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A Modeling Analysis of Dissolved Carbon Dioxide Discharged from Howard F. Curren Advanced Wastewater Treatment Plant

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A Modeling Analysis of Dissolved Carbon Dioxide

Discharged from Howard F. Curren Advanced Wastewater Treatment Plant

by

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of the requirements for the degree of
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Dedication

I would like to dedicate this work to my loving fiancée, Kristen Green, who has stood by me during my three years here at USF. Through all of the stress, headaches, and late nights encountered not just with this project, but throughout the course of my studies, you have been my rock even from some 2500 miles away. You have helped keep me focused and upbeat during the times when I didn't think I could handle all of the stress and I don't know if I could have done this without your love and support. I love you with all of my heart.

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Abstract

Currently, the US Environmental Protection Agency primarily regulates the discharge of dissolved nitrogen and phosphorous from wastewater treatment plants in the United States. A recent study has shown that the treated effluent of many plants contains concentrations of dissolved carbon dioxide well above the expected theoretical equilibrium concentration of 0.6 mg/L, indicating that carbon dioxide may have been overlooked as a possible pollutant in receiving waters. For this reason, it is necessary to examine the possible presence of a discharge plume containing high levels of dissolved CO_2 downstream from the outfall of a major wastewater treatment plant in Tampa, Florida.

To examine this possibility, discharge data at the Howard F. Curren Advanced Wastewater Treatment Plant was collected over a two-week period and fed into the UM3 submerged discharge model to simulate discharge conditions at peak ebb tide. In all, five separate runs of the model were performed and compared to examine plume rise, spreading rate, average dissolved CO_2 concentration, and plume path. The model predicts that, for this scenario, the plume rises fairly rapidly and is also quickly diluted to near-ambient concentrations of dissolved carbon dioxide within a short distance of being discharged. While this would seem to indicate that the effects of Howard F. Curren on Tampa Bay, in terms of dissolved CO_2, are negligible major limitations of the UM3 model make it difficult to say this with a great deal of certainty.

1 Introduction

1.1 Literature Review

Current regulatory guidelines for wastewater treatment effluent, as set forth by the US Environmental Protection Agency, focus primarily on dissolved nitrogen and phosphorous in order to effectively maintain water quality in receiving waters. However, dissolved carbon dioxide may have been overlooked as a potential pollutant in the degradation of the quality of these waters. A recent study involving multiple wastewater treatment facilities found that the effluent streams consistently contained levels of dissolved CO_2 far in excess of what would be expected at equilibrium with the atmosphere (Morris, Smith, & Stroot, 2009). Given a Henry's constant (H) value of 28.8 bar/M at 25 °C (Benjamin, 2002) and the current atmospheric CO_2 concentration of approximately 380 ppmv, the equilibrium concentration in the water should theoretically be ~0.6 mg/L. The dissolved effluent CO_2 concentrations measured, however ranged from 6 – 16 mg/L (Morris, et al., 2009). These elevated levels could potentially have some negative ecological impacts on the receiving waters.

Elevated levels of atmospheric CO_2 have been linked to various ecological impacts in aqueous environments due to the associated increase in the aqueous-phase concentration. With the only difference being the source of CO_2, it can most likely be assumed that many ecological impacts associated with an atmospheric source would be similar to those associated with an aqueous source. While at first glance, it would seem that a significant increase in the concentration of dissolved CO_2 resulting from an

aqueous source would have an impact on the chemistry of the receiving waters by, at the very least, altering its pH. However, this is not likely to be the case as the treated effluent is strictly regulated by the US EPA in regards to pH, which must be neutral. A major potential impact of interest is the possible affects that elevated levels of dissolved carbon dioxide may have on the biota in the receiving waters. Increases in dissolved CO_2 could result in algae blooms, in addition to their associated adverse effect, as carbon dioxide is a major carbon source for photosynthetic organisms.

An increase in the amount of dissolved CO_2 may also have a profound impact on the aquatic ecosystem by directly increasing the rate of photosynthesis in both algae and aquatic plants. While it is normally understood that this would occur in clear waters, it has also been observed in waters where light is otherwise limiting as elevated levels of dissolved CO_2 allow for more efficient photosynthesis (Urabe, Togari, & Elser, 2003). This, in turn, increases the organism's growth rate with the degree of this increase being largely dependent on the affinity of the individual species for either CO_2 or HCO_3^-, or both. Those organisms which have a high affinity will be less sensitive to increased levels of carbon dioxide and vice versa (Schippers, Vermaat, de Klein, & Mooij, 2004). While the individual growth rate will vary depending on the organism, in general, most species of algae and aquatic plants have been shown to exhibit a significantly increased growth rate in response to higher levels of CO_2 (Schippers, et al., 2004; Urabe, et al., 2003). This link between elevated concentrations of dissolved CO_2 and increased growth rates in algae and phytoplankton could be important as it pertains to red tide which is known to be caused by a particular type, known as dinoflagellates.

As was mentioned previously, an organism's sensitivity to elevated CO_2 levels depends on its affinity for a particular carbonate species. It should also be noted that many species of algae and aquatic plants are able to utilize inorganic carbon, in the form of bicarbonate, through various carbonate-concentrating mechanisms (CCMs). This is important as the elevated concentration of dissolved carbon dioxide could potentially lead to elevated levels of bicarbonate at neutral pH. The CCM process involves the active transport of both CO_2 and HCO_3^- into the cell as well as the active transformation of bicarbonate to carbon dioxide with the help of the enzyme carbonic anhydrase (Urabe, et al., 2003). This plays an important factor when other nutrients, such as phosphorous or nitrogen, are limiting as they generally are in treated wastewater effluent in that the CCMs become less efficient due to their high metabolic costs (Urabe, et al., 2003). As such, the organism becomes less able to utilize bicarbonate for photosynthesis and must instead rely more heavily on carbon dioxide. A secondary consequence of this nutrient limitation is the effect it has on the fitness of primary grazers such as *Daphnia*. These are microscopic invertebrates commonly found in many freshwater environments. Algae are a primary food source for these organisms. Even though the algae may exhibit a significant increase in growth rates, experimental data have shown a significant reduction in the ratio of phosphorous:carbon (P:C) which, in turn, results in decreased growth rates for *Daphnia* (Urabe, et al., 2003). A reduction in the fitness of a primary grazer, such as *Daphnia,* could potentially have a cascade effect up to higher trophic levels by significantly reducing their food source.

Figure 1: Study site. Location of the study site within Tampa Bay (NASA, 2004).

For the purposes of this study, a single wastewater treatment plant in Tampa, Florida was modeled to determine the downstream region that its discharge plume is potentially affecting. The particular treatment plant that was examined was the Howard F. Curren Advanced Wastewater Treatment Plant. This plant uses an advanced aeration treatment process with a capacity of 96 MGD and discharges the treated waste into Tampa Bay. Figure 1 indicates the relative location within Tampa Bay as well as the outfall location for Howard F. Curren, which is specifically located in a region of Tampa Bay known as Hillsborough Bay.

1.2 Motivation

The primary motivation for this study was not to determine the impacts of wastewater treatment plants on receiving waters as they relate to elevated dissolved CO_2 concentrations. Rather it was to determine if a more thorough and detailed analysis of this potential problem is warranted. As dissolved carbon dioxide is a major carbon source for aquatic photosynthetic organisms, its potential as a pollutant may have been overlooked since elevated levels have been shown to result in increased growth rates for a wide range of aquatic photosynthetic organisms. The potential of dissolved carbon dioxide as a point-source pollutant could be the greatest after a rain event, as the greatest source of nutrient pollution in aquatic environments is nonpoint-source in the form of fertilizer run-off.

