Application of Watershed Deposition Tool to Estimate from CMAQ Simulations the Atmospheric Deposition of Nitrogen to Tampa Bay and Its Watershed

Noreen Poor
Kivmetrics, LLC, 4600 Explorer Dr., No. 102, West Melbourne, FL 32904

Ray Pribble
Janicki Environmental, Inc., 1155 Eden Isle Dr., NE, St. Petersburg, FL 33704

Donna Schwede
U. S. Environmental Protection Agency, National Exposure Research Laboratory, Atmospheric Modeling and Analysis Division, Research Triangle Park, NC 27711

ABSTRACT

The USEPA has developed Watershed Deposition Tool (WDT) to calculate from the Community Multiscale Air Quality (CMAQ) model output the nitrogen, sulfur, and mercury deposition rates to watersheds and their sub-basins. The CMAQ model simulates from first principles the transport, transformation, and removal of atmospheric pollutants. We applied WDT to estimate the atmospheric deposition of reactive nitrogen (N) to Tampa Bay and its watershed. For 2002 and within the boundaries of Tampa Bay's watershed, modeled atmospheric deposition rates averaged 13.3 kg N ha^{-1} yr^{-1} and ranged from 6.24 kg N ha^{-1} yr^{-1} at the bay's boundary with Gulf of Mexico to 21.4 kg N ha^{-1} yr^{-1} near Tampa's urban core, based on a 12-km x 12-km grid cell size. CMAQ-predicted loading rates were 1,080 metric tons-N yr^{-1} to Tampa Bay and 8,280 metric tons-N yr^{-1} to the land portion of its watershed. If we assume a watershed-to-bay transfer rate of 18 % for indirect loading, our estimates of the 2002 direct and indirect loading rates to Tampa Bay were 1,080 metric tons-N and 1,490 metric tons-N, respectively, for an atmospheric loading of 2,570 metric tons-N or 71 % of the total N loading to Tampa Bay. To evaluate the potential impact of USEPA's Clean Air Interstate Rule (CAIR, replaced with Cross-State Air Pollution Rule), Tier 2 Vehicle and Gasoline Sulfur Rule, Heavy Duty Highway Rule, and Non-

Road Diesel Rule, we compared CMAQ outputs between 2020 and 2002 simulations, with only the emissions inventories changed. CMAQ-projected change in atmospheric loading rates between these emissions inventories was 857 metric tons-N to Tampa Bay, or about 24 % of the 2002 total N loading to Tampa Bay from all sources.

IMPLICATIONS

Air quality modeling reveals that atmospheric deposition of reactive nitrogen (N) contributes a significant fraction to Tampa Bay's total N loading from external sources. Regulatory drivers that lower nitrogen oxide emissions from power plants and motor vehicles are important to bay management strategies, which seek to improve water quality through N load reduction.

INTRODUCTION

Tampa Bay is a 100,000-ha subtropical, shallow, tidal estuary on the western coast of central Florida and eastern side of Gulf of Mexico. Land use in Tampa Bay's 600,000-ha watershed is predominantly urban in its western and northern sectors, agricultural in its southern and eastern sectors, and industrial in ports on the bay's coastline (Figure 1). Fluxes of reactive nitrogen (N) to the bay and recycling of accumulated nutrients within the bay contribute to algal blooms, which shade the water column and create conditions that are unfavorable for sea grasses (Conley et al., 2009; Greening et al., 2011; Wang et al., 1999). Sea grasses are important to the estuary as a nursery for fish and shellfish and for their ability to retain sediment (Greening et al., 2011). The bay management strategy seeks to reduce N inputs and to re-establish lost sea grass beds (Greening and Janicki, 2006). Through management actions, N inputs have been reduced. The success of this strategy is evidenced by improved water clarity, lower chlorophyll α concentrations, and expansion of seagrass acreage in apparent response to significant reductions in N loading to Tampa Bay (Conley et al., 2009; Greening and Janicki, 2006; Sherwood, 2010).

New N enters Tampa Bay from non-point sources (62 %), direct atmospheric deposition (22 %), point sources (12 %), groundwater discharge (4 %), and accidental fertilizer losses (1 %) (Greening and Janicki, 2006). Atmospheric N that deposits first to land surface within the watershed and then moves either with stormwater runoff or via groundwater to the bay is referred to as indirect atmospheric deposition and is a non-point source. From the above percentages, between 22 % and 84 % of the new N reaching Tampa Bay is from atmospheric N deposition. Reductions of atmospheric contributions to N loading are important to achieving bay water quality goals.

Measurements of atmospheric N deposition near Tampa Bay are scarce. Therefore, air quality modeling is an important source of deposition estimates and for assessments of the change in deposition due to changes in emission inventories. The Community Multiscale Air Quality (CMAQ) model simulates from first principles the transport, transformation, and removal of atmospheric pollutants (Byun and Schere, 2006). The USEPA has developed the Watershed Deposition Tool (WDT) to calculate from the CMAQ model output N, sulfur, and mercury deposition rates to watersheds and their basins (Schwede et al., 2009). Figure 2, for example, shows WDT's display for annual atmospheric N deposition by basins and bay segments within Tampa Bay's watershed for 2002.

We applied WDT to estimate the atmospheric deposition of N to Tampa Bay and its watershed, to look at temporal trends in N deposition, and to evaluate the aggregate impact to Tampa Bay of the USEPA's health-driven regulatory drivers associated with the 1990 CAA. CMAQ-modeled and measured monthly wet N deposition rates were compared for a National Atmospheric Deposition Program (NADP) site near the southern boundary of Tampa Bay's watershed.

EXPERIMENTAL METHODS

CMAQ Modeling

CMAQ v4.7 chemical transport model simulated horizontal and vertical advection, horizontal and vertical diffusion, gas-phase and aqueous phase reactions, cloud mixing, aerosol dynamics, size distribution and chemistry, and deposition of gases and aerosols to Earth's surface (Byun and Schere, 2006; Schwede et al., 2009). CMAQ v4.7 included revisions to the cloud model, improvements to treatment of secondary organic aerosols and dinitrogen pentoxide (N_2O_5)

parameterization, and added dynamic mass transfer for coarse-mode aerosols, as examples (Foley et al., 2010). Computations for wet deposition included in-cloud scavenging and below-cloud washout of air pollutants based on Henry's Law partitioning for gases and absorption of aerosols into cloud or rain water; dry deposition estimates assumed turbulent transfer of gases and aerosols to the surface and resistance to gas transfer at the surface (Byun and Schere 2006; Schwede et al. 2009).

We used CMAQ v4.7 model simulations for 2002 – 2006 from Appel et al. (2011) that had been post-processed for the WDT. For these simulations, the modeling domain covered the eastern 2/3 of United States (US), southern Canada, and northern Mexico, with a 12-km x 12-km grid cell size and where boundary conditions were provided by a separate 36-km x 36-km continental US simulation (Appel et al., 2011; Foley et al., 2010). Year-specific meteorology was modeled with the Fifth Generation Penn State University/ National Center for Atmospheric Research (NCAR) mesoscale model (MM5; Grell et al., 1994). Sparse Matrix Operator Kernel Emission (SMOKE; Houyoux et al. 2000) gridded hourly emissions were built from USEPA's 2002 national emission inventory (NEI) v3 with year-specific adjustments for emissions from major point sources, mobile sources, and fires. Details of the meteorological modeling, emissions processing, CMAQ inputs and CMAQ model configuration can be found in Appel et al. (2011). CMAQ-modeled species included reduced N: ammonia (NH_3) and ammonium (NH_4^+), and oxidized N: nitrogen oxide (NO), nitrogen dioxide (NO_2), nitrate (NO_3^-), nitrous acid (HNO_2), nitric acid (HNO_3), dinitrogen pentoxide (N_2O_5), nitrate (NO_3^-), organic nitrate, peroxyacetyl nitrate (PAN) and higher PANs.

