7 Section 7: Land-to-Water

7.1 Introduction

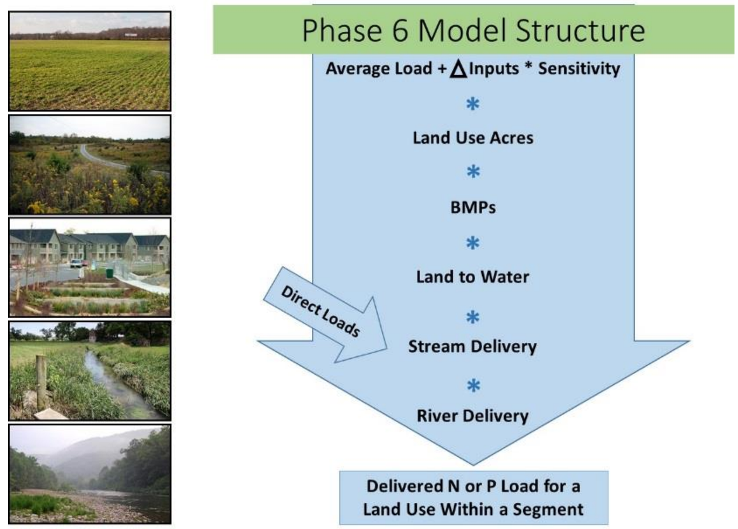


Figure 7-1: Phase 6 model structure

Phase 6 of the Chesapeake Bay Program partnership's Watershed Model (Phase 6) has the overall structure shown in Figure 7-1. Land-to-water factors represent the effect of transport processes prior to delivery to streams. As discussed in Section 1, nutrient land simulation targets do not represent edge-of-field (EOF) nutrient export, but rather the average edge-of-stream (EOS) nutrient export, without regard to variation in nutrient delivery. In Phase 6, the variation in delivery due to watershed setting is represented by land-to-water factors, calculated based on USGS Spatially Referenced Regression on Watersheds (SPARROW) simulations of the Chesapeake Bay Watershed (Ator et al 2011). Since the average loads already represent EOS-scale nutrient loads, the weighted average for all land-to-water factors is constrained to equal one. The RUSLE-based sediment loads described in Section 2, in contrast to nutrients, represent sediment mobilization at the field scale. The land-to-water processes for sediment represent hillslope transport that connect the field-scale losses with the EOS and are therefore true sediment delivery ratios that decrease the total sediment flux by roughly an order of magnitude.

Previous versions of the CBP Watershed Model did not have externally-calculated land-to-water factors. Prior to Phase 5, spatial differences in land use loading rates were calibrated based on fewer than 20 water quality monitoring stations that aggregated many land uses and watersheds. In Phase 5, spatial differences in loading rates were specified by a calibrated 'regional factor' that applied to all land above a given monitoring station. These regional factors did not have explanatory power aside from matching observed water quality data. The CBP partnership prioritized removal of the Phase 5 'regional factors' in favor of factors that were explainable based on observable properties of the watershed. In the Phase 6 Watershed Model, the land-to-water factors replace the regional factors with values that vary according to watershed properties. The Phase 6 land-to-water factors follow similar spatial patterns as the Phase 5 regional factors, but with much greater explanatory power and on a finer scale.

As discussed in Section 1, the multiple modeling approach permits Phase 6 to represent processes on a finer scale than previous versions of the Watershed Model. Table 7-1 provides an overview of the transport processes for nutrients and sediment represented in Phase 6. Groundwater effects are included in the transport processes for nitrogen. Because of the key role SPARROW plays in determining the land-to-water factors and the delivery factors for nutrients and sediment in small streams discussed in Section 9, this section will open with an extended discussion of SPARROW, before turning to the land-to-water factors themselves.

Table 7-1: Transport Processes Represented in the Phase 6 Watershed Model

Process	Phase 6 Nutrients	Phase 6 Sediment
Edge-of-Field	Average loads + input load variability + land-to-water factors	RUSLE estimates
Hillslope		Interconnectivity factors
Groundwater		NA
Small Stream	SPARROW stream-to-river factors Average Streambank Erosion and Floodplain Deposition	SPARROW stream-to-river factors Average Streambank Erosion and Floodplain Deposition Streambank Erosion Due to Impervious Cover
Large River	HSPF River simulation	HPSF River simulation

7.1.1 Definition of Land-to-Water Factors

The term 'land-to-water' has different meanings in the SPARROW model and the Phase 6 Watershed Model. This can easily cause confusion, so in Section 7, these will be referred to as 'SPARROW land-to-water variables', 'SPARROW land-to-water coefficients', and 'Phase 6 land-to-water factors'. Elsewhere in the Phase 6 documentation, 'land-to-water factors' refers to Phase 6 land-to-water factors.

A SPARROW land-to-water variable refers to an input variable with a value that is related to pollutant transport by a SPARROW land-to-water coefficient. For example, in the example of the SPARROW model in Section 7.2, groundwater recharge rate is positively related to nitrogen transport. Areas with high groundwater recharge have a greater nitrogen load, all else being equal. 'Groundwater recharge' is the SPARROW land-to-water variable which is related to transport by a SPARROW land-to-water coefficient.

SPARROW land-to-water variables are centered such that the average value of the variables used to estimate the SPARROW equation is zero. Therefore, the interpretation of a SPARROW land-to-water variable combined with a SPARROW land-to-water coefficient is not a delivery factor that reduces load through watershed processes. Rather, it represents the deviation from the average transport. The combined effect of all SPARROW land-to-water variables and coefficients for a particular area is known as a Delivery Variance Factors (DVF) as defined by Hoos and McMahon (2009). The name reflects the interpretation as a factor that is an estimate of spatial variability in transport rather than an estimate of the transport itself.

Phase 6 land-to-water factors are DVFs derived from selected SPARROW land-to-water variables and constrained such that the weighted average value is equal to 1. The definition of these terms is revisited in Section 7.3.

Appropriately, the land class average loads described in Section 2 and depicted in Figure 7-1 assume average transport conditions to the EOS. For a given segment, only the product of the input-modified average land class load and the Phase 6 land-to-water factors has a physical meaning as the EOS load.

7.2 SPARROW

SPARROW is a non-linear regression model which predicts time-averaged constituent fluxes on the basis of reach and catchment attributes. SPARROW can best be explained by example. In this case, it is convenient to choose the latest version of the SPARROW models of total nitrogen and total phosphorus loads in the Chesapeake Bay watershed, CBTN_v4 and CBTP_v4 respectively. As the model names suggest, these are the fourth versions of SPARROW models of the Chesapeake Bay watershed. Ator et al (2011) documents the development of the models and analyzes their results in detail.

7.2.1 Spatial Structure

The catchments and reaches used in CBTN_v4 and CBTP_v4 are taken from the National Hydrography Dataset Plus (NHDPlus), version 1.1 (Horizon Systems, 2010). NHDPlus catchments and river reaches are delineated at a much finer scale than Phase 6. Over 80,000 reaches and catchments are represented in NHDPlus in the Chesapeake Bay watershed. The average catchment size is about 500 acres. Figure 7-2 illustrates the difference in scale between NHD and Phase 6. It shows the NHDPlus reaches and catchments and the Phase 6 land-river segments in Montgomery County, MD.

The Phase 6 Model uses an overlapping scheme of land segments and river segments. Land segments are generally counties while river segments are watersheds. Land-river segments are the intersection of these two segmentation schemes. Section 11 describes the Phase 6 segmentation scheme in more detail. Montgomery County is a single land segment in the Phase 6 Model. Multiple river segments overlay the Montgomery County land segment. The intersection of the single land segment and the intersecting river segments are represented in Figure 7-2 as colored regions named for the watersheds in the legend. The darker blue lines show the river Phase 6 reaches represented in the county. It is clear from Figure 7-2 that a single land-river segment may contain just a few NHDPlus catchments or up to dozens of NHDPlus catchments.

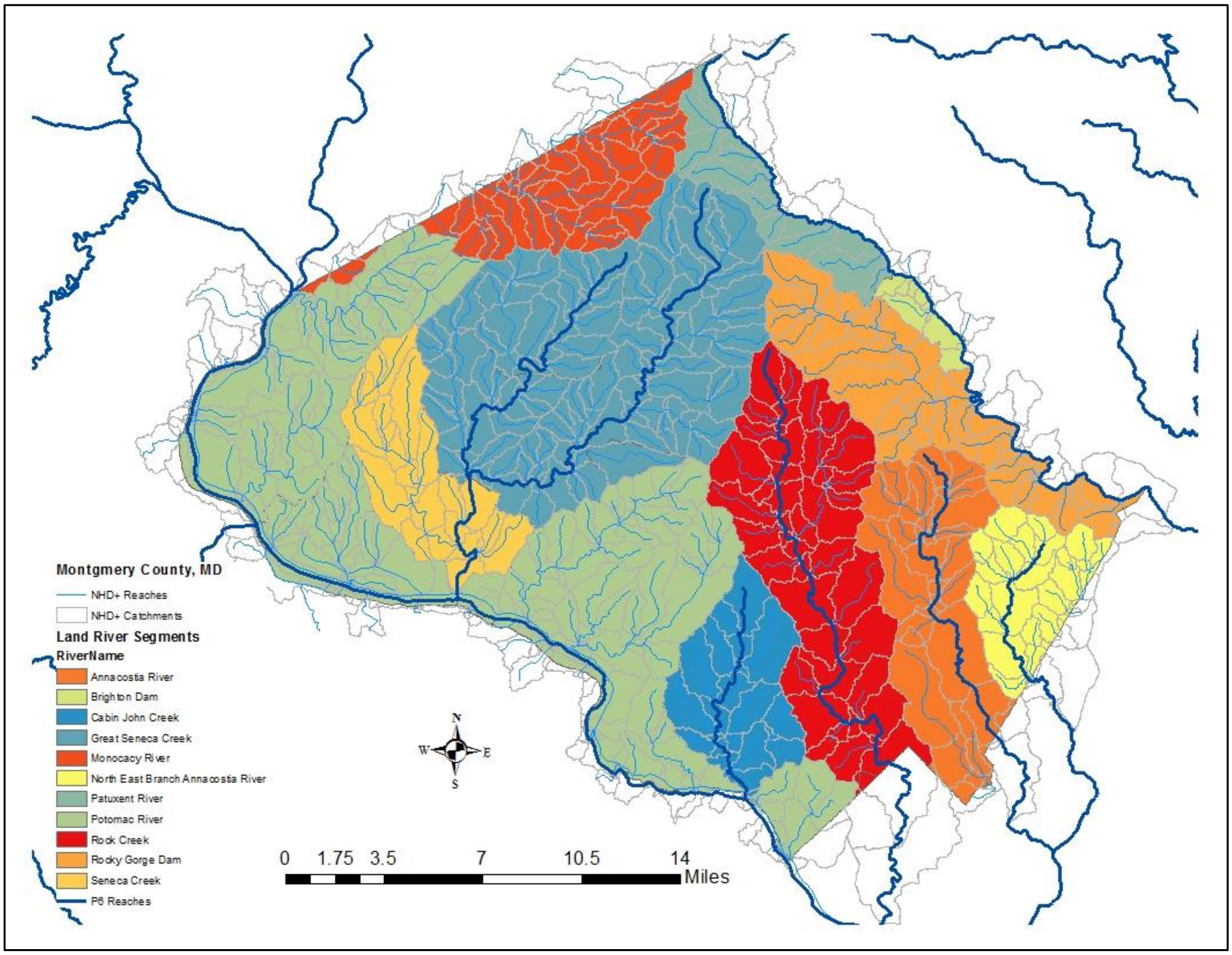


Figure 7-2: Comparison of NHDPlus catchments and Phase 6 Watershed Model land-river segments

7.2.2 Estimated Equation

Reach and catchment attributes are the independent variables used in the non-linear regression model of nitrogen and phosphorus fluxes in the Chesapeake Bay watershed. The attributes can be divided into three groups: (1) sources of nutrients; (2) attributes which control the transport of sources from land-to-water; and (3) reach characteristics which determine nutrient losses (aquatic decay) in the reach network. The coefficients that determine the land-to-water factors in Phase 6 are derived only from the land-to-water attributes (2).

