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. Using gridded output of atmospheric deposition from the Community Multiscale Air Quality (CMAQ) model, the Watershed Deposition Tool (WDT) calculates average per unit area and total deposition to selected watersheds and subwatersheds. CMAQ estimates the wet and dry deposition for all of its gaseous and particulate chemical species, including ozone, sulfur species, nitrogen species, secondary organic aerosols, and hazardous air pollutants at grid scale sizes ranging from 4 to 36 km. An overview of the CMAQ model is provided. The somewhat specialized format of the CMAQ files is not easily imported into standard spatial analysis tools. The WDT provides a graphical user interface that allows users to visualize CMAQ gridded data and perform further analyses on selected watersheds or simply convert CMAQ gridded data to a shapefile for use in other programs. Shapefiles for the 8-digit (cataloging unit) hydrologic unit code polygons for the United States are provided with the WDT; however, other user-supplied closed polygons may be used. An example application of the WDT for assessing the contributions of different source categories to deposition estimates, the contributions of wet and dry deposition to total deposition, and the potential reductions in total nitrogen deposition to the Albemarle-Pamlico basin stemming from future air emissions reductions is used to illustrate the WDT capabilities.

(KEY TERMS: atmospheric deposition; nitrogen loading; management tool; Total Maximum Daily Load; watershed analysis.)


INTRODUCTION

Atmospheric wet and dry deposition can be important nonpoint-source contributors to total pollutant loadings to water bodies, both through direct deposition to water bodies and deposition to watersheds with subsequent transport into water bodies. For example, in a study of the nitrogen budgets of 16 catchments in the northeastern United States (U.S.), Boyer et al. (2002) found that atmospheric deposition was the largest source of nitrogen input to the...
catchments, contributing about 31% to the overall budget. Atmospheric deposition can affect ecosystems in numerous ways including acidification and eutrophication. Acidification of lakes and streams is primarily caused by atmospheric deposition of sulfur (S) and reactive nitrogen (Nr) to watersheds with some impact from direct deposition to lakes. The deposited chemicals undergo subsequent biogeochemical cycling and transfer of chemicals to surface water systems. Acidic deposition causes a number of adverse effects in aquatic and terrestrial ecosystems including reductions in species diversity, increased vulnerability of forest species to pests and diseases, and shifts in species composition (Driscoll et al., 2001; Dennis et al., 2007; Sullivan et al., 2008). Atmospheric deposition of Nr can be an important contributor (10-40%) to over-enrichment, leading to eutrophication in coastal ecosystems (Paerl and Whithall, 1999; Paerl et al., 2001, 2002; Valigura et al., 2001; Howarth et al., 2002). The majority of the loading of Nr from atmospheric deposition to coastal systems stems from deposition to the watersheds and subsequent delivery to streams and rivers; however, in large water bodies direct deposition to the water surface can also be important (Valigura et al., 2001; Alexander et al., 2001; Howarth, 2008). Atmospheric deposition of mercury also affects both aquatic and terrestrial ecosystems. Mercury is deposited from the atmosphere to both water and land surfaces where it undergoes transformation to methylmercury. Methylmercury is a neurotoxin associated with adverse physiological and reproductive effects (Driscoll et al., 2007; Knightes et al., 2007).

Quantification of the amount of atmospheric deposition of each of these atmospheric constituents is important to water-quality studies. Watershed-scale fate and transport models such as the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) and Hydrological Simulation Program – Fortran (HSPF) (Bicknell et al., 1997) and watershed regression models such as Spatially Referenced Regression on Watershed attributes (SPARROW) (Smith et al., 1997; Alexander et al., 2001; McMahon et al., 2003) use this information in estimating loadings to rivers and watersheds for use in Total Maximum Daily Loading (TMDL) determinations and other water-quality assessment and management plans. However, obtaining good estimates of atmospheric wet and dry deposition can be challenging. Direct measurement of deposition, particularly dry deposition, can be difficult and very expensive to monitor at several sites in a watershed, much less over an entire watershed.