Additional files representing 2020 projected emissions based on expected growth and emission reductions due to the Clean Air Interstate Rule (CAIR, replaced with Cross-State Air Pollution Rule), Tier 2 Vehicle and Gasoline Sulfur Rule, Heavy Duty Highway Rule, and Non-Road Diesel Rule (Houyoux, 2005; USEPA, 2011a; USEPA, 2011b) were used to evaluate the effects on N deposition of proposed air quality regulations. These 2020 CMAQ files were made available by the USEPA and were based on the same MM5 meteorology as the 2002 CMAQ runs from Appel et al. (2011) with only the emissions inventory changed.

The Watershed Deposition Tool (WDT)

USEPA has developed the WDT to facilitate the extraction and analysis of CMAQ gridded output data for irregular spatial delineations such as basins and watersheds (Schwede et al., 2009). We downloaded the WDT (USEPA, 2011c) and available CMAQ v4.7 output files (USEPA, 2011d). Watershed basin polygons obtained from the Tampa Bay Estuary Program's (TBEP's) on-line technical resources were modified to better define water and land polygons and to achieve a finer spatial resolution (TBEP, 2011). In WDT, CMAQ's grid cells were superimposed over the watershed basins and bay segments as shown in Figure 3. WDT calculates N deposition for each watershed basin or bay segment as the summed product of deposition for each grid cell and the fraction of the overlay area between grid cell and polygon. Average N deposition rates are calculated as basin or bay segment N deposition divided by its area (Widing, 2006).

N Loading Estimates

For direct N loading to Tampa Bay, we integrated the bay segment-specific loading rates; for indirect N loading, we integrated basin-specific rates and assumed that 18 % of atmospherically-deposited N was transferred from land to bay (Pollman and Poor, 2003). Atmospheric loading rates were calculated separately for dry- and wet-deposited N and for oxidized and reduced N.

Modeled versus Measured Wet Deposition

Long-term monthly rainfall amount and N concentration data were available for Verna Wellfield (FL 41), a NADP National Trends Network (NTN) site (NADP, 2011), which is located in Sarasota County and is proximate to the southern boundary of Tampa Bay's watershed (Figure 1). From the Verna Wellfield data, wet deposition rates were calculated according to eq 1, where *C* is the monthly volume-weighted rainfall concentration of either NO_3^- -N or NH_4^+ -N and has units of mg l^{-1}, *D* is the rainfall depth and has units of cm mo^{-1}, and *F* is the deposition rate (i. e., flux) and has units of kg N ha^{-1} mo^{-1}. Concentration and precipitation data for August 2005 were not available in the downloaded file.

$$F = 0.100 \cdot C \cdot D \quad (1)$$

From the simulations of Appel et al. (2011), we obtained CMAQ-modeled precipitation amount and HNO_3, NO_3^-, NH_3, and NH_4^+ wet N deposition rates, as well as oxidized N and reduced N wet deposition rates for the 12-km x 12-km grid cell that enclosed NADP's Verna Wellfield (FL 41) site. CMAQ-modeled oxidized N deposition rates for Verna Wellfield were ~99% aerosol NO_3^- with minor contributions from NO_x, HNO_3, organic N, PAN, and other oxidized N species. For this reason we have labeled our graphics and tables as NO_3^--N rather than oxidized N wet deposition rates. CMAQ-modeled reduced N deposition rates for Verna Wellfield were ~100% aerosol NH_4^+ with minor contributions from NH_3.

Pearson correlation coefficient (*r*), normalized mean bias (*NMB*, eq 2), normalized mean error (*NME*, eq 3), and root mean squared error (*RMSE*, eq 4) were computed and plots prepared to assess agreement between modeled and observed wet N deposition rates (Nolte et al., 2008).

$$NMB = 100\ \% \cdot \Sigma\ (C_{\mathrm{mod}} - C_{\mathrm{obs}}) \ /\ \Sigma\ C_{\mathrm{obs}} \quad (2)$$

$$NME = 100\ \% \cdot \Sigma\ |C_{\mathrm{mod}} - C_{\mathrm{obs}}| \ /\ \Sigma\ C_{\mathrm{obs}} \quad (3)$$

$$RMSE = \sqrt{(1/n) \cdot \Sigma\ (C_{\mathrm{mod}} - C_{\mathrm{obs}})^2}, \text{ where } n \text{ is the number of observations} \quad (4)$$

RESULTS AND DISCUSSION

N Loading to Tampa Bay and Its Watershed

The CMAQ model yielded loading rates of 1,080 metric tons N yr^{-1} to Tampa Bay and 8,280 metric tons N yr^{-1} to the land portion of its watershed. If we assume a watershed-to-bay transfer rate of 18 % (Poor and Pollman, 2003), atmospheric direct and indirect loading rates to Tampa Bay were 1,080 metric tons N yr^{-1} and 1,490 metric tons N yr^{-1}, respectively, or an atmospheric loading rate to the bay of 2,570 metric tons N yr^{-1}. Table 1 shows N loading rates by bay segment.

Poe et al. (2005) estimated direct atmospheric and total loading rates for 2002 to Tampa Bay of 840 metric tons N and 3,400 metric tons N, respectively. To determine the relative fraction of CMAQ-modeled atmospheric loading to total loading, we first adjusted the 2002 total N loading rate from Poe et al. (2005) for the CMAQ-modeled direct atmospheric N loading rate (3,400 – 840 + 1,080 = 3,640 metric tons) and second computed the fraction of atmospheric to total loading rates (2,570 metric tons N/3,640 metric tons N), which was 71 % and a significant fraction of Tampa Bay's total N loading rate. JEI (2008) estimated direct atmospheric and total N loading rates to Tampa Bay for 2003 through 2006 (Table 2). Using the approach just described, we calculated from the CMAQ-model output the direct and indirect atmospheric N loading and fraction of total N loading that is atmospheric for 2003 through 2006 (Table 2). Atmospheric loading rates ranged from 1,950 to 2,260 metric tons N yr^{-1}, with significant fractional contributions that ranged from 35 % to 63 %. Contemporary published values for atmospheric loading rates to Tampa Bay vary from 1,100 metric tons N yr^{-1} to 3,030 metric tons N yr^{-1}. The broad range in estimates suggests significant differences in measurement techniques, computational tools, and methodical assumptions (Poor et al., in preparation).

The WDT's graphical results for atmospheric N deposition rates are shown Figures 3, 4, and 5. For 2002, the CMAQ-modeled average atmospheric deposition rate across the bay and its watershed was 13.3 kg N ha^{-1} yr^{-1}. Based on the 12-km x 12-km grid cell size, deposition rates ranged from 6.24 kg N ha^{-1} yr^{-1} to 21.4 kg N ha^{-1} yr^{-1}, with the lowest rates predicted over the Gulf of Mexico and highest rates centered on Tampa's urban core, which reflected emissions from the underlying human settlements (Figure 3). These N deposition rates are characteristic of an estuary and watershed with moderate N pollution (Dentener et al., 2006; Holland et al., 2005).