The nutrient load in reach *i* is determined by the following equation (Preston and Brakebill, 1999):

Equation 7-1: Sparrow

$$L_i = \sum_{n=1}^{N} \sum_{j \varepsilon J(i)} \beta_n s_{n,j} e^{(-\alpha Z_j)} e^{(-\delta T_{i,j})}$$

Where:
L_i = load in reach i;
n,N = source index where N is the total number of considered sources;
J(i) = the set of all reaches upstream and including reach i, except those containing or upstream of monitoring stations upstream of reach i;
β_n =estimated source parameter;
$s_{n,j}$ = contaminant mass from source n in drainage to reach j;
α = estimated vector of land-to-water delivery coefficients;
Z_j = land surface characteristics associate with drainage to reach j;
δ = estimated vector of instream-loss parameters (for river reaches); and
$T_{I,j}$ = channel transport characteristics.

For reservoirs, the term for instream losses takes the following form:

$$\frac{1}{(1 + \gamma * q_i^{-1})}$$

Where:
q_i = hydraulic loading rate
γ = estimated coefficient

The reach and catchment attributes used in CBTN_v4 and CBTP_v4 are shown in Tables 7-2 and 7-3. These attributes represent conditions in 2002. The α's, β's, and δ's are estimated through non-linear regression. These parameters are adjusted to minimize the sum of the square differences between modeled fluxes and empirically calculated mean annual fluxes.

7.2.3 Calculation of Fluxes

The empirically calculated fluxes are determined using the USGS software FLUXMASTER. FLUXMASTER estimates concentrations based on the following linear regression model:

Equation 7-2: FLUXMASTER

$$C_t = \gamma_0 + \gamma_1 * q_t + \gamma_2 * q^2_t + \gamma_3 * T_t + \gamma_4 * T^2_t + \gamma_s * \sin(2\pi T_t) + \gamma_c * \cos(2\pi T_t) + e_t$$

where

C_t = natural log of concentration at time t;
q_t = natural log of daily average flow at time t;
T_t = time in years as decimal;
e_t = error term; and
γ's = estimated coefficients

FLUXMASTER uses Tobit regression to treat censored concentration values and corrects for retransformation bias (in converting back from natural log units) using a method that approximates that used in the USGS software LOADEST (Runkle *et al,* 2004). FLUXMASTER was used to calculate mean annual detrended nitrogen and phosphorus loads, using water quality data from 1994 through 2009. Loads were adjusted to reflect mean hydrologic conditions over a 30-year flow period. Thus, although

SPARROW attributes represent watershed conditions in 2002, model loads represent long-term conditions centered on that year.

There were 181 FLUXMASTER load estimates used to calibrate the parameters in the nitrogen model and 184 load estimates used in the phosphorus model. Tables 7- 2 and 7-3 show the estimated parameters for the nitrogen and phosphorus models, respectively.

7.2.4 Nutrient Sources

There are five sources of nitrogen simulated in the SPARROW CBTN_v4: (1) manure; (2) fertilizer and fixation; (3) atmospheric deposition; (4) urban land; and (5) point sources. All of these sources are simulated in Phase 6. Nitrogen loads from urban land and point sources are explicitly simulated in Phase 6, while the impact of manure, fertilizer, fixation and atmospheric deposition are simulated through the sensitivity of nitrogen export to inputs, described in Section 4.

The sources of phosphorus in CBTP_v4 are more heterogeneous. Like CBTN_v4, they include (1) manure; (2) fertilizer; (3) urban land; and (4) point sources, but they also include the area underlain by (5) siliciclastic rocks and (6) crystalline rocks. Phosphorus loads from urban land and point sources are explicitly simulated in Phase 6, while phosphorus export is impacted by water-extractable phosphorus and soil phosphorus storage. Phosphorus in manure and fertilizer directly influence soil phosphorus storage in Phase 6 while and rock type probably implicitly influences the observations of soil storage on which the modeled soil storage is based. Section 3 of this documentation describes the estimation of soil phosphorus storage and Section 4 describes the influence the above factors have on phosphorus loads.

7.2.5 SPARROW Land-to-Water Variables

Four watershed properties control the transport of nitrogen from the sources to the reaches: (1) mean enhanced vegetation index (EVI); (2) mean soil available water capacity (AWC); (3) mean groundwater recharge; and (4) percent of catchment area in Piedmont carbonate. All of these variables are log-transformed before being used in the model. The EVI provides a measure of nitrogen lost through plant uptake. Soils with higher organic matter and finer texture are expected to have higher values of AWC: these soils can be expected to be saturated more frequently and provide reducing conditions which enhance denitrification. Increased groundwater transport, as indicated by groundwater recharge, can also be expected to enhance denitrification. Groundwater transport is particularly dominant in areas underlain by carbonate rocks in the Piedmont.

The CBTP_v4 has four land-to-water watershed variables which control the transport of phosphorus from sources to reaches: (1) soil erodibility; (2) percent of well-drained soils; (3) percent of area in the Coastal Plain; and (4) mean annual precipitation. Phosphorus is primarily transported in overland runoff and particularly in eroded sediment in runoff. Higher values of precipitation and soil erodibility indicate enhanced phosphorus transport, while a larger percent of well-drained soils (soils in Hydrologic Group A) would indicate less runoff and less erosion. Because phosphorus application rates have exceeded crop needs on the Eastern Shore, the Coastal Plain is associated with increased phosphorus concentrations in the soil; therefore, greater phosphorus losses can be expected from that region. Soil erodibility and percent area in the Coastal Plain land-to-water variables are not applied to the rock type sources. Phosphorus loads in the Phase 6 Model are dependent on stormwater runoff and sediment washoff as discussed in Section 4.

7.2.6 Nutrient Losses in Streams, Rivers, and Reservoirs

In CBTN_v4, nitrogen decay occurs in free-flowing streams and rivers as well as reservoirs and other impoundments. The amount of decay in streams and rivers is a function of travel time: the longer it takes to travel through a reach, the greater the capacity for denitrification. The rate of decay is also a function of stream size, as measured by mean annual flow, and the 30-year (1971-2000) average maximum air temperature. Smaller streams and streams in warmer climates have greater decay rates. Nitrogen losses in reservoirs are a function of the hydraulic loading rate, calculated as the mean annual outflow from an impoundment divided by its surface area. The larger the hydraulic loading rate, the more riverine-like the water body, and the smaller the nitrogen losses. The coefficient can be interpreted as an apparent settling velocity (Ator et al 2011), which includes, in addition to settling, other processes such as denitrification or algal uptake that contribute to the loss of nitrogen in impoundments.

Phosphorus losses in streams and rivers are not included in CBTP_v4, however phosphorus losses in reservoirs and impoundments are. Like nitrogen, they are a function of the hydraulic loading rate. Ator et al (2011) suggest that the larger apparent settling rate for phosphorus, compared to nitrogen, implies that that physical settling is the dominant loss mechanism for phosphorus in impoundments.

Tables 7-2 and 7-3 show the results of the Chesapeake SPARROW version 4 (Ator et al 2011), for nitrogen and phosphorus, respectively. The mean square error (MSE) for the nitrogen model is 0.0836. The R^2 on fluxes is 0.978 and the R^2 on yields is 0.858. For phosphorus, the MSE for the phosphorus model is 0.225. The R^2 for fluxes is 0.951 and for yields is 0.730. The parameter estimates used to derive the Phase 6 land-to-water factors were based on these models and the DVFs which resulted.

Table 7-2: Estimated Coefficients and Statistics from SPARROW Nitrogen Model of the Chesapeake Bay Watershed, Version 4

Variable	Estimate	90% Confidence Interval	Standard Error	P-value
Sources				
Point sources (kg yr^{-1})	0.774	0.375 – 1.17	0.242	0.0008
Crop fertilizer and fixation (kg yr^{-1})	0.237	0.177 – 0.297	0.0363	< 0.0001
Manure (kg yr^{-1})	0.0582	0.0138 – 0.103	0.0269	0.0157
Atmospheric deposition (kg yr^{-1})	0.267	0.179 – 0.355	0.0533	< 0.0001
Urban2 (km^2)	1090	707 – 1480	234	< 0.0001
Land-to-Water Delivery				
ln[Mean EVI for WY02 (dimensionless)]	-1.7	-2.65 – -0.737	0.58	0.0039
ln[Mean soil AWC (fraction)]	-0.829	-1.26 – -0.401	0.26	0.0016
ln[Groundwater recharge (mm)]	0.707	0.499 – 0.916	0.126	< 0.0001
ln[Piedmont carbonate (percent of area)]	0.158	0.0755 – 0.241	0.05	0.0018
Aquatic Decay				
Impoundments				
Inverse hydraulic load (yr m^{-1})	5.93	0.271 – 11.6	3.42	0.0424
Streams, time of travel (d) MAQ =mean annual flow; T30 = 30 year mean maximum temperature				
Small (MAQ ≤ 3.45 m^3 s^{-1})	0.339	0.0936 – 0.585	0.148	0.0118
Large (MAQ > 3.45 m^3 s^{-1}) T30 > 18.5°C	0.153	0.0622 – 0.245	0.0551	0.003
Large (MAQ > 3.45 m^3 s^{-1}) T30 ≤ 15°C	0.0131	-0.111 – 0.137	0.0751	0.431

Table 7-3: Estimated Coefficients and Statistics from SPARROW Phosphorus Model of the Chesapeake Bay Watershed, Version 4

Variable	Estimate	90% Confidence Interval	Standard Error	P-value
Sources				
Point sources (kg yr^{-1})	0.877	0.573 – 1.18	0.183	< 0.0001
Crop fertilizer (kg yr^{-1})	0.0377	0.0171 – 0.0583	0.0125	0.0014
Manure (kg yr^{-1})	0.0253	0.0144 – 0.0362	0.00658	0.0002
Siliciclastic rocks (km^2)	8.52	6.10 – 10.9	1.46	< 0.0001
Crystalline rocks (km^2)	6.75	3.25 – 10.2	2.12	0.0009
Urban2 (km^2)	49	30.4 – 67.7	11.3	< 0.0001
Land-to-Water Delivery				
Soil erodibility (K factor)	6.25	3.55 – 8.95	1.63	0.0002
ln[Well-drained soils (percent)]	-0.1	-0.153 – -0.0478	0.0317	0.0019
Coastal Plain (percent of area)	1.02	0.681 – 1.35	0.204	< 0.0001
ln[Precipitation3 (mm)]	2.06	0.567 – 3.55	0.903	0.0237
Aquatic Decay				
Impoundments- inverse hydraulic load (yr m^{-1})	54.3	12.1 – 96.5	25.5	0.0174

7.2.7 SPARROW Simulation with Land Classes as Sources

The USGS performed new SPARROW simulations of nitrogen and phosphorus in the Chesapeake Bay watershed explicitly to help inform Phase 6 land class average loading rate as described in Section 2. These simulations used the acreage of the land classes—cropland, pasture, developed land, and natural land—as source categories, in place of the original source categories in the CB_V4 SPARROW models. The only source category retained from CB_v4 was point sources, though estimates of point source loads were updated using information from Phase 6. Combined sewer overflows were also added as a source which, like point sources, is directly applied to river reaches.

Like the SPARROW CB_v4 models, the new SPARROW simulations were set up to simulate inputs under 2002 conditions. The 2002 Phase 6 land use, which is tabulated at land-river segment scale, was disaggregated to the NHDPlus scale appropriate for inputs into SPARROW. The land use disaggregation was based on the 10m-resolution raster datasets from the Chesapeake Bay Land Change Model (CBLCM) used in the beta versions of Phase 6. Table 7-4 shows the mapping of CBLCM classes to land classes. Land class acreage, based on the 2002 Phase 6 land use, was assigned to catchments using the following steps:

1. CBLCM land class area was determined for each catchment;
2. These areas were aggregated to Phase 6 land classes according to Table 7-4;
3. For each catchment, the ratio of the area of the Phase 6 land class to the total area of the Phase 6 land class in the land-river segment was calculated;
4. The 2002 Phase 6 land use was aggregated into land classes by land-river segment; and

5. For each catchment and each land class, the total 2002 land class area in the land-river segment was multiplied by the area ratio in Step 3 to obtain the area of a land class in a catchment.

This method of disaggregating land use does not necessarily preserve catchment area, but was deemed appropriate, since the land class acreages are only being used as sources of nutrients, and not catchment areas, which are derived directly from NHDPlus.

