Appendix 9A: Stream to River

During the development of the Phase 6 Watershed Model, multiple methods for determining coefficients were often attempted. In some cases, the methods are averaged or otherwise combined. In cases where one method is clearly superior to others, a single method is used, and other potential methods are dropped. Two promising methods of estimating the effects of streams on the delivery of material that were investigated but not used in the final Phase 6 Model are described here.

Application of USGS Chesapeake Floodplain Network Regression Models to the Chesapeake Bay Watershed

The USGS (Noe and others, 2015a, b, 2016; Hopkins and others, in preparation) has developed predictive models of sediment, nitrogen, and phosphorus fluxes from streambank erosion and floodplain deposition, and applied those models across the Chesapeake Bay watershed. The effort has three components: (1) an empirical study of streambank erosion rates and floodplain deposition rates at sites in the USGS Chesapeake Floodplain Network; (2) development of regression models that predict erosion and deposition rates on the basis of watershed and geomorphic characteristics; and (3) an analysis of LiDAR data to determine geomorphic properties of river reaches at the NHD catchment scale.

The Chesapeake Floodplain Network (CFN) consists of 43 sites in the Piedmont, the Ridge and Valley, and Coastal Plain physiographic provinces. The sites are located in proximity to Nontidal Network gages where there are flow measurements as well as long-term estimates of sediment and nutrient loads. The areas of the watersheds above the gages range from 8 to 770 square miles. The floodplain at the sites in the network must have trees and must be free of vegetative clearing or soil disturbance. At each site a 100-meter reach was selected for analysis.

Dendrogeomorphic analysis was used to estimate long-term fluxes of streambank erosion and floodplain deposition. The burial or exposure of tree roots provides a way of measuring sediment deposition on the floodplain or bank erosion. For sediment deposition the vertical distance between the soil surface and tree roots were measured; for streambank erosion the length of roots exposed was measured. These measurements and their relation to deposition or erosion are illustrated in Figure 9-18. The time it took for the erosion or deposition to occur is determined from the number of tree rings. The average streambank erosion rate per reach length (g/m/yr) is the product of the average exposed root length (m), bank height (m), and bulk density (g/m^3), divided by time as determined by the number of tree rings. Similarly, the average floodplain deposition rate per reach length (g/m/yr) is the product of the average depth to roots (m), floodplain width (m), and bulk density (g/m^3), divided by time. In addition to floodplain width and bank height, other geomorphic variables, such as channel width, are measured at each site for use in subsequent analysis. Metal pins were also placed in both the banks and the floodplain to facilitate measurement of fluxes. Figure 9-3 shows the estimated sediment fluxes from streambank erosion and floodplain deposition at the Chesapeake Floodplain Network sites. On average across the sites, the sediment flux from streambank erosion is balanced by sediment deposition on the floodplain, indicating that on average there is no net contribution to sediment loads from these two sources.

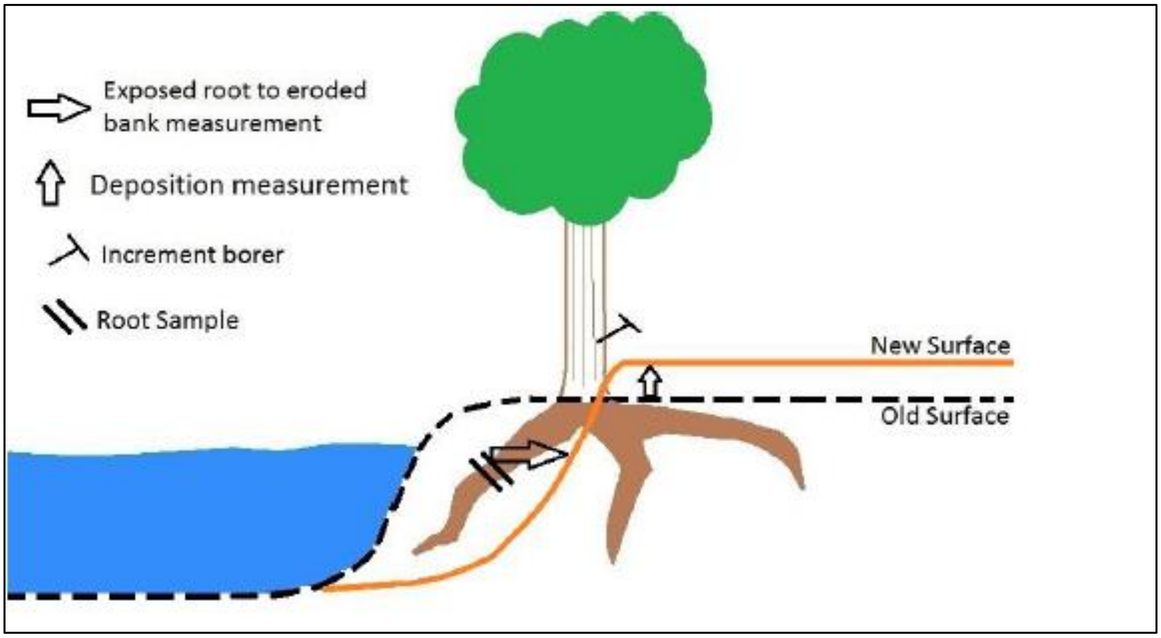

Figure 0-18: Dendrogeomorphic analysis of streambank erosion and floodplain deposition (from Noe and others, 2015a)

In the second stage of the project, the geomorphic data collected at the Chesapeake Floodplain Network sites, augmented by watershed characteristics, was used to develop predictive models of streambank erosion and floodplain deposition of nitrogen, phosphorus, and sediment. Regression models were estimated using backward step-wise regression for (1) models with only watershed characteristics as independent variables; and (2) models using both watershed and geomorphic characteristics. Tables 9-7 and 9-8 show the coefficients used in the streambank erosion and floodplain deposition models, respectively, using only watershed characteristics. Tables 9-9 and 9-10 show the coefficients used in the models for these fluxes using both watershed and geomorphic characteristics. Models using both geomorphic variables and watershed characteristics generally had higher R^2 values than models using only watershed characteristics. Streambank erosion models also tended to have higher adjusted R^2 values than models of floodplain deposition.

The third component of the effort attempts to obtain the geomorphic variables used in the regression models from LiDAR data. LiDAR stands for Light Detection and Ranging. It is a remote sensing technique which uses laser pulses to measure the distance to the earth surface from an elevated observation point such as a satellite, airplane or helicopter. Near-infrared laser are capable of mapping topography on the land surface, while green lasers can measure bathymetry beneath oceans, lakes, and rivers (http://oceanservice.noaa.gov/facts/lidar.html).

The USGS (Noe and others, 2015b, 2016) is analyzing LiDAR data in an attempt to determine geomorphic variables at the NHD reach scale. The USGS has developed a tool, the Stream Channel and Floodplain Metric Toolbox, to facilitate using final scale topographic data from LiDAR to estimate geomorphic properties of stream channels and floodplains. Using version 1.3 of the tool, geomorphic variables were determined for 47 percent of the HUC12 watersheds in the Chesapeake Bay watershed. The areas missing were primarily in New York, southwestern Virginia (primarily in the James River basin) or portions of the West Virginia panhandle (in the Potomac River basin).

Where geomorphic variables were available, they were used in combination with watershed characteristics to predict streambank erosion and floodplain deposition fluxes at the NHDPlus scale. In areas without available geomorphic variables, the regression models using watershed characteristics only were used to estimate nitrogen, phosphorus, and sediment fluxes from streambank erosion and floodplain deposition. Figure 9-19 shows where fluxes were estimated using regressions with both geomorphic and watershed characteristics or regressions with just watershed characteristics.

Table 9-7: CFN Streambank erosion regression model coefficients, watershed variables only

Coefficient	Nitrogen	Phosphorus	Sediment
Intercept	0.2206	0.1466	555.1
Area		-2.572E-05	-0.02691
Baseflow index		-0.2159	-329.4
P6 Cropland		0.1646	
Evapotranspiration	0.000716		
Horton flow Index	-27.76		-12800
Housing density 2010		-8.529E-06	-0.01391
P6 Pasture	-0.664		-329.2
Precipitation	-0.00063		-0.3253
1974 production land use		-0.1963	
Adjusted R^2	**0.3941**	**0.4845**	**0.4415**

Table 9-8: CFN floodplain deposition regression model coefficients, watershed variables only

Coefficient	Nitrogen	Phosphorus	Sediment
Intercept	-5.3641	-1.114	-907.4
Evapotranspiration	0.006157	0.001243	
Housing density 2010	-0.00067	-0.00027	-0.3563
P6 Road impervious cover	49.61193	19.04	23820
K factor	3.323203	0.8302	1756
LS factor	0.124589		
Net upland erosion			-71.63
Precipitation		0.001152	1.939
Topographic wetness index		-0.199	-262.3
Adjusted R^2	**0.2768**	**0.3008**	**0.4255**

Table 9-9: CFN streambank erosion regression model coefficients, watershed and geomorphic variables