For dry- and wet-deposited N, the 2002 modeled average atmospheric deposition rates were 7.70 kg N ha^{-1} yr^{-1} and 5.64 kg N ha^{-1} yr^{-1}, respectively (Figure 4). Over land, the dry and wet loading rates were 4,800 metric tons N yr^{-1} and 3,490 metric tons N yr^{-1}, respectively; over water, the dry and wet loading rates were 608 metric tons N yr^{-1} and 474 metric tons N yr^{-1}, respectively. Assuming an 18 % transfer rate of N from land to water, atmospheric loading rates to Tampa Bay were 57 % dry and 43 % wet N deposition. Dry N deposition rates were higher in sectors with major traffic corridors and power generation plants near Tampa Bay. Modeled spatial gradients of wet N deposition were flatter than corresponding dry deposition N gradients (Figure 4).

For oxidized and reduced N, the 2002 modeled average atmospheric deposition rates were 9.73 kg N ha^{-1} yr^{-1} and 3.61 kg N ha^{-1} yr^{-1}, respectively (Figure 5). Over land, the oxidized and reduced loading rates were 5,990 metric tons N yr^{-1} and 2,300 metric tons N yr^{-1}, respectively; over water, the oxidized and reduced loading rates were 842 metric tons N yr^{-1} and 240 metric tons N yr^{-1}, respectively. Assuming an 18 % transfer rate of N from land to water, atmospheric loading rates to Tampa Bay were 75 % oxidized N and 25 % reduced N. The distribution of reduced N deposition was higher east of the bay over a region of industrial NH_3 emissions, a trend also seen for wet N deposition (Figure 4).

CMAQ-Modeled Temporal Trends in N Deposition

Between 2005 and 2010, Florida's annual and ozone season oxidized N emissions from power plants had dropped by 0.11 million metric tons (63%) and 0.054 million metric tons (65%), respectively (USEPA, 2011b), and continued a decade-long downward trend in both power plant NO_x emissions and NO_x concentrations measured at urban monitors near Tampa Bay (Poor et al., in preparation). The observed downward trend in atmospheric NO_x concentrations may have important consequences for N deposition to Tampa Bay. According to CMAQ modeling results, dry N deposition dominates both spatial and temporal N deposition rates within Tampa Bay and its watershed. These results suggest that within a watershed monitoring dry N deposition may be as important as monitoring wet N deposition.

By comparison, between 2002 and 2006 the CMAQ-modeled annual average N deposition rates to Tampa Bay and its watershed suggested a modest decline of 3.1 kg N ha^{-1} yr^{-1}. Of this decline, 0.66 kg N ha^{-1} yr^{-1} was from dry deposition of oxidized N, 0.70 kg N ha^{-1} yr^{-1} from wet deposition of reduced N, and 1.77 kg N ha^{-1} yr^{-1} from wet deposition of oxidized N; dry deposition of reduced N increased by 0.03 kg N ha^{-1} yr^{-1} (Figure 6). We investigated whether a decline in wet N deposition could be discerned at Verna Wellfield (FL 41), which is the NADP site nearest to Tampa Bay's watershed (Figure 1). We applied an unpaired, two-sided Student's t-test to test the hypothesis that between the first 30 months and the second 30 months of the 5-yr period the means of log-transformed NO_3^--N or NH_4^+-N deposition rates were equal. This hypothesis was not rejected for either NO_3^--N or NH_4^+-N deposition rates ($p = 0.67$ and $p = 0.17$, respectively). Our approach was repeated for rainfall rates and for NO_3^- or NH_4^+ concentrations with similar results. Thus, no significant downward trend in N wet deposition was evident at Verna Wellfield. Small changes in N deposition are likely difficult to discern over short time periods and among the large swings in rainfall and wet deposition rates (Figure 7).

In Figure 7 we illustrate for Tampa Bay and its watershed the temporal variation in modeled monthly dry and wet N deposition rates, which for the 5-year period shown, had means (± standard deviation) of 0.605 (± 0.081) and 0.365 (± 0.340), respectively. Given their relatively low coefficient of variation (CV), dry N deposition rates were well-predicted by an average value. This was clearly not the case for wet N deposition rates, as temporal gradients were steep with the highest rates seen in mid-summer. Dry-to-wet N deposition ratios were 5.99 (± 5.17) when averaged over the drier months September through May, and 0.801 (± 0.172) when averaged over the wetter months June through July. Annual watershed dry-to-wet N deposition ratios varied from 3.03 in 2002 to 6.48 in 2006 (a dry year) if calculated as the average of monthly dry-to-wet ratios, and from 1.36 in 2002 to 2.22 in 2006 if calculated as the average of annual dry deposition to wet deposition. One can see the challenges in using dry-to-wet N deposition ratios to predict from wet N deposition the dry N deposition to the watershed.

Comparison of Modeled and Observed Wet N Deposition Rates

Long-term wet deposition monitoring at an NADP NTN station proximate to the southern end of Tampa Bay's watershed offered us an opportunity to assess the agreement between CMAQ modeling and observations of rainfall and wet N deposition rates. This comparison was of a predicted grid cell average and a point measurement of rainfall amount or N deposition rate, which is by itself a source of error (Davis and Swall, 2006).

Gases of HNO_3, HONO, and NH_3 are water soluble and are thus scavenged by rainfall. Precipitation acidity in the range of pH 4-5 (Strayer et al., 2007) favors the disassociation of these compounds into NO_3^-, NO_2^-, and NH_4^+ in rainfall samples. Water-dissolved NO_2^- slowly oxidizes to NO_3^- (Finlayson-Pitts and Pitts, 2000) during the collection, transport, and storage of rainfall samples prior to their analysis at NADP's central laboratory. Aerosols containing NO_3^- and NH_4^+ are also removed by rainfall, albeit with differing size-related removal efficiencies (Finlayson-Pitts and Pitts, 2000). Gases of NO and NO_2 are poorly water soluble but may interact with an aerosol surface to form HONO; N_2O_5 readily dissolves in water to form NO_3^- and NO_2^-(Finlayson-Pitts and Pitts, 2000). Thus, NADP-reported concentrations of NO_3^- and NH_4^+ include both gas and particle contributions.

In CMAQ-modeled wet N deposition, error is present in the emissions inventory, meteorology, and mechanistic representations of atmospheric chemistry and physics. Such errors are discussed by Gilliland et al. (2006), who proposed corrections to the NEI for seasonality of NH_3 emissions; by Davis and Swall (2006), based on their examination of the effect of MM5's simulation of precipitation on CMAQ-modeled NH_4^+ wet deposition; and by Chemel et al. (2011) from their investigation of CMAQ's ability to predict a power plant's contribution to N deposition, as examples.

Error is present both in CMAQ-modeled and observed wet N deposition rates, so care must be taken not to assign all of the disagreement to modeling. According to Wetherbee et al. (2006), for example, "atmospheric wet deposition is slightly underestimated in 48 to 68 percent of the NADP/NTN samples, depending on the analyte." This underestimate is a consequence of analyte loss during field exposure, sampling handling, and/or shipping. Atmospheric wet deposition is overestimated if the sample is marginally contaminated; gross contamination, however, leads to sample rejection and loss of data, which if uncorrected, causes an underestimate in cumulative atmospheric wet deposition.