Point estimates of atmospheric concentration and deposition are provided by national and state monitoring networks that are operated in the U.S. The National Atmospheric Deposition Program (NADP) operates the National Trends Network, which measures atmospheric concentration and wet deposition on a weekly basis at 250 sites across the U.S. and the Mercury Deposition Network, which measures weekly average wet deposition of total mercury at 85 sites (NADP, 2008). The Clean Air Status and Trends Network (CASTNET) (USEPA, 2008a) provides measured atmospheric concentration and modeled dry deposition estimates at 86 sites across the U.S. While these measurements are extremely valuable, using them in water-quality analyses presents some challenges. Not all chemical species that deposit from the atmosphere are measured at any of the sites. Therefore, the networks do not provide a complete picture of the chemical budgets. Also, dry deposition is not directly measured at any of the sites, but rather is calculated at the CASTNET sites from an inferential method whereby measured concentrations are paired with modeled deposition velocities to compute the deposition flux (Clarke et al., 1997; Meyers et al., 1998; Finkelstein et al., 2000). The deposition velocity model is driven by meteorology taken at a single tower. For forests, the tower is placed in a clearing and therefore the data may not be representative of the land use of interest (Hicks, 2006). Additionally, the locations of the measurement sites are not representatively distributed across the U.S. They are mainly concentrated in the eastern U.S. and are located in rural areas away from major sources. Deposition is greatly influenced by the underlying land-surface characteristics and topography. This, in conjunction with the sparse density of measurement sites, makes spatial interpolation of the measured data difficult and inadequate, as the technique does not consider the intermediary landscape and its influence on atmospheric deposition.

More sophisticated techniques that use network information in conjunction with other data such as elevation to create regression models for providing improved spatial patterns of wet atmospheric deposition have shown some promise. Ollinger et al. (1993) combined ion concentration measurements from network sites with observed precipitation measurements from many additional precipitation sites to obtain wet deposition patterns for the Northeastern U.S. Dry deposition estimates were made by combining concentration measurements with average chemical species dependent deposition velocities; however, dependence of dry deposition on land surfaces or sitespecific meteorology was not considered. For the eastern U.S., Grimm and Lynch (2004) developed more sophisticated wet deposition estimates that have finer spatial resolution and account for orographic effects of the topography, but did not attempt to estimate dry deposition. The regression models show promise for wet deposition, but dry deposition
cannot be simulated in the same manner due to the strong dependence on the underlying land surface and local meteorology. Further, regression models exhibit limited capacity to predict future deposition rates. Consequently, other methods are needed to obtain estimates of dry deposition.

The regional-scale multipollutant Community Multiscale Air Quality model (CMAQ) (Byun and Schere, 2006), provides an alternative method for obtaining spatially and temporally explicit air concentrations and dry and wet deposition. CMAQ is able to capture spatial variations at the watershed or subwatershed scale (4-12 km grid size) and provides high temporal resolution (1 h) data for use in further studies. CMAQ offers several advantages over regression models for obtaining estimates of atmospheric deposition. For example, CMAQ provides estimates of both wet and dry deposition and provides the capability to account for the complete atmospheric nitrogen, sulfur, and mercury budgets by modeling the full set of chemical species. Also, the dry deposition algorithm explicitly accounts for the impacts of underlying land surface on the deposition processes. Furthermore, CMAQ models the long-range transport and transformation processes, which provides a more sophisticated representation of spatial changes in chemistry and meteorology than can be obtained from a regression model. Extensive emissions data is used with CMAQ, while widely spaced monitoring sites with rural siting criteria may miss hot spots of emissions. Additionally, CMAQ accounts for the large size of airsheds in estimating effects of management actions, which allows impacts on deposition from national air quality improvement programs to be included in water-quality analyses. CMAQ also provides the capability to examine the impact of future scenarios of growth in emissions and land use change on atmospheric deposition.