Table 7-4: Phase 6 Land Classes for CBLCM Land Use Classes

Phase 6 Land Class	CBLCM Land Use Class
Developed	Impervious Roads
Developed	Impervious Non-Roads
Developed	Turf Grass
Developed	Tree Canopy over Impervious
Developed	Tree Canopy over Turf Grass
Natural	Tree Canopy over Open Space
Natural	Open Space
Natural	Forest
Natural	Floodplain Wetlands
Natural	Other Wetlands
Natural	Tidal Wetlands
Crop	Cropland
Pasture	Pasture

Table 7-5 and 7-6 give the coefficients for nitrogen and phosphorus, respectively, which were estimated by SPARROW in the simulations using land classes as sources. The coefficients SPARROW calculates for these land-class sources provide an estimate of the average export rate of nutrients (in kg/km^2/yr) across the Chesapeake Bay watershed. These nutrient export rates were used to estimate the ratio of nutrient export among the land classes as described in Section 2. The MSE for the nitrogen model is 0.106 and the MSE for the phosphorus model is 0.279. For nitrogen, the R^2 on fluxes is 0.971 and the R^2 on yields is 0.820. For phosphorus, these R^2's are 0.936 and 0.665, respectively.

Table 7-5: Estimated Coefficients and Statistics from SPARROW Nitrogen Model of the Chesapeake Bay Watershed, Phase 6 2002 Land Class Acreage as Sources

Variable	Estimate	Standard Error	t-value	P-value
Sources				
Crop (km^2)	2,552.46	357.80	7.13	2.83E-11
Pasture (km^2)	1,070.23	232.23	4.61	8.02E-06
Developed (km^2)	873.69	153.95	5.68	5.99E-08
Natural (km^2)	51.82	34.94	1.48	1.40E-01
Point sources (kg yr^{-1})	0.90	0.27	3.29	1.23E-03

Septic systems (kg yr^{-1})	0.94	0.42	2.25	2.54E-02
Land-to-Water Delivery				
ln[Mean EVI for WY02 (dimensionless)]	-1.99	0.62	-3.20	1.64E-03
ln[Groundwater recharge (mm)]	0.57	0.16	3.65	3.54E-04
ln[Mean soil AWC (fraction)]	-1.09	0.30	-3.58	4.52E-04
ln[Piedmont carbonate (percent of area)]	0.19	0.06	3.29	1.22E-03
Aquatic Decay				
Impoundments				
Inverse hydraulic load (yr m^{-1})	14.19	5.80	2.45	1.55E-02
Streams, time of travel (d) MAQ =mean annual flow; T30 = 30 year mean maximum temperature				
Small (MAQ ≤ 3.45 $m^3 s^{-1}$)	0.17	0.16	1.09	2.79E-01
Large (MAQ > 3.45 $m^3 s^{-1}$) T30 > 18.5°C	0.16	0.06	2.60	1.02E-02
Large (MAQ > 3.45 $m^3 s^{-1}$) T30 ≤ 15°C	0.09	0.09	0.95	3.43E-01

The results of the nitrogen SPARROW model using land use as a source are consistent with other efforts as discussed in Section 2 of this documentation. The source terms for point sources and septic should be close to 1 given that these loads are direct inputs to streams. The values of 0.90 and 0.94 are indicators that the model was effectively estimated.

Table 7-6: Estimated coefficients and statistics from SPARROW Phosphorus Model of the Chesapeake Bay watershed, Phase 6 2002 land class acreage as sources

Variable	**Estimate**	**Standard Error**	**t-value**	**P-value**
Sources				
Crop (km^2)	106.50	20.87	5.10	8.75E-07
Pasture (km^2)	35.26	13.33	2.64	8.93E-03
Developed (km^2)	35.98	9.31	3.86	1.57E-04
Natural (km^2)	7.43	2.24	3.31	1.13E-03
Point sources (kg yr^{-1})	0.38	0.11	3.35	9.96E-04
CSOs (kg yr^{-1})	3.49	3.37	1.03	3.02E-01
Land-to-Water Delivery				
Soil erodibility (K factor)	5.13	1.29	3.97	1.07E-04
ln[Well-drained soils (percent)]	-0.14	0.03	-3.92	1.26E-04
Coastal Plain (percent of area)	0.95	0.20	4.83	3.01E-06
ln[Precipitation3 (mm)]	0.55	0.92	0.59	5.53E-01
Aquatic Decay				
Impoundments- inverse hydraulic load (yr m^{-1})	89.09	38.02	2.34	2.03E-02

The DVFs calculated in both the land use version of sparrow and the version 4 as presented above are similar and within the standard errors of each other. One difference that stands out is the higher estimate of the effect of impoundments in the land use version of SPARROW for nitrogen. Version 4 DVFs were used for Phase 6 land-to-water factors, rather than the land class sparrow. Since Phase 6 land-to-water factors are responsible for estimating spatial variability, any spatial variability in the manure, fertilizer, and atmospheric deposition sources that is spatially correlated with the DVF variables will be incorporated in to the DVFs and therefore introduce bias in the DVFs of the land use SPARROW. For example, since cropland in the Piedmont carbonate happens to have higher fertilization rates than cropland in other areas, the DVF for Piedmont carbonate in the land use model would likely be higher than the DVF for Piedmont carbonate in the model that incorporated cropland inputs. Since the Phase 6 Watershed Model also uses spatial variability in inputs, it is appropriate to use the version 4 SPARROW model for Phase 6 land-to-water factors. Version 4 was also used in the calculation of the small stream and impoundment factors as described in Section 9.

7.2.2 SPARROW Simulation of Sediment in the Chesapeake Bay Watershed

The USGS recently completed an updated of a SPARROW model (Brakebill, et al, 2010) which simulates sediment in the Chesapeake Bay watershed. Sediment sources included land use acreage in agricultural, forest, or developed land. Table 7-7 shows the estimated coefficients. The MSE is 0.878, the R^2 for fluxes is 0.84, and the R^2 for yields is 0.55. The model estimates that sediment storage occurs in impoundments anywhere in the watershed but only in coastal plain streams.

Table 7-7: Estimated coefficients and statistics from SPARROW Sediment Model of the Chesapeake Bay watershed

Variable	**Estimate**	**Standard Error**	**P-value**
Sediment Sources			
Agriculture	71.024	15.019	<0.001
Development	2041.51	1096.131	0.032
Forest	5.634	2.977	0.03
Land-to-Water Delivery			
Piedmont Uplands	0.1	0.031	0.001
K-Factor	8.77	3.013	0.002
Aquatic Storage			
Streams in the Coastal Plain			
Storage, all streams BFL	1.27	0.419	0.003
Impoundments			
Reservoir Settling Velocity	137.45	61.05	0.013

The results of the SPARROW sediment model 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.*

7.3 Phase 6 Land-to-Water Factors

7.3.1 Calculation of Phase 6 Land-to-Water Factors

As noted in Section 7.1.1, SPARROW land-to-water variables are input into the regression model centered on their average values. The overall effect of the land-to-water variables has been called the delivery variation factor (DVF) (Hoos and McMahon, 2009):

Equation 7-3: Delivery Variation Factor

$DVF_i = \exp(\alpha * Z_i)$ where

α = vector of estimated land-to-water coefficients: and
Z_i = vector of land-to-water variables for catchment i, centered on average value for the Chesapeake Bay watershed.

When all catchment variables equal the average value of the variables, the DVF is equal to one. The DVFs can be greater or less than 1, depending on the relative size of the catchment variables and the sign of the land-to-water coefficients. Therefore, a DVF is not a true delivery factor, but a measure of the deviation from average effects of transport from land to reaches. The overall effects of aquatic decay, on the other hand, can never be greater than one and can be interpreted as a true delivery factor.

The Phase 6 land-to-water factors are based on the DVFs from SPARROW with one important difference. DVFs are calculated from regressions with centered variables. Their aggregate effect is not constrained to be zero since there are spatial differences in loads. In contrast, the Phase 6 land-to-water factors are re-centered with consideration of spatial differences so that they have no aggregate effect on loads. For illustration, consider a simple example with two watersheds. Watershed A has an initial edge-of-stream (EOS) load of 3000 with a DVF of 1.2. Watershed B has an initial EOS load of 1000 with a DVF of 0.8. The average DVF is 1, but the aggregate, weighted average DVF is 1.1. To convert these to land-to-water factors, both DVFs are divided by the weighted average DVF. Watershed A now has a land-to-water factor of 1.09 and watershed B now has a land-to-water factor of 0.73. The total EOS load before and after the land-to-water factors are applied is now 4000.

DVFs are calculated by land classes (crop, pasture, natural, and developed land) and applied at the land-river segment scale. Each NHDPlus catchment had a single DVF from SPARROW. However, the four land classes were not evenly distributed between different catchments within a Phase 6 land-river segment. Weighting each catchment by the fraction of catchment in each land class allowed the development of separate DVFs for each of the four land classes for each land-river segment in the Phase 6 Model.

A DVF for a land class at the land-river segment scale is the average DVF at the NHDPlus catchment scale, weighted by the land class's area in the catchment in the land-river segment, according to the formula

Equation 7-4: Area-weighted delivery variance factors

$$DVF_{LR,k} = \sum_{i=1}^{N} DVF_i * A_{i,k} / A_{LR,k}$$

Where:
$DVF_{LR,k}$ = DVF for land class k at land-river segment scale
DVF_i = DVF in NHDPlus catchment *i*
$A_{i,k}$ = Area of land class k in catchment *i* in land-river segment
$A_{LR,k}$ = Total area of land class k in land-river segment
N = number of catchments wholly or partially in the land-river segment

The land class areas for each catchment were taken from the 2013 High Resolution Land Cover, described in Section 5. Land use from the High-Resolution Land Cover was aggregated to the NHDPlus catchment scale and further aggregated to land class acreage according to Table 7-4.

7.3.2 Selection of SPARROW Land-to-Water Variables

The structure of the Phase 6 Watershed Model and the CBTN_v4 and CBTP_v4 SPARROW models is similar in that input loads such are fertilizer and manure are multiplied by coefficients that relate to export loads and in that the loads are further modified by spatial factors related to watershed and riverine transport. This allows the use of SPARROW land-to-water variables as Phase 6 land-to-water factors with some modifications. Some land-to-water variables in SPARROW are counted as inputs in Phase 6 or are covered by other processes. Discussion of Phase 6 sensitivities to inputs is in Section 4.

The Phase 6 Phosphorus land use average loads are modified locally to incorporate sensitivity to runoff and erosion. The Phase 6 sensitivity to runoff and erosion captures the impact that the SPARROW land-to-water variables of precipitation and erosivity have on phosphorus transport. For that reason, these two factors were dropped from the calculation of phosphorus DVFs on Phase 6 land uses with runoff and erosion sensitivities. Similarly, areas of high soil phosphorus, as measured by Mehlich-3 soil P, are generally found on the Coastal Plain. Ator et al (2011) suggested that the significantly positive coastal plain land-to-water coefficient in the CBTP_v4 model was likely due to high levels of soil phosphorus which were not used as an input due to data limitations. Since soil phosphorus is already an important determinant of land use loads in the Phase 6 Watershed Model, the land-to-water factor for percent Coastal Plain is redundant. Therefore, phosphorus DVFs were calculated based on the percent well-drained soils. All land-to-water factors except percent area in the Coastal Plain were used to calculate DVFs for permitted feeding space and non-permitted feeding space land uses, where the sensitivity to runoff or erosion was not used at a prior point in the calculation. Section 7.3.5 discusses land-to-water delivery from feeding space land uses in more detail.

Duplication also occurs between nitrogen land-to-water factors and sensitivities. Ator et al (2011) state that the EVI probably represents the effect of plant uptake on nitrogen transport. The larger the EVI, the less nitrogen is transported from fields to streams. Phase 6 already accounts for plant uptake by using plant uptake as a sensitivity factor for adjusting average land use nitrogen export. Additional reasons speak against retaining the EVI in the nitrogen DVF. Land use, which is directly accounted for in Phase 6, is highly correlated with density of vegetation. The presence of impervious areas tends to lead to low values of EVI and consequently high values of nitrogen DVF. The presence of the EVI leads to a wide range of values in the nitrogen DVF. With the EVI, the maximum DVF at the land-river segment scale is 7.35; without the EVI, it is only 2.42. As shown in Figure 7-3, these high values tend to be concentrated in urban areas like Baltimore City, Alexandria, or Virginia Beach, or in shoreline areas where the EVI is influenced by barren shore or water. Most of these areas are downstream of SPARROW calibration stations and therefore the EVI's contribution to high DVFs cannot be justified on the basis of SPARROW. Therefore, the EVI land-to-water factor was dropped from the calculation of the nitrogen DVF.