This potential can be demonstrated by using the method taken from Rittman and McCarty. This method uses a series of biochemical half reactions in order to determine the overall reaction (R) and to estimate theoretical stoichiometric ratios of interest necessary for cell growth (Rittman & McCarty, 2001). These half-reactions include the electron acceptor half-reaction (R_a), the cell half-reaction (R_c), and the electron donor half-reaction (R_d). The cell half-reaction represents the biochemical half-reaction of cell synthesis, represented by the chemical formula $C_5H_7O_2N$ (Rittman & McCarty, 2001). These three terms are used to develop the overall energy reaction for the organism (R_e) as well as the overall synthesis reaction (R_s). These two terms are defined by Rittman as follows:

$$R_e = R_a - R_d \qquad 1.2.1$$

$$R_s = R_c - R_d \qquad 1.2.2$$

This method also takes into consideration the fraction of energy used by the organism for energy production (f_e) as well as the fraction used for cell synthesis (f_s). As these terms are fractions, it is understood that the sum is unity. The overall reaction is the sum of the energy reaction and synthesis reaction which results in the following equation:

$$R = f_e(R_a - R_d) + f_s(R_c - R_d) \quad 1.2.3$$

This equation can then be simplified to the form:

$$R = f_e R_a + f_s R_c - R_d \quad 1.2.4$$

In the case of treated wastewater, the ratio of interest is that of dissolved carbon dioxide to total nitrogen, expressed as ammonium (NH_4^+-N). NH_4^+-N was chosen as the nitrogen source as manure is a major component of many commercial fertilizers and ammonium is the primary form of nitrogen in manure. Therefore, it will be assumed that all nitrogen present in the system will be in the form of NH_4^+-N.

Using the half-reactions provided by Rittman, the following overall reaction and stoichiometric relationship can be generated for this system:

$$R_a: \frac{1}{5}CO_2 + \frac{1}{20}HCO_3^- + \frac{1}{20}NH_4^+ + H^+ + e^- \rightarrow \frac{1}{20}C_5H_7O_2N + \frac{9}{20}H_2O \quad 1.2.5$$

$$R_c: \frac{1}{5}CO_2 + \frac{1}{20}HCO_3^- + \frac{1}{20}NH_4^+ + H^+ + e^- \rightarrow \frac{1}{20}C_5H_7O_2N + \frac{9}{20}H_2O \quad 1.2.6$$

$$-R_d: \frac{1}{2}H_2O \rightarrow \frac{1}{4}O_2 + H^+ + e^- \quad 1.2.7$$

The donor half-reaction was selected to reflect the fact that water is the electron donor for photosynthesis in green plants and algae (Madigan, Martinko, Dunlap, & Clark, 2009). In this case, since the acceptor and cell reactions are identical and the terms f_e and f_s must sum to unity, the overall reaction can effectively be simplified to Equation 1.2.1 or Equation 1.2.2. Summing either of these equations provides the overall reaction:

$$R\text{: } \frac{1}{5}CO_2 + \frac{1}{20}HCO_3^- + \frac{1}{20}NH_4^+ + \frac{1}{20}H_2O \rightarrow \frac{1}{20}C_5H_7O_2N + \frac{1}{4}O_2 \qquad 1.2.8$$

From this reaction, it then becomes possible to estimate the minimum, theoretical threshold of dissolved CO_2 necessary for cell growth. Using the EPA mandated discharge limit for total dissolved nitrogen of 3 mg/L and Equation 1.2.8 shows that, theoretically, approximately 38 mg/L of dissolved CO_2 would need to be present in order to fully utilize all of the available nitrogen in the system. Using the assumption that all nitrogen present in the system is in the form of NH_4^+-N, this translates to a ratio of CO_2:total nitrogen of approximately 12:1. This indicates that a theoretical minimum of 12 mg/L of dissolved CO_2 is needed for every 1 mg/L of NH_4^+-N present in the system. This minimum threshold falls comfortably within the range of dissolved CO_2 concentrations measured by Morris et al.

1.3 Model Description

The model used for this study was the three-dimensional Updated Merger (UM3) model from the EPA's Visual Plumes modeling suite. The model is a Lagrangian integral model for submerged single and multi-port discharges and is coded in Delphi Pascal (Frick et al., 2003). UM3 works by following thin, cross-sectional slices of the plume as they are discharged and move away from the outfall. As it is a Lagrangian model, integration is performed with time (Davis, 1999). The model assumes that all of the properties within each cross-section are uniform with the only variations being along the trajectory path (Davis, 1999). Entrainment of ambient fluid is assumed to occur either via forced entrainment due to ambient currents or through the surface area of the cross-sectional slice (Davis, 1999).

The UM3 model uses a series of conservation equations in order to generate predictions of pollutant concentration, trajectory, and position. Properties being conserved are: mass, momentum, energy, and species (Davis, 1999). The following equations presented in the model description are taken from technical documentation provided by Davis (1999). A detailed definition of each term, including the identification of appropriate units, can be found in Appendix A.

$$\frac{dm}{dt} = E_{amb} + E_{\alpha} \tag{1.3.1}$$

This equation describes how the mass of water within the slice is conserved with time where E_{amb} is the term which describes the forced entrainment due to ambient velocities. E_{α} describes aspiration entrainment. The entrainment function, E_{amb}, is given as:

$$E_{amb} = \rho A_p \left|\vec{U}\right| \tag{1.3.2}$$

where ρ is the fluid density, A_p is the surface area of the leading and trailing faces of the cross-sectional slice as seen by the approaching ambient fluid, and $\vec{U}$ is the relative vector velocity of the ambient fluid. Aspiration entrainment is given by:

$$E_{\alpha} = \alpha \rho A_T |\vec{v}| \tag{1.3.3}$$

The magnitude of the velocity of the plume across the slice in the direction of flow is given by $|\vec{v}|$, A_T is the surface area of the slice normal to the ambient fluid, and α is an entrainment function. In this case, where velocity is assumed to be constant across a given cross-section, α is set to 0.1.

$$\frac{dm\vec{v}}{dt} = \frac{dm}{dt}\vec{U} - m\vec{g}\frac{(\rho_{\infty} - \rho)}{\rho} \tag{1.3.4}$$

This is the equation that the UM3 model uses to calculate conservation of momentum. In this particular equation, $\vec{U}$ is the relative vector velocity of the approaching ambient fluid,

$\vec{g}$ is gravity, and ρ is density. The density of the fluid is calculated from the temperature and salinity. The subscript, ∞ is used to denote ambient properties. The first term is a vector term which describes the total change in momentum within the slice, the second term describes the change of momentum which results from the entrainment of ambient fluid, and the final term is the vertical momentum change due to the density difference between the plume and the ambient fluids.

$$\frac{d[mC_p(T-T_\infty)]}{dt} = C_p(T-T_\infty)\frac{dm}{dt} \quad 1.3.5$$

The above equation is the energy conservation equation. Temperature is given by T, with C_p indicating specific heat. All energy is assumed to be thermal energy.

$$\frac{dmC_i}{dt} = C_\infty \frac{dm}{dt} - \kappa m C_i \quad 1.3.6$$

Equation 1.3.4 describes the conservation of mass of the chemical species of interest within the plume where C_i is the mass concentration for the species of interest, in this particular case dissolved CO_2. In order to account for chemical reactions, a first order reaction is given by the last term in the equation with κ indicating the first-order reaction coefficient.

For all of the above-described equations, the mass of water within the slice is described by:

$$m = \rho \pi b^2 h \quad 1.3.7$$

where b and h are the average radius and thickness of the slice, respectively. As the trailing and leading faces of the plume slice are assumed to be traveling at different velocities, the thickness of the slice can vary with time. Equation 1.3.1 is used to calculate the rate at which the mass of water within the plume slice is changing. From

this, the changes in momentum, energy, and concentration can then be determined using known properties.