Coefficient	Nitrogen	Phosphorus	Sediment
Intercept	4.599	1.249	2500
Area	-0.00012	-7.6E-05	-0.1614
Area/slope		1.79E-08	3.1E-05
Total cross-sectional area/bankfull area	0.000409	0.000427	0.2337
Bank Angle	0.004457		-2.878
Bankfull Area	0.007503	-0.00159	
Baseflow index	-0.7731		-256.3
Bank height	-0.3854	0.1024	
Bank Height/Channel Width	1.62	-3.698	-4782
Bank Height/Floodplain Width	16.92		
Change developed land 1974-2012	3.23	0.2303	
Change production land 1974-2012	1.054		
Channel Width/Floodplain Width	-0.9513		-103.4
P6 Cropland	-2.457	0.6612	
Dam drainage density	0.06885	0.05081	64.15
2012 Developed land use	-6.599	0.8682	669.2
Evapotranspiration	-0.00379	-0.00117	-1.741
P6 Forested	-3.046		-784
Floodplain elevation range		0.04462	82.79
Floodplain width	-0.00088		-0.5756
Horton flow Index	-269.4		
Housing density 2010	0.000474	4.57E-05	0.05923
P6 Road impervious cover		-11.62	-17690
K factor	1.435	-0.5881	-737.8
Ksat	-3.9E-07		-4.8E-05
LS factor	0.07801	-0.0496	-36.36
Bankfull width/width over banks	0.07462	0.01332	25.34
P6 Pasture	-2.886	0.6136	-164.8
Precipitation	0.000774	-0.00028	
1974 production land use	-0.6295	-0.6729	-734.6
Sediment delivered to stream		0.09932	
Stream profile slope	3.893	12.43	17360
Topographic wetness index	0.07016		
Adjusted R^2	**0.991**	**0.9371**	**0.9433**

Table 9-10: CFN floodplain deposition regression model coefficients, watershed and geomorphic variables

Coefficient	Nitrogen	Phosphorus	Sediment
Intercept	-18.505	-8406	-2814.34
Area/slope		-2.8E-05	-2.8E-05
Total cross-sectional area/bankfull area	-0.00338		-0.00338
Bank Angle	-0.02715	-9.605	-3.21977
Bankfull Area	-0.0026		-0.0026
Baseflow index	-0.6286	-1505	-752.814
Bank Height/Channel Width		-6782	-6782
Bank Height/Floodplain Width	-38.56		-38.56
Change developed land 1974-2012		2439	2439
Change production land 1974-2012	6.588		6.588
Channel Width/Floodplain Width	1.63585		1.63585
Dam drainage density	-0.175		-0.175
2012 Developed land use	-1.66	-6079	-3040.33
Evapotranspiration	0.015748	3.013	1.014832
P6 Forested	4.488	2063	690.6587
Floodplain width	-0.00116	-1.168	-0.39011
Horton flow Index	408.6		408.6
Housing density 2010	-0.00169	-0.8915	-0.29829
P6 Road impervious cover	156.91	120300	40204.61
K factor	4.2835	3461	1156.522
Ksat	4.29E-07	0.000146	4.91E-05
LS factor	0.2133	132.8	44.40887
Net upland erosion	0.2098		0.2098
Bankfull width/width over banks	-0.09432		-0.09432
Precipitation	0.002644	4.546	1.517096
1974 production land use	2.729	657.4	220.9527
Stream profile slope	-32.685	-35490	-11851.8
Topographic wetness index	0.1686		0.1686
Adjusted R^2	**0.9264**	**0.9066**	**0.8571**

All results reported in Sections 9.3.1 and 9.5 from the CFN and the application of the Stream Channel and Floodplain Metric Toolbox are preliminary and are subject to the following disclaimer from the USGS:

> *This information is preliminary or provisional and is subject to revision. It is being provided to meet the need for timely best science. The information has not received final approval by the U.S. Geological Survey (USGS) and is provided on the condition that neither the USGS nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of the information.*

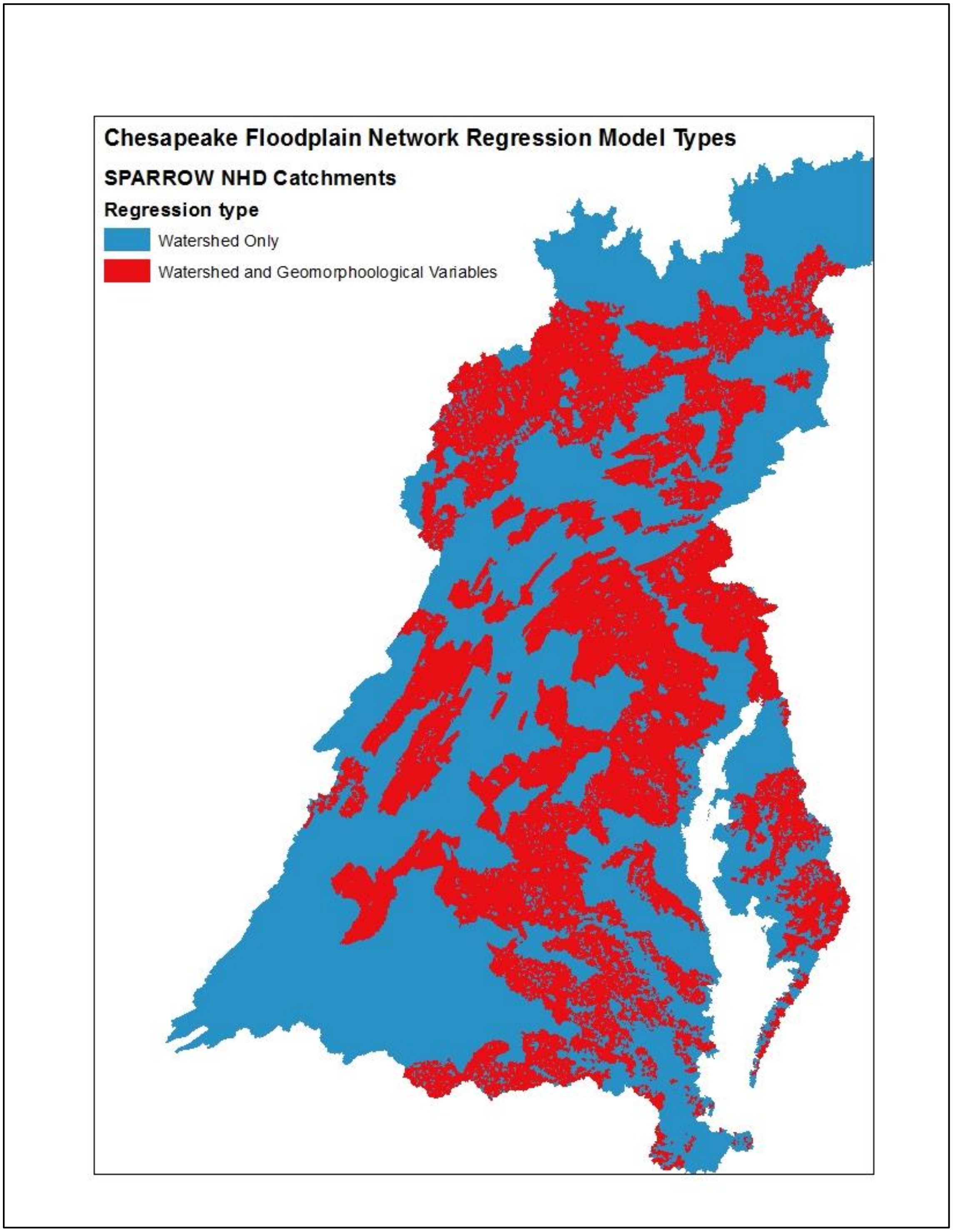

Figure 9-18: CFN regression model types by NHDPlus catchment

Trial Simulation of Streambank Erosion and Floodplain Deposition in Phase 6

The nutrient and sediment fluxes predicted by the USGS regression models were incorporated into the Beta 4 version of Phase 6. Average annual nitrogen, phosphorus, and sediment fluxes from streambank erosion and sediment deposition were aggregated from NHDPlus to the land-river segment scale. Contributions from Phase 6 reaches simulated using HSPF were omitted from the aggregation, since the instream processes are calibrated in the Phase 6 river simulation as were NHDPlus reaches with impoundments, where the analysis is not applicable. Figures 9-20, 9-21, and 9-22 show the nitrogen, phosphorus, and sediment fluxes, respectively, from streambank erosion. Figures 9-23, 9-24, and 9-25 show the nitrogen, phosphorus, and sediment fluxes, respectively, from floodplain deposition. Positive fluxes are exported from the land-river segment, while negative fluxes mean the stream process is a sink in the land-river segment.

The performance of the model with and without the fluxes from streambank erosion and floodplain deposition were compared. Figure 9-26 compares average annual sediment loads from WRTDS and the Phase 6 Model without including the fluxes from streambank erosion and floodplain deposition. Figure 9-27 shows the same comparison when the fluxes from streambank erosion and floodplain deposition are included. As the figures show, there is considerably less agreement between WRTDS and Phase 6 when the fluxes are included. Figures 9-28 and 9-289 show the same contrast for phosphorus loads. Model performance is again worse when the phosphorus fluxes streambank erosion and floodplain deposition are simulated. Nitrogen fluxes from streambank erosion and floodplain deposition are too small to have a noticeable effect on the calibration.

The fact that the simulation without streambank and floodplain contributions performed better than the simulation which includes the contributions of these sources suggests that the net contribution of streambank erosion and floodplain deposition to sediment loads is close to zero. This is consistent with the empirical determination of long-term streambank and floodplain sediment fluxes in the Chesapeake Floodplain Network (Figure 9-4), which shows that although there is considerable variability in the net sediment flux from streambanks and floodplains, there is no effect overall on sediment loads from these two sources. After consideration of this outcome, streambank erosion loads and floodplain accumulation were assumed on average to be in equilibrium and were therefore set equal and opposite to each other, as discussed in Section 9.3.1.

