold and italicized indicate a Kappa < 0.41 or a Sensitivity or Specificity score < 0.40.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  | Sensitivity | | |  | Specificity | | |
| Metric | AUC | Accuracy | Kappa | Diminished | Indeterminant | Inflated |  | Diminished | Indeterminant | Inflated |
| HF\_DUR | 0.87 | 0.77 | 0.62 | 0.81 | 0.89 | 0.45 |  | 0.87 | 0.78 | 0.97 |
| HF\_FRE | 0.80 | 0.65 | 0.44 | ***0.37*** | 0.69 | 0.76 |  | 0.91 | 0.68 | 0.85 |
| HF\_MAG | 0.76 | 0.58 | ***0.36*** | 0.42 | 0.73 | 0.56 |  | 0.92 | 0.74 | 0.73 |
| HF\_SEA | 0.78 | 0.69 | 0.47 | 0.81 | 0.80 | ***0.07*** |  | 0.77 | 0.72 | 0.99 |
| HF\_VAR | 0.74 | 0.56 | ***0.32*** | ***0.38*** | 0.75 | 0.47 |  | 0.95 | 0.63 | 0.75 |
| LF\_DUR | 0.85 | 0.76 | 0.59 | 0.78 | 0.86 | ***0.27*** |  | 0.85 | 0.84 | 0.93 |
| LF\_FRE | 0.79 | 0.71 | 0.54 | ***0.31*** | 0.86 | 0.73 |  | 0.90 | 0.77 | 0.89 |
| LF\_MAG | 0.76 | 0.56 | ***0.33*** | ***0.34*** | 0.86 | 0.42 |  | 0.84 | 0.66 | 0.83 |
| LF\_SEA | 0.76 | 0.67 | 0.46 | 0.70 | 0.85 | ***0.19*** |  | 0.76 | 0.76 | 0.94 |
| LF\_VAR | 0.74 | 0.63 | ***0.40*** | 0.57 | 0.80 | ***0.25*** |  | 0.83 | 0.74 | 0.85 |
| SKEW | 0.75 | 0.57 | ***0.32*** | ***0.25*** | 0.77 | 0.55 |  | 0.95 | 0.65 | 0.72 |
| RISES | 0.79 | 0.66 | 0.47 | 0.53 | 0.87 | 0.53 |  | 0.87 | 0.73 | 0.89 |