The above differential equations are integrated in UM3 using simple separation of variables. For example, the mass of water at the new time step is calculated from:

$$m_{t+dt} = m_t + (E_{amb} + E_\alpha)dt \tag{1.3.8}$$

The conservation equations for momentum, energy, and concentration are calculated in a similar manner. From these calculations, new values of the slice in its new position are obtained for the following terms: m, $m|\vec{v}|$, $C_p(T - T_\infty)$, and mC_i. As the volume of the cross-sectional slice can be approximated by:

$$V \approx \pi b^2 h \tag{1.3.9}$$

the new mass of water can be evaluated as:

$$m_{t+dt} = (\rho \pi b^2 h)_{t+dt} \tag{1.3.10}$$

The new momentum can then be defined as:

$$\text{new momentum} = (\rho \pi b^2 h|\vec{v}|)_{t+dt} = (m|\vec{v}|)_{t+dt} \tag{1.3.11}$$

If the integration time step, dt, is taken to be

$$dt = \frac{h}{|\vec{v}|} \tag{1.3.12}$$

this can be rearranged and evaluated to yield

$$\Delta h = \Delta|\vec{v}|dt \tag{1.3.13}$$

From this relationship, a relationship between the new thickness and plume velocity can be defined such that:

$$h_{t+dt} = h_t + \left(\frac{|\vec{v}|_{t+dt}}{|\vec{v}|_t}\right) \tag{1.3.14}$$

Equations 1.3.10, 1.3.11, and 1.3.14 are then solved simultaneously to provide new values for b, h, and $|\vec{v}|$ at the new time step.

2 Materials and Methods

2.1 Materials

The model used for this analysis was the three-dimensional Updated Merge (UM) model, otherwise known as UM3, and was taken from the Visual Plumes modeling suite provided by the US EPA. This is a time-series model which assumes the plume is at steady-state (Frick, et al., 2003). In other words, the discharge plume as a unit, is not changing relative to the ambient fluid.

Relevant water chemistry data, such as dissolved CO_2 concentrations, conductivity, and temperature were measured using an OxyGuard® CO2 Portable Carbon Dioxide Analyser in conjunction with a Hydrolab® Quanta water quality sonde. The portable carbon dioxide probe was used to measure dissolved CO_2 levels with the Hydrolab being used to measure the other physical and chemical properties of the treated wastewater. When taking measurements at the outfall, the Hydrolab® was not available; therefore, a Lowrance® LMS-520C fishfinder was used to measure the ambient temperature. The OxyGuard® CO2 probe was again used to measure ambient CO_2 concentrations within Hillsborough Bay as well as the outfall CO_2 concentration for the purposes of comparison with the model predictions.

2.2 Methods and Model Parameters

The model parameters for the discharge conditions were obtained from the measurements taken over a two-week period at the wastewater treatment facility. The flow rate was provided by the plant operators with all other necessary parameters

obtained via direct measurement. In all, five measurements were taken in order to provide sufficient data to run the model five times. This was partially necessitated by security measures at the Port of Tampa, where the Howard F. Curren treatment facility is located. Table 1 lists the various discharge conditions which were input into the model for each run. The physical discharge port parameters, such as direction, elevation, and diameter, were taken from technical schematics provided by the treatment plant. The single discharge port had a diameter of 78 in and the bottom of the port was set flush to floor of the channel. It had a vertical angle of 0°, meaning the mouth of the discharge conduit was perfectly horizontal relative to the floor of the channel. The discharge pipe was oriented due south with a mean centerline depth of 25.25 ft.

Table 1: Discharge conditions. The discharge conditions used for the UM3 model for each scenario.

n	Total Flow Rate (MGD)	Effluent Conductivity (mmho/cm)	Temperature (°C)	Dissolved CO_2 Concentration (ppm)
1	53.0	1.65	27.52	10.0
2	65.0	1.66	28.04	11.0
3	61.25	1.82	28.04	10.0
4	68.88	1.65	27.16	10.0
5	57.44	1.63	27.32	12.0

Due to some model limitations, which will be discussed later, the ambient conditions for each model run were held constant. Ambient parameters were also set in order to reflect conditions of peak ebb tide. Unlike the discharge parameters, which were produced from direct measurements, some assumptions were made in order to produce the ambient parameters.

The ambient current speed was taken from current data provided by the National Oceanographic and Atmospheric Association. Current data were only available for two

locations within Tampa Bay: Old Port Tampa and the Sunshine Skyway Bridge. For both locations, peak ebb tide was consistently around 2 knots (NOAA, 2011). For this reason, 2 knots (1.0 m/s) was used as the ambient current velocity at the outfall location for the purposes of this analysis.

The ambient direction of the current was estimated using trigonometry from the technical drawings of the outfall. Using this method, and assuming ebb tidal flow, the current direction was estimated to be approximately 155° measured relative to north. Ambient salinity was assumed to be that of open seawater; therefore, ambient salinity at the outfall was assumed to be 35 psu. Ambient temperature was assumed to be 70 °F. While this property was measured by the Lowrance® LMS-520C fishfinder when outfall CO_2 concentrations were measured, it varied within the immediate area between approximately 68 °F – 71 °F and the model requires a constant temperature be input.

A rather unique value used by the model and described by the provided manual as the "dispersion coefficient" was defined as 0.0003 $m^{2/3}/s^2$ as this was the recommended conservative value provided in the manual for the model. However, a more appropriate description for this term would be a "correction factor" or "proportionality constant." This value is used by the model in the Brooks Farfield Diffusion Algorithm to estimate dilution within the plume once that plume has achieved maximum plume rise, that is the centerline trajectory has leveled off and remains constant; this portion of the discharge plume is referred to as the farfield plume (Baumgartner, Frick, & Roberts, 1994). This algorithm, taken from the 3rd Edition of the Visual Plumes manual, is defined as:

$$S = \frac{S_a}{erf\left(\sqrt{\frac{d^2}{16\beta d^{4/3} t}}\right)} \qquad 2.2.1$$

For Equation 2.2.1, S is the centerline dilution of the farfield plume, S_a is the initial dilution that occurs at maximum plume rise, *erf* is the error reducing function, β is the "proportionality constant," b diameter of the plume, and t is the time of travel from initial dilution to the point of interest. It should be worth noting that, for each scenario in this analysis, the plume rose to the surface before maximum plume rise could be achieved. Therefore, Equation 2.2.1 was not invoked by the model.

Lastly, the background CO_2 concentration within Tampa Bay at the outfall location was estimated in the same manner as described in the Introduction using the atmospheric concentration of CO_2 and the appropriate Henry's constant. From this, a theoretical concentration of 0.6 mg/L was estimated. Finally, as it was assumed that the dissolved CO_2 was non-reactive and ignoring removal processes such as interphase mass transfer and biological processes, it was assumed that all pollutant mass was completely conserved; therefore the decay coefficient was taken to be 0.0 s^{-1}. Once the individual scenarios were run, the data was analyzed using Microsoft Excel 2007 in order to facilitate a graphical comparison between the model runs.

3 Results

Five separate cases of the UM3 model were run to reflect each instance of data collection at the wastewater treatment facility. For all five cases, the only modeling parameters which were changed were the discharge conditions. Ambient conditions were held constant as the manual provided for the model was not clear on how to create the necessary time series files to allow for changing conditions with time and the provided contact information for the model developers was out of date. These included ambient temperature, current velocity, conductivity, and background contaminant concentration. Speciation was ignored for the purposes of this study. To reflect this assumption, the pollutant decay rate was set to be zero. The ambient direction was chosen to reflect the channel into which the plant was discharging its treated effluent.

A graphical analysis was made to compare any similarities that may exist among the modeling runs. This was done for the centerline discharge plume rise, discharge plume width, average discharge plume CO_2 concentration, and the predicted path of the plume after discharge. For a more detailed examination of the results from each individual model run, please refer to Appendix B.