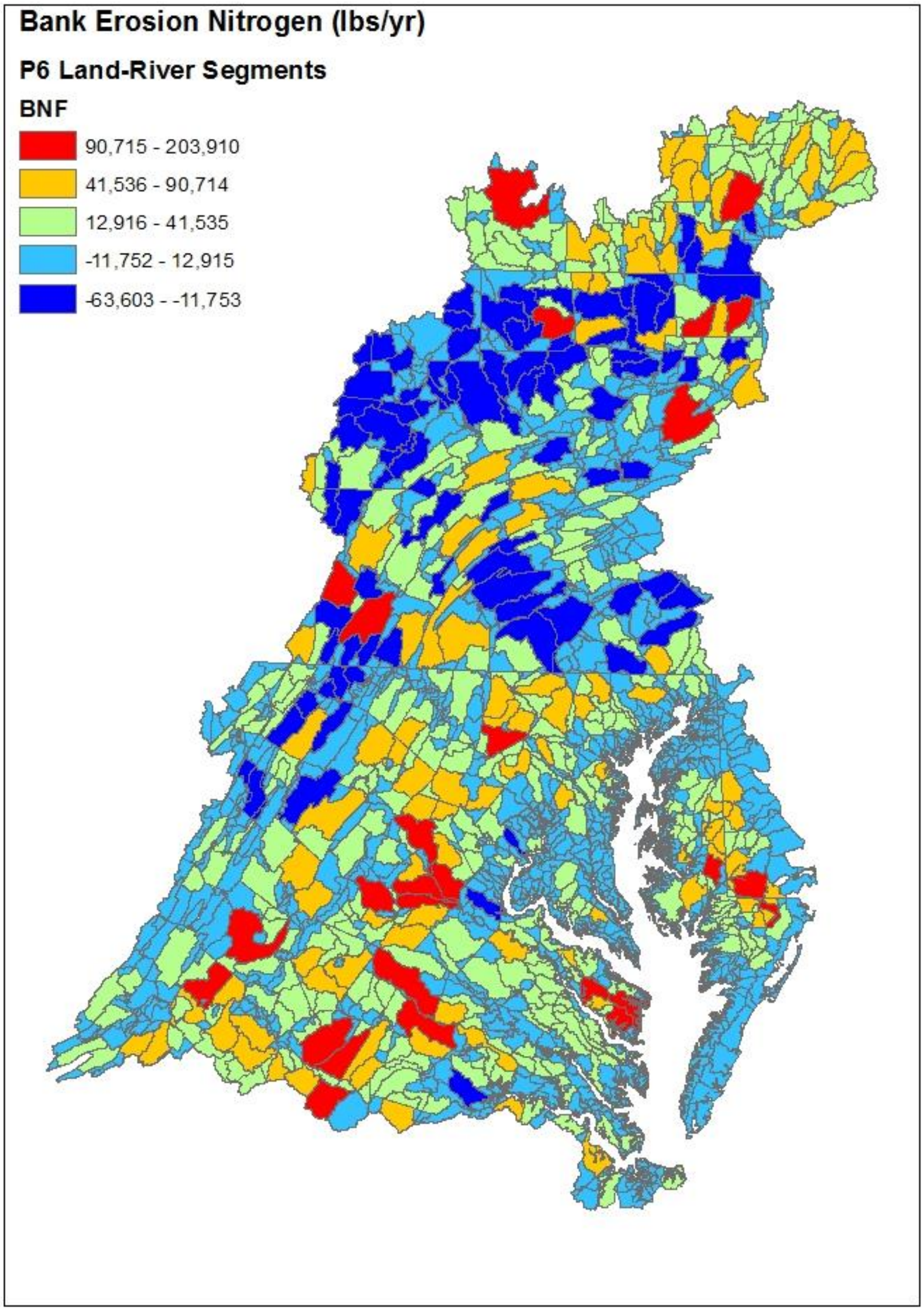

Figure 9-20: Nitrogen flux from streambank erosion (lbs/yr)

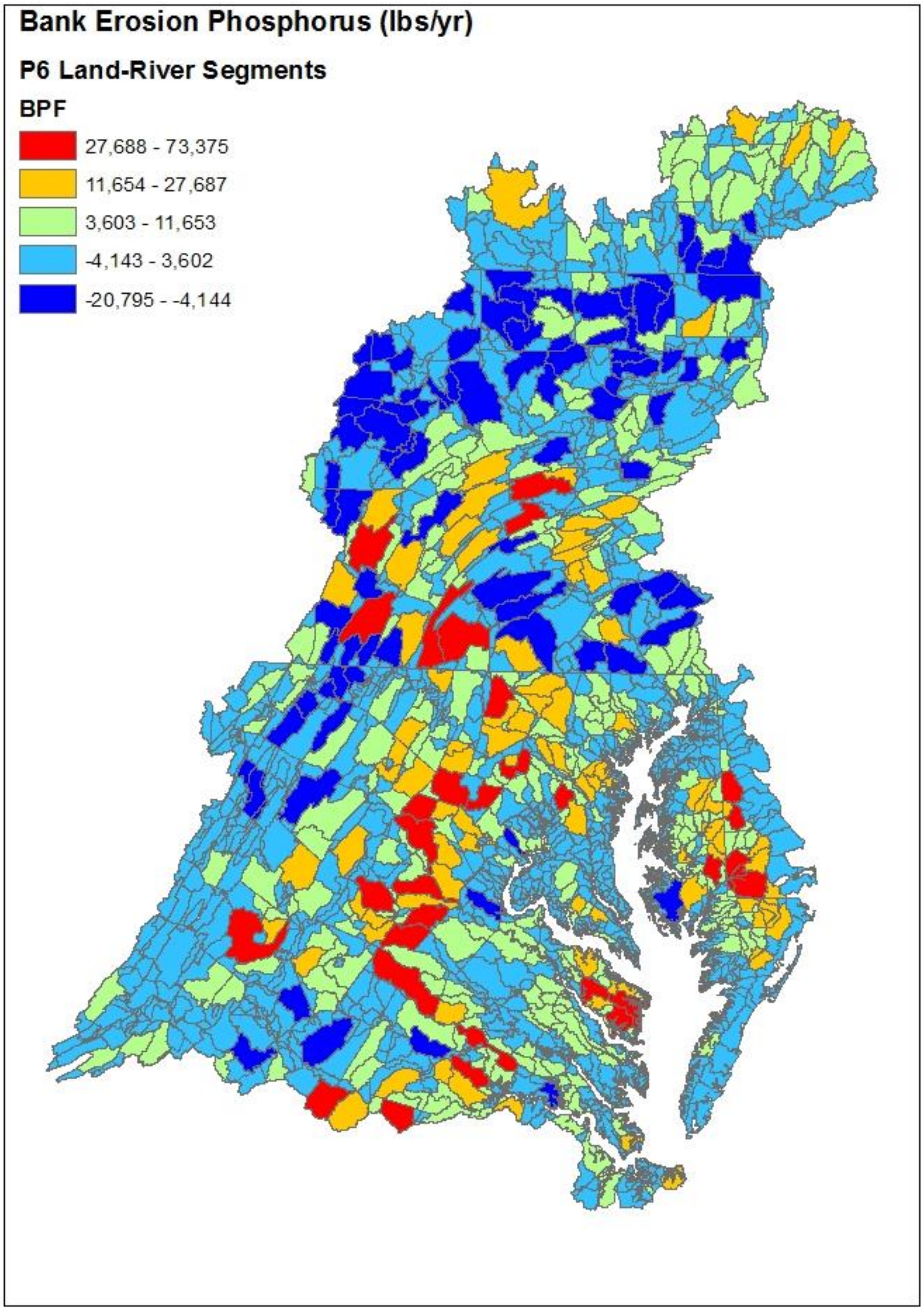

Figure 9-21: Phosphorus flux from streambank erosion (lbs/yr)