CMAQ outputs are already being used in TMDL and critical load analyses. For example, the Chesapeake Bay Program has previously used the Regional Acid Deposition Model, the precursor to CMAQ, and is now using CMAQ to provide monthly dry deposition values of nitrogen for input to the watershed model and the Bay model for a 2002 base year of emissions (Linker, 1996; Linker et al., 1996, 2000; Koroncai et al., 2003). For this application, CMAQ estimates are used to complement estimates of wet deposition from the Grimm and Lynch model (Grimm and Lynch, 2004). CMAQ also provides the relative change in wet and dry nitrogen deposition from the base to estimate the impact of future (2010, 2020, and 2030) air regulations on deposition to the Chesapeake Bay watershed. The Tampa Bay Estuary Program is using CMAQ to provide annual wet and dry nitrogen deposition values for the Tampa watershed segments and Tampa Bay as well as the relative change in wet and dry deposition from the 2002 base year due to local Tampa air regulations and national 2010 air regulations. In addition, CMAQ dry deposition estimates to lakes in the northeast are a key input to critical loads analyses (Jason Lynch, personal communication) and will be used to project the change in deposition loads (wet + dry) due to air regulations for critical loads assessments.

As the output from CMAQ is produced for a grid, methods must be used to read the CMAQ file formats and allocate the data from the grids to the spatial delineations of watersheds to provide the linkage between air and water needed for TMDL and related nonpoint-source watershed analyses. Each of the above applications required geographical information systems (GIS) expertise and software and a strong interaction with CMAQ modelers to produce the needed results. To simplify the use of CMAQ data in water-quality analyses, a special-purpose Microsoft Windows® based software application, the Watershed Deposition Tool (WDT), was developed that provides an easy way to access the CMAQ gridded deposition outputs and map them on to basins, watersheds, subwatersheds, and other water bodies. The WDT further allows water-quality managers to consider the impacts of future reductions in atmospheric deposition resulting from Clean Air Act regulations as ecological and health effects driven reductions in NOx and SOx criteria pollutants are expected to reduce sulfur and nitrogen deposition by significant amounts in the future (Pinder et al., 2008).

The purpose of this paper is to describe the WDT and demonstrate the power of CMAQ and the WDT to provide estimates of atmospheric deposition that can be used as input to watershed-scale fate and transport models. Overviews of CMAQ and the WDT are presented. An example application of the WDT to the Albemarle-Pamlico Basin (APB) in North Carolina is also provided to demonstrate the types of analyses that can be performed using the tool.

ATMOSPHERIC DEPOSITION ESTIMATES: CMAQ

The CMAQ Modeling System simulates the input of air emissions, their transport, and transformation to air concentrations, and subsequent deposition to Earth’s surface. An overview of the modeling system is provided in this section, while a thorough description of the model algorithms is provided in Byun and Schere (2006). In CMAQ, multiple pollutants are modeled simultaneously within a fixed three dimensional grid over the earth using an approach that
relies predominantly on a first-principles description of the atmosphere so that it can be applied for any modeling domain. The model is not calibrated for a specific application and algorithms are continually improved to reduce error. The chemical transport model in CMAQ ingests meteorology and emissions data and invokes science process modules forhorizontal and vertical advection, horizontal and vertical diffusion, cloud mixing, gas phase and aqueous phase chemistry, aerosol dynamics and chemistry, and wet and dry deposition. Details of the science processors are provided in Byun and Schere (2006) and the references therein. Of particular interest to water-quality analyses are the deposition modules. CMAQ estimates the wet and dry deposition of the full set of transported gaseous and particulate chemical species, including ozone, sulfur species, nitrogen species, secondary organic aerosols, and hazardous air pollutants. In CMAQ, wet deposition results from both in-cloud scavenging and below-cloud washout of pollutants based on Henry’s Law; cloud deposition is not modeled. Dry deposition depends on the turbulent state of the atmosphere, the characteristics of the underlying surface, and the nature of the chemical being deposited. The set of flux processes are modeled as a set of resistances that represent how the landsurface characteristics such as leaf cuticle and stomatal resistances interact with turbulent transfer of chemical species from the atmosphere to the receptor and molecular diffusion across the laminar sublayer of air at the receptor surface (aerodynamic and boundary layer resistances). These processes factor into the calculated deposition velocity, which is then paired with the concentration to estimate the flux on a subhourly time step.

