The Watershed Deposition Tool: A tool for assessing the contribution of atmospheric deposition to total watershed loading

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Abstract. A tool for providing the linkage between air and water quality modeling needed for determining the Total Maximum Daily Load (TMDL) and for analyzing related nonpoint-source impacts on watersheds has been developed. The Watershed Deposition Tool (WDT) takes gridded output of atmospheric deposition from a regional-scale air quality model, and calculates average per unit area and total deposition to selected watersheds and watershed segments. Default boundary descriptions are 8-digit hydrologic unit codes; however, user-supplied delineations may also be used. The tool also provides the capability to compare results from two different modeled atmospheric deposition scenarios. The resulting calculations can be output to a variety of formats for further analyses. An example application of the WDT for assessing potential reductions in total nitrogen deposition to the Albemarle-Pamlico basin stemming from future air emissions reductions is provided.

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[*] In partnership with the U.S. Environmental Protection Agency

Key words: atmospheric deposition, nitrogen loading, management tool, TMDL, watershed analysis

Introduction

Atmospheric wet and dry deposition can be important contributors to total pollutant loadings in watersheds and can have significant effects on terrestrial and aquatic ecosystems. In a study of large watersheds in the northeastern U.S., van Breeman et al. (2002) estimated that atmospheric deposition contributes about 33% to the total nitrogen loading for those watersheds. Deposition of acidic chemical species to terrestrial ecosystems can cause acidification of lakes and damage to forests and can significantly stress or kill biota (Driscoll et al., 2001). Along the eastern U.S. coast, deposition of atmospheric nitrogen accounts for 10-40% of nitrogen loadings to estuaries (Paerl et al., 2002). In coastal systems, increases in nitrogen loadings have been tied to eutrophication (Paerl and Whithall, 1999). Clearly, quantifying atmospheric deposition contributions to watersheds is important to non-point source management strategies in these areas; however, estimating the contribution of atmospheric deposition to total watershed loadings is not straight-forward since the atmospheric source region (airshed) does not align with the watershed (Dennis, 1997; Paerl et al., 2002). Airsheds are typically much larger than watersheds and are multi-state in size. Regional-scale air quality models, such as the multi-pollutant Community Multiscale Air Quality model (CMAQ) (Byun and Schere, 2006), are particularly useful for quantifying the atmospheric contribution from different airsheds by providing continental U.S coverage. Tools are then needed to link the gridded atmospheric model outputs with watershed models.

The Watershed Deposition Tool (WDT) is a Microsoft® Windows-based software application that takes gridded atmospheric deposition estimates from the CMAQ model and allocates them to 8-digit HUCs (hydrologic unit codes) within a watershed, state or region. It is an easy-to-use tool for providing the linkage between air and water needed for TMDL and related nonpoint-source watershed analyses. This linkage further allows water quality managers to consider the impacts of reductions in atmospheric deposition resulting from Clean Air Act regulations as ecological and health effects oriented reductions in NO_x and SO_x criteria pollutants are expected to reduce sulfur and nitrogen deposition by significant amounts in the future.

Atmospheric Deposition Estimates

Atmospheric deposition, particularly dry deposition, can be difficult and expensive to monitor over an entire watershed. Measurements of dry deposition are scarce and wet deposition measurements are available only as point measurements which tend to be more concentrated in the eastern U.S. Complete continental coverages of atmospheric deposition can be obtained from regional-scale air quality models such as CMAQ. CMAQ is an Eulerian air quality model that simulates the effect of air emissions, their transport and transformation to air concentrations, and subsequent deposition to the Earth’s surface. The ambient concentration and deposition of multiple pollutants is modeled using a “one-atmosphere” approach that relies predominantly on a “first-principles” description of the atmosphere. Modeling is performed at various spatial scales, ranging from urban to regional. Typical grid cell sizes used in the model are 36, 12, and 4 km; however, airshed size domains typically require 36 and 12 km grid sizes, unless there is a strong urban focus. Gridded meteorological data to drive CMAQ can be provided by the Fifth Generation Penn State University/National Center for Atmospheric Research Mesoscale Model (MM5) (Grell et al., 1995) or the Weather Research and Forecasting (WRF) model (Klemp et al., 2007; Skamarock et al., 2005). Emissions information is provided via the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system (http://www.smoke-model.org). The USEPA compiles information from state and local agencies to produce a national emissions inventory (NEI) (http://www.epa.gov/ttn/chief/net/critsummary.html). SMOKE is used to spatially and temporally allocate the NEI emissions to hourly, gridded values. Emissions data are routinely prepared for current conditions and for future emissions reductions that are expected to reflect rules such as the Clean Air Interstate Rule (CAIR) and the Clean Air Mercury Rule (CAMR). Output from CMAQ is in Models-3 Input/Output Application Programming Interface (I/O API) (Coats et al., 1999) format, which is a metadata structure layered on top of the network Common Data Form (netCDF) data format (Rew and Davis, 1990).

CMAQ estimates the wet and dry deposition of a number of gaseous and particulate chemical species, including criteria air pollutants and hazardous air pollutants. Wet deposition results from both in-cloud scavenging and below-cloud washout of pollutants. Dry deposition results from a complex series of deposition flux processes that depend on the turbulent state of the atmosphere, the characteristics of the underlying Earth’s surface, and the nature of the chemical being deposited. These processes factor into the calculated deposition velocity which is then paired with the concentration to estimate the flux. An example CMAQ simulation of total nitrogen deposition for the continental U.S. is presented in Figure 1.