For eastern US, MM5 -simulated precipitation rates were underestimated for synoptic-scale storm systems and overestimated for sub-grid scale convective storm systems (Appel et al., 2011; Davis and Swall, 2006). A similar trend is evident at NADP's Verna Wellfield (FL 41) site, where reasonable agreement was seen between modeled and observed rainfall rates for cooler and drier months when rainfall was more likely produced by a synoptic system but a moderate positive bias was seen for summertime (wetter) months when rainfall was more likely generated in convective storms (Figure 8). Over a 5-yr period, the modeled and measured precipitation rates were moderately correlated, with averages of 16.3 cm and 12.3 cm, respectively (Table 3); 62 % of the modeled monthly rainfall rates were within a factor of two of observed rainfall rates (Figure 8). Since deposition rates are the product of N concentration and rainfall rate (eq 1), a bias in rainfall rate will contribute to a bias in N wet deposition.

The CMAQ model predictions of wet deposition rates agreed remarkably well for NO_3^- -N and NH_4^+ -N, with a only small positive bias relative to observations (Table 3) as shown in Figures 9 and 10; 75 % and 54 % of the data points for wet deposition rates of NO_3^- -N and NH_4^+ -N were within a factor of two, respectively (Figures 9 and 10). The N wet deposition biases were not as large as the precipitation bias, which suggested that errors in precipitation rates were offset by errors in N concentrations; in other words, NO_3^- and NH_4^+ concentrations were biased low. Appel et al. (2011) found that for eastern US, CMAQ-modeled wet deposition of both NO_3^- -N and NH_4^+ -N were underestimated but that these biases were diminished when model simulations were corrected for lightning-generated NO and bi-directional NH_3 exchange. The better model performance for NO_3^--N relative to NH_4^+-N wet deposition reflects, perhaps, differences in spatial and temporal resolution of NO_x and NH_3 emissions inventories (Appel et al., 2011; Gilliland et al., 2006) and the lower uncertainty in the NOx emissions compared to NH3 emissions.

2002 and 2020 N Emission Scenarios

Through the Clean Air Interstate Rule (CAIR, replaced with Cross-State Air Pollution Rule), Tier 2 Vehicle and Gasoline Sulfur Rule, Heavy Duty Highway Rule, and Non-Road Diesel Rule (USEPA, 2011c, d), USEPA seeks to improve air quality by phased reductions in air pollutant emissions from both fixed and mobile sources. A fully implemented CAIR, for example, removes 6.7 million metric tons of NO_x emissions from all states in continental US, of which 5.2

million metric tons are from states in eastern US (Houyoux, 2005). By 2020, NH_3 emissions are expected to grow by 0.44 million metric tons for all states in the continental US, however, of which 0.22 million metric tons of NH_3 emissions are from states in the eastern US (Houyoux, 2005). Moreover, slated reductions in sulfur dioxide (SO_2) emissions will shift aerosol NH_4^+ to gaseous NH_3 and thus favor localized dry deposition of reduced N (Pinder et al., 2008).

For 2002, the CMAQ-modeled direct plus indirect atmospheric loading rate to Tampa Bay was 2,570 metric tons N. Using WDT, we calculated the potential impact of fully implemented CAIR (now Cross-State Air Pollution Rule), Tier 2 Vehicle and Gasoline Sulfur Rules, Heavy Duty Highway Rule, and Non-Road Diesel Rule. Between the 2002 and 2020 emission scenarios, the projected change in atmospheric N loading was 857 metric tons N, which represented 33 % less atmospheric N loading and 24 % less total N loading to Tampa Bay.

Changes in atmospheric N deposition rates across Tampa Bay and its watershed between the 2002 and 2020 emissions scenarios are shown in Figure 11 and revealed a broad decrease of 1 to 2 kg N ha^{-1} over the entire watershed (orange color in Figure 11 A) but as high as 6 to 7 kg N ha^{-1} in the vicinity of major power plant and industrial sources (gray color in Figure 11 A). Thus, both regional and local emissions controls explain reductions in atmospheric N deposition under the future emissions scenario.

CONCLUSIONS

The Water Deposition Tool (WDT) offers a user-friendly interface with CMAQ model output to calculate atmospheric deposition of N to watersheds and their basins. Output made available includes wet and dry reduced N deposition and wet and dry oxidized N deposition on a 12-km x 12-km grid scale. With WDT we were able to estimate N deposition to both land and bay portions of the watershed and thereby include direct and indirect atmospheric deposition components. Modeled atmospheric N loading represented a substantial fraction of the total N loading to Tampa Bay. WDT also opened the door for trend analysis of CMAQ model output. As examples, CMAQ modeling indicated that during an extended dry season, dry N deposition dominated N deposition rates to Tampa Bay and its watershed. Moreover, oxidized N deposition rates greatly exceeded reduced N deposition rates. With WDT we had the opportunity to compare past and future emissions scenarios to assess the impact of emissions controls on N deposition to Tampa Bay and its watershed. Simulations of a fully-implemented CAIR (now Cross-State Air Pollution Rule) along with transportation-related rules translated into a significant reduction in total N loading to Tampa Bay.

ACKNOWLEDGMENTS

This research was funded by Florida Department of Environmental Protection (FDEP) through Tampa Bay Estuary Program (TBEP) under FDEP Contract AQ206. Noreen Poor is affiliated with the University of South Florida College of Public Health. The United States Environmental Protection Agency through its Office of Research and Development collaborated in the research described here. It has been subjected to Agency review and approved for publication.

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TABLES

Table 1. Estimated 2002 direct and indirect atmospheric N loading rates within Tampa Bay's watershed. Water area includes embayment, canals, and major tributaries apportioned by bay segment; land area includes watershed drainage surface by bay segment.

Bay Segment	Water Area, ha	Land Area, ha	Direct Atmospheric Loading, metric tons N	*Indirect Atmospheric Loading, metric tons N	Atmospheric Loading, metric tons N
Old Tampa	22,451	67,326	261	181	441
Hillsborough	10,852	330,364	211	843	1050
Middle Tampa	29,450	79,924	286	194	480
Lower Tampa	25,265	8,437	218	19.2	237
Boca Ciega	6,188	21,353	43.6	52.5	96.1
Terra Ceia	1,650	2,851	20.6	6.48	27.1
Manatee River	3,460	92,416	42.1	196	238
Totals	99,317	602,669	1,080	1,490	2,570

*Assumes an 18 % transfer rate from watershed to bay.

Table 2. Modeled atmospheric deposition (AD) and total N loading to Tampa Bay 2002-2006.

	Previous Estimates*			Current Estimates			
Year	Direct AD N Loading, metric tons	Total N Loading, metric tons	§Adjusted Total N Loading, metric tons	Direct AD N Loading, metric tons	Indirect AD N Loading, metric tons	AD N Loading, metric tons	Total N Loading that is AD Loading, %
2002	840	3,400	3,640	1,080	1,490	2,570	70.6
2003	1,150	6,690	6,440	903	1,340	2,240	34.8
2004	801	5,930	6,010	885	1,240	2,120	35.4
2005	603	3,230	3,570	950	1,310	2,260	63.3
2006	552	2,980	3,230	803	1,150	1,950	60.5

*JEI, 2008; TBNMC, 2010; §Previous estimate of total N loading – previous estimate of direct AD N loading + current estimate of direct AD N loading

Table 3. Statistics to assess agreement between modeled vs. observed monthly rainfall and wet N deposition rates. Units are cm on mean modeled, mean observed, and RMSE precipitation; units are kg ha^{-1} mo^{-1} on mean modeled, mean observed, and RMSE N deposition rates.