Table S6. Confusion matrices for observed and predicted flow alteration for each of the 12 hydrologic metrics for all sites and subset of sites with upstream drainages <200 km2. Bold and italicized highlight rows where misclassified predictions were higher than correctly classified.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | Predicted Flow Alteration | | | | | | |
| Hydrologic Metric | Observed Flow Alteration |  | All sites |  |  | Only sites <200 km2 upstream drainage | | |
| Diminished | Indeterminant | Inflated |  | Diminished | Indeterminant | Inflated |
| HF\_DUR | Diminished | 53 | 7 | 16 |  | 35 | 3 | 4 |
|  | Indeterminant | 15 | 72 | 17 |  | 7 | 31 | 7 |
|  | Inflated | 10 | 15 | 104 |  | 1 | 1 | 9 |
| HF\_FRE | Diminished | 98 | 20 | 18 |  | ***7*** | ***7*** | ***0*** |
|  | Indeterminant | 19 | 70 | 21 |  | 9 | 29 | 9 |
|  | Inflated | 9 | 9 | 45 |  | 3 | 6 | 28 |
| HF\_MAG | Diminished | 123 | 24 | 9 |  | 15 | 3 | 2 |
|  | Indeterminant | 21 | 71 | 9 |  | 8 | 32 | 6 |
|  | Inflated | ***21*** | ***14*** | ***17*** |  | ***13*** | ***9*** | ***10*** |
| HF\_SEA | Diminished | 66 | 23 | 15 |  | 34 | 8 | 5 |
|  | Indeterminant | 21 | 78 | 16 |  | 7 | 33 | 9 |
|  | Inflated | 11 | 25 | 54 |  | ***1*** | ***0*** | ***1*** |
| HF\_VAR | Diminished | 96 | 26 | 16 |  | 14 | 3 | 0 |
|  | Indeterminant | 20 | 70 | 15 |  | 11 | 33 | 9 |
|  | Inflated | ***30*** | ***16*** | ***20*** |  | ***12*** | ***8*** | ***8*** |
| LF\_DUR | Diminished | 112 | 15 | 9 |  | 39 | 5 | 3 |
|  | Indeterminant | 22 | 73 | 9 |  | 5 | 38 | 5 |
|  | Inflated | ***31*** | ***14*** | ***23*** |  | ***6*** | ***1*** | ***3*** |
| LF\_FRE | Diminished | ***24*** | ***17*** | ***21*** |  | ***5*** | ***3*** | ***5*** |
|  | Indeterminant | 14 | 68 | 14 |  | 7 | 32 | 7 |
|  | Inflated | 22 | 14 | 115 |  | 4 | 2 | 33 |
| LF\_MAG | Diminished | 36 | 8 | 23 |  | ***10*** | ***2*** | ***9*** |
|  | Indeterminant | 16 | 72 | 17 |  | 11 | 31 | 10 |
|  | Inflated | 21 | 18 | 98 |  | 8 | 3 | 14 |
| LF\_SEA | Diminished | 105 | 12 | 28 |  | 30 | 5 | 8 |
|  | Indeterminant | 15 | 70 | 18 |  | 9 | 33 | 5 |
|  | Inflated | 11 | 18 | 32 |  | ***4*** | ***1*** | ***3*** |
| LF\_VAR | Diminished | 122 | 18 | 15 |  | 24 | 6 | 5 |
|  | Indeterminant | 17 | 76 | 16 |  | 8 | 40 | 7 |
|  | Inflated | ***19*** | ***12*** | ***14*** |  | ***10*** | ***4*** | ***4*** |
| SKEW | Diminished | 116 | 25 | 6 |  | 6 | 2 | 2 |
|  | Indeterminant | 24 | 72 | 15 |  | 7 | 33 | 12 |
|  | Inflated | ***18*** | ***12*** | ***21*** |  | ***11*** | ***8*** | ***17*** |
| RISES | Diminished | ***8*** | ***9*** | ***16*** |  | ***8*** | ***1*** | ***10*** |
|  | Indeterminant | 9 | 71 | 28 |  | 5 | 33 | 11 |
|  | Inflated | 12 | 22 | 134 |  | 2 | 4 | 24 |