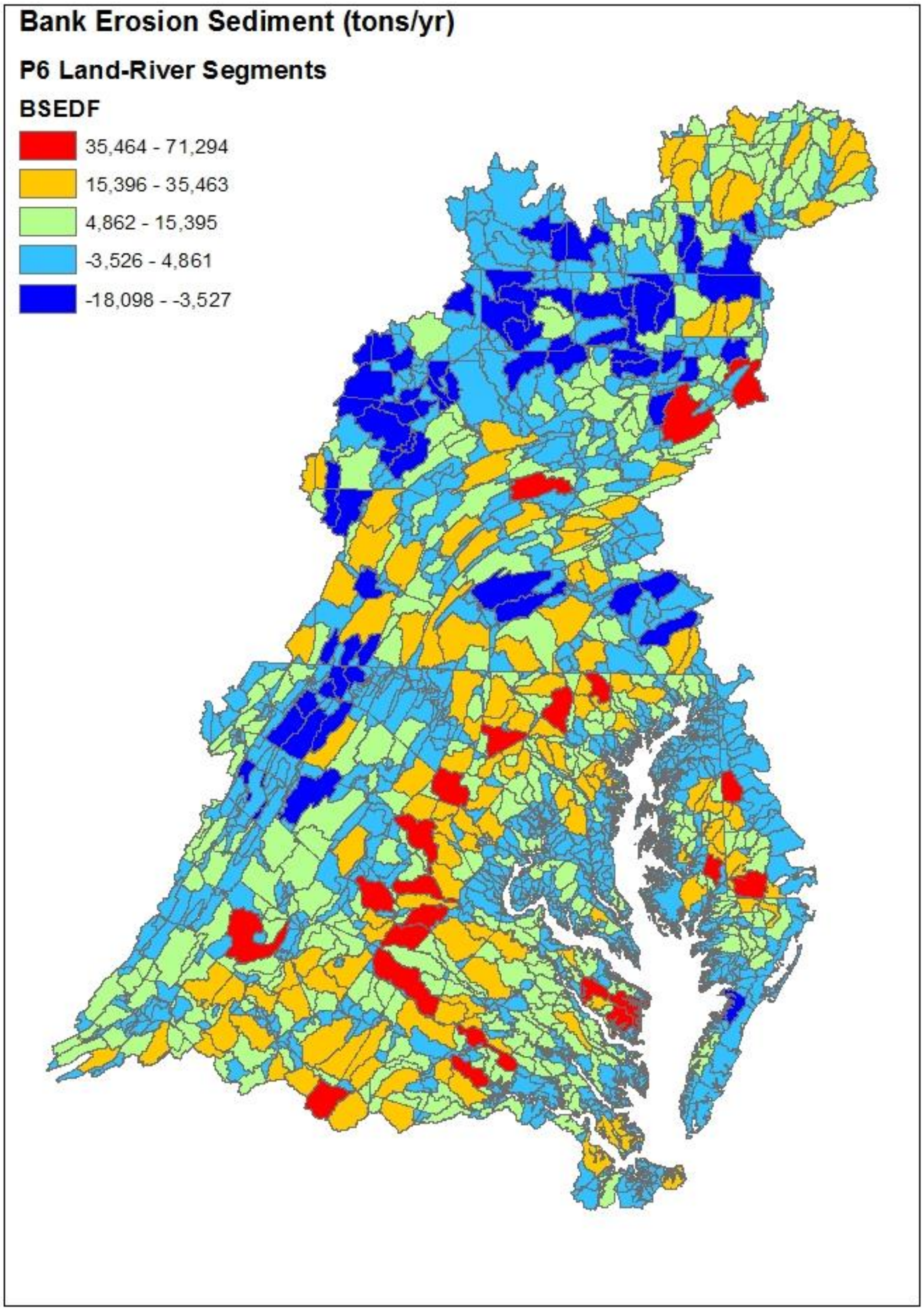

Figure 9-22: Sediment flux from streambank erosion (tons/yr)

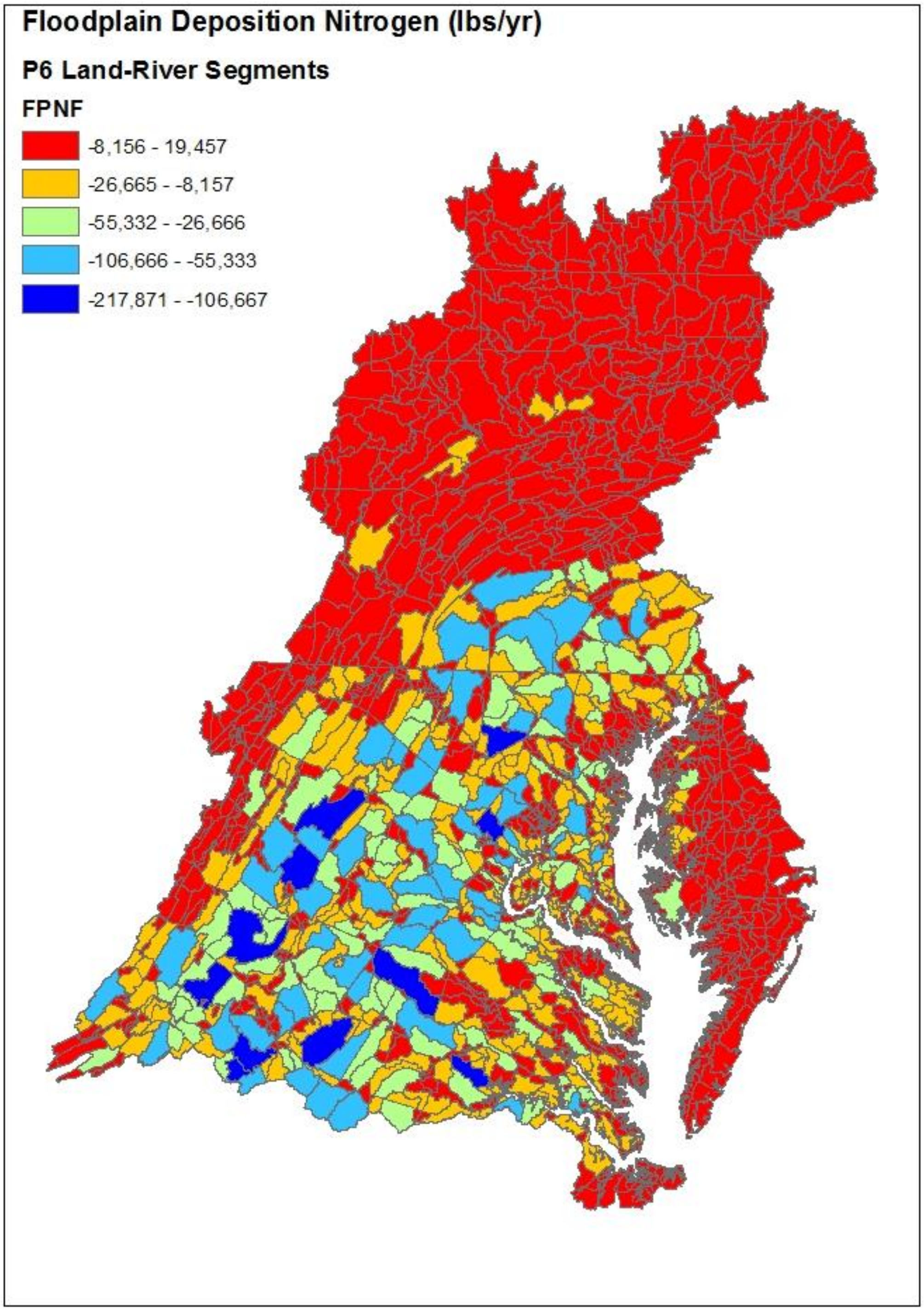

Figure 9-23: Nitrogen flux from floodplain deposition (lbs/yr)

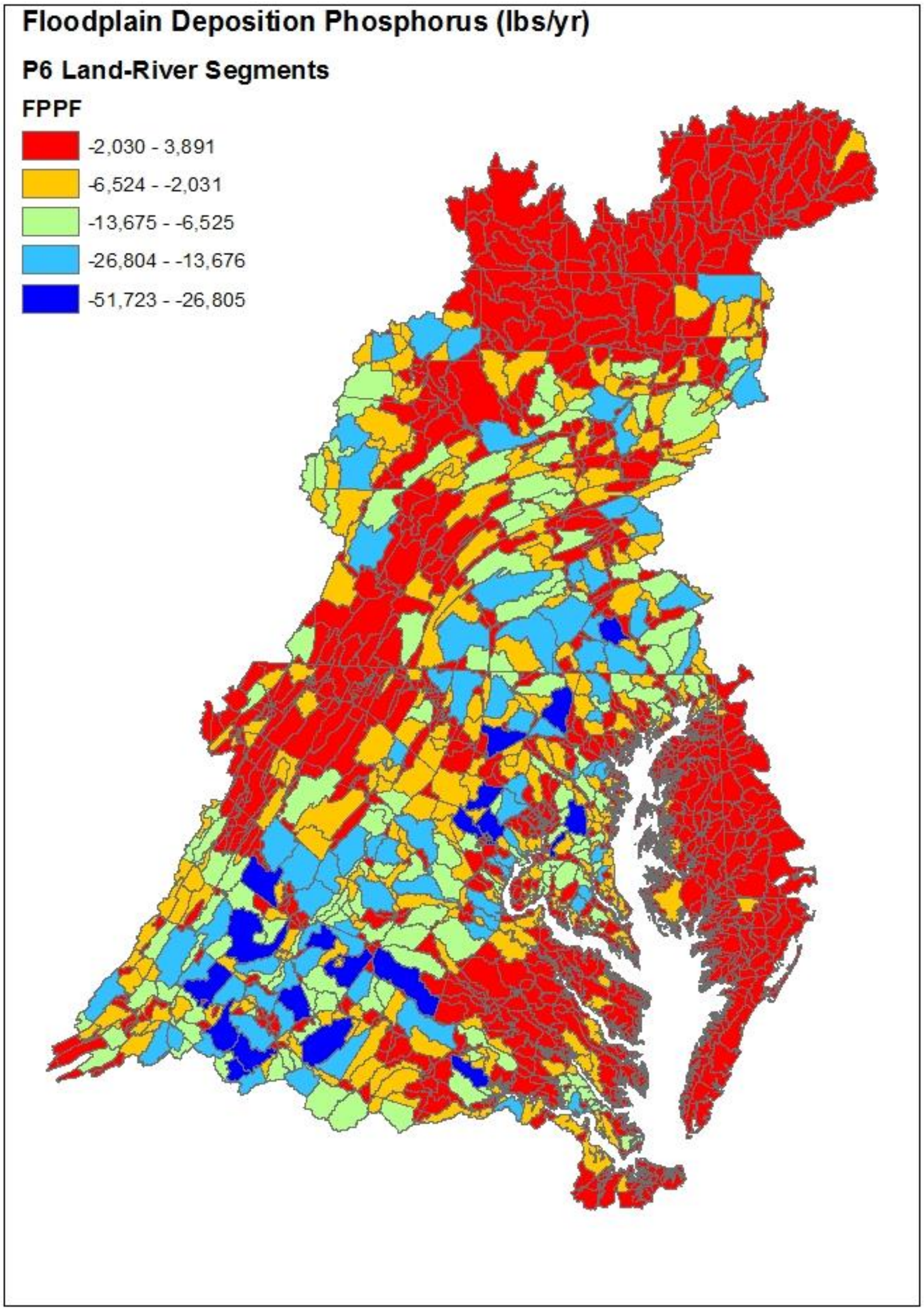

Figure 9-24: Phosphorus flux from floodplain deposition (lbs/yr)