The basic domain for CMAQ modeling covers the continental U.S., southern Canada and northern Mexico so that all emissions under continental U.S. control are included in the modeling domain. Additional emissions information is included for Canada (USEPA, 2008c) and Mexico (USEPA, 2008d). The model can also be used for other regions (e.g., Europe and China) subject to the availability of input data. Lateral boundary conditions are obtained from a global model. Modeling can be performed at various spatial scales, ranging from urban to regional. Typical grid cell sizes used in the model are 4, 12, and 36 km, with 12 km increasingly being the most common. The 4 km grid size is typically reserved for cases with a strong urban focus. Output from CMAQ is on an hourly basis, with the calculations being performed at a much smaller time step. Output from CMAQ is in Models-3 Input/Output Application Programming Interface (L/OAPI) (Coats et al., 1999) format, which is a metadata structure layered on top of the network Common Data Form data format (Rew and Davis, 1990).

The modeling system includes three main components: meteorological, emissions, and chemical transport (CMAQ) models. Key inputs to CMAQ are provided by the meteorological and emissions models. Gridded meteorological data (e.g., wind speed, air temperature, ground temperature, solar radiation, surface pressure, snow cover, soil temperature, and soil moisture) to drive CMAQ are 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 model (Skamarock et al., 2005; Klemp et al., 2007). Emissions input data is provided via the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system (UNC, 2008). The U.S. Environmental Protection Agency (USEPA) compiles information from state and local agencies to produce a national emissions inventory (NEI) (USEPA, 2008b). SMOKE is used to spatially and temporally allocate the NEI emissions to hourly, gridded values. Biogenic emissions and sea salt emissions are included into CMAQ separately from the NEI. Emissions from lightning NOx are a current research area. Emissions data are routinely prepared for current conditions and for future emissions conditions that are expected to reflect rules such as the Clean Air Interstate Rule (CAIR).

Evaluation studies for CMAQ have focused primarily on the modeling system’s ability to estimate concentration (Appel et al., 2007, 2008; Sarwar et al., 2008). Few wet deposition comparisons have been published, but recent model results shown in Figures 1 and 2 indicate that the model generally predicts the pattern of wet deposition of sulfate and nitrate well in comparison to NADP measured wet deposition values. The wet deposition estimates from the model are, of course, influenced by the meteorological model’s ability to model the timing, location, and intensity of precipitation (Davis and Swall, 2006). The meteorological model precipitation error, shown in Figure 3, is an important component of the scatter shown in Figures 1 and 2. The model used for dry deposition was evaluated against two field studies where ozone flux was measured. Overall, the deposition model predicted deposition velocities that agreed well with the observed values. Details of these comparisons are provided in Pleim et al. (2001).

WATERSHED DEPOSITION TOOL OVERVIEW

The WDT enables users to easily extract from CMAQ simulations the deposition that would affect selected watersheds and map the deposition or the
difference in deposition between alternative air quality management scenarios to the selected watersheds. The specialized Models-3 I/OAPI format of the CMAQ files is not easily imported into standard spatial analysis tools. Therefore, the WDT was designed to provide a user-friendly graphical user interface for manipulation of files, selection of species to analyze, and analysis of the data. Designed to meet the needs of a range of users, from novices to GIS experts, the WDT allows users to visualize CMAQ gridded data, map the data, and perform further analyses or simply convert CMAQ gridded data to a shapefile for use in other programs. It also includes a wizard to guide novice users through the software operation.

Example “Base Case” and “Future Scenario” files containing CMAQ predictions of annual wet, dry, and total deposition of nitrogen and sulfur species for a 36 km grid size are provided with the WDT download. The base case uses emissions from 2001 while the future scenario represents potential reductions in emissions expected due to several air quality rules proposed to be in place by 2020 including the CAIR, Clean Air Mercury Rule, Heavy Duty Diesel Rule, and Non-road Diesel Rule. Shapefiles for the 8-digit (cataloging unit level) hydrologic unit codes (HUC) polygons for the entire U.S. are also provided with the WDT, as well as for the different USGS Water Resources Regions of the U.S. In addition to the standard watershed delineations provided with the WDT, users have the option of supplying their own closed polygon delineations. CMAQ data are provided in a Lambert Conformal projection which is not a common projection for watershed delineations. The WDT provides an interface for supplying projection information to assure appropriate mapping of all data and polygons. The WDT optionally displays the gridded CMAQ data, total area-weighted deposition to selected watersheds or area-weighted average per unit area deposition to selected watersheds for each CMAQ data file. To calculate the deposition to a HUC polygon, the WDT calculates the area of the polygon and 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 polygon. The average deposition for the polygon is simply the total deposition divided by the area of the polygon. Additionally, differences between two CMAQ model simulations, expressed as absolute difference or percentage difference, can be displayed. The Microsoft Windows® screen capture function can be used to capture figures displayed by the WDT or figures may be printed to a Portable Document File or Tagged Image Format file for later use. The results of the calculations performed by the WDT can be exported to comma separated value files or shapefiles for further analysis.