Watershed Deposition Tool Overview

The Watershed Deposition Tool (WDT) enables environmental analysts to extract from air quality simulations the deposition that would affect selected watersheds or the difference in deposition between alternative air quality management scenarios. While analysts familiar with GIS and CMAQ model output formats could perform these computations with combinations of off-the-shelf software, many people who study these issues do not have the necessary technical expertise. To support the interpretation and use of air deposition modeling results by these users, an easy-to-use, special purpose software tool was developed to calculate deposition to selected regions from gridded CMAQ data. The WDT operates on the Microsoft® Windows platform.

The Watershed Deposition Tool was designed to meet the needs of a range of users, from novices to GIS experts. The opening menu of the tool reflects this broad applicability. On startup, WDT users have the option of using a wizard to guide them through the file selection process, starting a session without the wizard, resuming a previous session, or exporting CMAQ data directly to shapefiles. Users select one or two CMAQ data files and select a variable for display. Example “Base Case” and “Future Scenario” files containing CMAQ predictions of wet, dry, and total deposition of nitrogen and sulfur species are provided with the WDT.

Users choose one or more HUC regions to use in their analysis. Shapefiles for the 8-digit HUCs for the entire U.S. are provided with the WDT, as well as for the different USGS Water Resources Regions of the U.S. Figure 2 shows the 8-digit HUCs for the southeast (Water Resources Region 3) overlaid on a CMAQ deposition map, zoomed-in to focus on North Carolina. In addition to the standard watershed delineations provided with the WDT, users have the option of supplying their own closed polygon delineations. The WDT optionally displays the gridded CMAQ data, total deposition to selected watersheds or area-weighted average per unit area deposition to selected watersheds for each CMAQ data file. Additionally, differences between two model simulations, expressed as absolute difference or percent difference, can be displayed. To calculate the deposition to a watershed segment, the WDT calculates the area of the polygon for the watershed segment and then calculates the area of overlay for each grid cell and the polygon. The area of overlay is then multiplied by the deposition for the grid cell and summed over the grid cells to obtain the total deposition for the watershed segment. The average deposition for the watershed segment is simply the total deposition divided by the area of the segment. The Microsoft® Windows screen capture function can be used to capture figures displayed by the WDT for later use. The results of the calculations performed by the WDT can be exported to CSV files or shapefiles for further analysis.

The WDT, as well as additional CMAQ model deposition output files (beyond the example files), can be downloaded from the USEPA Atmospheric Modeling Division website (http://www.epa.gov/asmdnerl/Multimedia/depositionMapping.html). The additional CMAQ files provide annual and seasonal deposition estimates for nitrogen, sulfur and mercury species. The files provided for use with the WDT are the result of post-processing the raw CMAQ output files to sum the deposition fluxes for individual chemical species to quantities of interest such as oxidized-nitrogen, reduced-nitrogen, total nitrogen, and total sulfur. The list of standard species is provided in Table 1. Alternate species lists can easily be accommodated by the software as well.

CMAQ files are available for both 36 km and 12 km grid cell sizes. The finer resolution CMAQ grids may be important for some applications as illustrated in the example in Figures 3-5, showing CMAQ total nitrogen deposition in North Carolina with the watershed delineations for the Cape Fear River Basin overlaid for reference. In Figure 3, CMAQ estimates based on a 36 km grid cell size are shown with the 8-digit HUC segments overlaid while in Figure 4, the CMAQ estimates using a 12 km grid cell size are shown for comparison. As expected, the area of high nitrogen deposition in North Carolina is more clearly depicted in the CMAQ results using the 12 km grid cell. In Figure 5, the 14-digit HUC segments are shown to illustrate the capability to import other polygon delineations as well as highlight the better spatial match between the CMAQ estimates using the 12 km grid cell size and the 14-digit HUC watershed segments

An Example Application of the Watershed Deposition Tool for the Albemarle-Pamlico Basin

The Albemarle-Pamlico Basin, located in eastern North Carolina, is one of the largest estuarine systems in the United States. This region is important for commercial fishing, recreation, and tourism. There are significant nitrogen sources upwind of this area due to the prevalence of agriculture and confined animal feed operations. As an example application of the Watershed Deposition Tool, we will examine the contribution of atmospheric deposition to the nitrogen loading in the basin and sub-basins in this estuary system for a base case and explore differences between the base case and a future scenario that represents potential reductions in emissions expected due to several air quality rules proposed to be in place by 2020 including the Clean Air Interstate Rule, Clean Air Mercury Rule, Heavy Duty Diesel Rule, and Non-road Diesel Rule.