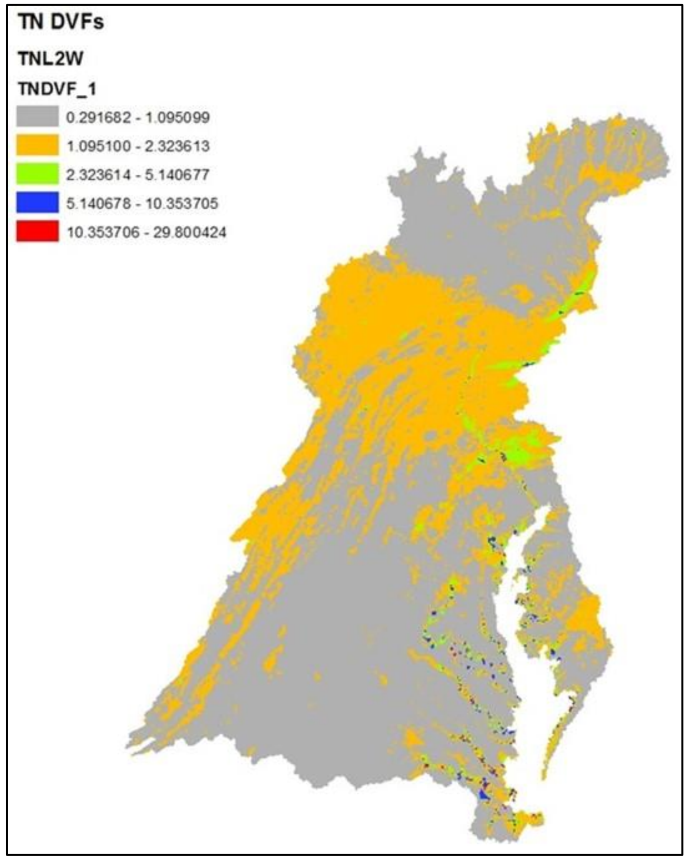


Figure 7-3: Delivery variance factors including EVI

7.3.3 Final Phase 6 Land-to-Water Factors

Figure 7-4 through Figure 7-7 show the nitrogen DVFs on the land-river segment scale for crops, pasture, developed land, and natural land. Figure 7-8 through Figure 7-11 show the corresponding phosphorus DVFs. **Error! Reference source not found.**8 lists the Phase 6 land uses assigned to each SPARROW land cover class. Feeding Space land uses and direct deposition from riparian pasture are special cases that are dealt with in the following section.

As discussed above, the individual land-to-water factors are centered on their average values, so the DVF measures the effects of transport as they deviate from average conditions. For this reason, the DVFs do not behave like sediment delivery factors which estimate the delivery from edge-of-field to edge-of-stream (EOS). The edge-of-field scale for nutrients is not defined in the Phase 6 Model.

In Phase 6, the DVFs are adjusted so that the Bay-wide total EOS load above the RIM stations is the same as the Bay-wide load from land simulation targets above the RIM stations and there is no net increase or decrease in the total EOS load from the application of the DVFs. The adjustment was made by subtracting 0.1125 from the nitrogen DVFs and 0.036 from the phosphorus DVFs at the land-river scale.