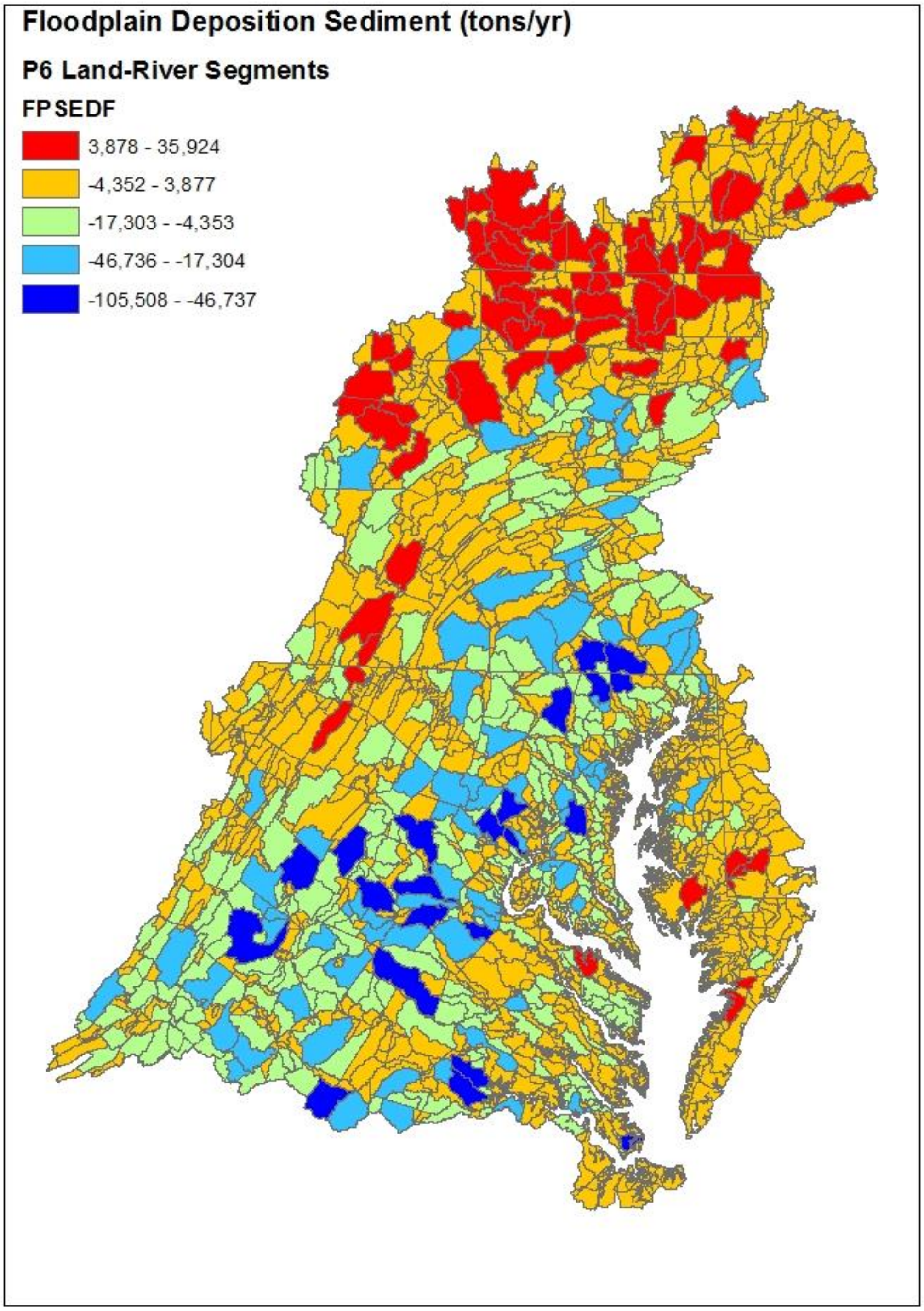

Figure 9-25: Sediment flux from floodplain deposition (tons/yr)

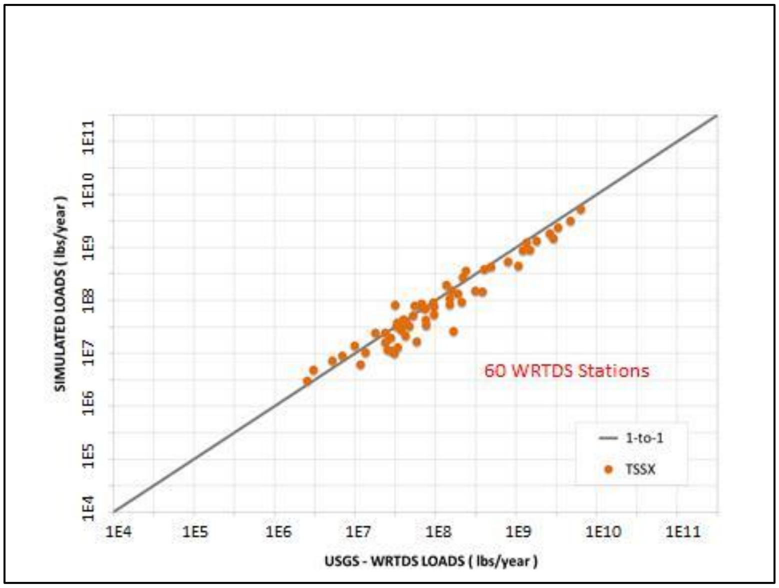

Figure 9-26: Average annual sediment, WRTDS, and Phase 6 Beta 4, without streambank erosion and floodplain deposition

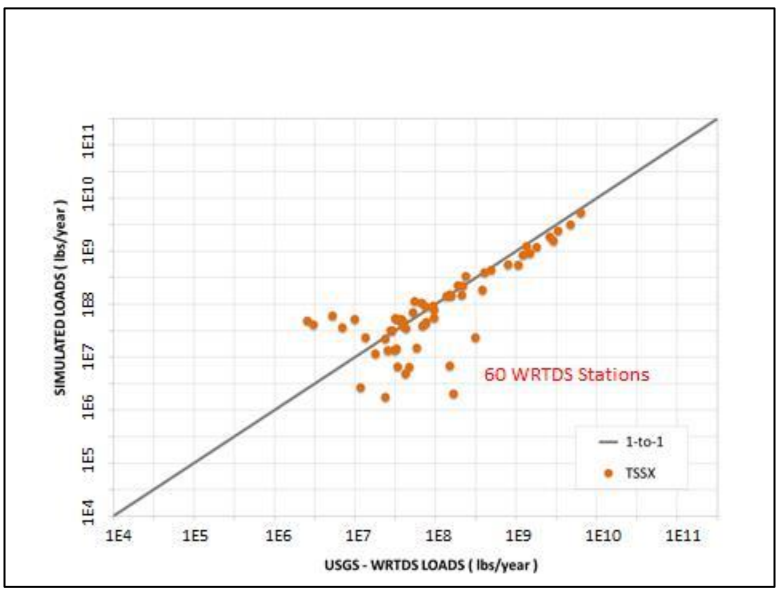

Figure 9-27: Average annual sediment loads, WRTDS, and Phase 6 Beta 4, with streambank erosion and floodplain deposition

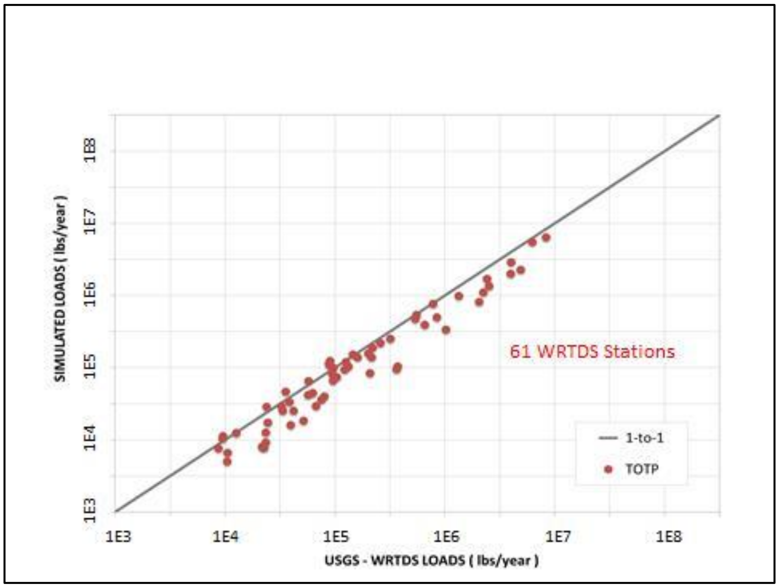

Figure 9-28: Average annual phosphorus loads, WRTDS, and Phase 6 Beta 4, without streambank erosion and floodplain deposition

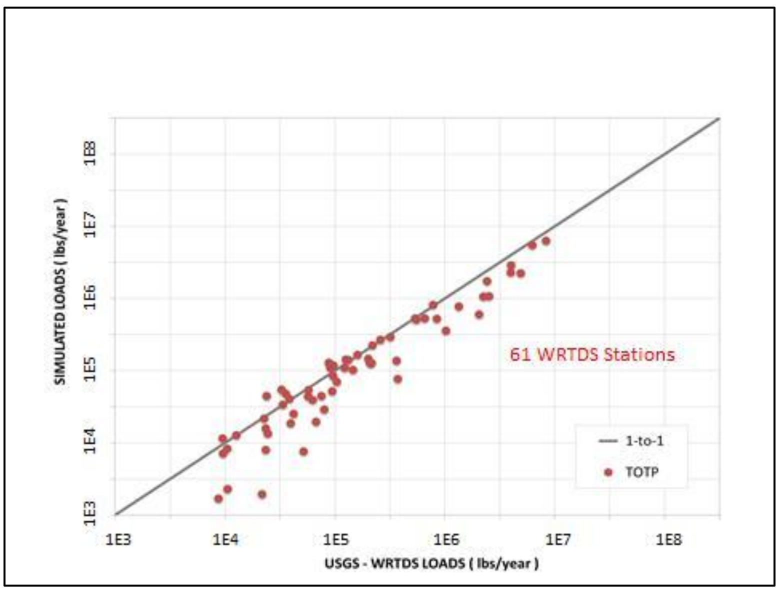

Figure 9-29: Average annual phosphorus loads, WRTDS, and Phase 6 Beta 4, with streambank erosion and floodplain deposition

Stream Source Ratio

Led by the Center for Watershed Protection (CWP 2015), a second effort at representing sediment deposition and scour in small streams is focused on urban streams. The key concept for this effort is the Stream Source Ratio (SSR) expressed in Equation 0-1. The SSR is the fraction of total watershed sediment load that comes from instream sources like bed erosion, bank erosion, and resuspension of floodplain sediments.