Species	Mean Modeled	Mean Observed	*r*, %	NMB, %	NME, %	RMSE
Precipitation	16.3	12.3	73.7	32.6	66.8	12.6
NH_4^+ -N	0.113	0.108	50.1	2.91	62.1	0.103
NO_3^- -N	0.173	0.166	78.6	0.416	43.4	0.107
Total N	0.287	0.274	73.7	1.39	43.3	0.186

FIGURE TITLES

Figure 1. Tampa Bay and its watershed. Black outlines indicate watershed basin and bay segments boundaries and darker shading shows municipal boundaries for major cities.

Figure 2. Watershed Deposition Tool (WDT) display for total annual N deposition by basins and bay segments within Tampa Bay's watershed for 2002.

Figure 3. Reactive nitrogen (N) atmospheric deposition rates for Tampa Bay and its watershed from 2002 CMAQ model simulations. A: gridded N deposition rates (kg N ha^{-1}); B: average N deposition rates by watershed basin and bay segment (kg N ha^{-1}).

Figure 4. Atmospheric average dry (A) and wet (B) N deposition rates for Tampa Bay and its watershed, by watershed basin and bay segment (kg N ha^{-1}), from 2002 CMAQ model simulations.

Figure 5. Atmospheric average oxidized (A) and reduced (B) N deposition rates for Tampa Bay and its watershed, by watershed basin and bay segment (kg N ha^{-1}), from 2002 CMAQ model simulations. White indicates deposition rates < 2 kg N ha^{-1}.

Figure 6. Modeled average wet and dry N deposition rates for Tampa Bay and its watershed.

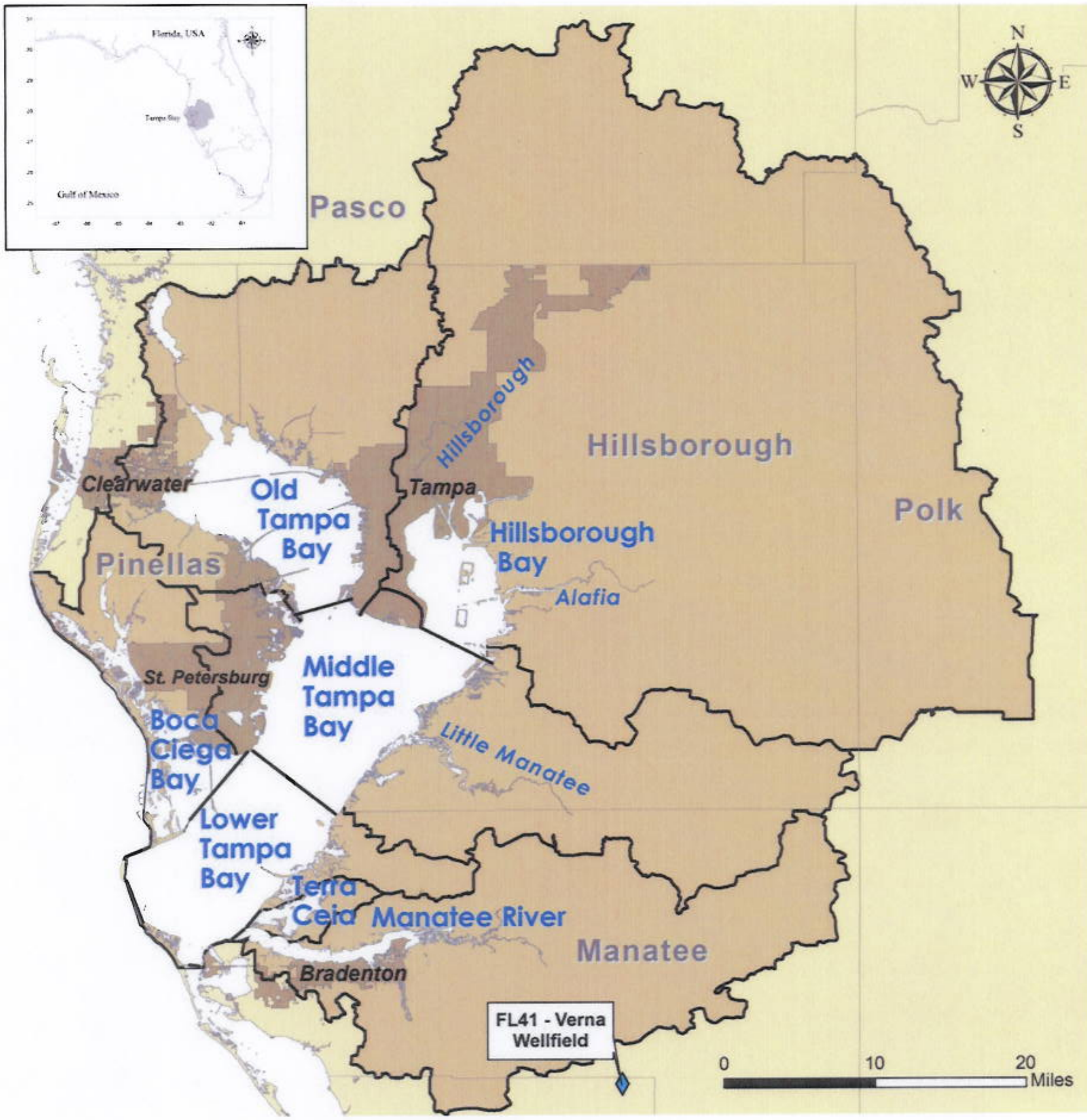
Figure 7. CMAQ-predicted 2002-2006 annual average N deposition rates for Tampa Bay and its watershed.

Figure 8. Comparison of CMAQ-modeled and observed precipitation rates for NADP's Verna Wellfield (FL41) site.

Figure 9. Comparison of CMAQ-modeled and observed NO_3^- wet deposition rates for NADP's Verna Wellfield (FL41) site.

Figure 10. Comparison of CMAQ-modeled and observed NH_4^+ wet deposition rates for NADP's Verna Wellfield (FL41) site.

Figure 11. CMAQ-modeled changes in watershed N deposition for 2002 base case and 2020 future scenario emissions for Tampa Bay and its watershed, processed with WDT from CMAQ 2002 12-km gridded scale output. A: change in gridded N deposition rates (kg-N ha^{-1}); B: change in average N deposition rates by watershed basin and bay segment (kg-N ha^{-1}).