To begin the analysis, we load the base case and future scenario files and select total (wet+dry) nitrogen as the variable for analysis. The WDT initially displays the gridded CMAQ deposition for the entire U.S. for this base case which utilizes emissions from the 2002 NEI (Figure 1). Next, we add the 8-digit HUCs for the southeastern U.S. to the map and zoom in on the area of interest (Figure 2). In Figure 6, the HUCs for the Albemarle-Pamlico watershed have been selected for analysis and the average deposition per unit area for the watershed segments making up this basin is shown for the base case. The average deposition per unit area of total nitrogen for segments in this basin ranges up to 18 kg/ha for this base case scenario. Since measurements of dry deposition are scarce, it has been common practice for water modelers to use a “rule of thumb” for determining total deposition, where total deposition is set equal to twice the measured wet deposition. This rule assumes that dry deposition equals wet deposition. Using the WDT, we can examine the accuracy of this rule for this application. In Figures 7 and 8, the average dry and wet nitrogen deposition per unit area for the Albemarle-Pamlico basin are shown. We can see from these figures that, close to local sources, this rule clearly does not apply. For example, in the Middle Neuse segment (in red in Figure 7), the average dry deposition is 11.3 kg/ha whereas the average wet deposition is 6.3 kg/ha. Using the "rule of thumb", the average wet+dry deposition for Middle Neuse would be underestimated by 29%. A similar analysis to examine the total deposition to the basin could be performed using the WDT. To assess the potential effects on nitrogen loading to the watershed resulting from changes in air quality, we can view the differences in average deposition per unit area estimates between this base case and a future scenario expressed as an absolute difference (not shown) or percent difference (Figure 9). The expectation is that future deposition of reduced nitrogen will increase (due to increases in NH_3 emissions), while future deposition of oxidized nitrogen will decrease (from decreases in NO_x emissions) due to Clean Air Act regulations. In Figure 9, we see that for areas that are agricultural hotspots of ammonia emissions, the increase in reduced nitrogen dominates and total nitrogen deposition is expected to increase. Away from the agricultural hotspots, the reductions in oxidized nitrogen deposition dominate the total nitrogen budget.

Summary

The Watershed Deposition Tool provides an easy way to include the contribution of atmospheric deposition into watershed management plans. The tool is flexible and allows:

- use of deposition estimates at different CMAQ model grid sizes,
- use of standard 8-digit HUC or user-provided watershed delineations,
- output of analyses in a number of formats including shapefiles,

Since atmospheric deposition is a significant component of total pollutant loadings, obtaining realistic estimates of deposition is important. The CMAQ model is capable of providing this information for both wet and dry deposition, and water modelers no longer need to rely on previous "rule of thumb" estimates of deposition for input to management scenarios. Additionally, air quality regulations, while most often targeted at reductions in atmospheric concentrations to mitigate human health effects, can also have notable effects on deposition, therefore improving ecosystem health. The WDT allows environmental analysts and policymakers to consider these impacts in their water quality management.

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Disclaimer

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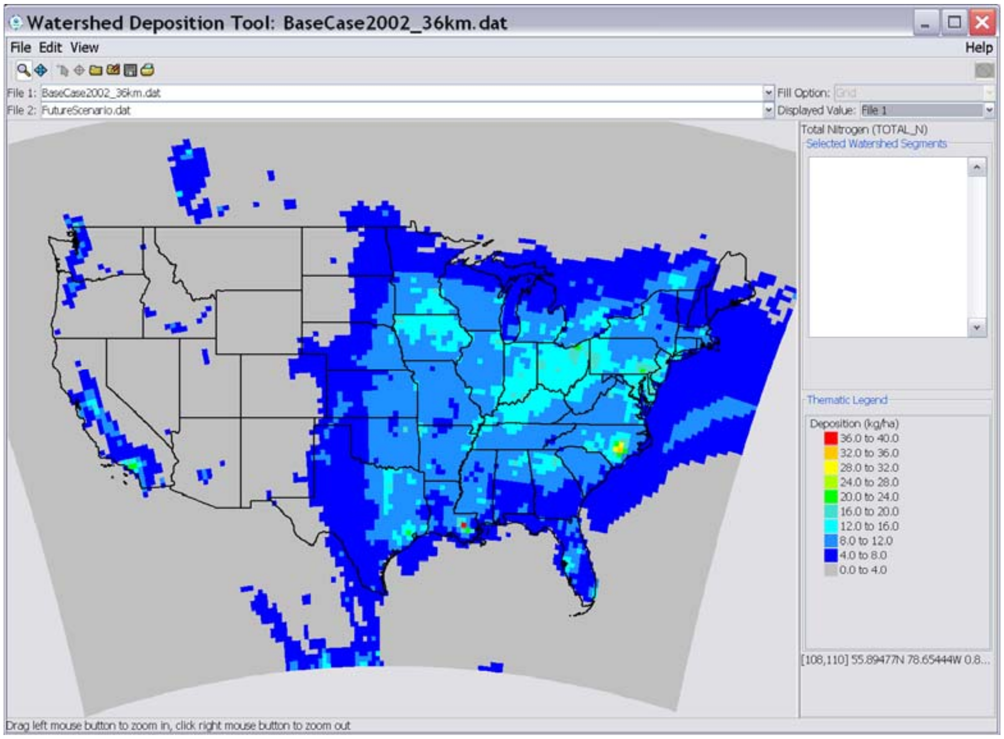
Figure 9. Screen capture showing the percent change in average (per unit area) annual total (wet+dry) nitrogen deposition to each watershed segment in the Albemarle-Pamlico basin between the future scenario and the base case.

Table 1. Variables included in the standard CMAQ data files provided with the WDT.