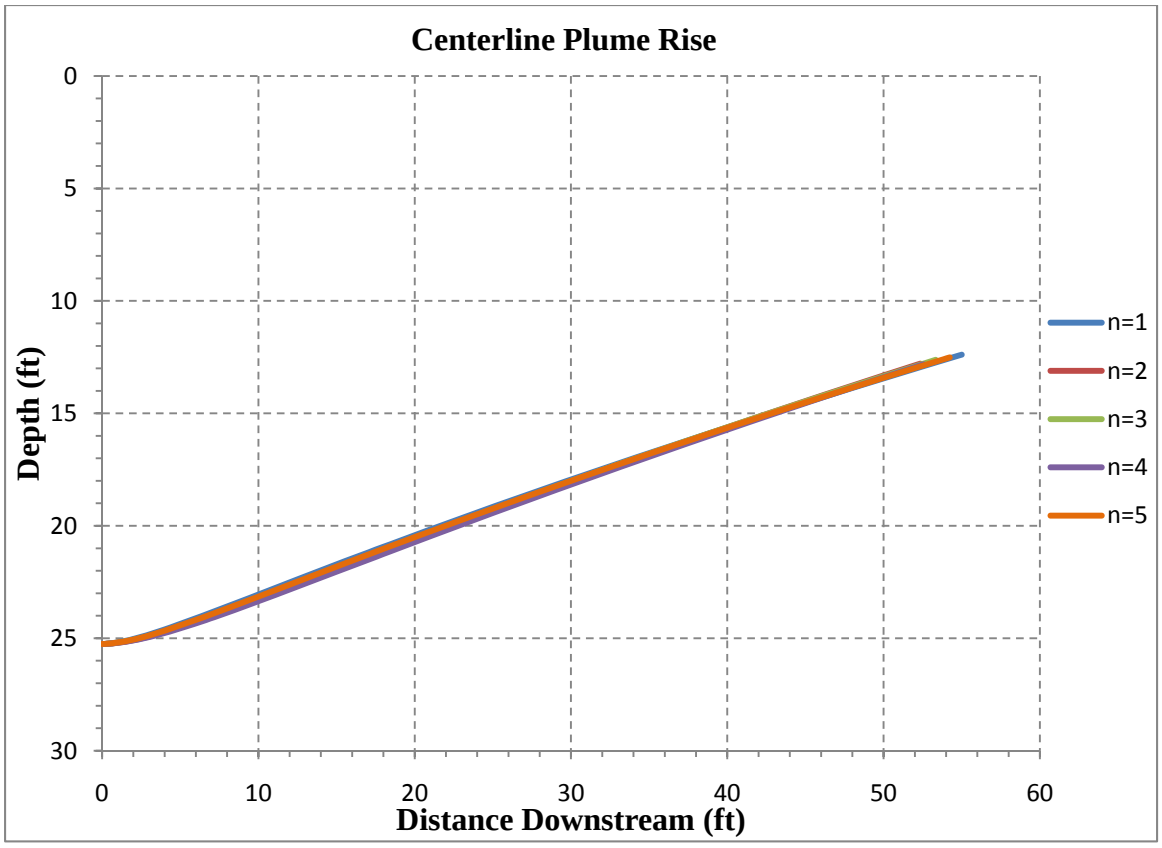

Figure 2: Centerline plume rise. This shows consistent predictions among the modeling runs for the depth of the discharge plume centerline.

Figure 1 indicates the change in centerline rises of the discharge plume as it moves downstream from the outfall. It predicts that the centerline of the plume will rise relatively quickly, at a rate of approximately 4 vertical inches per foot traveled. All five model runs were very consistent in not only this prediction, but the final depth reached by the centerline before the edge of the plume reached the surface, ending the simulation. The model indicates that the centerline of the discharge plume will reach a minimum depth of 12.4 ft for run n_1 and a maximum depth of 12.8 ft for run n_4. This was to be expected as neither the temperature nor the conductivity, which both influence the density of the discharge fluid, did not vary much from one run to the next.

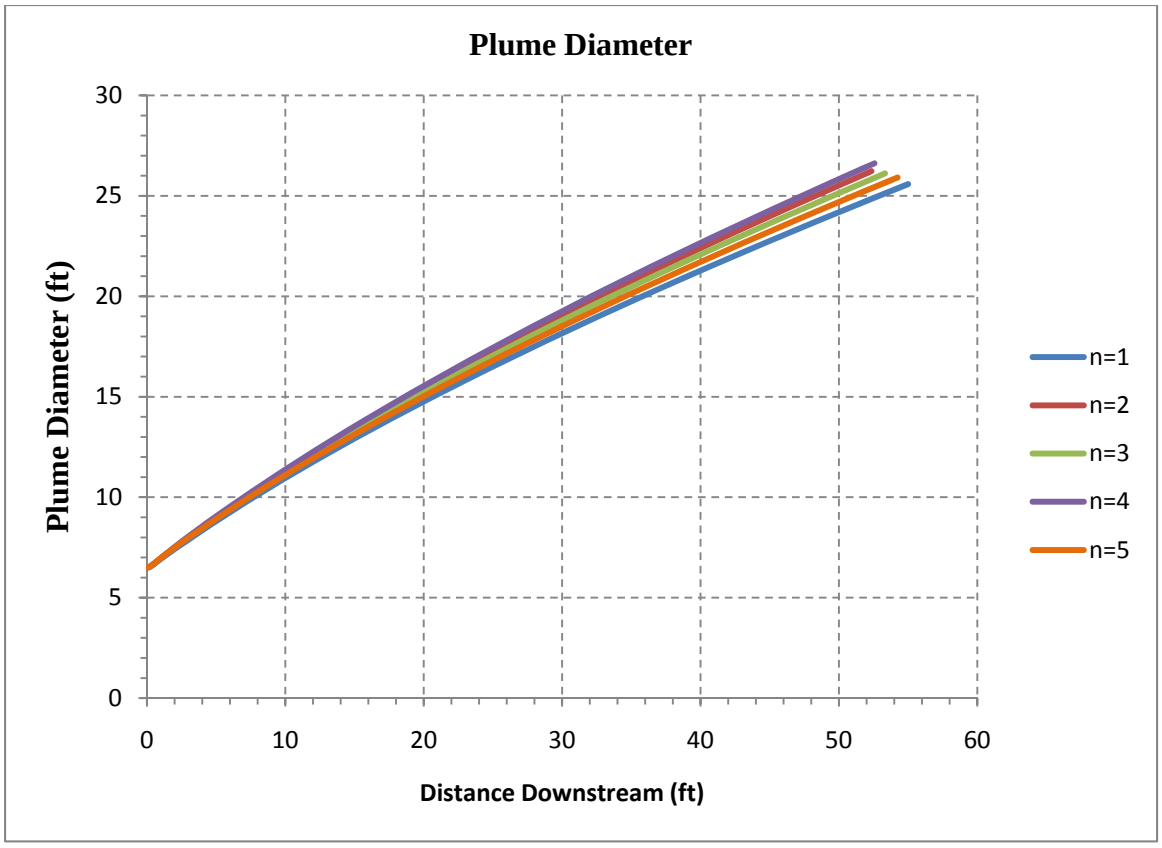

Figure 3: Plume diameter. Changing plume diameter with distance downstream from the outfall location.

The rate of plume spreading can be seen in Figure 2. Again, all five runs of the model predicted a consistent spread in terms of, not only the rate of spreading, but the final plume diameter once the plume reached the surface. The UM3 model predicts that the discharge plume will achieve a maximum diameter of approximately 25 – 26 ft by the time it breaks the surface. Run n_1 indicated a final diameter of 25.6 ft with run n_4 predicting a final diameter of 26.6 ft. This is consistent with effluent flow rates for the runs. Run n_1 had a discharge flow rate of 53 MGD whereas run n_4 discharged at a reported rate of 68.88 MGD. This indicates that the effluent fluid velocity plays a large role in the dispersion rate.