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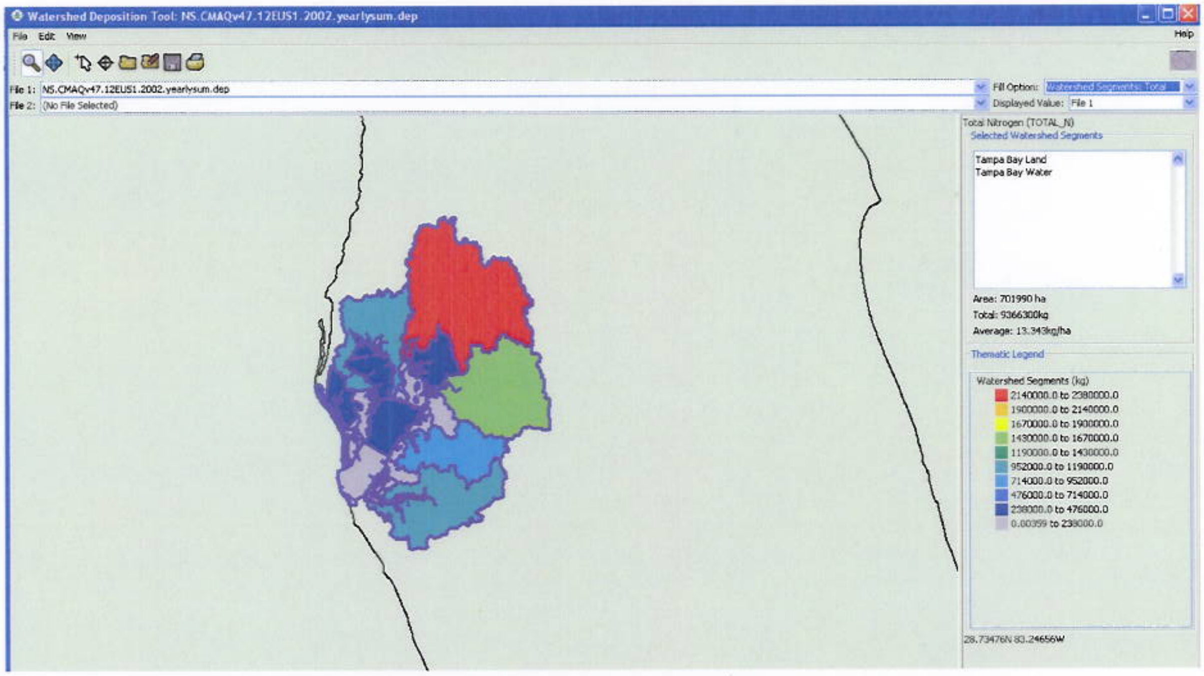

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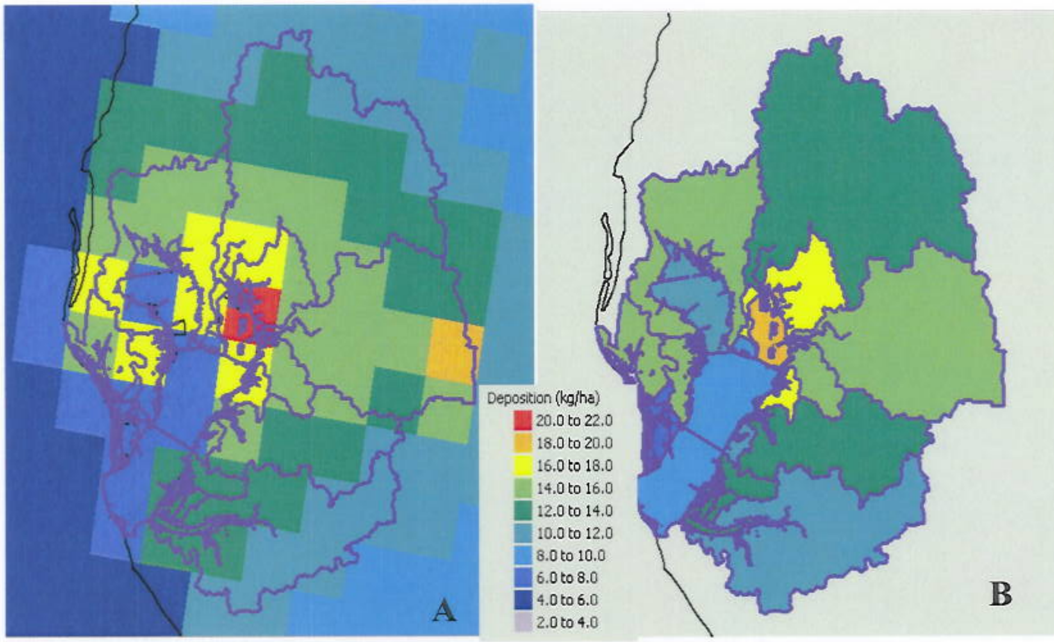

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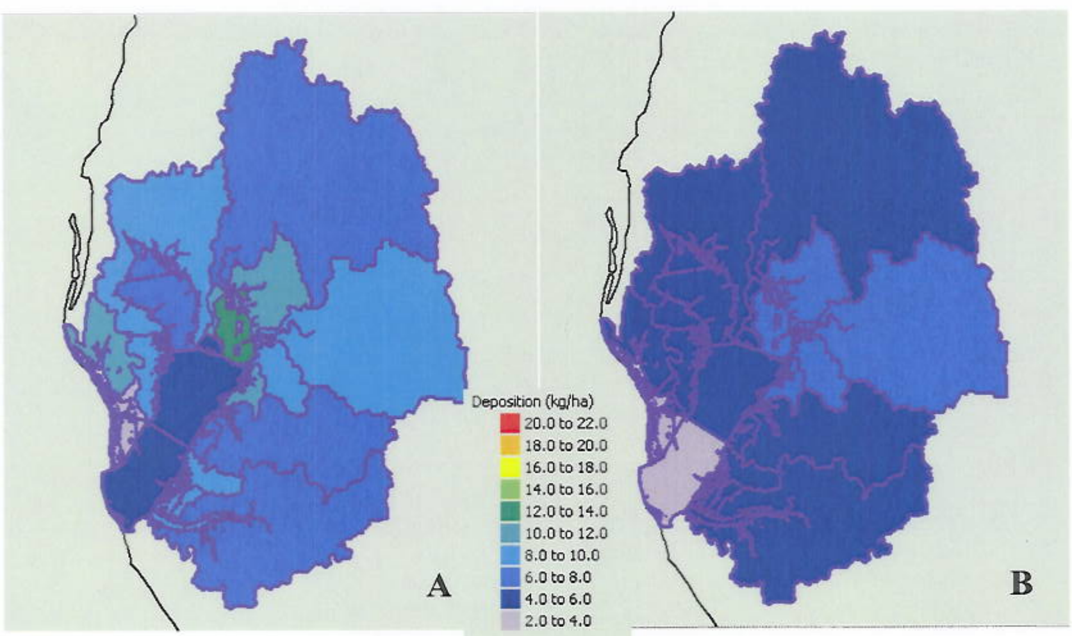


Figure 4. Atmospheric average dry (A) and wet (B) N deposition rates for Tampa Bay and its watershed, by watershed basin and bay segment (kg N ha^{-1}), from 2002 CMAQ model simulations.