Variable	Component species
Total dry oxidized nitrogen	NO_2 + NO + N_2O_5 + HNO_3 + HONO + NO_3 + Organic NO_3 + PAN
Total dry reduced nitrogen	NH_3 + NH_4
Total dry nitrogen	dry oxidized nitrogen + dry reduced nitrogen
Total wet oxidized nitrogen	N_2O_5 + NO_3
Total wet reduced nitrogen	NH_4
Total wet nitrogen	wet oxidized nitrogen + wet reduced nitrogen
Total oxidized nitrogen	dry oxidized nitrogen + wet oxidized nitrogen
Total reduced nitrogen	dry reduced nitrogen + wet reduced nitrogen
Total nitrogen	total oxidized nitrogen + total reduced nitrogen
Total dry sulfur	SO_2 + SO_4
Total wet sulfur	SO_4
Total sulfur	total dry sulfur + total wet sulfur
Total mercury	total wet mercury + total dry mercury



File 1: BaseCase2002_36km.dat

File 2: FutureScenario.dat

Fill Option: Grid

Displayed Value: File 1

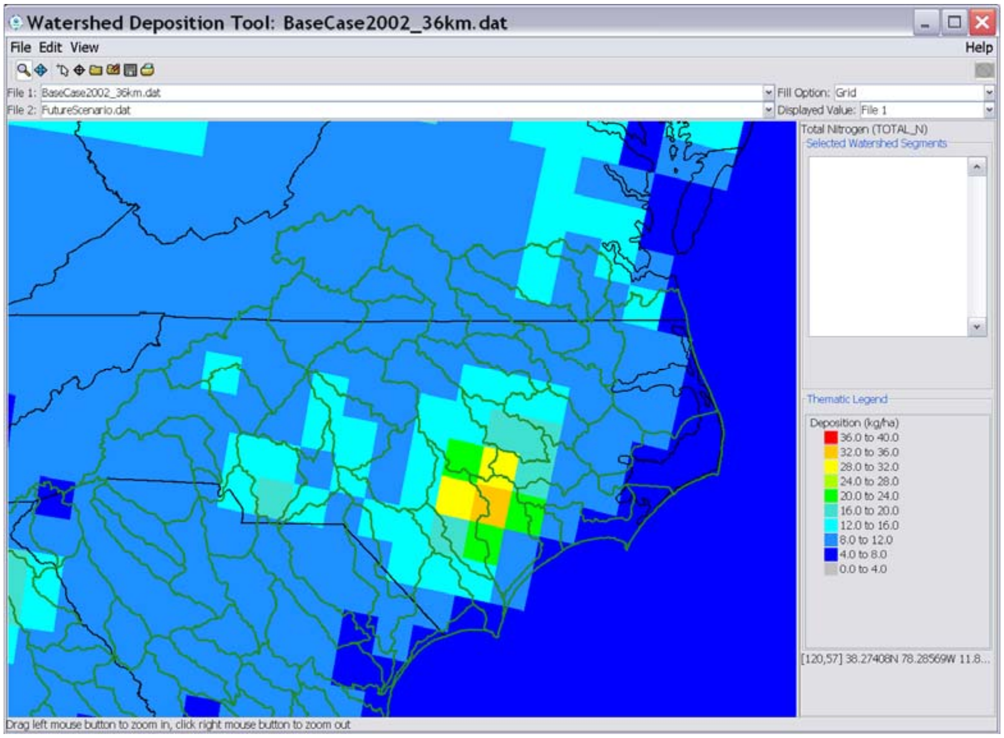
Total Nitrogen (TOTAL_N)

Deposition (kg/ha)
🟥 36.0 to 40.0
🟧 32.0 to 36.0
🟨 28.0 to 32.0
🟩 24.0 to 28.0
🟩 20.0 to 24.0
🟦 16.0 to 20.0
🟦 12.0 to 16.0
🟦 8.0 to 12.0
🟦 4.0 to 8.0
⬜ 0.0 to 4.0

[108,110] 55.89477N 78.65444W 0.8...

Drag left mouse button to zoom in, click right mouse button to zoom out

Figure 1. Screen capture showing the gridded values of annual total (wet+dry) nitrogen deposition (kg-N/ha) predicted by CMAQ for the 2002 base case.