Equation 0-1: Stream Source Ratio Definition

$$SSR = 1 - \frac{Upland\ Load}{Total\ Watershed\ Load}$$

where the upland load is the load from land-based sources.

The SSR is dimensionless, and the loads in the equation can be expressed as a rate (tons/ac/yr) or absolute values (lbs or tons) as long as upland load and total watershed load are measured in the same units. Based on a literature survey, CWP (2013) estimated that SSR ranges from 40 percent to 80 percent.

The goal of the CWP's project is to estimate a regression model which predicts SSR from watershed characteristics. The regression model was developed from a study of nine urban watersheds shown in Table 9-11. Two sites, both in the Difficult Run watershed, are in Northern Virginia. The rest of the watersheds are in Maryland. For each watershed, CWP estimated the long-term average annual upland load, total watershed load, and SSR. The estimated SSRs were then used as the dependent variable in estimating the regression model. The calculation of upland loads and total watershed loads, as well as the development of the regression model, are discussed below.

Upland loads were identified as the storm sewer outfall load in watershed. They were calculated using a sediment event mean concentration (EMC) and modeled flows for each the watershed. The sediment EMC was taken from the average storm water outfall EMC concentration from the county reported in the National Stormwater Water Quality Database which was nearest the watershed. A single average value was used for each watershed. Average EMC concentrations ranged from 32.4 mg/l to 94.6 mg/l with an average value of 49.9 mg/l. Hourly flows were taken from the simulation of pervious and impervious land, 1984-2005, from the Phase 5.3.2 Watershed Model. The percent impervious land was a watershed characteristic calculated for the project. For pervious land, total flow, including baseflow and interflow, was used in the calculation. Total flow is the sum of the product of the hourly flows and pervious and impervious areas.

The calculation of the total watershed load was a multi-stage process. The starting point was instream sediment EMCs paired with instream flow measurements on an event basis. The following steps were then performed for each watershed:

1. On an event basis, the instream concentration-flow relation was converted to a sediment load-flow relation, with both sediment loads and flows normalized by area.
2. Using the paired load-flow relations, a log-log relation, Unit load = A*Unit flow^B, was estimated for each watershed.
3. Total watershed load was estimated from the modeled hourly time series of flows and the unit flow to unit load relation for the period 1984 to 2005, i.e.,

Equation 0-2: Total Watershed Load

$$Total\ Watershed\ Load\ = \sum_{i=0}^{hours\ 1984\ to\ 2005} A * Modeled\ Hourly\ Flow^{B}$$

where A and B are the regression parameters estimated in step 2. Loads were averaged over the 22 year simulation period.

Table 0-11: Characteristics of watersheds used to estimate Stream Source Ratio

Watershed	Drainage Area (mi^2)	Impervious Cover (fraction)	Forest Cover (fraction)	Group C or D Soils (fraction)	Riparian Buffer Length (fraction)	Estimated SSR
Difficult Run 1	5.99	0.184	0.392	0.370	0.340	0.917
Difficult Run 2	55.2	0.184	0.356	0.278	0.502	0.843
Paint Branch	12.1	0.130	0.266	0.238	1.00	0.562
Breewood	0.10	0.331	0.181	0.729	0.750	0.820
Moore's Run	3.52	0.300	0.070	0.895	0.385	0.579
Stoney Run	2.20	0.694	0.306	0.438	0.385	0.909
WB Herring Run	2.13	0.277	0.116	0.449	0.405	0.319
Beaver Run	14.0	0.015	0.276		0.681	0.930
Scott's Level	3.42	0.246	0.029	0.641	0.767	0.314
Powder Mill Run	3.64	0.378	0.041	0.954	0.656	0.691

From the upland loads and total watershed loads, SSRs can be calculated for each of the nine watersheds. These SSRs were then regressed against watershed characteristics taken from (1) the USGS's National Water Information System, (2) the EPA's Watershed Assessment and Tracking Environmental Results System (WATERS), (3) the Web Soil Survey,(4) NHD+, and (5) Google Earth. The best-fitting regression model is shown in Equation 0-3.

Equation 0-3: SSR full regression equation

$$SSR = 0.001364*DA + 0.282962*Imp + 2.456579*Forest + 0.807264*CD + 0.128841*Riparian - 0.441092$$

where

DA = drainage area (mi^2)
Imp = Impervious cover (fraction of watershed area)
Forest = forest cover (fraction of watershed area)
CD = Hydrologic Soil Group C, D, and C/D soils (fraction of watershed area)
Riparian = Riparian Buffer Length (fraction of streams)

Table 9-11 gives the values of the independent variables for each watershed. The regression model had a coefficient of determination (R^2) of 0.9778, and the slope of the linear relation between predicted and estimated SSRs was, 0.9978, which is very close to a 1:1 relation. However, six parameters estimated from 10 observations indicates poor confidence in the regression coefficients. Evidence of over-fitting can be seen in the forest parameter where a high percentage of forest could easily result in an SSR greater than one.

The CWP (2105) also provided a simple two-parameter regression model, Equation 0-4, based on impervious cover and soil type, which is used to estimate SSR:

Equation 0-4: reduced parameter SSR equation

SSR = 1.4085*Imp + 0.5341*CD -0.2828

Figure 9-30 compares predicted and estimated SSRs from the two-parameter model. Defining 'total watershed load' as the combination of land source and stream source and rearranging Equation 0-1, the stream source in pounds can be derived as follows

Equation 0-5: Stream Source

Stream Source Load = Land Source Load * SSR / (1 – SSR)

Where SSR is calculated in Equation 0-4 and the land source is the combination of developed land use loads in a land-river segment.

Figure 0-30: Predicted and Eestimated Stream Source Ratios (from CWP, 2015)

Inspection of Equation 0-4 and Equation 0-5 reveals that SSRs less than zero and greater than one are possible with certain combinations of impervious fraction and CD soil fraction. This would lead to a negative stream source ratio in either case. While a negative stream source load for an SSR less than zero may have the physical meaning of net stream storage in highly pervious and well-drained areas, it is unlikely to occur in developed areas. Additionally, BMPs that treat the stream load of sediment would have no modeled effect if no load is accounted for in the calculation. An SSR higher than one has no physical meaning. Reasonable limits must be set on SSR for both high and low values. The CWP (2015) found SSRs in the nine watersheds ranging from about 0.32 to 0.92. Langland and Cronin (2003) estimated SSR to be approximately two thirds on average. Limits of 0.10 and 0.95 are chosen for SSR resulting in ratios of Stream Source to Land Source between 0.11 and 19. The lower limit affects 7.8 percent of land-river segments and the upper limit affects 0.7 percent of land-river segments.

At several points in the Phase 6 development process, applying the SSR approach to developed land uses while using the USGS Chesapeake Floodplain Network Regression Models for rural land uses was under consideration; However, in the end, the SSR approach was not implemented in Phase 6, due to the limited number of sites used to generate the two-parameter regression model and the uncertainty associated with model inputs, as expressed by Easton and others (2017) in their review of Phase 6 for the Scientific and Technical Advisory Committee (STAC).

The Soil Survey Geographic (SSURGO version 2.2) dataset was downloaded for Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia, and the District of Columbia. The table in the companion Excel worksheet provides a summary of the survey areas, along with version information for the spatial and tabular dataset publically available for download (accessed in March 2016). The *soil component* (tabular/comp.txt) tables for soil survey areas were combined. The hydrologic soil group for a map unit was designated based on highest representative value. The tabular hydrologic soil group dataset was joined to the spatial (vector) layer based on the SSURGO map units (map unit keys, MUKEY). For the purpose of GIS spatial analysis with the raster land use dataset, the hydrologic soil group dataset was converted to a raster dataset (Figure 2). The raster pixels with hydrologic soil groups C, D, and C/D were selected for further analysis (Figure 3).

Phase 6 developed land use categories (local land use version 2) were combined into a single raster dataset (Figure 1). The raster layer with C, D, and C/D hydrologic soil group were intersected with the developed land use layer to remove non-developed hydrologic soil group (Figure 4). A zonal raster analysis was performed on the resulting raster layer to summarize with C and D hydrologic group in the developed area for the Phase 6 watershed model land-river segments. A similar zonal summary for developed land use dataset. Using these two zonal summary tables fraction developed area with hydrologic soil group C, D, and C/D were computed for land-river segments (Figure 5).