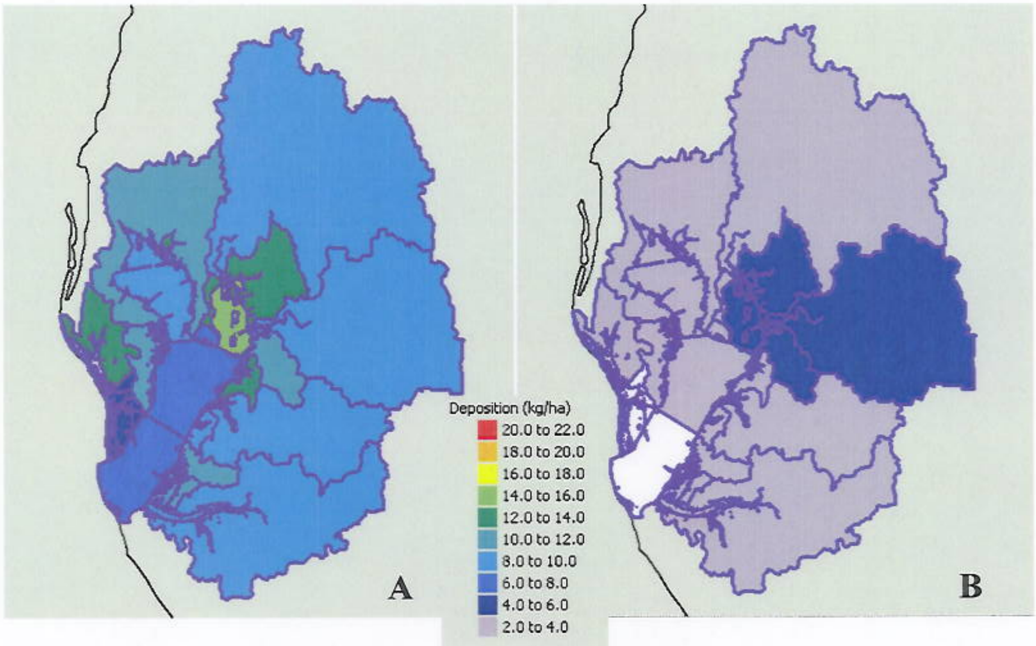


Figure 5. Atmospheric average oxidized (A) and reduced (B) N deposition rates for Tampa Bay and its watershed, by watershed basin and bay segment (kg N ha^{-1}), from 2002 CMAQ model simulations. White indicates deposition rates < 2 kg N ha^{-1}.

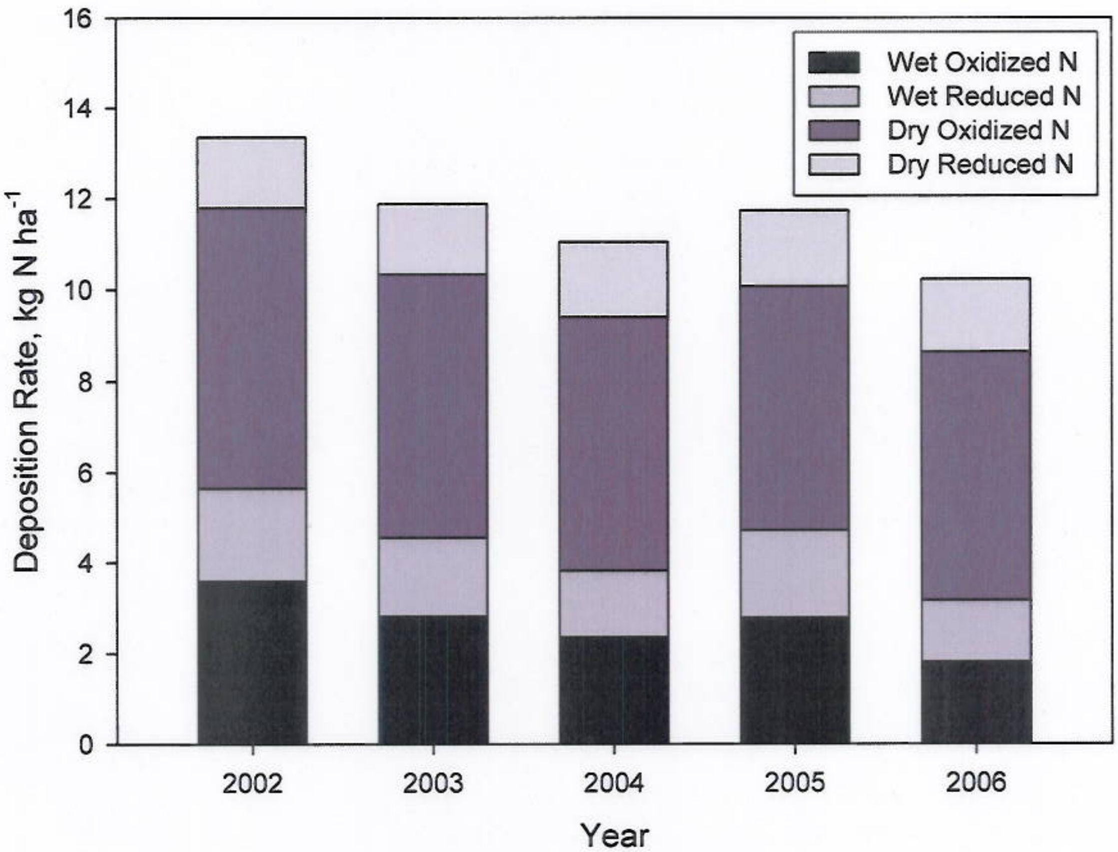


Figure 6. CMAQ-modeled 2002-2006 annual average N deposition rates for Tampa Bay and its watershed.

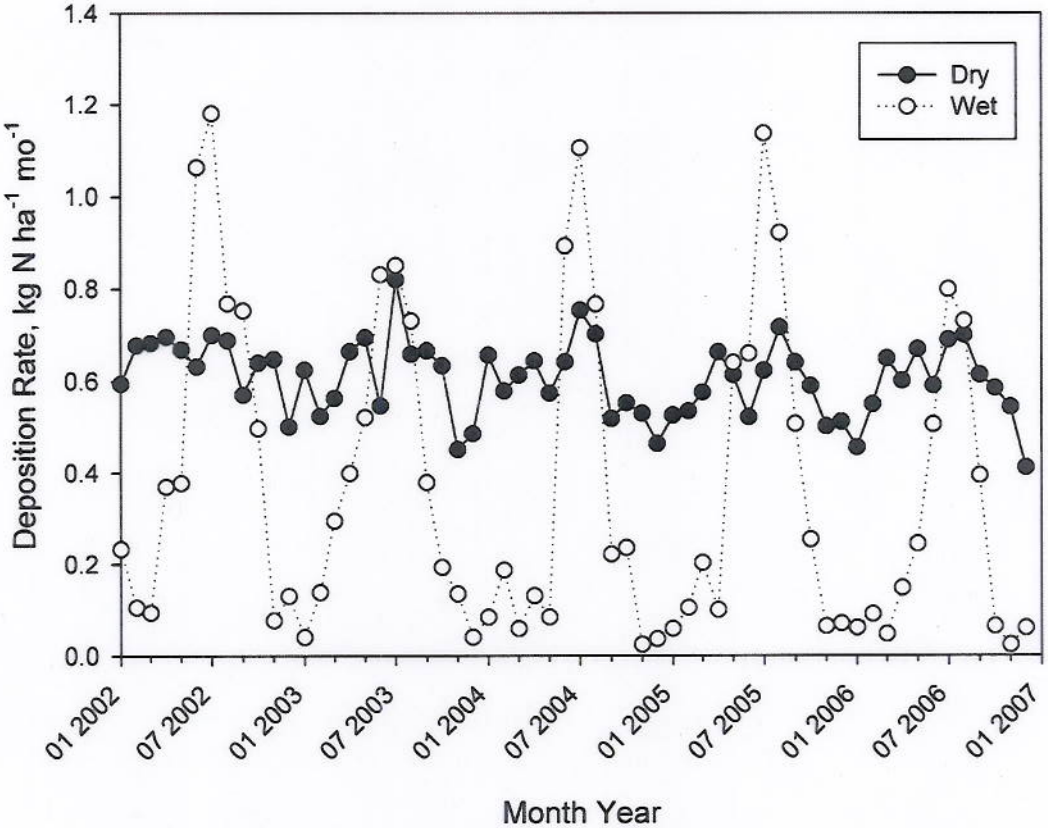


Figure 7. Modeled average wet and dry N deposition rates for Tampa Bay and its watershed.