Table S7. Results of Fisher’s Exact Test for each data set for each level of the flow alteration intensity score depicting the odds of a degraded macroinvertebrate condition in a flow-altered site. Not Degr. = Not Degraded, Degr. = Degraded, NA = Fisher’s Exact test not run due to 0 flow-altered sites.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | Entire | | | | |  | Urban | | | | |  | Agriculture | | | | |
| HM Cutoff |  | Stream Condition | |  | Fisher's Exact Test | |  | Stream Condition | |  | Fisher's Exact Test | |  | Stream Condition | |  | Fisher's Exact Test | |
| Flow | Not Degr. | Degr. |  | p-value | Odds Ratio |  | Not Degr. | Degr. |  | p-value | Odds Ratio |  | Not Degr. | Degr. |  | p-value | Odds Ratio |
| 1 | Not Altered | 2253 | 913 |  | < 2.2e-16 | 3.9 |  | 111 | 39 |  | < 2.2e-16 | 8.9 |  | 640 | 299 |  | 1 | 1.0 |
|  | Altered | 527 | 829 |  |  | (3.4 - 4.4) |  | 36 | 114 |  |  | (5.2 - 15.7) |  | 11 | 5 |  |  | (0.3 - 3.1) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 2 | Not Altered | 2390 | 1071 |  | < 2.2e-16 | 3.8 |  | 114 | 41 |  | < 2.2e-16 | 9.4 |  | 648 | 302 |  | 0.6559 | 1.4 |
|  | Altered | 390 | 671 |  |  | (3.3 - 4.4) |  | 33 | 112 |  |  | (5.4 - 16.6) |  | 3 | 2 |  |  | (0.1 - 12.5) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 3 | Not Altered | 2429 | 1101 |  | < 2.2e-16 | 4.0 |  | 115 | 41 |  | < 2.2e-16 | 9.7 |  | 648 | 303 |  | 1 | 0.7 |
|  | Altered | 351 | 641 |  |  | (3.5-4.7) |  | 32 | 112 |  |  | (5.6 - 17.3) |  | 3 | 1 |  |  | (0.01 - 8.9) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 4 | Not Altered | 2461 | 1130 |  | < 2.2e-16 | 4.2 |  | 116 | 41 |  | < 2.2e-16 | 10.1 |  | 650 | 303 |  | 0.5355 | 2.1 |
|  | Altered | 319 | 612 |  |  | (3.6- 4.9) |  | 31 | 112 |  |  | (5.8 - 18.1) |  | 1 | 1 |  |  | (0.03 - 168.4) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 5 | Not Altered | 2488 | 1159 |  | < 2.2e-16 | 4.3 |  | 116 | 42 |  | < 2.2e-16 | 9.8 |  | 650 | 304 |  | 1 | 0.0 |
|  | Altered | 292 | 583 |  |  | (3.7 - 5.0) |  | 31 | 111 |  |  | (5.6 - 17.5) |  | 1 | 0 |  |  | (0.0 - 83.4) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 6 | Not Altered | 2508 | 1179 |  | < 2.2e-16 | 4.4 |  | 118 | 42 |  | < 2.2e-16 | 10.6 |  | 651 | 304 |  | 1 | NA |
|  | Altered | 272 | 563 |  |  | (3.7 - 5.2) |  | 29 | 111 |  |  | (6.1 - 19.2) |  | 0 | 0 |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 7 | Not Altered | 2532 | 1205 |  | < 2.2e-16 | 4.5 |  | 119 | 43 |  | < 2.2e-16 | 10.8 |  | 651 | 304 |  | 1 | NA |
|  | Altered | 248 | 537 |  |  | (3.8 - 5.4) |  | 28 | 110 |  |  | (6.1 - 19.4) |  | 0 | 0 |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 8 | Not Altered | 2553 | 1242 |  | < 2.2e-16 | 4.5 |  | 119 | 44 |  | < 2.2e-16 | 10.4 |  | 651 | 304 |  | 1 | NA |
|  | Altered | 227 | 500 |  |  | (3.8 - 5.4) |  | 28 | 109 |  |  | (5.9 - 18.8) |  | 0 | 0 |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 9 | Not Altered | 2578 | 1275 |  | < 2.2e-16 | 4.7 |  | 120 | 46 |  | < 2.2e-16 | 10.2 |  | 651 | 304 |  | 1 | NA |
|  | Altered | 202 | 467 |  |  | (3.9 - 5.6) |  | 27 | 107 |  |  | (5.8 -18.5) |  | 0 | 0 |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 10 | Not Altered | 2599 | 1318 |  | < 2.2e-16 | 4.6 |  | 123 | 53 |  | < 2.2e-16 | 9.6 |  | 651 | 304 |  | 1 | NA |
|  | Altered | 181 | 424 |  |  | (3.8 -5.6) |  | 24 | 100 |  |  | (5.4 - 17.5) |  | 0 | 0 |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 11 | Not Altered | 2626 | 1377 |  | < 2.2e-16 | 4.5 |  | 126 | 62 |  | 2.36E-16 | 8.7 |  | 651 | 304 |  | 1 | NA |
|  | Altered | 154 | 365 |  |  | (3.7 - 5.6) |  | 21 | 91 |  |  | (4.9 - 16.2) |  | 0 | 0 |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 12 | Not Altered | 2672 | 1474 |  | < 2.2e-16 | 4.5 |  | 133 | 77 |  | 7.04E-15 | 9.3 |  | 651 | 304 |  | 1 | NA |
|  | Altered | 108 | 268 |  |  | (3.5 - 5.7) |  | 14 | 76 |  |  | (4.8 - 19.1) |  | 0 | 0 |  |  |  |