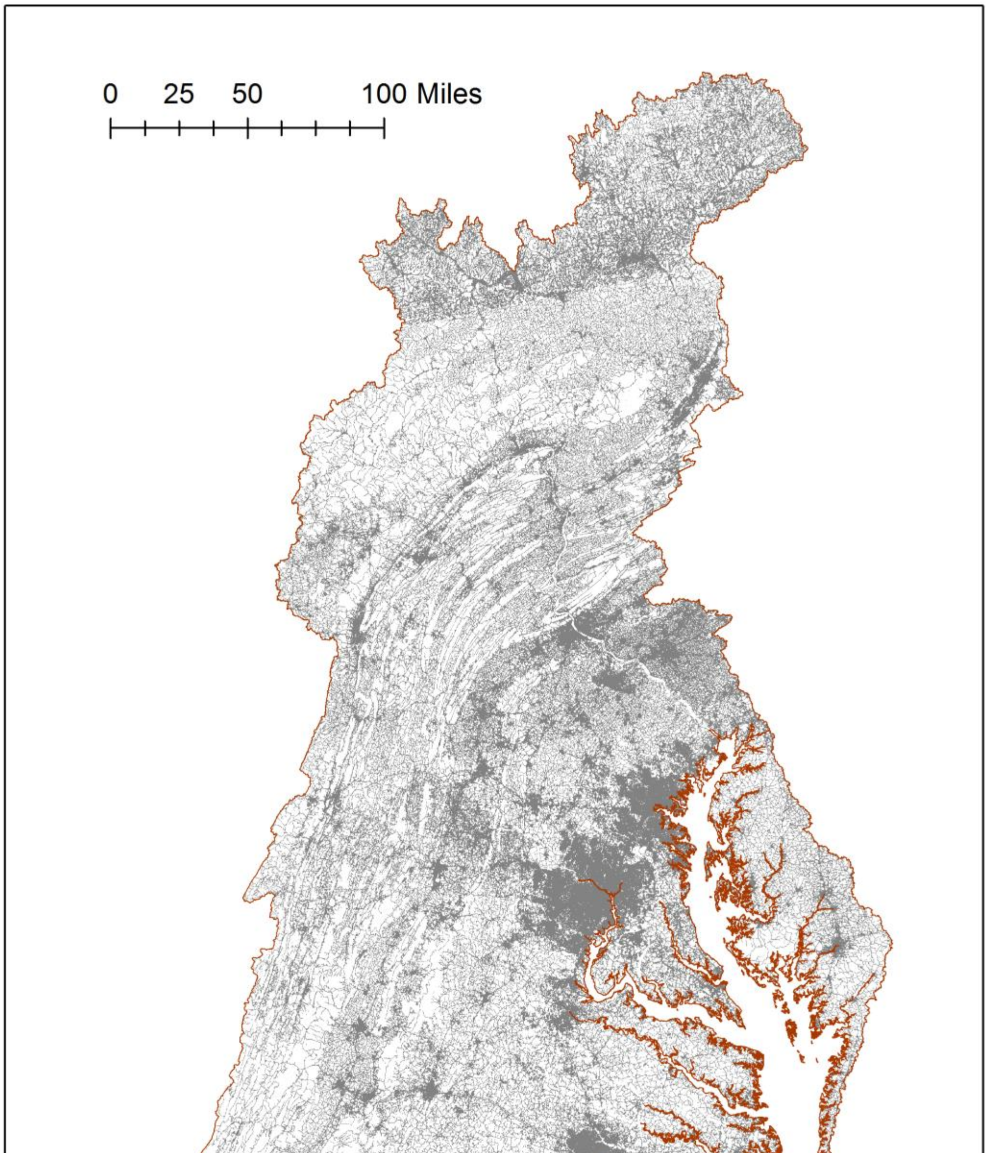

Figure 1: Developed land use

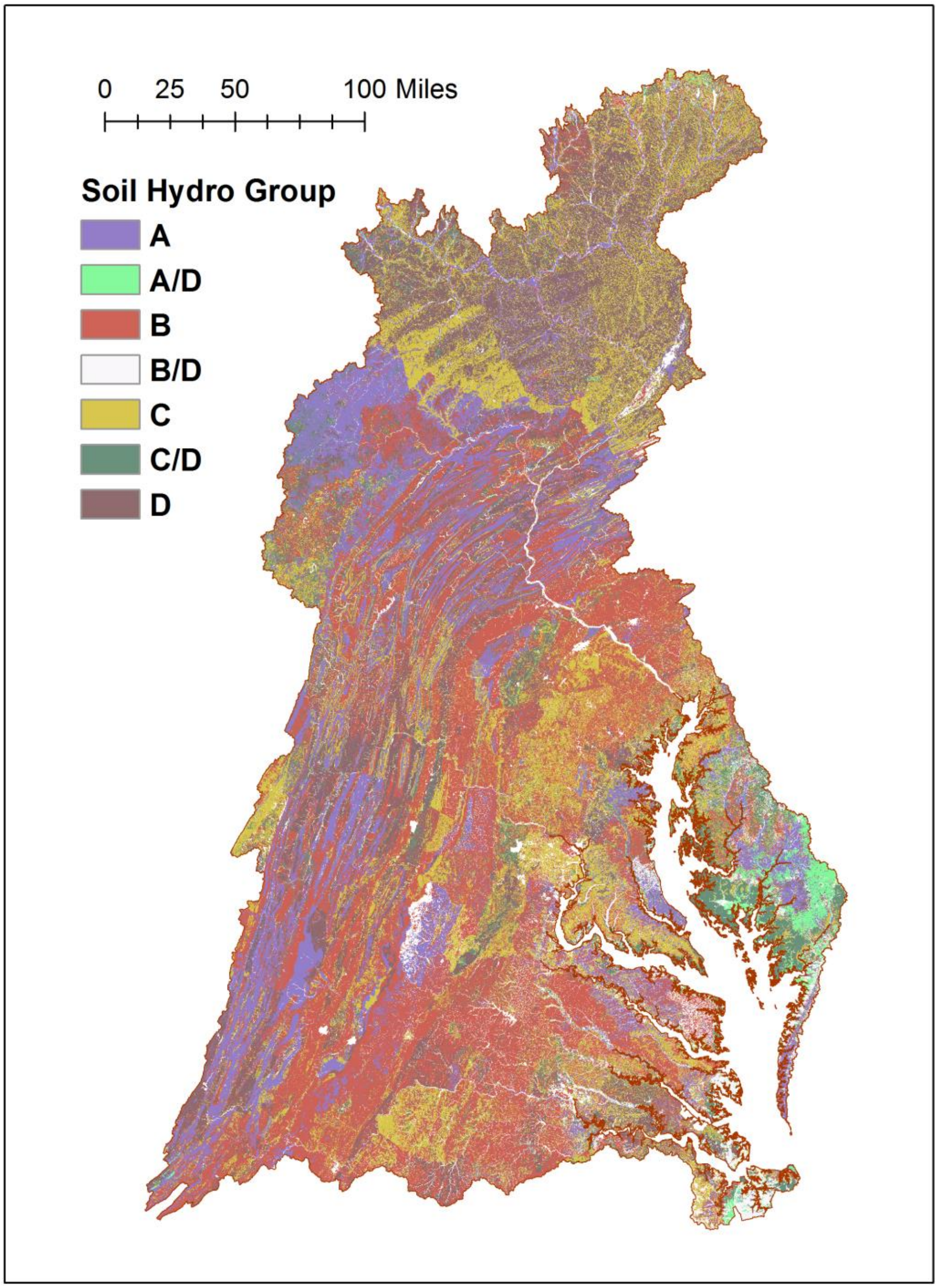

Figure 2: Hydrologic Soil Group from Soil Survey Geographic (SSURGO-2) database.