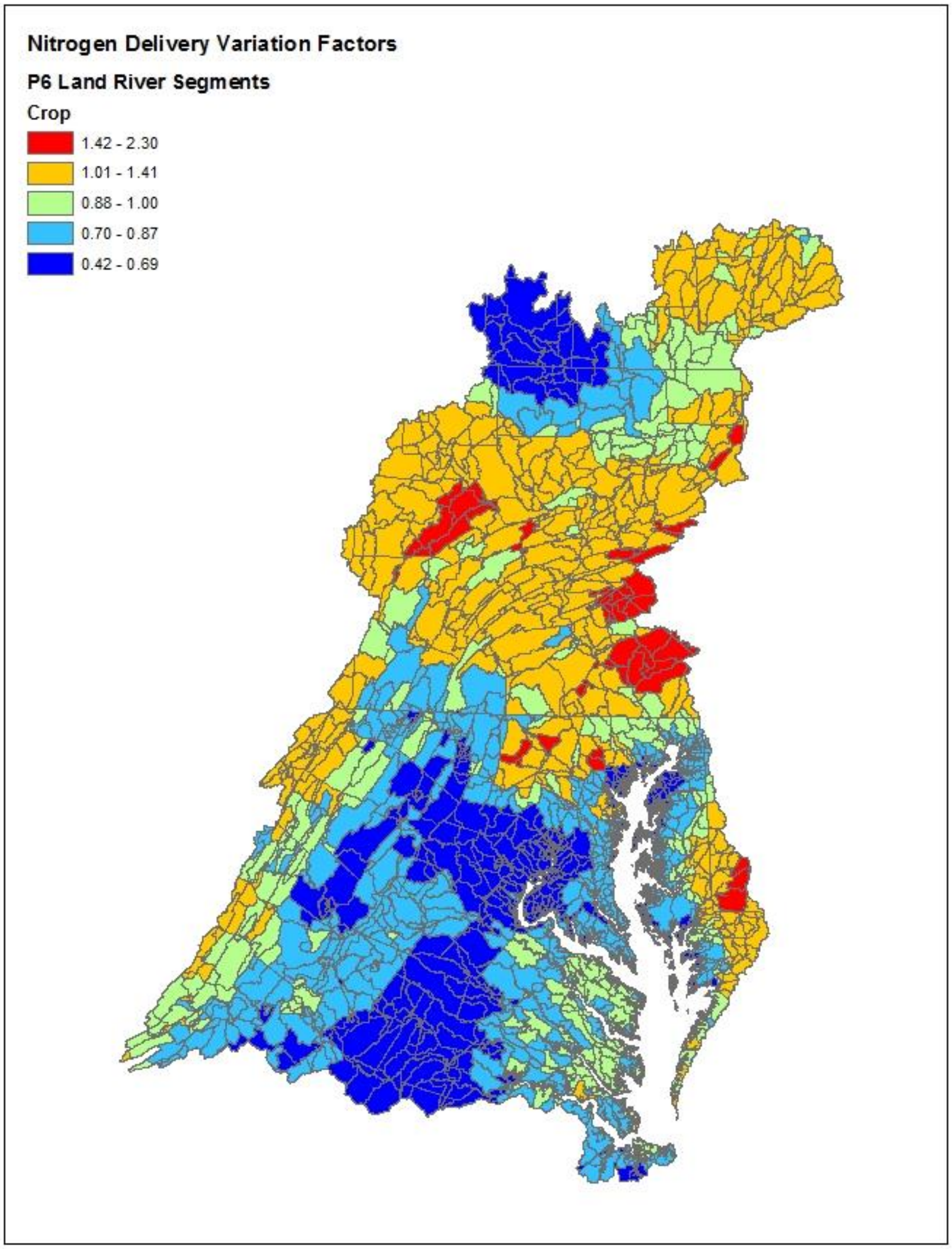


Figure 7-4: Nitrogen crop delivery variation factors, final Phase 6

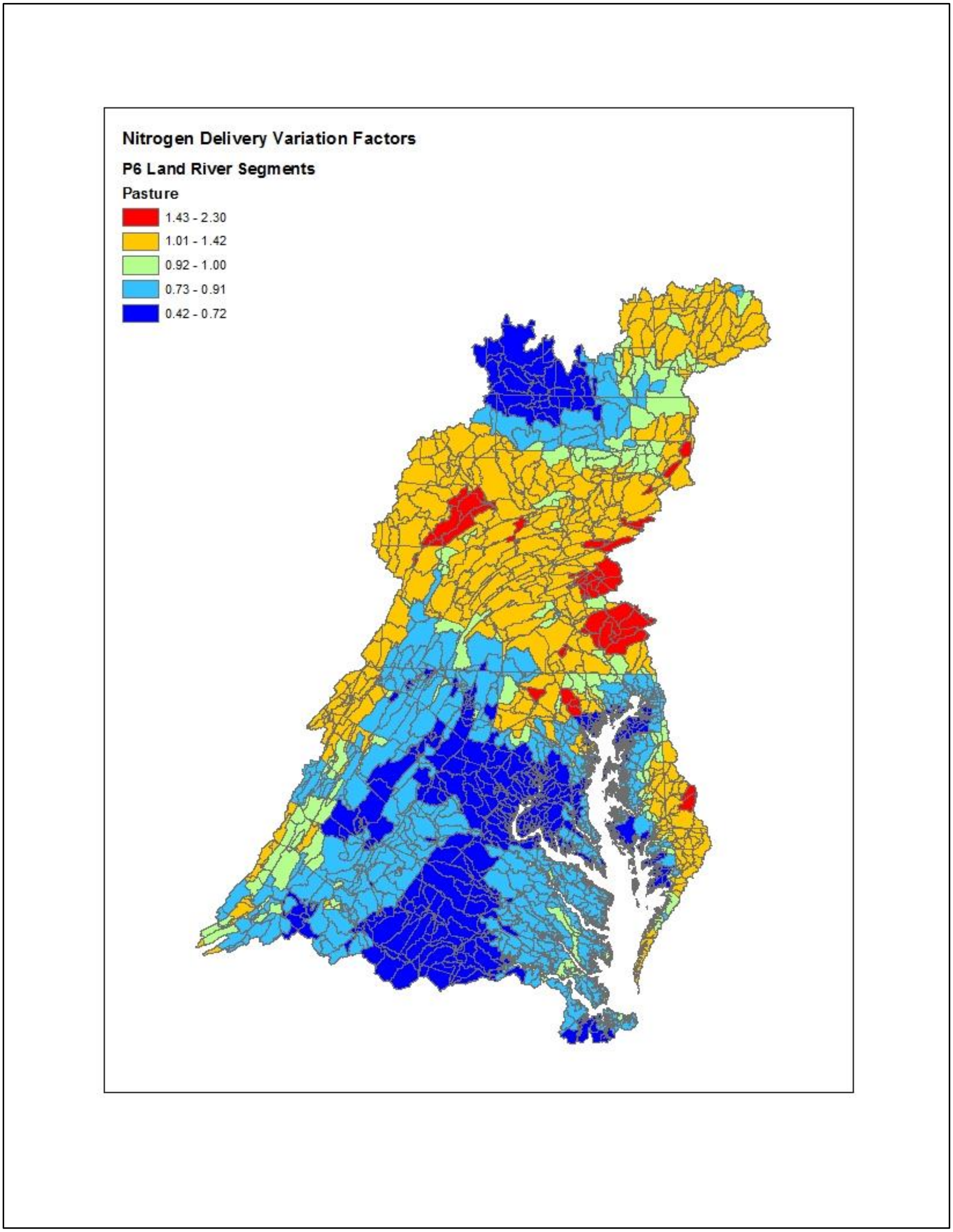


Figure 7-5: Nitrogen pasture delivery variation factors, final Phase 6

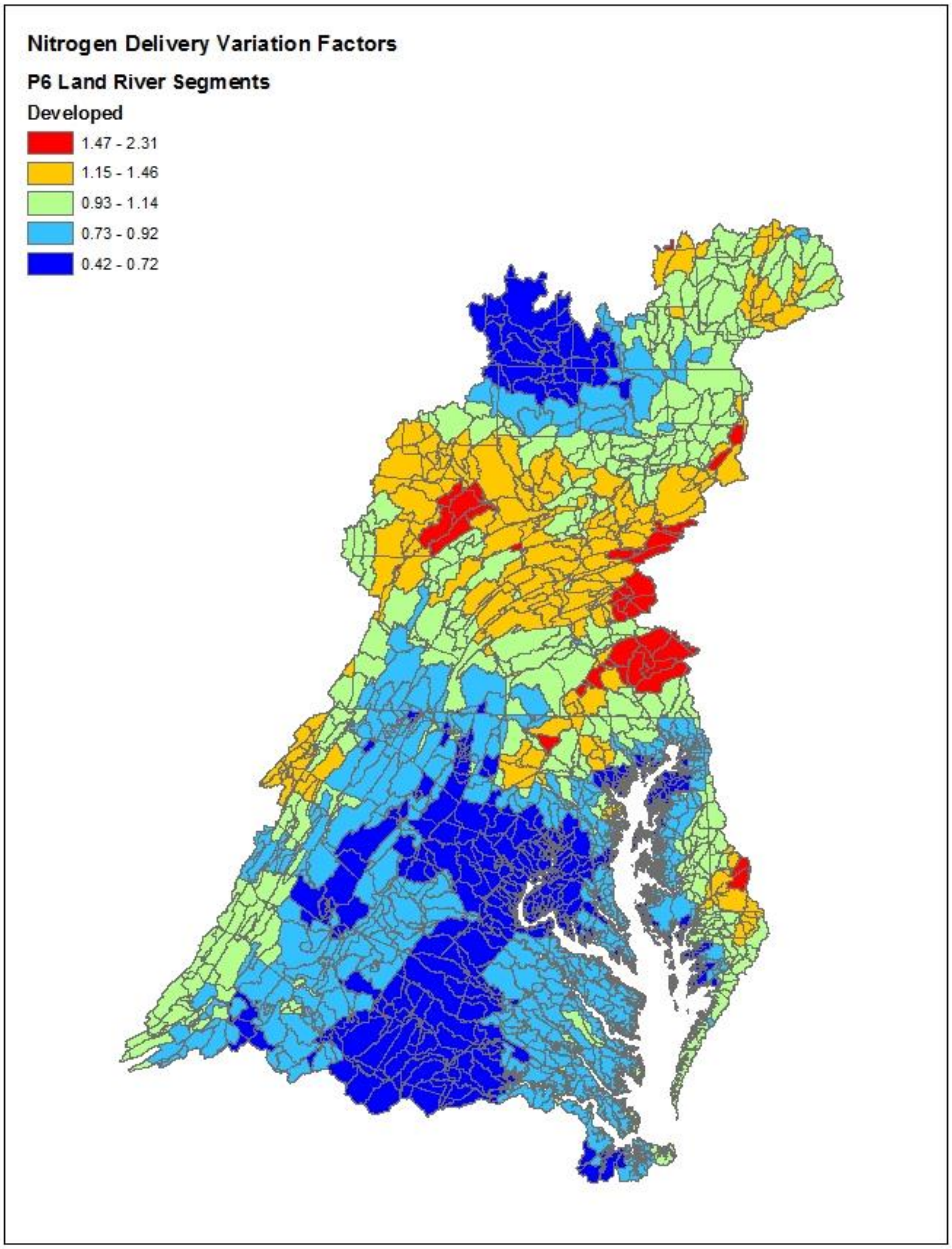


Figure 7-6:Nitrogen developed delivery variation factors, Final Phase 6

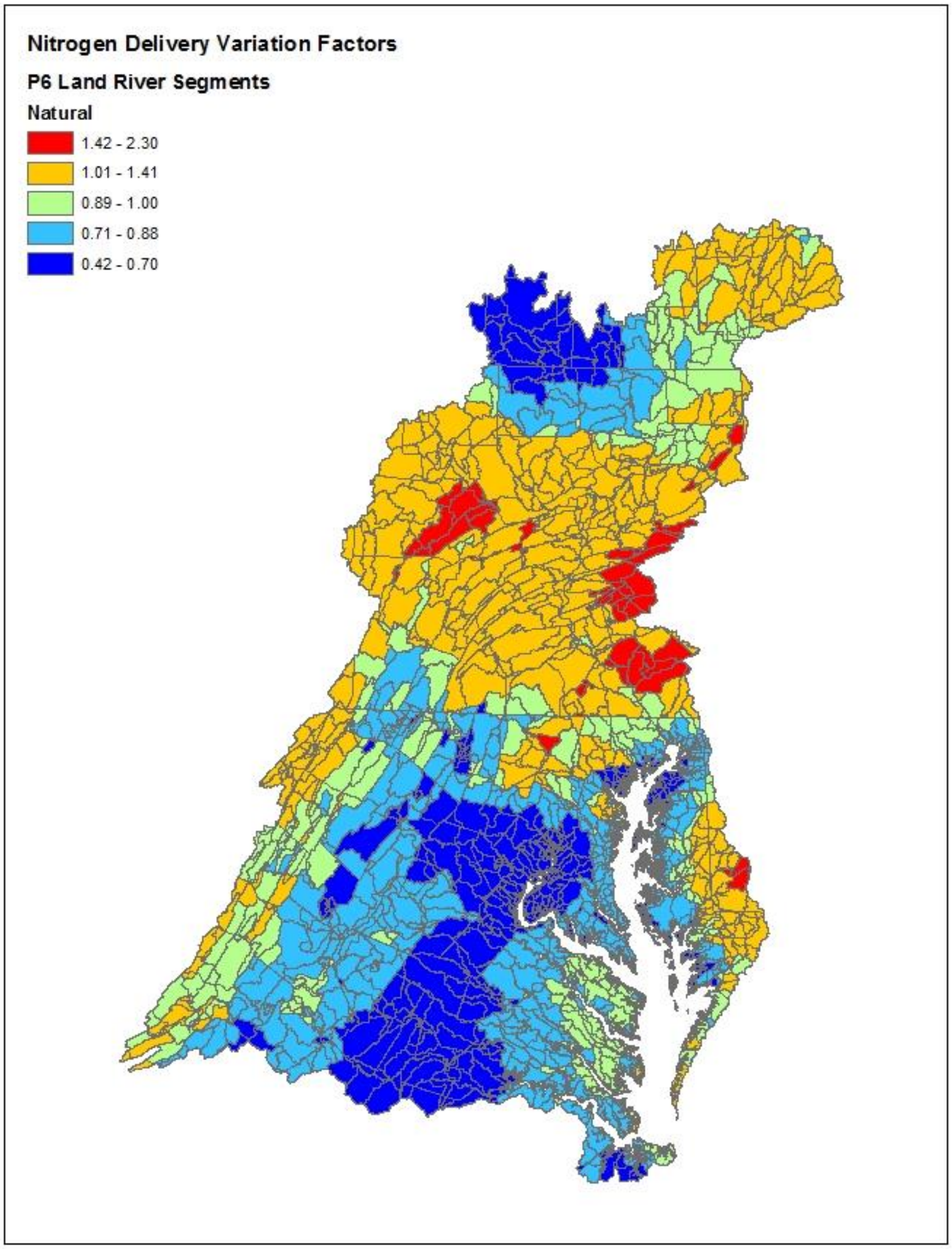


Figure 7-7:Nitrogen natural delivery variation factors, final Phase 6

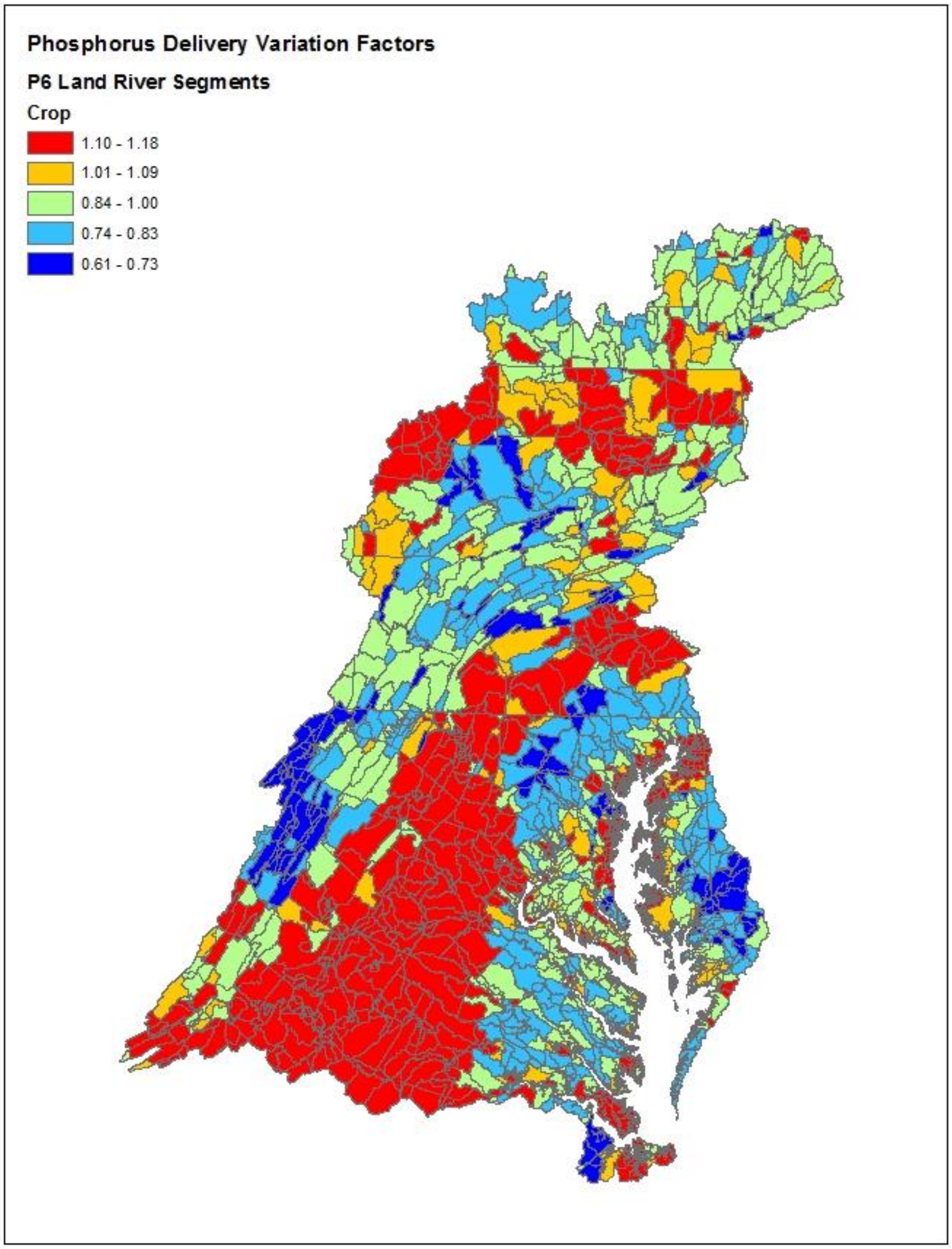


Figure 7-8: Phosphorus crop delivery variation factors, final Phase 6

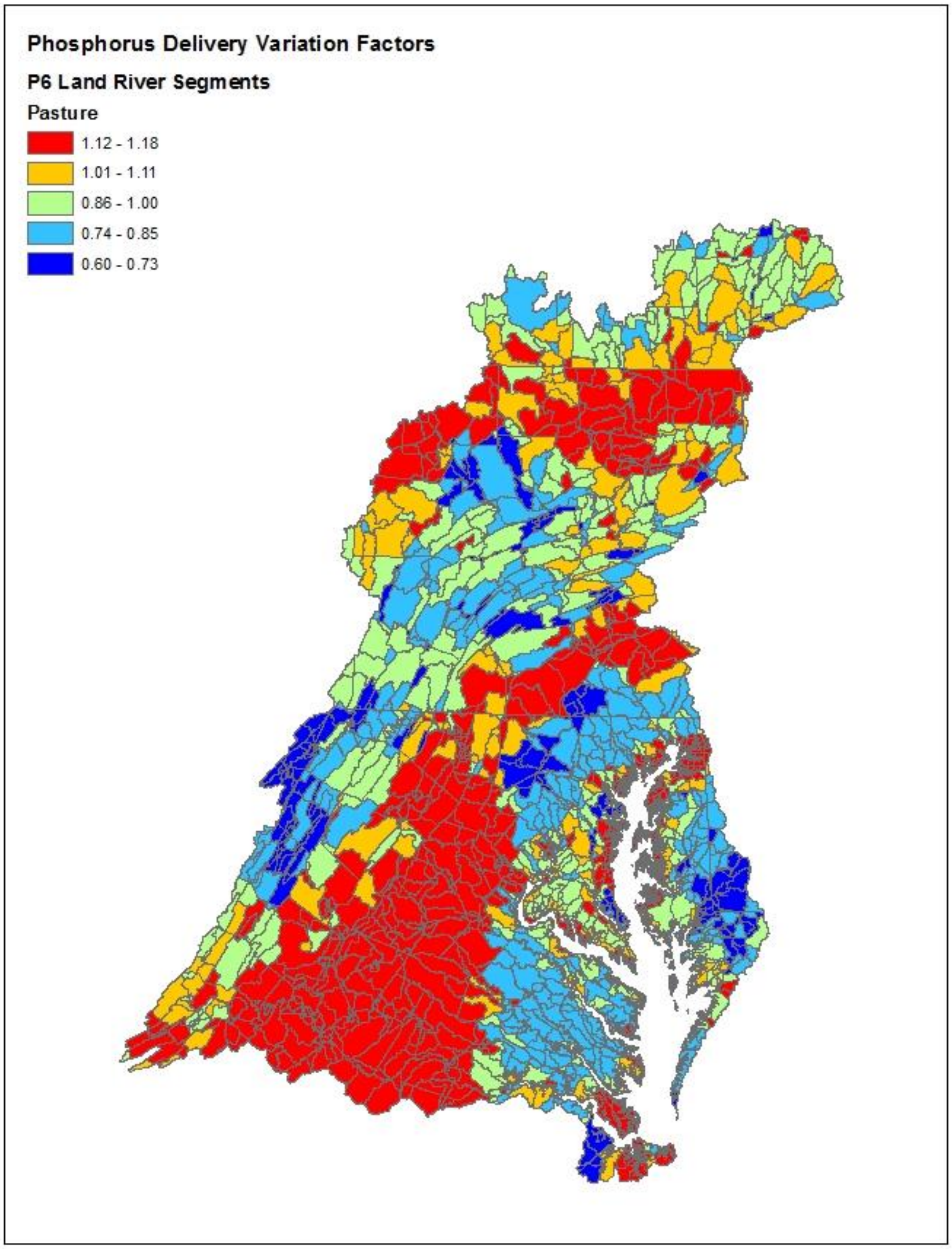


Figure 7-9: Phosphorus pasture delivery variation factors, final Phase 6

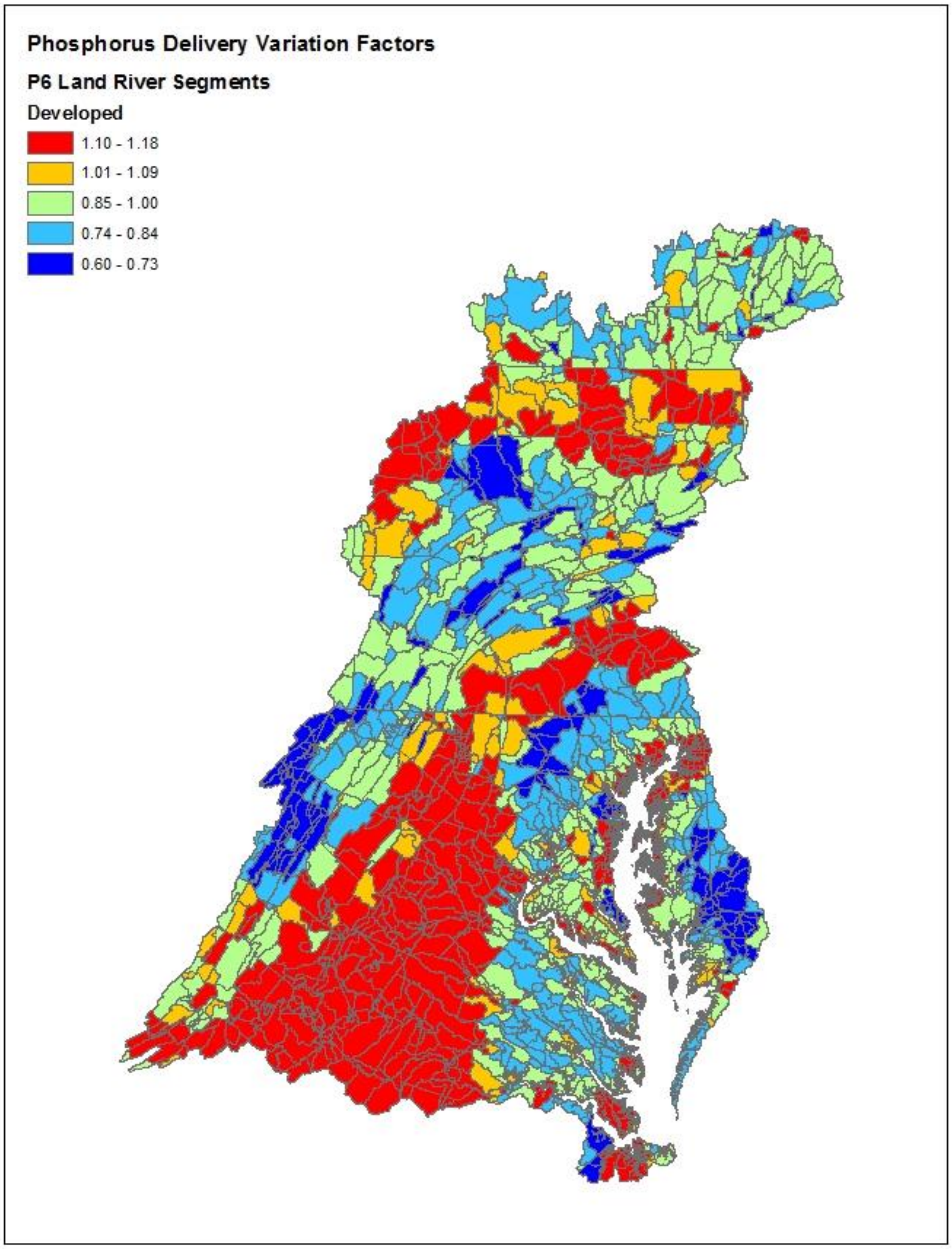


Figure 7-10: Phosphorus developed delivery variation factors, final Phase 6

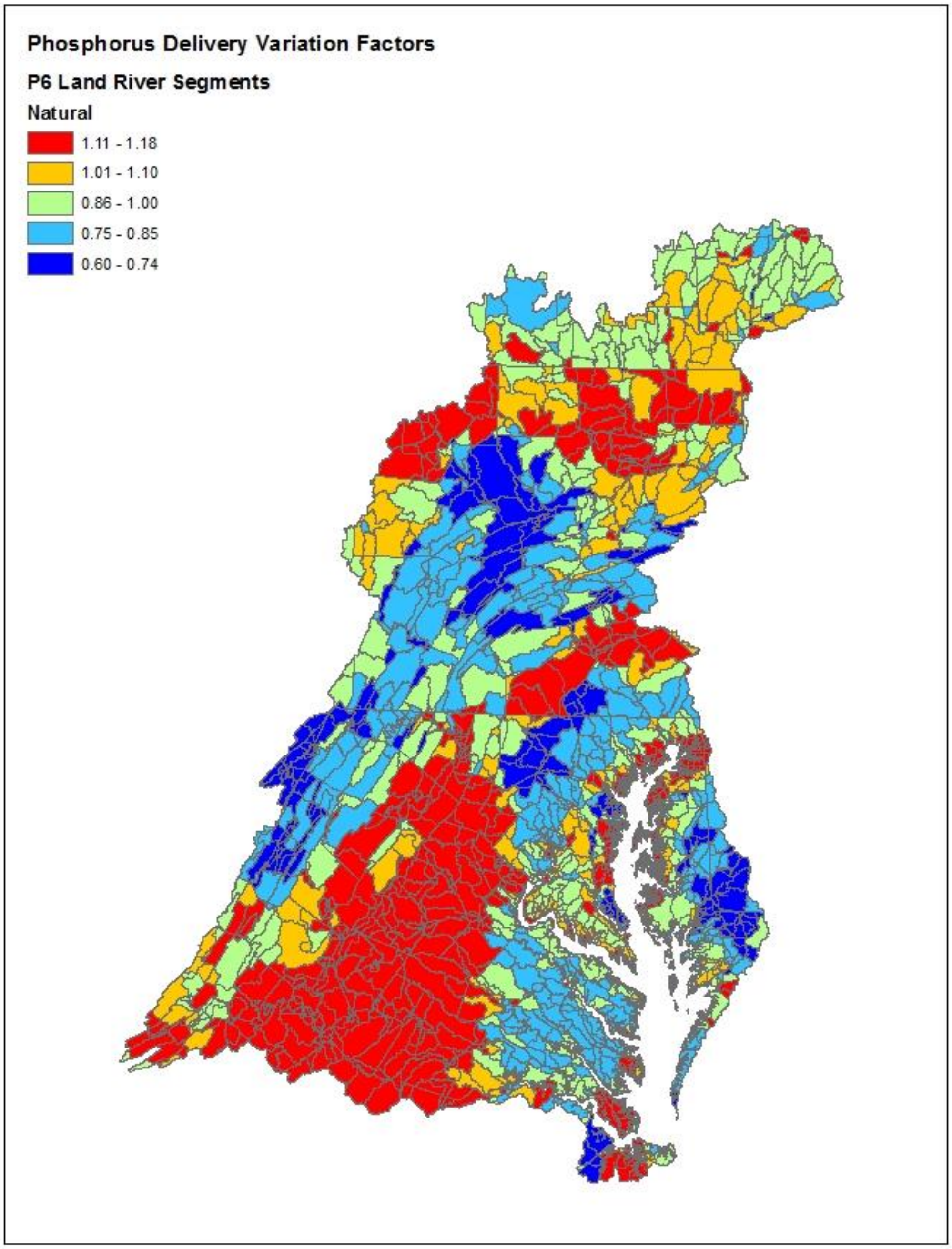


Figure 7-11: Phosphorus natural delivery variation factors, final Phase 6

Table 7-8: Phase 6 land class and land uses

Phase 6 Land Class	Phase 6 Land Use Abbreviation	Phase 6 Land Use
crop	aop	Ag Open Space
crop	dbl	Double Cropped Land
crop	gom	Grain without Manure
crop	gwm	Grain with Manure
crop	lhy	Legume Hay
crop	oac	Other Agronomic Crops
crop	ohy	Other Hay
crop	sch	Specialty Crop High
crop	scl	Specialty Crop Low
crop	sgg	Small Grains and Grains
crop	sgs	Small Grains and Soybeans
crop	som	Silage without Manure
crop	soy	Full Season Soybeans
crop	swm	Silage with Manure
developed	cch	CSS Tree Canopy over Turfgrass
developed	cci	CSS Tree Canopy over Impervious
developed	ccn	CSS Construction
developed	cir	CSS Roads
developed	cnr	CSS Buildings and Other
developed	ctg	CSS Turf Grass
developed	mch	MS4 Tree Canopy over Turfgrass
developed	mci	MS4 Tree Canopy over Impervious
developed	mcn	MS4 Construction
developed	mir	MS4 Roads
developed	mnr	MS4 Buildings and Other
developed	mtg	MS4 Turf Grass
developed	nch	Non-Regulated Tree Canopy over Turfgrass
developed	nci	Non-Regulated Tree Canopy over Impervious
developed	nir	Non-Regulated Roads
developed	nnr	Non-Regulated Buildings and Other