File 1: BaseCase2002_36km.dat

File 2: FutureScenario.dat

Fill Option: Grid

Displayed Value: File 1

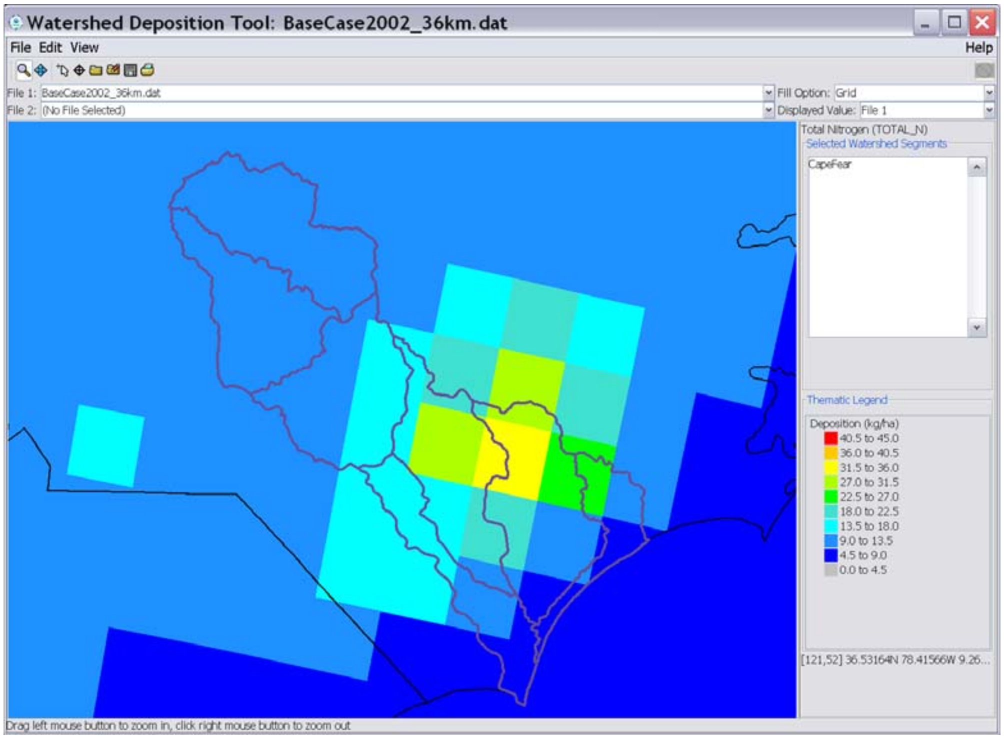
Total Nitrogen (TOTAL_N)

Deposition (kg/ha)
🟥 36.0 to 40.0
🟧 32.0 to 36.0
🟨 28.0 to 32.0
🟩 24.0 to 28.0
🟩 20.0 to 24.0
🟦 16.0 to 20.0
🟦 12.0 to 16.0
🟦 8.0 to 12.0
🟦 4.0 to 8.0
⬜ 0.0 to 4.0

[120,57] 38.27408N 78.28569W 11.8...

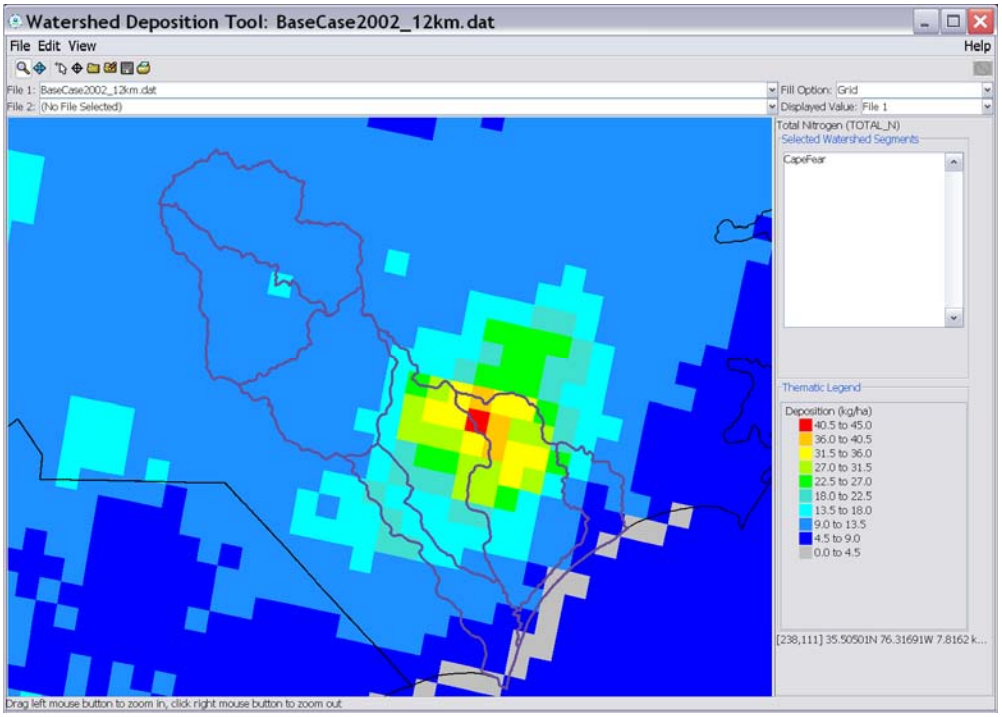
Drag left mouse button to zoom in, click right mouse button to zoom out

Figure 2. Screen capture showing a zoomed-in view of Figure 1, focused on North Carolina, with 8-digit HUC watershed delineations for the southeast overlaid.



File 1: BaseCase2002_36km.dat
File 2: (No File Selected)
Fill Option: Grid
Displayed Value: File 1
Total Nitrogen (TOTAL_N)
Selected Watershed Segments
CapeFear
[121,52] 36.53164N 78.41566W 9.26...
Drag left mouse button to zoom in, click right mouse button to zoom out

Figure 3. Screen capture showing the CMAQ annual total (wet+dry) nitrogen deposition (kg-N/ha) for the 36 km grid size in North Carolina with the 8-digit HUC watershed delineations for the Cape Fear River Basin overlain for reference.