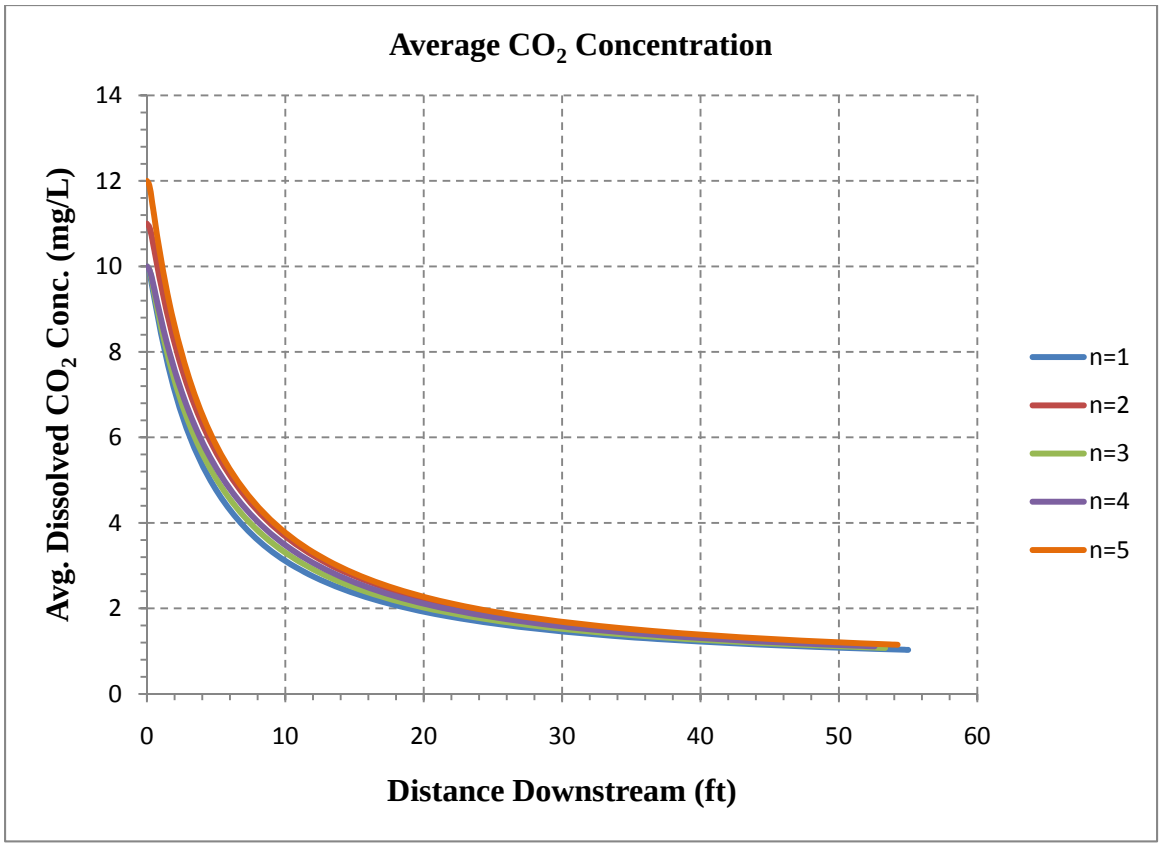

Figure 4: Average CO_2 concentration. Average plume concentration for each modeling run.

Changes in the average plume concentration are indicated in Figure 3. Regardless of the initial effluent concentration of dissolved carbon dioxide, the model appears to predict a constant dilution rate as the plume moves downstream. Additionally, Figure 3 indicates convergence of the final concentration around 50 ft downstream from the outfall location which indicates consistent entrainment for the particular scenario modeled in this study. The maximum final concentration predicted by UM3 was 1.151 mg/L with a minimum final concentration of 1.031 mg/L. Both predicted concentrations were reached within 55 ft of the outfall location. This would seem to indicate that, regardless of the discharge conditions (assuming standard operating conditions for the treatment plant), the

concentration of dissolved CO_2 within the discharge plume will be diluted at a fairly steady rate.

The actual concentration of dissolved CO_2 at the outfall location, however, was measured to be between 1 – 2 mg/L which indicates that the discharge plume is being diluted to just above the theoretical ambient concentration of 0.6 mg/L almost immediately, virtually eliminating any chance of a downstream plume of dissolved CO_2 being present. This concentration was measured directly over the outfall location. However, due to vigorous upwelling from the discharge port, this concentration was only measured at the surface as it was impossible to get the dissolved CO_2 below the surface without risking serious damage to the equipment. It should also be noted that Figure 4 indicates the average CO_2 concentration across the diameter of the plume. For a more detailed graphical representation of the predicted dilution within the discharge plume, including both average dilution and centerline dilution, please see Appendix B.

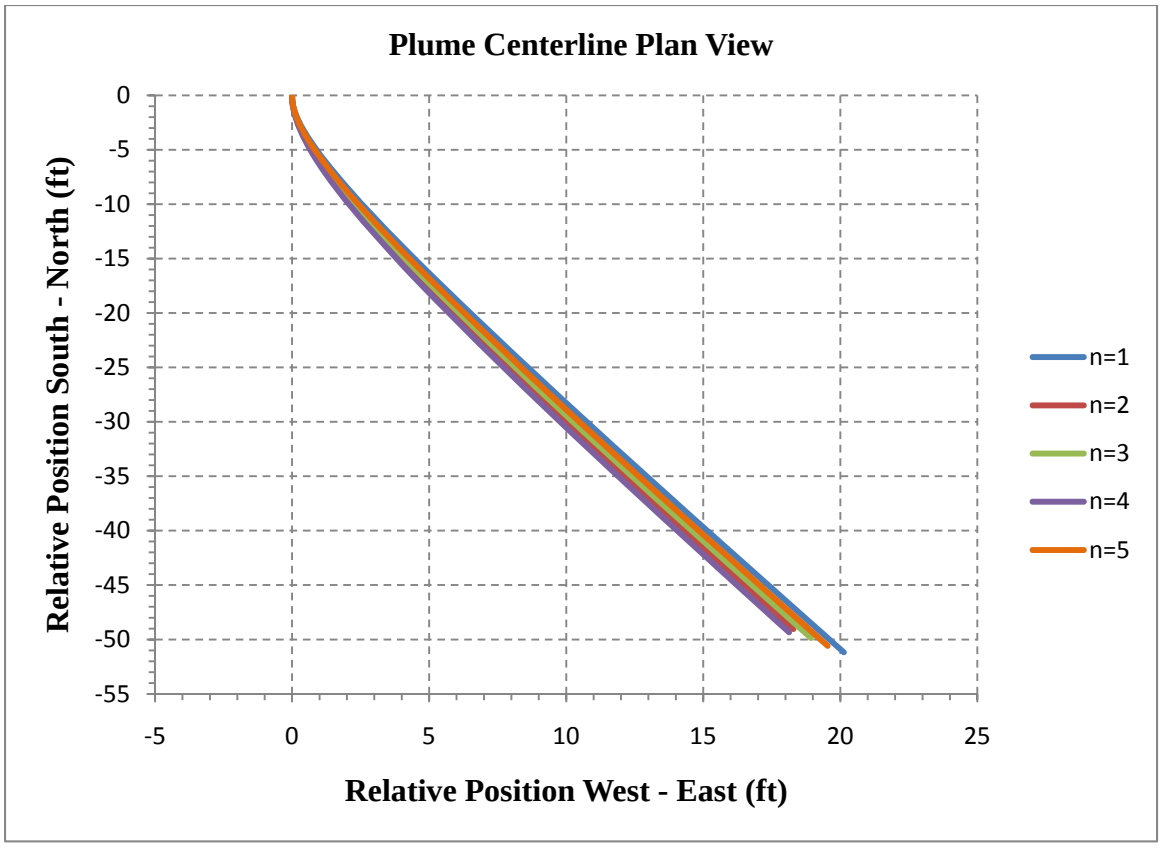

Figure 5: Plume centerline trajectory. Predictions for the plume path as viewed from above relative to the discharge point.

As with the other plume properties examined, Figure 5 also indicates consistency among the model runs for the predicted path of the discharge plume as it leaves the outfall location. There is little variation in not only the path traveled by the plume, but the final point reached before the edge of the plume reaches the surface. Run n_1 predicted a final position of only 20 ft east and 51 ft south of the outfall, which was the furthest distance predicted among the five runs of the model. Runs n_2 and n_4 both predicted the shortest distance traveled before reaching the surface with a final position of 18 ft east and 49 ft south, relative to the discharge point. As with the spreading rate of

the plume, the effluent velocity appears to play a dominant role in how quickly the plume travels downstream.

4 Discussion

4.1 Conclusion

Based on the data generated by each of the five runs of the UM3 model, it appears that there is no significant discharge plume of dissolved CO_2 resulting from treatment operations at the Howard F. Curren Advanced Wastewater Treatment Plant. This could be the result of several factors. When measurements of the concentration of dissolved CO_2 were taken at the outfall location, it was observed that mixing conditions at the outfall were extremely turbulent. This turbulence, combined with the high Henry's constant for CO_2, are likely to be the dominant factors behind the rapid dilution of the discharge stream.