Table S8. Results of logistic regression model using the entire data set (training data set, n = 3,391), Bold and italicized highlight predictors significant at p = 0.05. Blue Ridge is the default contrast for Bioregion in the model. Dashed line (-----) indicates Odds Ratio not calculated.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Variable | Estimate | Std. Error | Lower | Upper | z value | Estimate | Lower CI | Upper CI | p-value |
| Intercept | -0.6574 | 0.6884 | -2.0088 | 0.6910 | -0.955 | **-----** | **-----** | **-----** | 0.339594 |
| Flow alteration intensity | **0.0367** | **0.0179** | **0.0016** | **0.0718** | **2.052** | **1.037** | **1.002** | **1.074** | **0.040164** |
| Bioregion: Central Appalachians | 0.0259 | 0.3794 | -0.7148 | 0.7744 | 0.068 | 1.026 | 0.489 | 2.169 | 0.94551 |
| Bioregion: Lower-Northern Piedmont | -0.4841 | 0.3209 | -1.1110 | 0.1492 | -1.508 | 0.616 | 0.329 | 1.161 | 0.131494 |
| Bioregion: Middle Atlantic Coastal Plain | **-2.7433** | **0.4885** | **-3.7040** | **-1.7876** | **-5.616** | **0.064** | **0.025** | **0.167** | **1.95E-08** |
| Bioregion: Northern Appalachian Plateau and Uplands | **-1.9121** | **0.3356** | **-2.5681** | **-1.2507** | **-5.698** | **0.148** | **0.077** | **0.286** | **1.21E-08** |
| Bioregion: North Central Appalachians | **-0.7374** | **0.3308** | **-1.3825** | **-0.0837** | **-2.229** | **0.478** | **0.251** | **0.920** | **0.025802** |
| Bioregion: Northern Ridge and Valley | **-1.2998** | **0.3195** | **-1.9237** | **-0.6689** | **-4.068** | **0.273** | **0.146** | **0.512** | **4.74E-05** |
| Bioregion: Piedmont | -0.3099 | 0.3498 | -0.9945 | 0.3788 | -0.886 | 0.733 | 0.370 | 1.461 | 0.375655 |
| Bioregion: Southeastern Plains | **-2.4589** | **0.4274** | **-3.2985** | **-1.6211** | **-5.753** | **0.086** | **0.037** | **0.198** | **8.75E-09** |
| Bioregion: Southern Great Valley | -0.4345 | 0.3756 | -1.1688 | 0.3058 | -1.157 | 0.648 | 0.311 | 1.358 | 0.247369 |
| Bioregion: Southern Ridge and Valley | **-1.0843** | **0.3143** | **-1.6965** | **-0.4622** | **-3.450** | **0.338** | **0.183** | **0.630** | **0.000561** |
| Bioregion: Upper-Northern Piedmont | **-1.4166** | **0.3305** | **-2.0631** | **-0.7655** | **-4.286** | **0.243** | **0.127** | **0.465** | **1.82E-05** |
| Drainage area | **-0.0021** | **0.0011** | **-0.0043** | **0.0000** | **-1.962** | **0.998** | **0.996** | **1.000** | **0.049789** |
| Elevation | **-0.0012** | **0.0004** | **-0.0020** | **-0.0004** | **-2.889** | **0.999** | **0.998** | **1.000** | **0.003863** |
| Clay soils | -0.0144 | 0.0101 | -0.0343 | 0.0055 | -1.421 | 0.986 | 0.966 | 1.005 | 0.155307 |
| Estimated mean depth to water table | **0.0171** | **0.0039** | **0.0095** | **0.0249** | **4.344** | **1.017** | **1.010** | **1.025** | **1.40E-05** |
| Percent Calcium Oxide in lithology | **0.0585** | **0.0090** | **0.0408** | **0.0762** | **6.481** | **1.060** | **1.042** | **1.079** | **9.09E-11** |
| Topographic wetness index | 0.0647 | 0.0428 | -0.0192 | 0.1487 | 1.511 | 1.067 | 0.981 | 1.160 | 0.130751 |
| Uniaxial Compressive Strength (UCS) | 0.0031 | 0.0021 | -0.0009 | 0.0072 | 1.510 | 1.003 | 0.999 | 1.007 | 0.131153 |
| Freshwater withdrawal | **-0.0013** | **0.0005** | **-0.0024** | **-0.0003** | **-2.535** | **0.999** | **0.998** | **1.000** | **0.011242** |
| Density NPDES locations | 0.0661 | 0.0418 | 0.0028 | 0.1801 | 1.581 | 1.068 | 1.003 | 1.197 | 0.113774 |
| Canal/ditch/pipeline | -0.0214 | 0.0143 | -0.0534 | 0.0037 | -1.500 | 0.979 | 0.948 | 1.004 | 0.133506 |
| Open water | **0.1592** | **0.0568** | **0.0580** | **0.2748** | **2.805** | **1.173** | **1.060** | **1.316** | **0.005036** |
| Barren land | **0.1471** | **0.0412** | **0.0684** | **0.2309** | **3.573** | **1.158** | **1.071** | **1.260** | **0.000353** |
| Shrub/scrub | 0.0354 | 0.0207 | -0.0059 | 0.0753 | 1.712 | 1.036 | 0.994 | 1.078 | 0.086834 |
| Grassland/herbaceous | **0.0540** | **0.0200** | **0.0152** | **0.0937** | **2.706** | **1.055** | **1.015** | **1.098** | **0.006819** |
| Development | **0.0375** | **0.0050** | **0.0278** | **0.0475** | **7.452** | **1.038** | **1.028** | **1.049** | **9.22E-14** |
| Agriculture | **0.0197** | **0.0033** | **0.0132** | **0.0262** | **5.921** | **1.020** | **1.013** | **1.027** | **3.20E-09** |
| Wetlands | **0.0371** | **0.0079** | **0.0217** | **0.0528** | **4.689** | **1.038** | **1.022** | **1.054** | **2.74E-06** |