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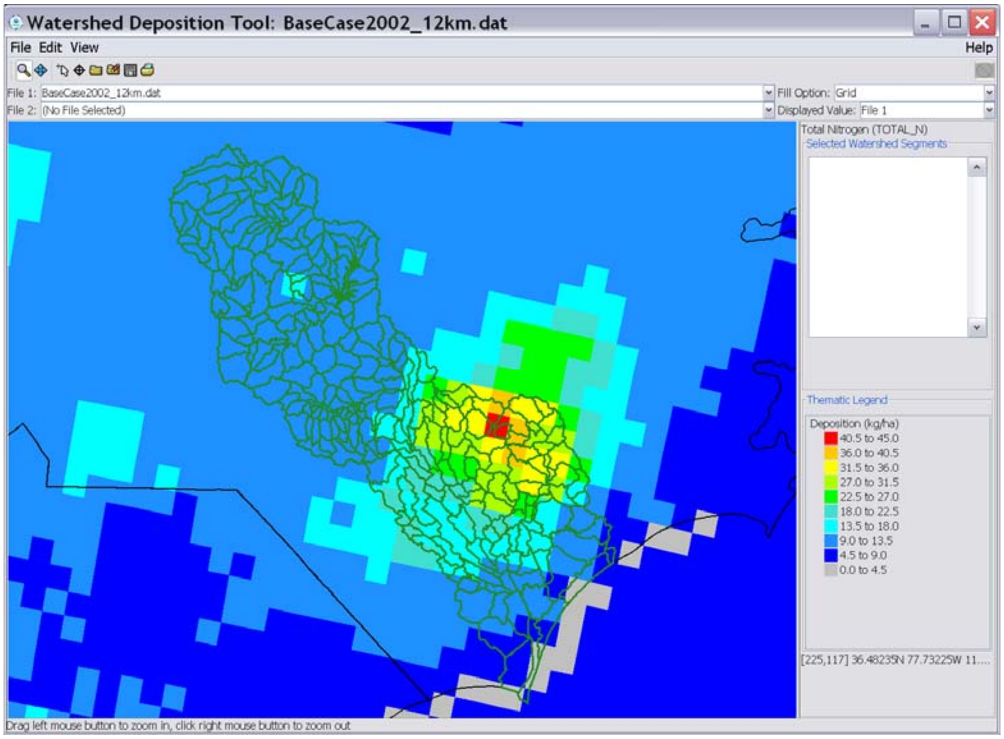
Fill Option: Grid
Displayed Value: File 1
Total Nitrogen (TOTAL_N)
Selected Watershed Segments
CapeFear
[238,111] 35.50501N 76.31691W 7.8162 k...
Drag left mouse button to zoom in, click right mouse button to zoom out

Figure 4. Screen capture showing the CMAQ annual total (wet+dry) nitrogen deposition (kg-N/ha) for the 12 km grid size in North Carolina with the 8-digit HUC watershed delineations for the Cape Fear River Basin overlain for reference.



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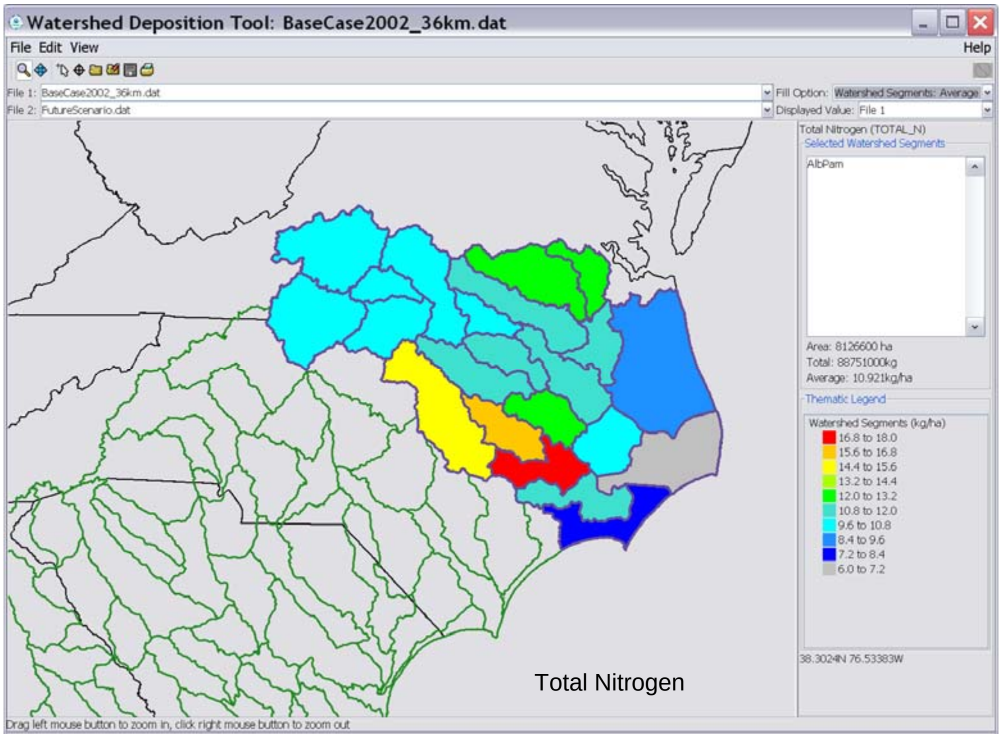
Fill Option: Grid
Displayed Value: File 1

[225,117] 36.48235N 77.73225W 11....