developed	ntg	Non-Regulated Turf Grass
natural	dfr	Disturbed Forest
natural	for	True Forest
natural	hfr	Harvested Forest
natural	osp	Mixed Open
natural	wfp	Non-tidal Floodplain Wetland
natural	wto	Headland or Isolated Wetland
pasture	pas	Pasture

7.3.4 Riparian Pasture

Loading from riparian pasture stream access is a direct load to the stream and therefore does not undergo any land-to-water processes. There is no delivery variance applied to this land use (rpa). Calculation of these loads is described in Section 3 and appendix 3B.

7.3.5 Feeding Space

Phase 6 has two Feeding Space land uses, permitted (fsp) and unpermitted (fnp). These loads are scaled to the edge-of-field rather to the edge-of-stream and so reductions must be taken to account for losses in transport. The Phase 5 pass-through factors (USEPA 2010a-10) of 0.7 for nitrogen on 0.1 for phosphorus are applied for this purpose. That is, 30 percent of the nitrogen and 90 percent of the phosphorus not otherwise accounted for in crop application, volatilization, or transport is assumed to be lost through watershed processes and does not reach the edge-of-stream. In addition, the nitrogen delivery variance factors for pasture are assigned to these land uses to account for differences in nitrogen watershed delivery. Phosphorus delivery variance factors include percent well-drained soils, erosivity, and precipitation. The final land-to-water factor is the product of these two numbers with a maximum value of 1.0

7.4 Sediment Delivery Ratios

In Phase 6 sediment loads from the land are scaled to the edge of field and therefore the Phase 6 land-to-water factors are true scaling factors that significantly reduce the overall load that reaches a small stream. This is in contrast to the nutrient factors described above that spatially distribute nitrogen and phosphorus loads, but don't change the aggregate total. Land-to-water factors are a common concept in sediment modeling and are generally referred to as sediment delivery ratios (SDRs).