Another major contributor to the rapid dilution of the discharge plume is the volume of water contained in Tampa Bay relative to the volume of treated wastewater being released by the treatment facility. According to the Florida Department of Environmental Protection, Tampa Bay contains 400 square miles of open water with an average depth of about 12 ft (Florida, 2011). This translates to a volume of approximately 3.8 billion cubic meters. Of the five samples collected at Howard F. Curren Treatment Plant, the highest flow rate reported was 68.88 MGD, with a maximum capacity of 96 MGD. The highest flow rate reported, assuming the flow remained constant over a 24 hr period, would only result in approximately 260×10^3 m^3 of treated water being released per day. If the plant were to operate at its capacity of 96 MGD, it

would release $360x10^3$ m^3 of treated waste per day. These are negligible when compared to the volume of Tampa Bay.

4.2 Model Limitations

Due to the severely limited nature of the data generated by the UM3 model, it is very difficult to say with any certainty how accurately the results reflect the actual conditions. While there does not appear to be a plume of elevated concentration of dissolved CO_2 being discharged by Howard F. Curren according to the model predictions, once some of the limitations addressed below are accounted for, it could very well be shown that a significant discharge plume is present.

The UM3 model has several major limitations, as they pertain to this study, which may affect the accuracy of its predictions. In order to account for these limitations, several assumptions and simplifications had to be made. The result of these assumptions and simplifications was a very conservative prediction of dissolved CO_2 concentrations within the plume made by the model. The first is that the model was designed to model more common pollutants such as TCE, petroleum, metals, or other similar pollutants. This means that the model may not be able to accurately account for chemical processes such as speciation which would result in a more rapid dilution than was predicted. The model also does not readily consider aerobic respiration as an ambient source or sink. While this process is likely negligible for large bodies of receiving water, it can potentially be significant for smaller bodies of receiving water or for receiving waters with a relatively high biomass. As the UM3 model only allows for the input of a single 1^{st}-order decay coefficient. An overall rate constant that accounts for all source and sink

processes would have to be estimated by the user in order for the model to provide a more accurate description. This proved to be beyond the scope of this particular study.

A major limitation which was discovered in running this modeling analysis was the fact that the model simulation terminates once the edge of the plume reaches the surface. For this particular study, this was not a factor as the dilution of the plume was fairly rapid. However, this has the potential of being a major flaw in the event that the discharge conditions of a different wastewater treatment facility results in a significant discharge plume of dissolved CO_2. If the plume is predicted to reach the surface relatively quickly, as was the case in this study, yet is still predicted to contain high levels of contamination in the form of dissolved CO_2, this limitation severely restricts the ability to examine the possible effects of the contamination further downstream.

The third major limitation of the UM3 model is that it does not provide a prediction of the concentration profile across the plume's cross-section. Rather, it only provides a prediction of the centerline concentration and the average cross-sectional concentration. This may very well be the model's greatest weakness as it severely limits the amount of detail provided in the results in terms of pollutant concentration within the plume. This particular limitation proved to be the most restrictive in being able to determine whether or not a significant plume of elevated dissolve CO_2 concentration was present. An attempt was made to generate these concentration profiles analytically, but this too proved to be beyond the scope of this study.

Another limitation results in the UM3 model's inability to account for turbulent mixing conditions at the outfall. This will rapidly increase the dilution effect, shortening the downstream length of the discharge plume. Finally, for this study, the UM3 model

was run under steady-state conditions. While the model appears to have a limited capability to allow for changing conditions with time, the manual provided with the modeling software was vague in describing how to do this. Also, attempts to contact the model developers in order to clarify these instructions were unsuccessful due to outdated contact information provided in the manual.

4.3 Possible Future Studies

If a similar modeling analysis is to be done in the future, either at this treatment plant or a different plant, it will be necessary to first make several significant modifications. The most important modification would be the development of a model which addresses the limitations discussed in the previous section. The use of a more dynamic model would be especially important for modeling the discharge conditions found at Howard F. Curren due to the fact that the treatment plant discharges its treated effluent directly into Tampa Bay. This is due to the changes in ambient current speed and direction which regularly result from tidal actions.

Additionally, it may be necessary in this case to account for the presence of an ambient salinity gradient associated with changing tides. As this study attempted to address the significance of dissolved CO_2 as a possible point-source pollutant, it would also be imperative to address the inherent difficulties associated with modeling a dissolved gas as a pollutant. This could be done by modifying an already existing dissolved oxygen model.

Finally, in order to facilitate the development of such a model for future analysis, it is recommended that it first be applied to a less complex system, such as a discharge into a river or stream, before being applied to a more complex system such as an estuary

or marine system. This will likely simplify the development process as there will be fewer variables to consider.

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Appendices

Appendix A: List of Terms

Table A.1: Detailed list of equation terms. This is a detailed description of all terms used by the UM3 model.

Term	Description	Units
m	The mass of water contained within a given cross-sectional plume slice; scalar quantity.	Mass
ρ	The fluid density of either the ambient fluid or the fluid within a given cross-sectional plume slice; scalar quantity.	Mass/Length^3
A_p	The surface area of each face of a given cross-sectional plume slice; scalar quantity.	Length^2
$\vec{U}$	Relative velocity of ambient fluid; vector quantity unless placed between vertical bars.	Length/Time
α	Entrainment function; scalar quantity.	Unitless
A_T	Surface area of a given cross-sectional plume slice normal to the ambient fluid; scalar quantity.	Length^2
$\vec{v}$	Velocity of the fluid within a given cross-sectional plume slice; vector quantity unless placed between vertical bars.	Length/Time
$\vec{g}$	Gravitational acceleration; vector quantity.	Length/Time^2
C_p	Specific heat capacity; scalar quantity.	Mass*Length^2/Time^2*Temp.
T	Fluid temperature; scalar quantity.	Temperature
C	Mass concentration of dissolved CO_2; scalar quantity.	Mass of CO_2/Mass of H_2O
κ	First-order reaction coefficient; scalar quantity.	Time^{-1}

Appendix A (continued)

Table A.1 (continued)

Term	Description	Units
b	The radius of a given cross-sectional plume slice; scalar quantity.	Length
h	The thickness of a given cross-sectional plume slice; scalar quantity.	Length
V	The volume of a given cross-sectional plume slice; scalar quantity.	Length^3