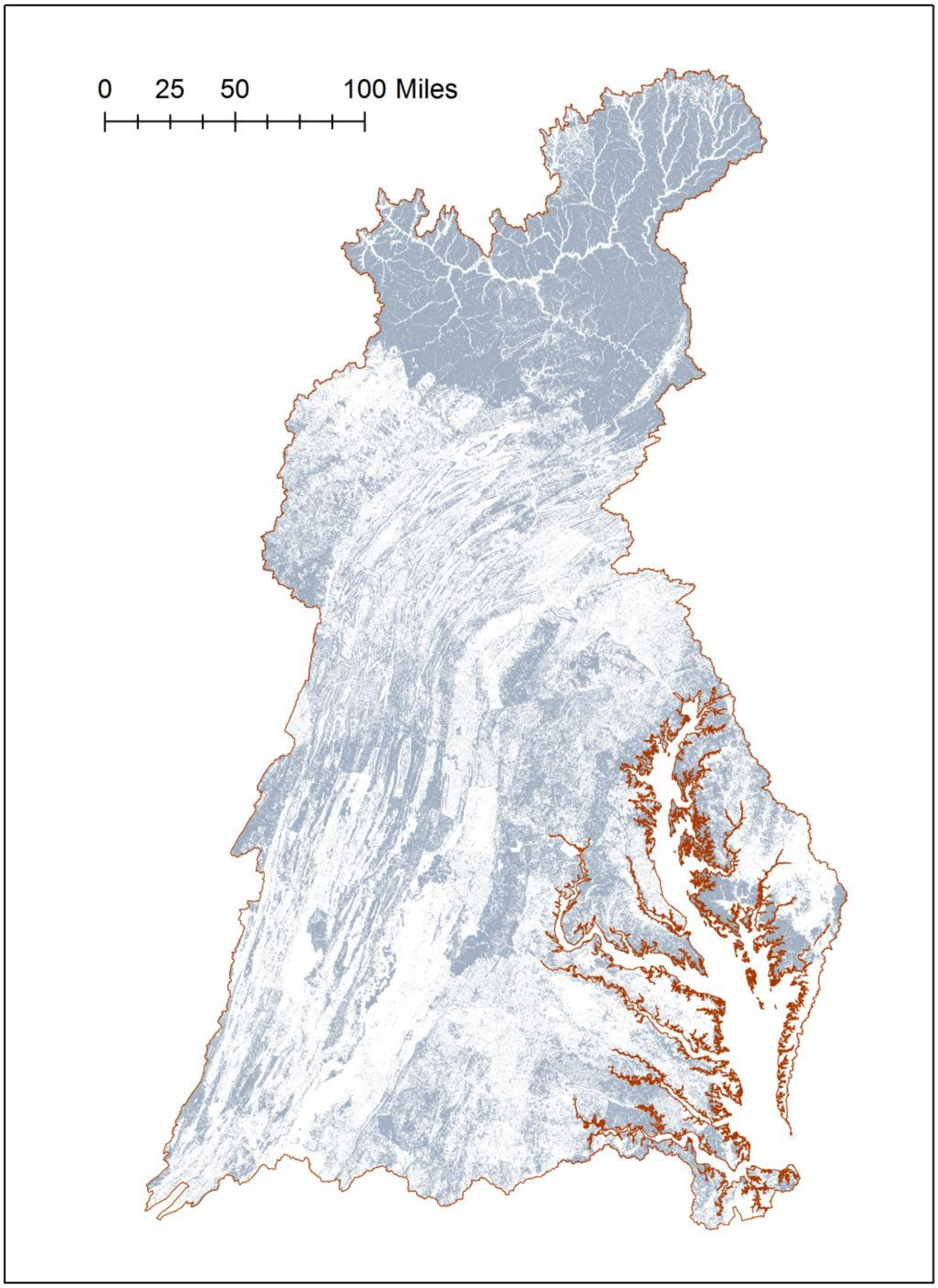

Figure 3: Hydrologic soil group C, D, and C/D.

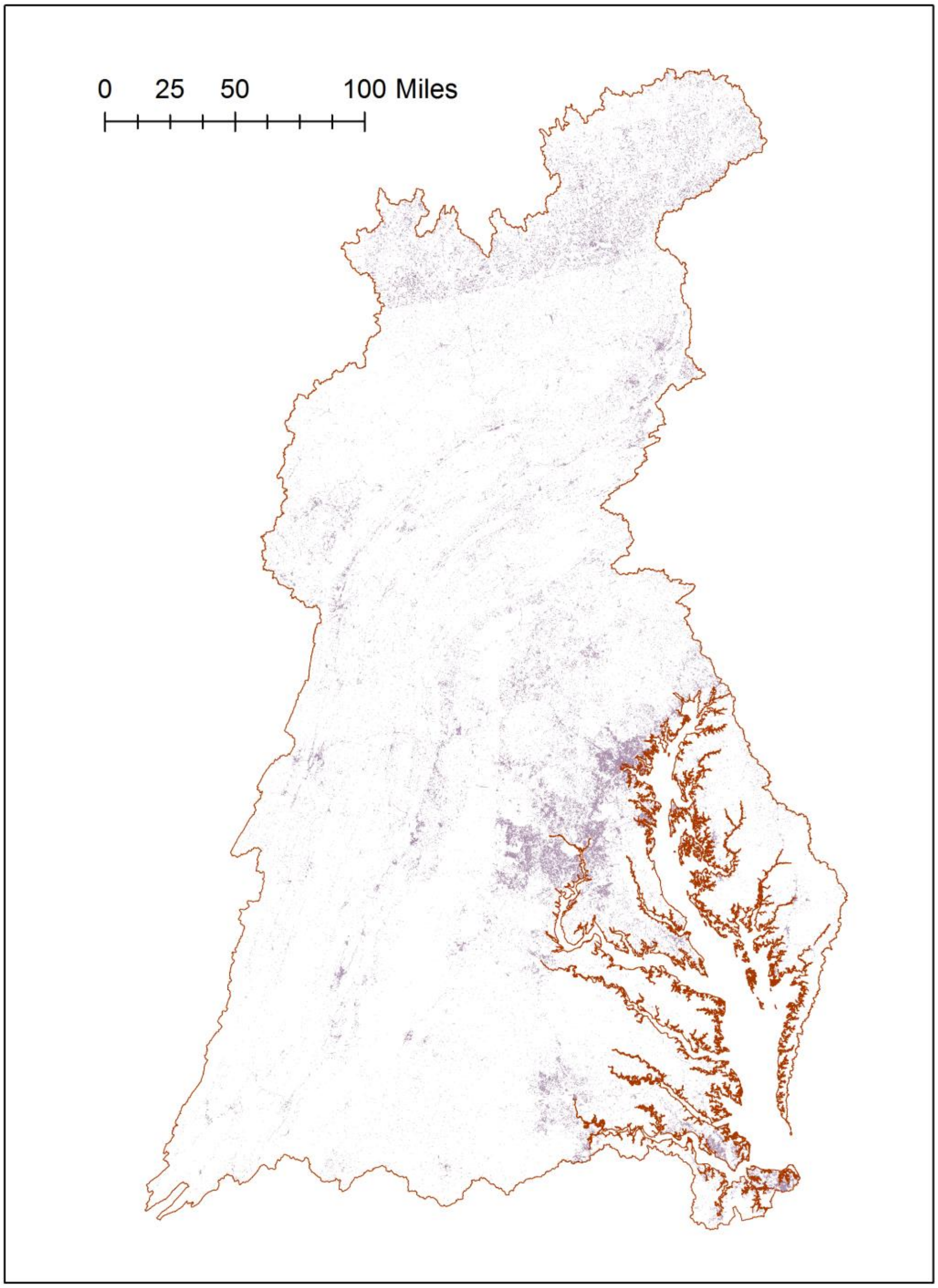

Figure 4: Hydrologic soil group C, D, and C/D that are co-located with developed land use.

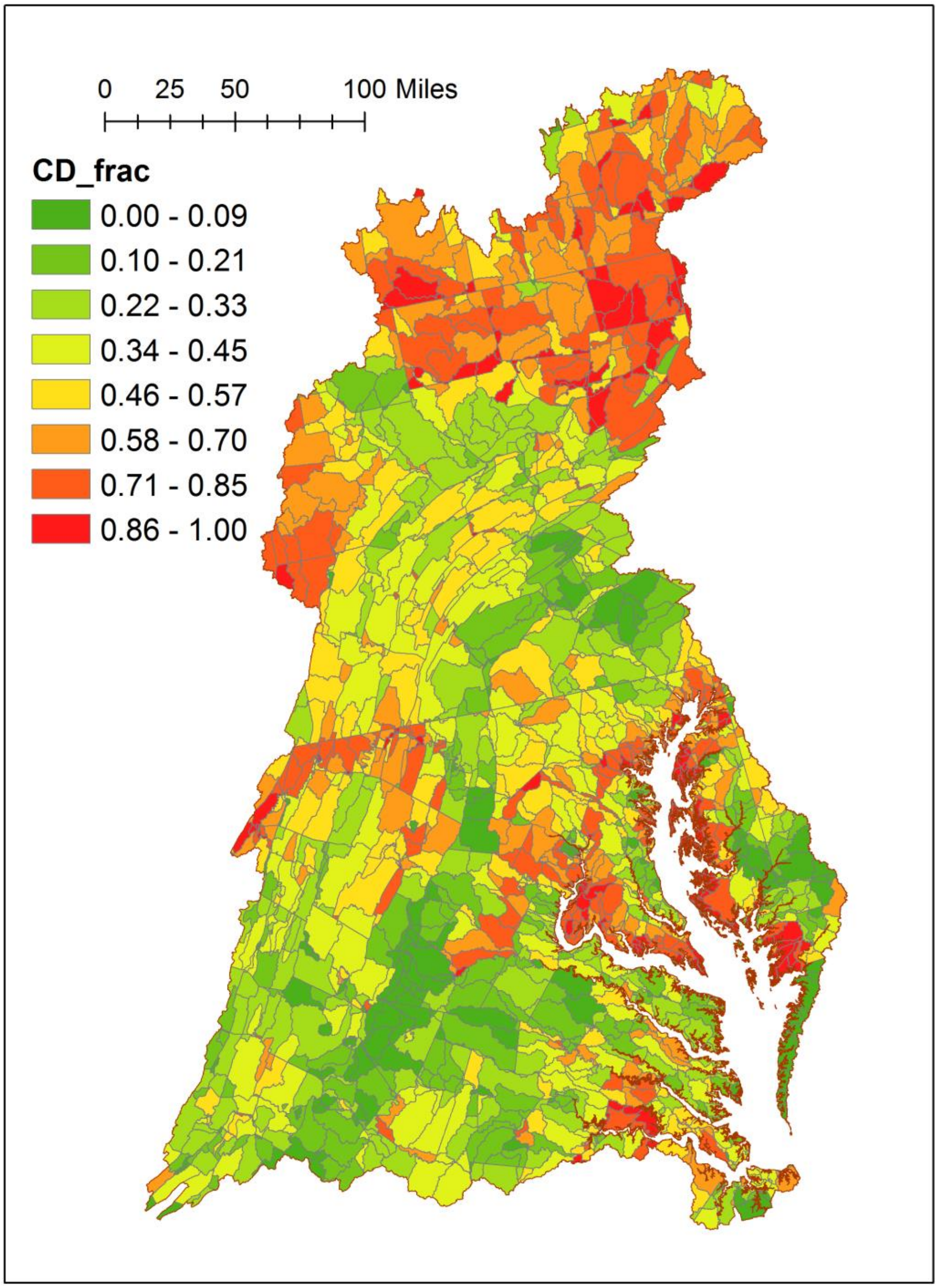

Figure 5: Fraction of developed area that are classified as hydrologic soil group C, D, and C/D.