7.4.1 Interconnectivity Factors

Phase 6 uses the Index of Connectivity (IC) in the calculation of SDRs. The IC is a measure of how connected the landscape is to certain features of interest (Cavalli et al 2013). In Phase 6, the feature of interest is a stream. An IC can be calculated for any given point on the landscape, as a combination of the properties of the upslope watershed and the downslope path to a stream. Figure 7-12 shows the upstream and downstream components in the calculation of IC. Variables shown in Figure 7-12 are defined in the equations below.

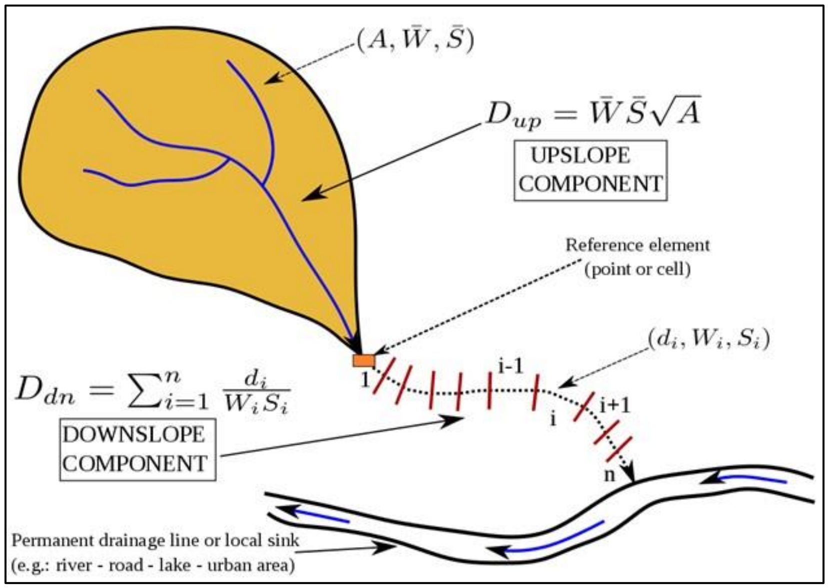


Figure 7-12: Components of the Index of Connectivity (IC)

The IC is calculated as:

Equation 7-5: IC definition

$$IC = log_{10}\left(\frac{D_{up}}{D_{dn}}\right)$$

Where D_{up} represents the upslope component of connectivity, and D_{dn} represents the downslope component. D_{up} is defined as:

Equation 7-6: Upslope Component of Connectivity

$$D_{up} = \overline{W}\,\overline{S}\sqrt{A}$$

Where:

$\overline{W}$ = the average weighting factor for the upslope area

$\overline{S}$ = the average slope of the upslope area

A = the upslope contributing area (m^2)

The downslope component is defined as:

Equation 7-7: Downslope Component of Connectivity

$$D_{dn} = \sum_i \frac{d_i}{W_i S_i}$$

Where:
d_i = the length of the flow path along the *i*th cell according to the steepest downslope direction (m)
W_i = the weighting factor of the *i*th cell
S_i = the slope gradient of the *i*th cell

The weighting factor (*W)* is a local measure of topographic surface roughness. It is defined as:

Equation 7-8: Weighting Factor

$$W = 1 - \left(\frac{RI}{RI_{MAX}} \right)$$

Where:
RI = the local roughness index
RI_{MAX} = the maximum roughness index of the study area.

The roughness index is defined as the standard deviation of the difference between the original Digital Elevation Model (DEM) and a DEM that has been smoothed by averaging the values of cells in a moving window of a defined size. Depressions in the a ten-meter resolution DEM of the Chesapeake Bay Watershed (CBW) were filled and small streams, defined as pixels with a contributing area greater than 60 acres, were nullified. The resulting DEM was then used as the input to the Surface Roughness tool in the SedAlp Connectivity Toolbox for ArcGIS (Cavalli et al 2014). The default settings of a rectangular 5 x 5 cell moving window were used to create a Roughness Index grid (RI). The weighting factor grid (W) was calculated using Raster Calculator.

The SedAlp Connectivity Toolbox has the capability to compute the IC, however, due to memory limitations it was more efficient to use an iterative script to calculate IC for smaller portions of the watershed. The pre-processed DEM, the weighting factor grid, a shapefile of all the HUC10 catchments in the CBW, and a text file containing a list of the HUC10 codes were used as inputs to an iterative IC script that was developed and provided by Tetra Tech. The script reads a HUC code from the list, buffers and clips the DEM to the corresponding HUC from the shapefile, and computes the IC for that HUC, as calculated by the Connectivity Toolbox. This process is repeated for each HUC code in the list. The resulting IC grids for each HUC10 were then mosaicked together in ArcMap to create a single IC grid for the CBW.

The grid of IC values and the 2013 high-resolution land cover data set described in Section 5 were overlaid and average IC values by land-river segment and land use were calculated. IC values were unable to be calculated for combinations of land-river segments and land use that had no acres associated with them. For completeness of the data set, an average for the land segment and land use was assumed to apply to each land-river segment and land use where necessary.

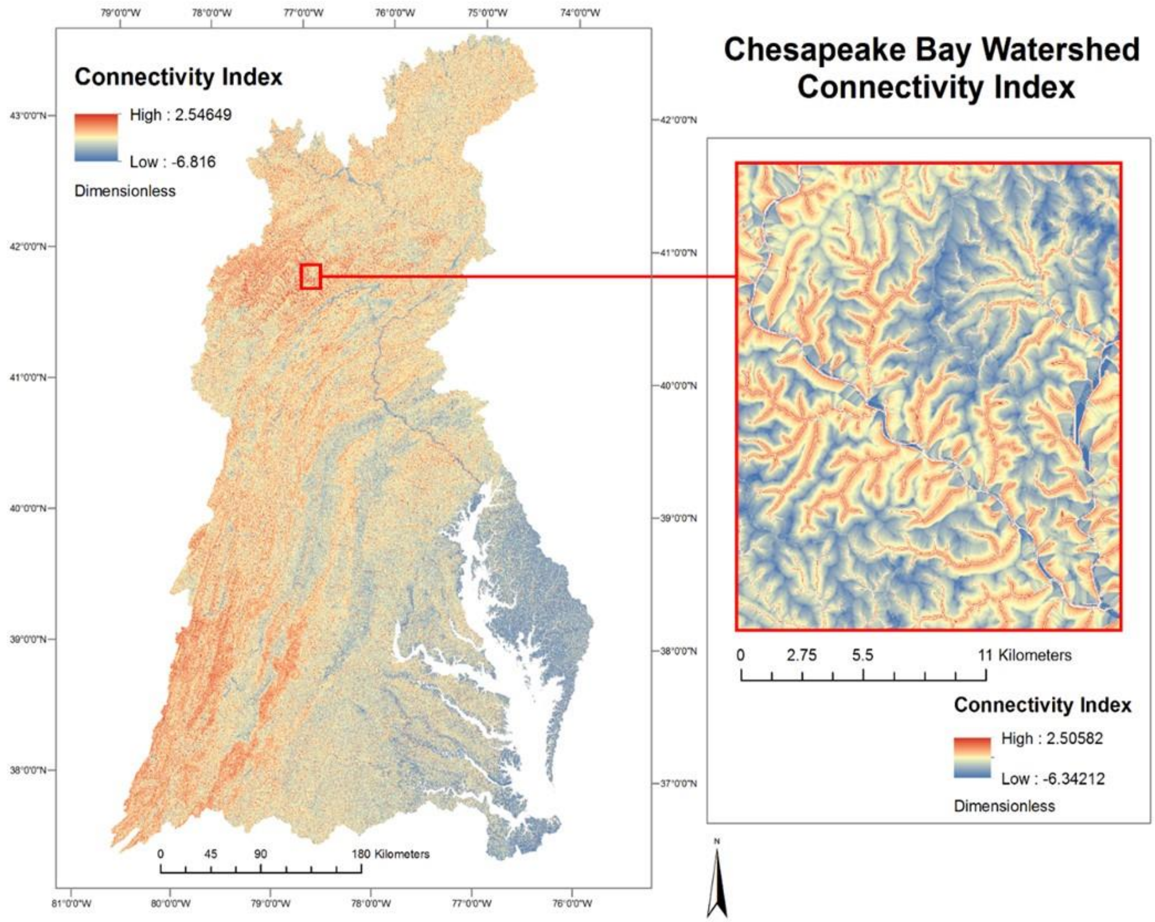


Figure 7-13: Interconnectivity index

Figure 7-13 above shows the spatial distribution of the IC. The scale is a unitless log scale that orders the propensity of the landscape to transport sediment. Both large scale and small scale patterns are evident in the figure. As expected, the high-slope areas of the Blue Ridge and Appalachian Plateau transport sediment much more readily than the low-slope Coastal Plain. The appearance of the slope term in the numerator and in the divisor of the denominator of the IC drive this behavior which matches intuition about the watershed. The inset shows how the IC is determined on a fine scale. The IC is inversely related to the flow-path distance from any point to the stream. Sediment is transported to the streams more readily from areas that are closer to a stream. Processing the IC overlaid with the land cover allowed for land covers closest to the stream to receive a higher IC.

7.4.2 Conversion to Sediment Delivery Ratios

Sediment IC factors described above are a relative delivery metric and cannot be directly used as delivery ratios. They generally range from -6 to 1 and follow a somewhat normal distribution as shown in Figure 7-14 below.

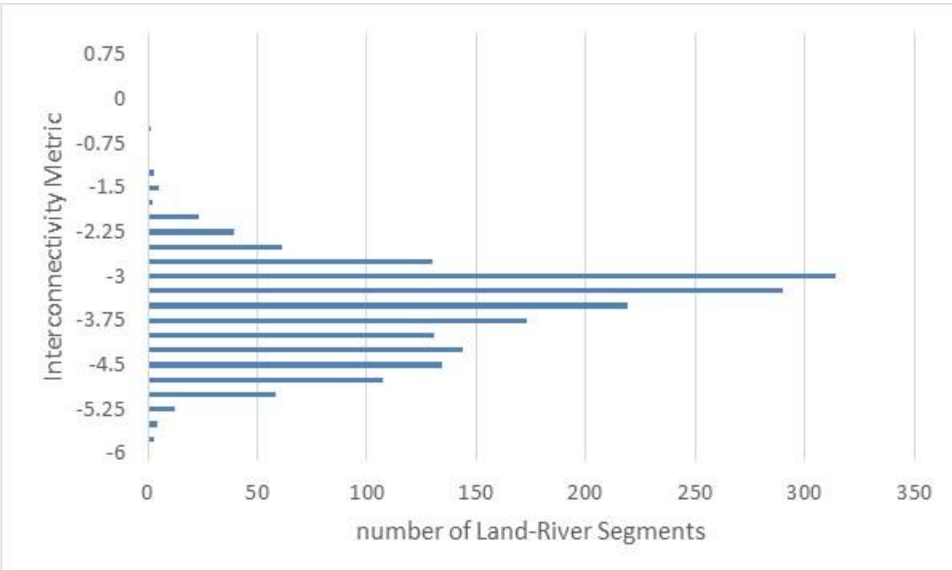


Figure 7-14: Distribution of indices of connectivity in pasture

The Sediment Delivery Ratios must have a maximum value of 1 and a minimum value of 0. The SDR must have an average value such that a reasonable calibration to observed data can be made given the information available at other modeling scales. That is, the SDR (shown as 'Land to Water' in Figure 7-15) must reduce the edge-of-field loads to an expected load to small streams that will results in a good calibration against observed data. Without additional information on the relationship between IC and SDR, a linear relationship is assumed.