Appendix B: Detailed Modeling Results by Scenario

B.1 Case 1

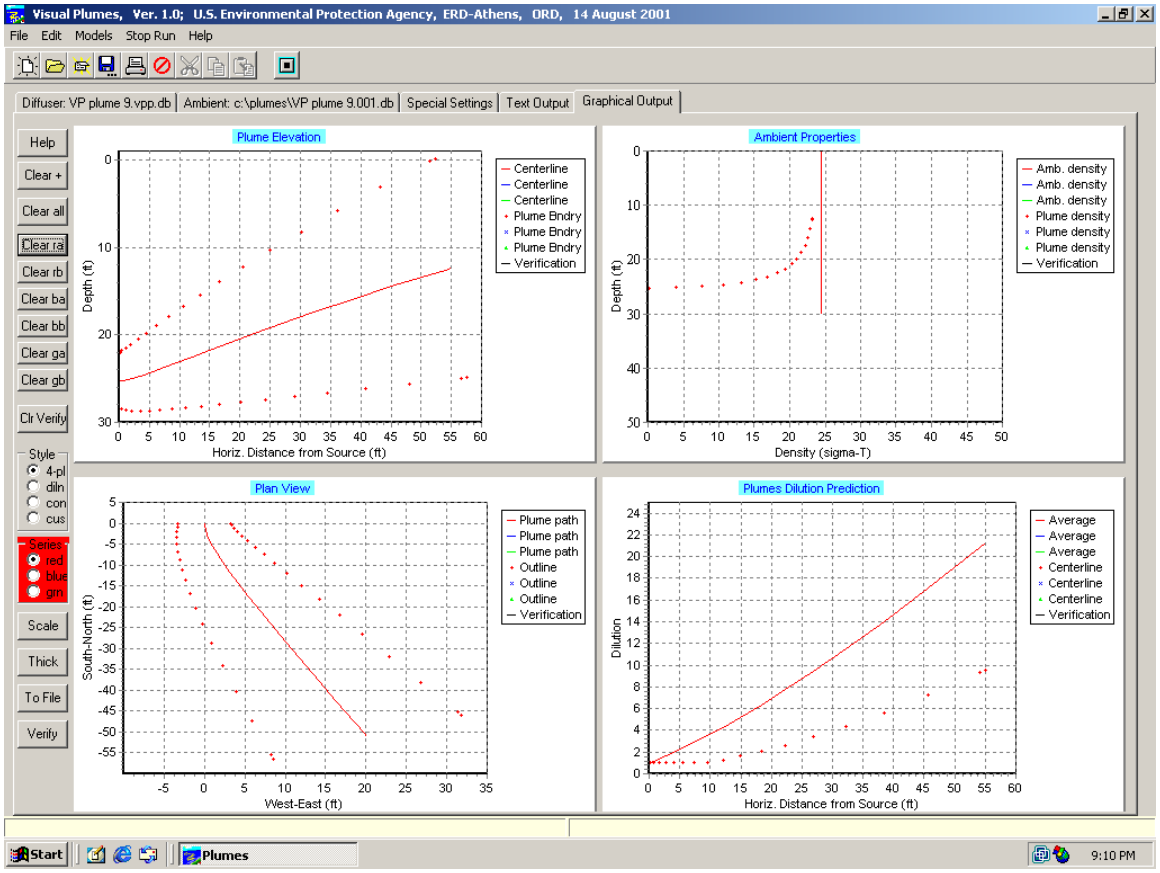

Figure B.1: Modeling scenario 1 results. Detailed graphical results for modeling scenario 1.

Appendix B (continued)

B.2 Case 2

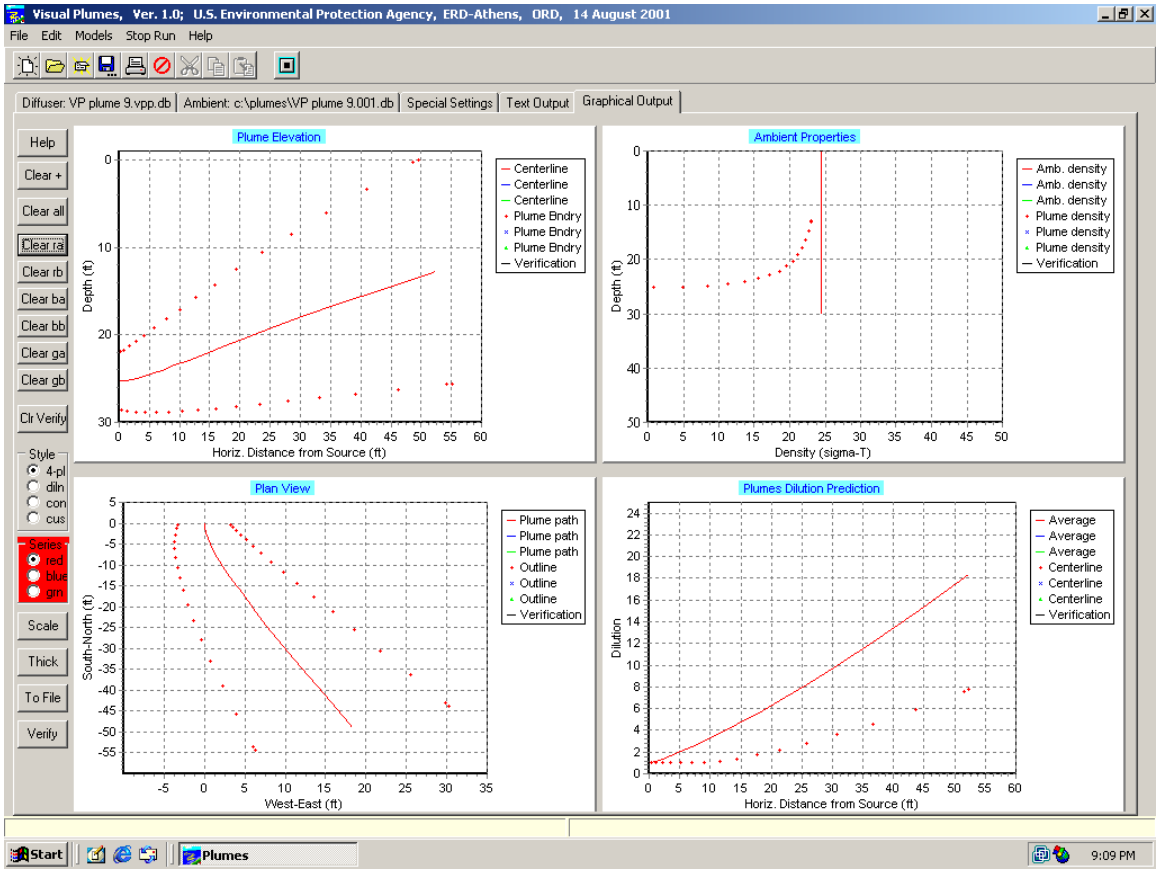

Figure B.2: Modeling scenario 2 results. Detailed graphical results for modeling scenario 2.

Appendix B (continued)

B.3 Case 3

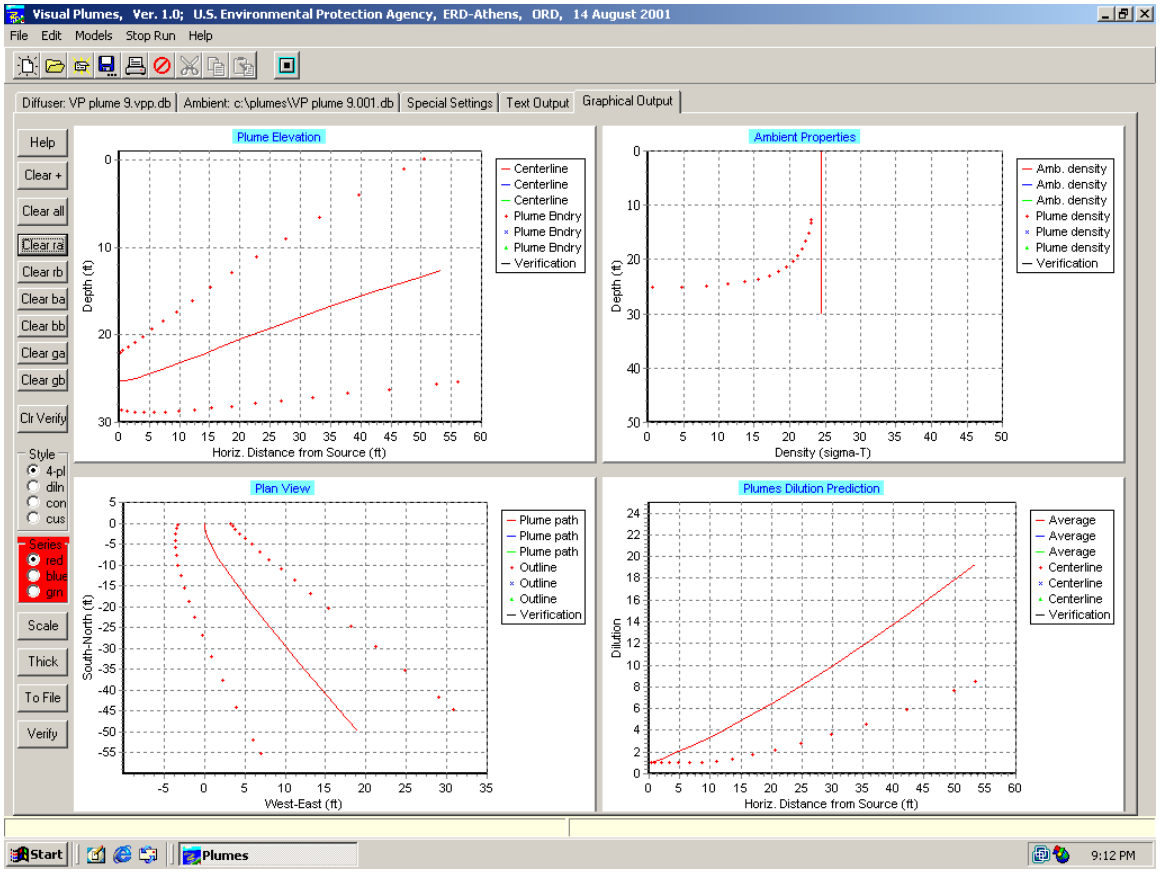

Figure B.3: Modeling scenario 3 results. Detailed graphical results for modeling scenario 3.