The WDT, as well as additional CMAQ model deposition output files (that are not part of the WDT download), can be downloaded from the USEPA.
Atmospheric Modeling and Analysis Division website (USEPA, 2008e). The additional CMAQ files provide annual and seasonal deposition estimates for nitrogen, sulfur, and mercury species. CMAQ files are available for both 36 and 12 km grid cell sizes. The files provided for use with the WDT are the result of postprocessing the raw CMAQ output files to sum the deposition fluxes for the individual chemical species to quantities of interest such as oxidized nitrogen, reduced nitrogen, total nitrogen, total sulfur, and total mercury for the period of interest (e.g., annual and seasonal). Additionally, the units have been converted so that deposition is in kg/ha of the element (e.g., N, S, or Hg). The list of standard species is provided in Table 1. Alternate species lists can easily be accommodated by the software as well as different time periods (e.g., daily, weekly, and monthly).

AN EXAMPLE APPLICATION OF THE WATERSHED DEPOSITION TOOL FOR THE ALBEMARLE-PAMLICO BASIN

The APB, located in eastern North Carolina, is the largest lagoonal estuarine system in the U.S. This region is important for commercial fishing, recreation, and tourism. There are significant nitrogen sources in the watershed of the APB due to the prevalence of agriculture and confined animal feeding operations and the presence of the Raleigh-Durham metropolitan area. Previous nutrient mass balance studies in this area estimated that atmospheric deposition contributes 27% of the total nitrogen input to the basin, although this estimate does not include the contribution from dry NH₃ deposition or deposition of organic nitrogen species (McMahon and Woodside, 1997; Paerl and Whithall, 1999). As an example application of the WDT, we examine the atmospheric deposition to the watershed that is contributing to the nitrogen loading in the river basin and subbasins in this estuary system. For this study, the base case deposition is from a CMAQ model run at the 12 km grid size with emissions from the 2002 NEI. We then further explore differences in deposition between this 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 2009, but also includes increases in some emissions sectors, such as agriculture, due to expected growth. These rules include the CAIR, NOₓ State Implementation Plan Call, and the Tier II Tailpipe controls. The files used for the case study are different than those provided with the WDT installation.

Figure 4 shows the gridded total nitrogen deposition (wet + dry and gases + aerosols) from CMAQ overlain with the 12-digit (subwatershed level) HUC polygons for the APB for the 2002 base case. Total nitrogen deposition in the region can exceed 40 kg-N/ha in

![Graph showing annual precipitation](image)

**TABLE 1. Variables Included in the Standard CMAQ Data Files Provided With the WDT.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Component Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total dry oxidized nitrogen</td>
<td>NO₂ + NO + N₂O₅ + HNO₃ + HONO + NO₃ + organic NO₃ + PAN</td>
</tr>
<tr>
<td>Total dry reduced nitrogen</td>
<td>NH₃ + NH₄</td>
</tr>
<tr>
<td>Total dry nitrogen</td>
<td>Dry oxidized nitrogen + dry reduced nitrogen</td>
</tr>
<tr>
<td>Total wet oxidized nitrogen</td>
<td>N₂O₅ + NO₃</td>
</tr>
<tr>
<td>Total wet reduced nitrogen</td>
<td>NH₄</td>
</tr>
<tr>
<td>Total wet nitrogen</td>
<td>Wet oxidized nitrogen + wet reduced nitrogen</td>
</tr>
<tr>
<td>Total oxidized nitrogen</td>
<td>Dry oxidized nitrogen + wet oxidized nitrogen</td>
</tr>
<tr>
<td>Total reduced nitrogen</td>
<td>Dry reduced nitrogen + wet reduced nitrogen</td>
</tr>
<tr>
<td>Total nitrogen</td>
<td>Total oxidized nitrogen + total reduced nitrogen</td>
</tr>
<tr>
<td>Total dry sulfur</td>
<td>SO₂ + SO₄</td>
</tr>
<tr>
<td>Total wet sulfur</td>
<td>SO₄</td>
</tr>
<tr>
<td>Total sulfur</td>
<td>Total dry sulfur + total wet sulfur</td>
</tr>
<tr>
<td>Total mercury</td>
<td>Total wet mercury + total dry mercury</td>
</tr>
</tbody>
</table>