Drag left mouse button to zoom in, click right mouse button to zoom out

Figure 5. Screen capture showing the CMAQ annual total (wet+dry) nitrogen deposition (kg-N/ha) for the 12 km grid size in North Carolina with the 14-digit HUC watershed delineations for the Cape Fear River Basin overlain for reference.



File 1: BaseCase2002_36km.dat
File 2: FutureScenario.dat
Fill Option: Watershed Segments: Average
Displayed Value: File 1

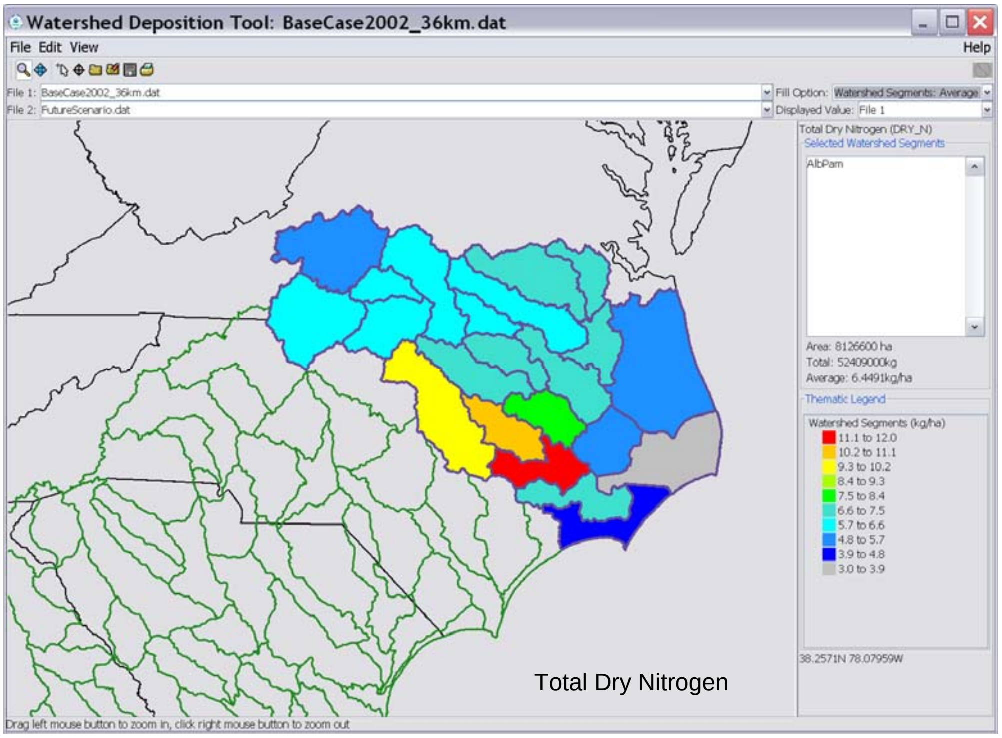
AlbPam

Area: 8126600 ha
Total: 88751000kg
Average: 10.921kg/ha

38.3024N 76.53383W

Drag left mouse button to zoom in, click right mouse button to zoom out

Figure 6. Screen capture showing the average (per unit area) annual total (wet+dry) nitrogen deposition (kg-N/ha) to each watershed segment in the Albemarle-Pamlico basin for the 2002 base case.



Watershed Deposition Tool: BaseCase2002_36km.dat

File 1: BaseCase2002_36km.dat

File 2: FutureScenario.dat

Fill Option: Watershed Segments: Average

Displayed Value: File 1

Total Dry Nitrogen (DRY_N)