Table S9. Results of Fisher’s Exact Test for the paired gage and Chessie BIBI sites (n = 50) for each of the 12 hydrologic metrics depicting the odds of a degraded macroinvertebrate condition in a flow-altered site.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Hydrologic Metric | Flow | Observed HM data | | | | |  | Modeled HM data | | | | |
| Stream Condition | |  | Fisher's Exact Test | |  | Stream Condition | |  | Fisher's Exact Test | |
| Not Degraded | Degraded |  | p-value | Odds Ratio |  | Not Degraded | Degraded |  | p-value | Odds Ratio |
| HF\_DUR | Not Altered | 14 | 12 |  | 0.1663 | 2.3 |  | 15 | 9 |  | 0.1713 | 2.2 |
|  | Altered | 8 | 16 |  |  | (0.6-8.6) |  | 11 | 15 |  |  | (0.6-8.2) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| HF\_REF | Not Altered | 15 | 11 |  | 0.09839 | 2.7 |  | 16 | 10 |  | 0.2571 | 2.2 |
|  | Altered | 8 | 16 |  |  | (0.8-10.1) |  | 10 | 14 |  |  | (0.6-8.1) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| HF\_MAG | Not Altered | 14 | 12 |  | 0.7775 | 1.4 |  | 16 | 9 |  | 0.1564 | 2.6 |
|  | Altered | 11 | 13 |  |  | (0.4-4.8) |  | 10 | 15 |  |  | (0.7-9.8) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| HF\_SEA | Not Altered | 14 | 12 |  | 0.272 | 1.9 |  | 16 | 9 |  | 0.1564 | 2.6 |
|  | Altered | 9 | 15 |  |  | (0.5-7.0) |  | 10 | 15 |  |  | (0.7-9.8) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| HF\_VAR | Not Altered | 14 | 12 |  | 0.4129 | 1.6 |  | 18 | 12 |  | 0.2484 | 2.2 |
|  | Altered | 10 | 14 |  |  | (0.5-5.8) |  | 8 | 12 |  |  | (0.6-8.4) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| LF\_DUR | Not Altered | 13 | 13 |  | 0.1588 | 2.4 |  | 16 | 8 |  | 0.0546 | 3.1 |
|  | Altered | 7 | 17 |  |  | (0.7-9.3) |  | 10 | 16 |  |  | (0.9-12.0) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| LF\_FRE | Not Altered | 13 | 13 |  | 0.265 | 2.0 |  | 17 | 8 |  | **0.0465** | 3.7 |
|  | Altered | 8 | 16 |  |  | (0.6-7.4) |  | 9 | 16 |  |  | (1.0-14.4) |