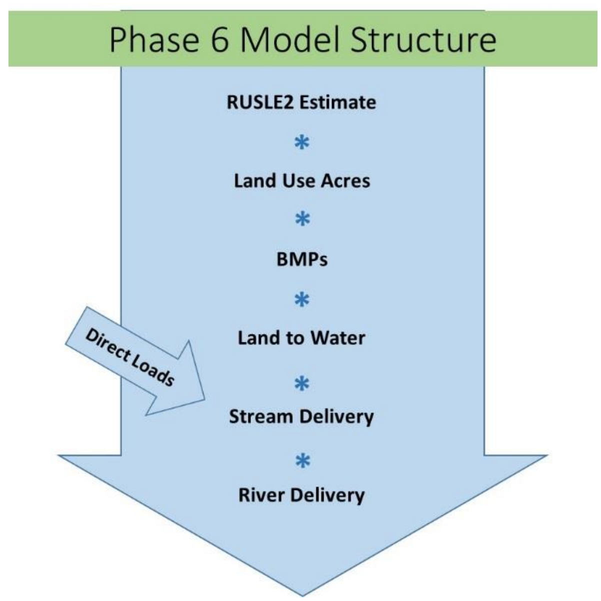


Figure 7-15: Phase 6 Model structure for sediment

The approach is to form a mass balance around the monitored portion of the watershed. Edge-of-field loads are produced by multiplying RUSLE loading rates as described in Section 2 by the land use acres and BMP effect. Edge-of-field loads are reduced by the land-to-water factors. These loads are then modified by stream delivery and river delivery factors to meet a monitored load. Direct loads are small and can be ignored.

Working from the bottom up, the average annual observed sediment load is taken from the CBP sediment load indicator:
http://www.chesapeakebay.net/indicators/indicator/sediment_loads_and_river_flow_to_the_bay

(accessed 3/24/16). Loads from their beginning in 1990 through 2010 were used. Loads for water year 2011 were strongly influenced by tropical storm Lee and the decreased trapping of the Conowingo pool. Loads from 2011 and later were not used since the river simulation is based on a reservoir with available trapping capacity. Stream delivery and river delivery are estimated using the same methods used for estimating the edge-of-small-stream phosphorus in Section 2.

Table 7-9 shows the sources of information to estimate stream and river losses. For more information on stream losses and non-simulated reservoir losses, see Section 9. Calculated sediment losses in the Conowingo reservoir were estimated through the regression model WRTDS using monitoring stations above and below the reservoir.

Table 7-9: Sources of information for mass balance

Stream or River	Type	Information Source
Stream	Reservoir	Sparrow
Stream	Non-reservoir	Assume no loss, consistent with Ator et al, 2011 and Noe et al 2015a, 2015b
River	Non-reservoir	Assume no loss, consistent with Ator et al, 2011 and Noe et al 2015a, 2015b
River	Conowingo Reservoir	WRTDS (after Zhang et al 2016)
River	Other Simulated Reservoirs	Phase 5.3.2 losses
River	Non-simulated Reservoirs	Sparrow

The BMP reduction was found by comparing the year 2000 edge of stream sediment in phase 5.3.2 with the 'No-BMP' run for that same year in Phase 5.3.2. Edge-of-Field loads are the RUSLE estimates described in Section 2. Note that the information sources in Table 7-9 are used in the calculation of the SDR. The final Phase 6 Model uses methods described in Section 10 to simulate rivers and reservoirs.

Observed load: 4.77 million tons/year
River Loss: 1.60 million tons/year
- ⇨ Load needed to River = 6.37 million tons/year

Stream Loss: 1.81 million tons/year
- ⇨ Load needed to stream = 8.18 million tons/year

Edge-of-Field: 18.52 million tons/year
BMP reduction: 10.7%
- ⇨ Post BMP Load = 16.53 million tons/year
- ⇨ Calculated weighted average land-to-water factor = 8.18 / 16.53 = 0.495

Figure 7-11: Calculation of average land-to-water factor

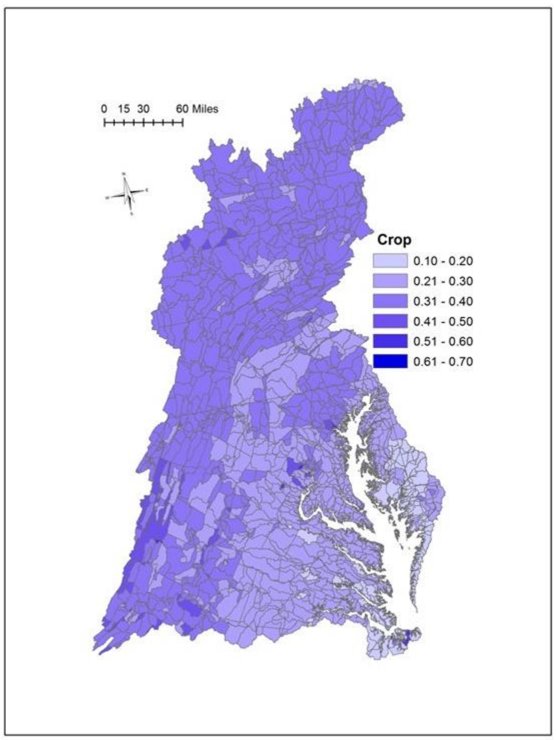
The calculation in Figure 7-11 results in a necessary weighted average sediment delivery ratio of 0.495. The weighted average of IC values is -3.23, so a point on the linear transformation curve is established at (-3.23, 0.495). Two points are needed to create a linear transformation function between the IC and a sediment delivery ratio. The second point is derived through moving out one standard deviation for both metrics. The standard deviation of the IC is 1.2. Chinnasamy et al (undated) found that standard deviations of the sediment delivery ratio in the Upper Mississippi basin were approximately 0.08. The

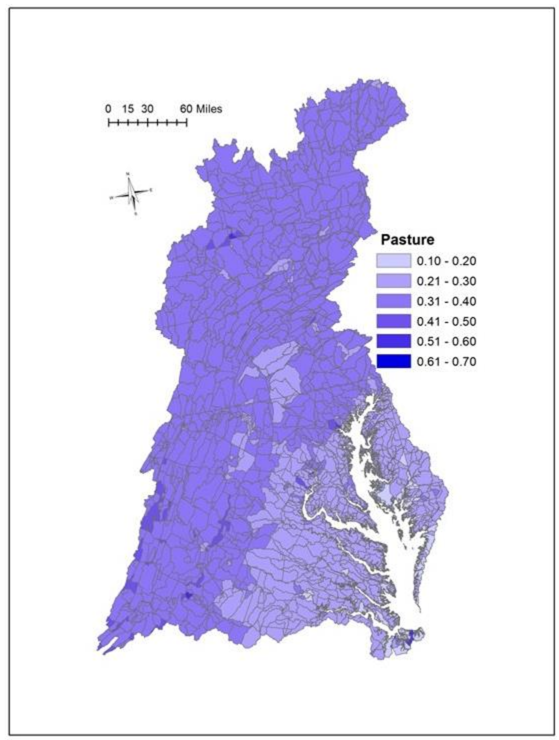
Phase 5.3.2 CBWM had a standard deviation in sediment delivery ratio of approximately 0.10 (USEPA 2010a-09). The CBWM is run on a smaller segmentation than the Upper Mississippi model so it could be expected that the standard deviations would be somewhat higher, therefore the value of 0.10 is used here. Subtracting the standard deviation of the interconnectivity from the interconnectivity mean and the standard deviation of the delivery ratio from the delivery ratio mean allows the establishment of a second point at (-4.43, 0.395). The equation of this line shown in Equation 7-9 below.

Equation 7-9: Interconnectivity conversion to sediment delivery ratio

$$SDR = 0.083 * IC + .764$$

The final sediment delivery ratios for land use classes are shown below. All six maps are plotted on the same scale to allow for comparison. Although general patterns hold throughout all land classes, there are some differences between classes driven by the spatial arrangement of the land classes within a land-river segment. For example, forest tends to have a high sediment delivery ratio, likely due to higher slopes and proximity to the streams.





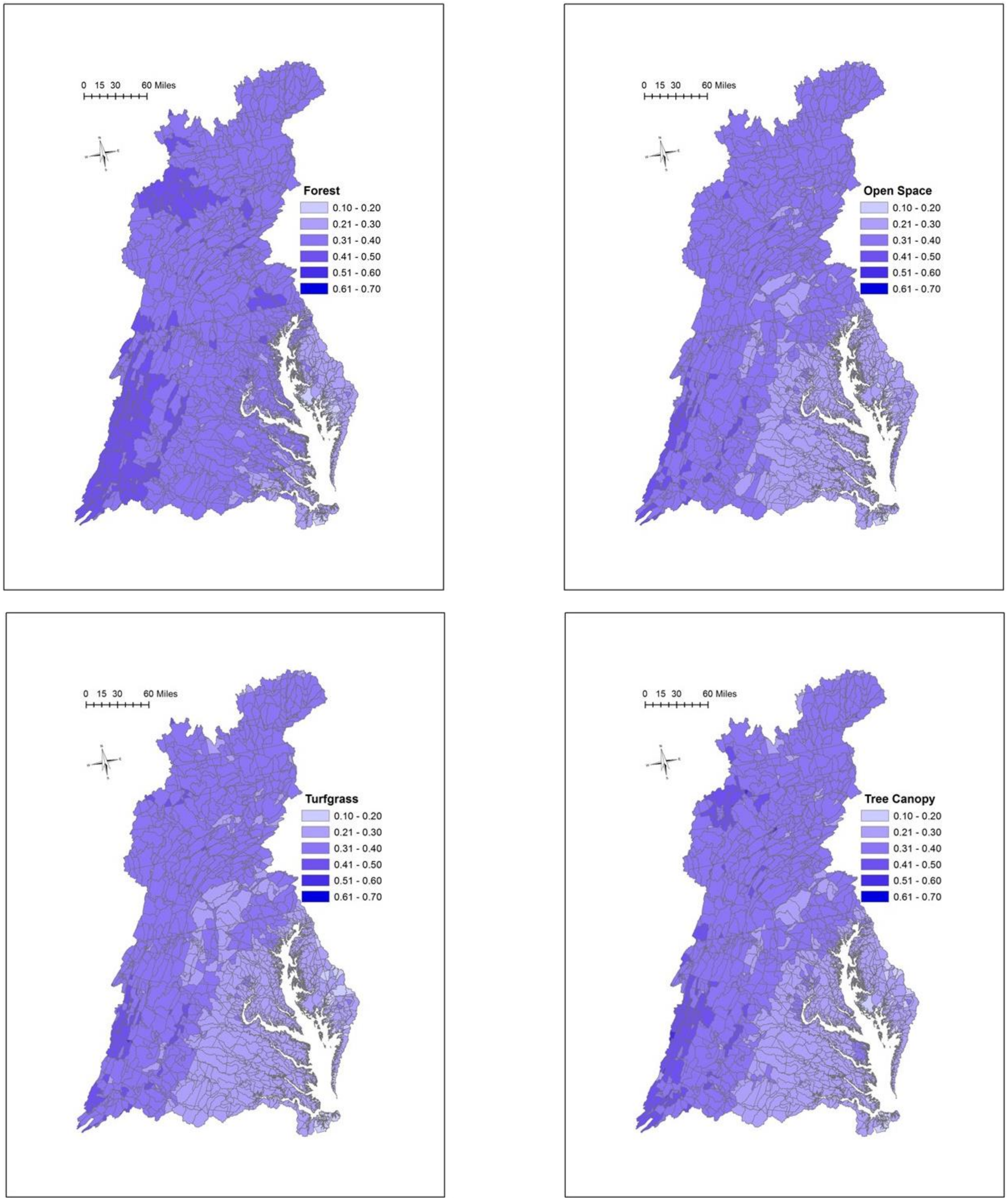


Figure 7-16: Sediment Delivery Ratios for land classes in the Chesapeake Bay watershed

7.4.3 Incorporation of Land-River Segment Loading Rates.

The RUSLE estimates of sediment loading discussed in Section 2 are provided on a land-river segment and land use basis. They are spatially averaged to land segment and land use to be used in the land simulation in the Phase 6 Watershed Model. Since land-to-water factors are applied on a land use and land-river segment basis we can incorporate the spatial variability in the RUSLE estimates as an additional factor. This is done simply by multiplying the SDR calculated above by the ratio of the land-river segment and land segment loading rates for each land use.

Equation 7-10: incorporation of land-river segment variability in loading rate

SDR = Land-River Segment Loading Rate / Land Segment Loading Rate * initial SDR