Selected Watershed Segments: AlbPam

Area: 8126600 ha

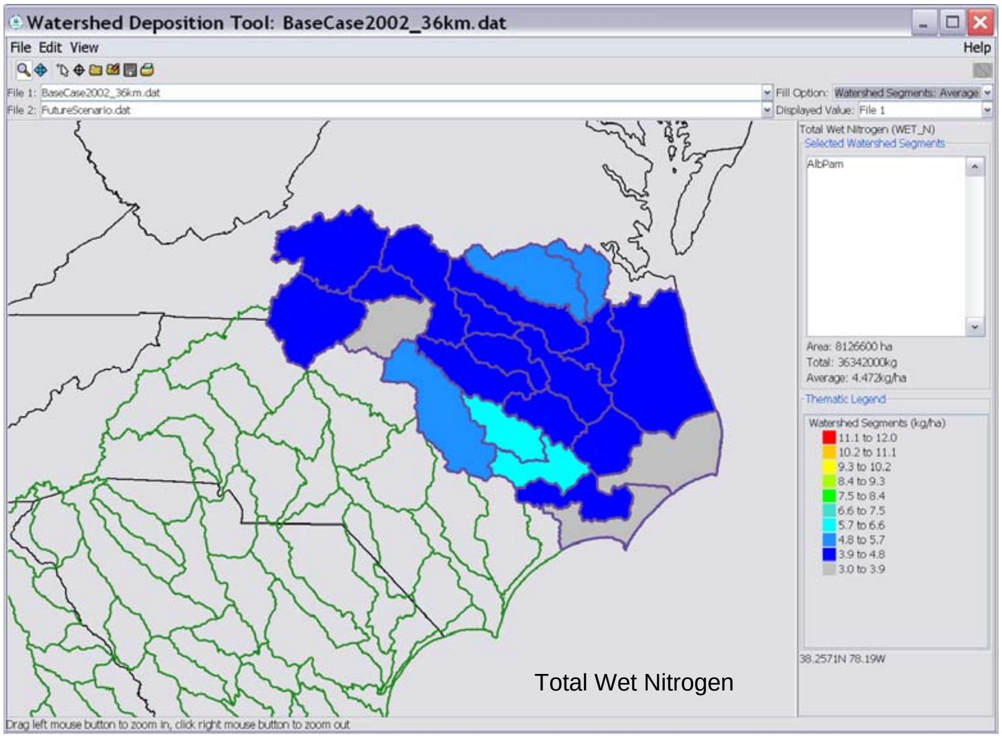
Total: 52409000kg

Average: 6.4491kg/ha

38.2571N 78.07959W

Drag left mouse button to zoom in, click right mouse button to zoom out

Figure 7. Screen capture showing the average (per unit area) annual dry nitrogen deposition per unit area (kg-N/ha) to each watershed segment in the Albemarle-Pamlico basin for the 2002 base case.



Watershed Deposition Tool: BaseCase2002_36km.dat

File 1: BaseCase2002_36km.dat

File 2: FutureScenario.dat

Fill Option: Watershed Segments: Average

Displayed Value: File 1

Total Wet Nitrogen (WET_N)

Selected Watershed Segments: AlbPam

Area: 8126600 ha

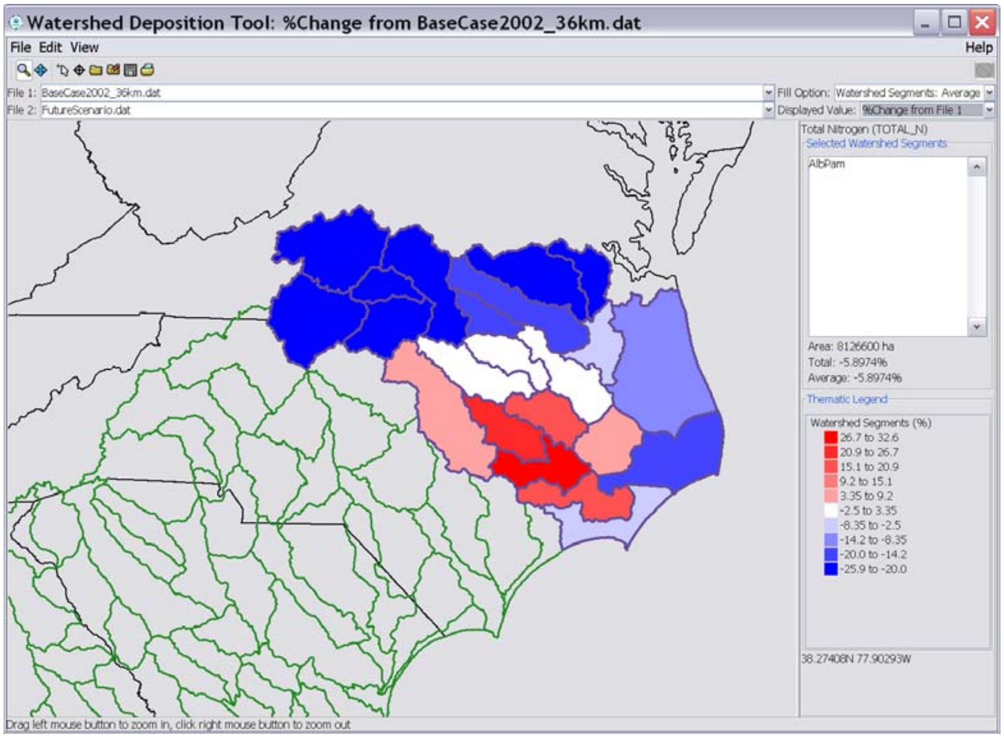
Total: 36342000kg

Average: 4.472kg/ha

38.2571N 78.19W

Drag left mouse button to zoom in, click right mouse button to zoom out

Figure 8. Screen capture showing the average (per unit area) annual wet nitrogen deposition per unit area (kg-N/ha) to each watershed segment in the Albemarle-Pamlico basin for the 2002 base case.



Watershed Deposition Tool: %Change from BaseCase2002_36km.dat

File 1: BaseCase2002_36km.dat

File 2: FutureScenario.dat

Fill Option: Watershed Segments: Average

Displayed Value: %Change from File 1

Total Nitrogen (TOTAL_N)

AlbPam

Area: 8126600 ha
Total: -5.8974%
Average: -5.8974%

Watershed Segments (%)

🟥 26.7 to 32.6
🟥 20.9 to 26.7
🟥 15.1 to 20.9
🟥 9.2 to 15.1
🟥 3.35 to 9.2
⬜ -2.5 to 3.35
🟦 -8.35 to -2.5
🟦 -14.2 to -8.35
🟦 -20.0 to -14.2
🟦 -25.9 to -20.0

38.27408N 77.90293W

Drag left mouse button to zoom in, click right mouse button to zoom out

Figure 9. Screen capture showing the percent change in average (per unit area) annual total (wet+dry) nitrogen deposition to each watershed segment in the Albemarle-Pamlico basin between the future scenario and the base case.