Appendix B (continued)

B.4 Case 4

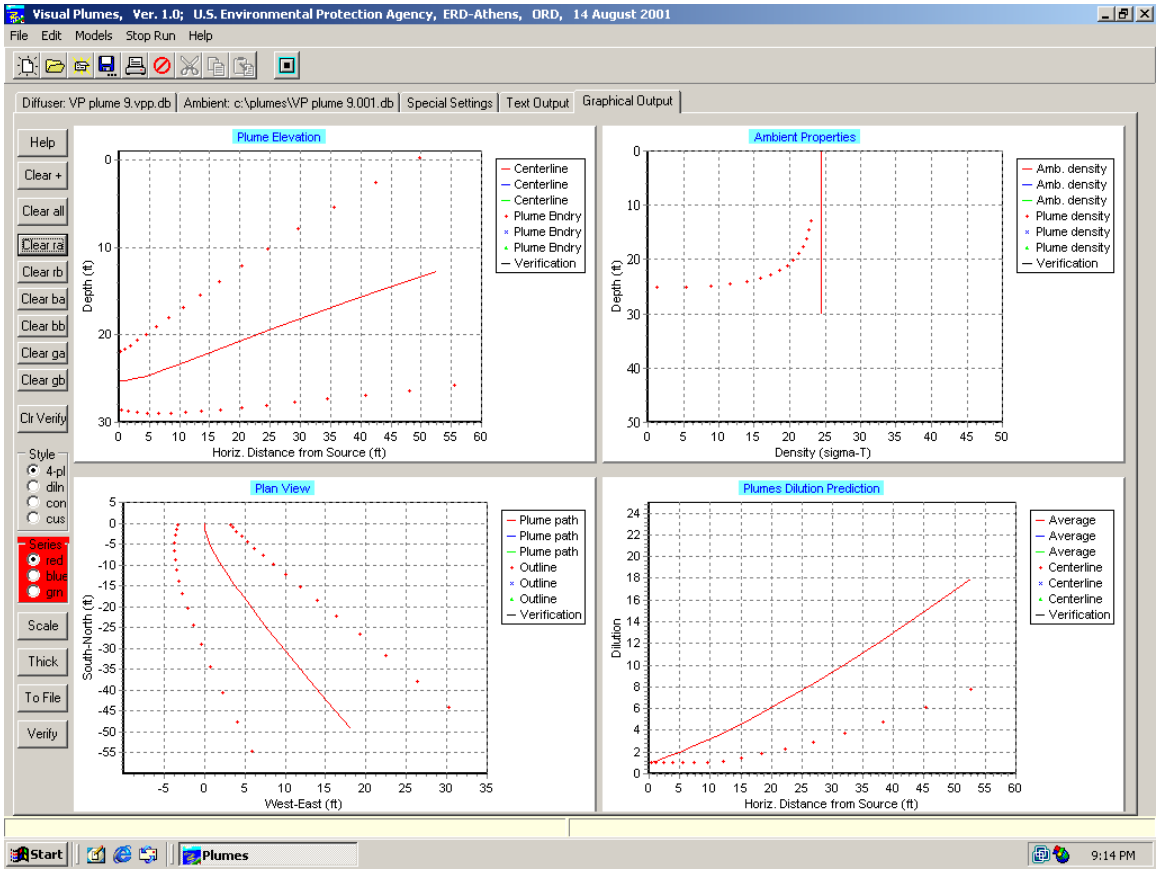

Figure B.4: Modeling scenario 4 results. Detailed graphical results for modeling scenario 4.

Appendix B (continued)

B.5 Case 5

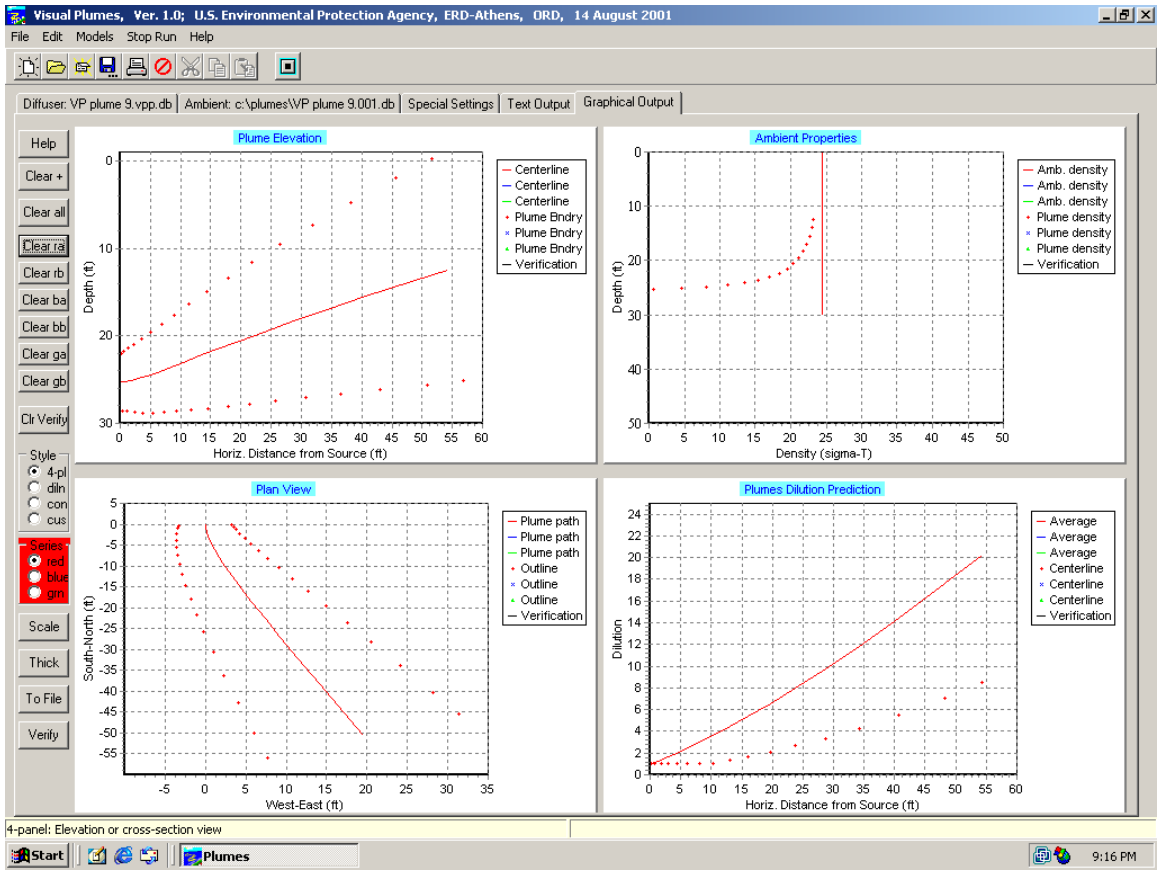

Figure B.5: Modeling scenario 5 results. Detailed graphical results for modeling scenario 5.

About the Author

Dustin Capps was born in Charleston, South Carolina in 1983 before moving to Woodbridge, Virginia, in the Washington, DC metro area in 1990. While living in Woodbridge, Dustin was very active in both soccer and Boy Scouts and developed an early passion for science and the environment. After graduating from Gar-Field Senior High School in 2001, he went on to Coastal Carolina University where he earned his BS in Marine Science and Biology, as well as a minor in chemistry. It was while at Coastal Carolina that he gained some early research experience by participating in shark population studies. Upon graduating in 2006, Dustin moved back to Woodbridge and took a two year hiatus from school. In the fall of 2008, he began his studies at the University of South Florida. After completion of his masters degree, he plans to move out west to be with his fiancée, Kristen Green, in San Diego, California.