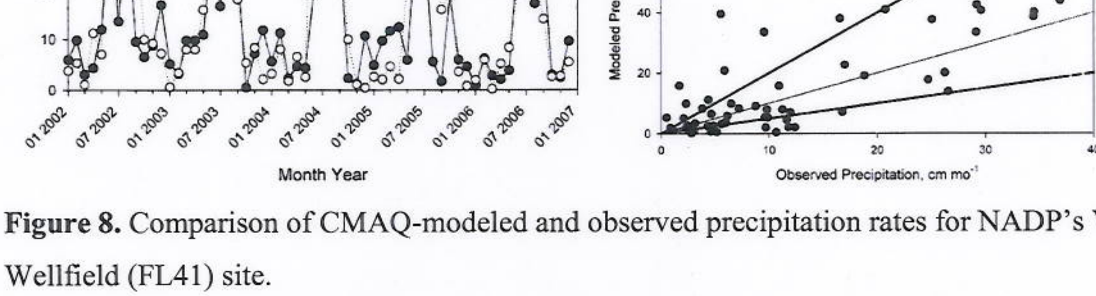


Figure 8. Comparison of CMAQ-modeled and observed precipitation rates for NADP's Verna Wellfield (FL41) site.

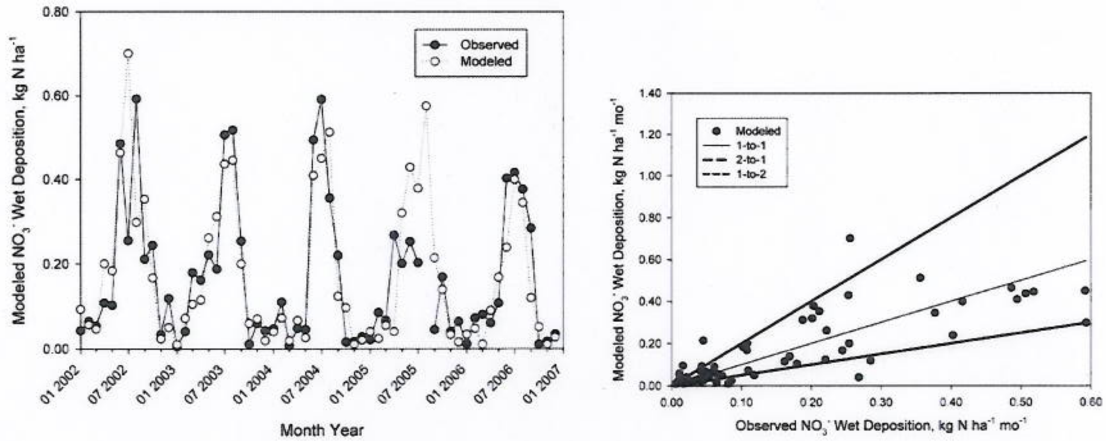


Figure 9. Comparison of CMAQ-modeled and observed NO_3^- wet deposition rates for NADP's Verna Wellfield (FL41) site.

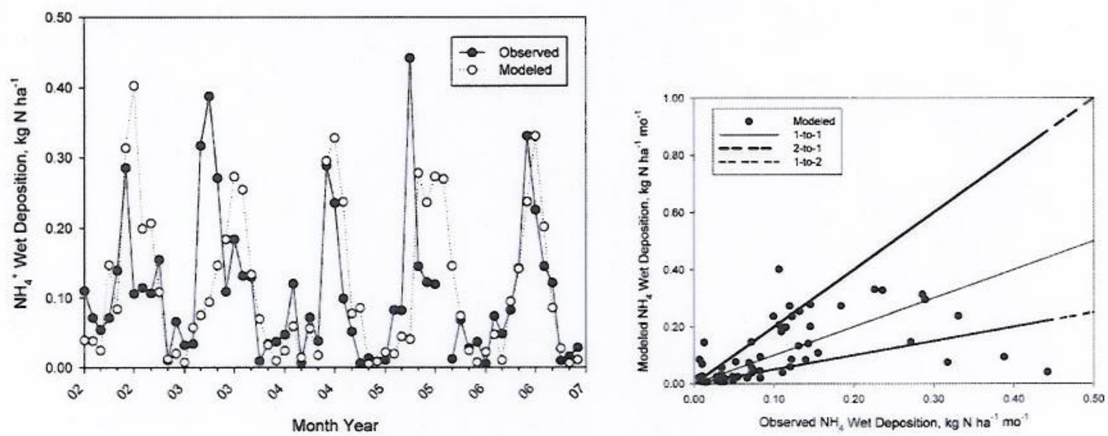
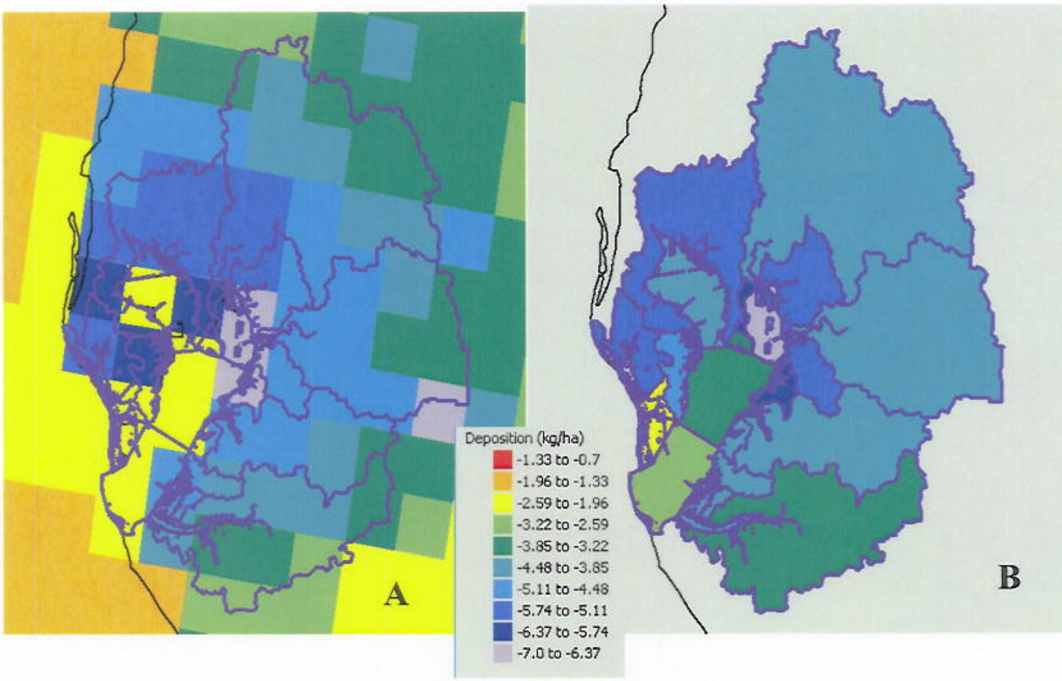


Figure 10. Comparison of CMAQ-modeled and observed NH_4^+ wet deposition rates for NADP's Verna Wellfield (FL41) site.



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