Notes: CMAQ, Community Multiscale Air Quality; PAN, peroxyacetyl nitrate; WDT, Watershed Deposition Tool.
some grid cells of the CMAQ modeling domain. The hotspot in eastern North Carolina reflects the presence of high emissions from agricultural and confined animal feeding operations sources, while deposition in the western part of the basin reflects urban and regional sources of nitrogen from the combustion of fossil fuels.
fuels. There is a strong gradient in the total nitrogen deposition away from the hotspot into the APB. Switching the fill option in the WDT to show the average deposition to each HUC (Figure 5), we can see that average deposition of total nitrogen in the HUCs comprising the APB ranges from 5 to 30 kg-N/ha.

As deposition flux is directly proportional to concentration, deposition gradients will follow concentration gradients. In the APB, where NH₃ emissions are relatively well characterized and there are also strong NH₃ emissions sources, NH₃ concentration gradients have been measured. In 2004, NH₃ concentrations were measured at several sites in the APB (Robarge et al., 2006; John Walker, personal communication). Figure 6 shows the distribution of the measured 12-h NH₃ concentrations for July for a site in a NC county with high hog-related NH₃ emissions (Kenansville), for an urban site (Raleigh) and a typical rural emission site (Lewiston) from this study. The difference between NH₃ concentrations at Kenansville and the other two sites is significant. Figure 6 also shows that CMAQ is able to capture the NH₃ concentration differences (hence, deposition gradients) across space. CMAQ reproduces the range of median concentrations reasonably well. CMAQ also reproduces the concentration range at the Kenansville site reasonably well, but produces higher maxima at Raleigh and Lewiston. Given this correlation, we can assume that the CMAQ deposition estimates from 2002 presented in the current example case (e.g., Figure 4) reasonably reflect the observed spatial variation.

To illustrate the contribution of fossil fuel vs. agricultural emissions sources to the total atmospheric nitrogen deposition, the deposition of oxidized and reduced nitrogen species is shown in Figure 7 (note the change in scale between a and b). As expected, the oxidized nitrogen deposition (Figure 7A) shows higher deposition in the western part of the basin which is closer to the regional sources of NOₓ. The reduced nitrogen deposition (Figure 7B) is higher close to the strong NH₃ emissions sources (e.g., confined animal feeding operations). Although not done for the example in Figure 7, CMAQ can be configured to calculate and output deposition for individual sources or source categories. These files could also be used with the WDT to perform more thorough analyses of source contributions.

We can also use the WDT to examine the relative contributions of wet and dry deposition to the total atmospherically deposited nitrogen (Figure 8, note different scales). As measurements of dry deposition of nitrogen species are scarce, but estimates of dry deposition are needed to estimate total nitrogen deposition, some modelers have adopted an approach of assuming that dry deposition equals the measured wet deposition. Using the CMAQ output and the WDT, we can compare the model results with this simplifying assumption. In the region colored in red in Figure 5, total nitrogen deposition is on the order of 20-30 kg-N/ha. Wet deposition as calculated by CMAQ (Figure 8A) contributes only 5-7 kg-N/ha to the total nitrogen while dry deposition (Figure 8B) contributes 15-24 kg-N/ha. Using the simplifying assumption that dry deposition equals wet deposition yields a total deposition of 10-14 kg-N/ha which is factor of two lower than the total deposition calculated by CMAQ. In the western part of the basin, where total nitrogen deposition is much lower and less influenced by agricultural emissions, wet deposition contributes only 40% of the total deposition. Thus, the relative contribution of wet and dry deposition can be highly variable across space. This example illustrates the strength of CMAQ and the WDT to capture the spatial gradients in deposition needed to appropriately distinguish between the contributions of wet and dry deposition to total deposition.