Table S9 continued.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Hydrologic Metric | Flow | Observed HM data | | | | |  | Modeled HM data | | | | |
| Stream Condition | |  | Fisher's Exact Test | |  | Stream Condition | |  | Fisher's Exact Test | |
| Not Degraded | Degraded |  | p-value | Odds Ratio |  | Not Degraded | Degraded |  | p-value | Odds Ratio |
| LF\_MAG | Not Altered | 14 | 12 |  | 0.775 | 1.4 |  | 17 | 12 |  | 0.3905 | 1.9 |
|  | Altered | 11 | 13 |  |  | (0.4-4.8) |  | 9 | 12 |  |  | (0.5-6.9) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| LF\_SEA | Not Altered | 14 | 12 |  | 0.272 | 1.9 |  | 16 | 10 |  | 0.2571 | 2.2 |
|  | Altered | 9 | 15 |  |  | (0.5-7.0) |  | 10 | 14 |  |  | (0.6-8.1) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| LF\_VAR | Not Altered | 14 | 12 |  | 0.4129 | 1.6 |  | 17 | 11 |  | 0.2542 | 2.2 |
|  | Altered | 10 | 14 |  |  | (0.5-5.8) |  | 9 | 13 |  |  | (0.6-8.1) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| SKEW | Not Altered | 19 | 7 |  | **0.04378** | 3.7 |  | 20 | 12 |  | 0.0765 | 3.3 |
|  | Altered | 10 | 14 |  |  | (1.0-14.8) |  | 6 | 12 |  |  | (0.9-13.6) |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| RISES | Not Altered | 13 | 13 |  | 0.5835 | 1.4 |  | 15 | 11 |  | 0.5716 | 1.6 |
|  | Altered | 10 | 14 |  |  | (0.4-5.0) |  | 11 | 13 |  |  | (0.5-5.7) |

A screenshot of a video game

Description automatically generated

Figure S1. Distribution of upstream drainage area for gages used to build random forest models for each hydrologic metric by aggregated Level III ecoregion.

Map

Description automatically generated

Figure S2. Map showing clustering of Chesapeake Bay Basin-wide Index of Biotic Integrity data for Maryland and Fairfax and Loudoun Counties (border highlighted in red) for Chesapeake Bay Watershed.

Diagram, engineering drawing

Description automatically generatedFigure S3. Partial dependence plots of the top three important predictors, from top to bottom, in each random forest model for the five high-flow hydrologic metrics. Partial dependence plots show the marginal effect of the selected predictor on the probability of an Indeterminant flow classification.

Diagram, engineering drawing

Description automatically generated

Figure S4. Partial dependence plots of the top three important predictors, from top to bottom, in each random forest model for the five low-flow hydrologic metrics. Partial dependence plots show the marginal effect of the selected predictor on the probability of an Indeterminant flow classification.

Diagram, engineering drawing, schematic

Description automatically generated

Figure S5. Partial dependence plots of the top three important predictors, from top to bottom, in each random forest model for skew (SKEW) and rises (RISES). Partial dependence plots show the marginal effect of the selected predictor on the probability of an Indeterminant flow classification.

Map

Description automatically generated

Figure S6. Maps showing spatial distribution of altered flow categories for the five high-flow hydrologic metrics for the Chesapeake Bay watershed. (See Table 1 for hydrologic metric definitions).

Map

Description automatically generated

Figure S7. Maps showing spatial distribution of altered flow categories for the five low-flow hydrologic metrics for the Chesapeake Bay watershed. (See Table 1 for hydrologic metric definitions).

A picture containing map

Description automatically generated

Figure S8. Maps showing spatial distribution of altered flow categories for the two symmetry and stochasticity hydrologic metrics for the Chesapeake Bay watershed. (See Table 1 for hydrologic metric definitions).

Chart, radar chart

Description automatically generated

Figure S9. Ternary plot showing gages used in random forest models by urban, agriculture, and forest covers. Size and color of circle represents drainage size. Figures created using the ggtern R package and function (Hamilton and Ferry, 2018).

Diagram

Description automatically generatedFigure S10. Ternary plot showing gages on small stream reaches (< 200 km2 upstream drainage) by urban, agriculture, and forest covers. Size and color of circle represents drainage size. Figures created using the ggtern R package and function (Hamilton and Ferry, 2018).

Map

Description automatically generatedFigure S11. Maps showing spatial representation of A) the depth to water table, B) percent wetland cover, C) total freshwater withdrawals, and D) calcium oxide in lithology for catchments with upstream drainages < 200 km2 (small streams) for the Chesapeake Bay watershed.

A picture containing lettuce

Description automatically generated

Figure S12. Map showing calcium oxide in lithology with karst geology overlain for the Chesapeake Bay watershed.

**References for supplements**

Hamilton NE, Ferry M (2018). ggtern: Ternary Diagrams Using ggplot2. Journal of Statistical Software, Code Snippets, 87(3), 1-17. doi: 10.18637/jss.v087.c03 (URL: https://doi.org/10.18637/jss.v087.c03).