Development of estimates of changes in atmospheric deposition due to the Clean Air Act regulations will be important to water-quality management plans. Taking these reductions into account can help planners reduce costs and more easily achieve target watershed loadings. Figure 9 illustrates the difference in atmospheric nitrogen deposition between the 2002 base case and the 2009 future scenario that results from air quality regulations, population growth, and subsequent increases in vehicular miles.
traveled. In Figure 9A, we see that the total nitrogen deposition is expected to decrease in 2009 with respect to 2002 levels in spite of growth. Splitting the analysis between wet deposition (Figure 9B) and dry deposition (Figure 9C), we see that wet deposition decreases across the APB while dry deposition increases in some areas. The decrease in wet deposition reflects a larger regional influence in which emissions reductions in NOx emissions are important overall, while the localized increase in dry deposition is due to expected localized increases in agricultural NH3 emissions.

The example application has demonstrated a variety of ways that the WDT can be used with CMAQ output. The combination can positively contribute to a better understanding of atmospheric deposition, providing a more complete and more accurate picture of it. The values of deposition to each watershed segment can be exported from the WDT to be used as input to watershed-scale fate and transport models such as SWAT, HSPF, and SPARROW. The WDT with CMAQ also brings the power to incorporate anticipated future changes in wet and dry atmospheric deposition into water-quality analyses. As
shown in the example, estimating deposition changes is nontrivial because of the large airsheds involved, the interplay between long-range transport and local influences, and the fact that the direction of change for reduced nitrogen is not the same as for oxidized nitrogen. In addition, different emissions sectors (e.g., mobile sources or power plants) are spread across the landscape in different patterns and are expected to reduce emissions differently. Thus, the relative change in wet and dry deposition will be highly variable across space.

### SUMMARY

Atmospheric dry and wet deposition is an important contributor to nonpoint-source loadings to watersheds and water bodies and obtaining defensible, or best available estimates of deposition is critical for effective management of nonpoint-source pollution problems. Quantifying the amount of deposition to land surfaces and water bodies is challenging, and measurements of deposition are sparsely distributed.
FIGURE 9. WDT Screen Capture Showing the Change in Average (per unit area) Annual Total (wet + dry) (A), Annual Wet (B), and Annual Dry (C) Nitrogen Deposition to Each 12-Digit HUC in the Albemarle-Pamlico Basin Between the 2002 and 2009 CMAQ Runs.
(wet deposition) or scarce (dry deposition). This paper describes how data from CMAQ, a regional air quality model, can be used via the WDT to provide additional estimates of atmospheric deposition for further use in water-quality studies. CMAQ provides gridded estimates, at grid scales ranging from 4 to 36 km, of wet and dry deposition of a number of chemical species by accounting for known emissions sources, transport and chemical transformations that occur in the atmosphere and subsequent deposition to specific surface types. CMAQ is also continually being updated. Current research areas include developing approaches for modeling the bidirectional surface exchange of ammonia and mercury, as well as calculating land use category specific deposition fluxes. CMAQ data are not in a format that is easily input to watersheds-scale fate and transport models and other water-quality analyses. The WDT was developed to facilitate the inclusion of CMAQ predictions of atmospheric deposition of sulfur, nitrogen, and mercury into watershed management plans. It makes CMAQ data accessible to a wide range of users with a convenient user interface and provides methods for mapping the grid-based estimates of deposition to watershed delineations. With the WDT, users can examine the spatial distribution of the deposition of various nitrogen, sulfur, and mercury species. While 8-digit (cataloging unit) HUC polygons for the U.S. are provided with the WDT, users can also provide their own polygons for use with the WDT. Therefore, a range of sizes of watershed and their subdivisions can be visualized with the tool. Additionally, users can calculate the difference in deposition between two air quality modeling scenarios. Using this feature, environmental analysts and policy makers can consider the benefit of future air quality regulations on reductions in atmospheric deposition in their water-quality management plans.

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DISCLAIMER

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LITERATURE CITED


