RECOVERY TIME ANALYSIS IN LAKE PONTCHARTRAIN AFTER HURRICANE KATRINA

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Abstract. After Hurricane Katrina hit the Gulf of Mexico in August 2005, floodwaters covering New Orleans were pumped into Lake Pontchartrain as part of rehabilitation process to make the city habitable again. The long term consequences of this environmentally critical decision were left to observation. This paper examines the likely response of Lake Pontchartrain to the load of contaminants that were possibly in the flood waters via modeling several hypothetical scenarios. As a preliminary outcome, this study provides a useful tool to assess the possible extent of damage inflicted on the natural water resources of Southern Louisiana or similar environments elsewhere. An unsteady state fugacity model is developed in order to examine the environmental effects of contaminants on surface water bodies which have different physicochemical characteristics. Since the available data on the event is limited, uncertainty analysis is necessary. Thus, as a secondary outcome, the study further investigates the effects of the uncertainty in the parameters used in the model on the outcome using Monte Carlo analysis. The results indicate that Lake Pontchartrain, which was recovering from earlier assaults on its water quality, will continue for a long while on its path to recovery. Application of the derived model to three contaminants shows that the recovery time of the lake for the contaminant levels to go back down to MCL (maximum contaminant levels) values range between about a year and sixty eight years for the three contaminants considered in this study.

INTRODUCTION

City of New Orleans was flooded and large sections of the city were declared inhabitable following Hurricane Katrina. The first and immediate attempt to make the city habitable again was to drain the floodwaters and assess the structural and environmental damage in the city. Even though draining the flood waters into Lake Pontchartrain seemed to be an effective solution at the time, the long term pollution effects of this process were not examined thoroughly as the water being drained into the lake contained various potentially hazardous contaminants. Since industrial complexes as well as chemical warehouses were flooded, it is most probable that hazardous chemicals were leaked into the floodwaters. In the news media there were reports of fish literally jumping out of water at or nearby discharge points. At the time, it was assumed that dilution and other natural processes in the lake would be effective in cleaning up these contaminants. In this study, we have examined the extent of the effect of these natural processes on the persistence of hypothetical loads of three potentially harmful constituents in the floodwaters. Our aim is to provide preliminary answers to the long term effects of the environmental decisions made at the time.

We have selected three chemicals, each with different physicochemical properties to answer the above question. Benzene is the first chemical of interest as it is a constituent of gasoline which was observed as abundant in the floodwaters since gasoline leakage has occurred during the flooding of New Orleans. In our case benzene is a representative of volatile compounds. The second chemical is atrazine. Atrazine is the most commonly used agricultural herbicide. This is another possible candidate to be found in floodwaters since warehouses that stored agricultural products were also inundated by flood waters. Atrazine is also a good representative of more water soluble chemicals which might potentially be in the flood waters. The third chemical that was selected is polychlorinated biphenyl (PCB). In spite of being banned in 1970s, PCBs are still abundant in nature. They are highly toxic and highly hydrophobic. PCBs are selected to represent group of hydrophobic contaminants. All three chemicals selected are potentially harmful to human health as well as biota in the lake.

All chemicals behave differently in the nature; they partition into different pathways when introduced into a surface water system such as a lake. Some of the contaminants volatilize, some of them adsorb to solid materials and some of them stay in aqueous phase. In any attempt to determine the fate of these chemicals in surface water environments, existence of sediment, suspended particles, and air phase must also be considered. This paper addresses the existence of three different phases through the application of fugacity analysis to Lake Pontchartrain. Using fugacity analysis, a chemical equilibrium between phases can be established and partitioning among different compartments can be predicted. With the fugacity approach, it is easier to follow a chemical as it passes from one phase to another since fugacity is continuous between phases whereas concentration is discontinuous (Mackay, 2001; Stumm and Morgan, 2000).

We do not have site specific information on pollutant levels in flood waters right after Hurricane Katrina. Extensive data collection, which is necessary to evaluate the consequences of pumping flood waters into Lake Pontchartrain, was not done due to the requirement of immediate emergency response decisions at the time. This study may provide one alternative approach to conduct this analysis. Nevertheless, lack of data would introduce significant uncertainties to the outcome. Thus, to evaluate the uncertainty effects we also introduced Monte Carlo analysis option to our model. For this purpose, instead of using single deterministic values, probability distributions for mass transfer coefficients, decay rate coefficients, and most importantly source rate are used in this study. Consequently, the recovery time of the lake becomes a probability density outcome instead of a single value outcome. This way, we may have a better understanding of what to expect regarding the pollution levels in Lake Pontchartrain as well as the recovery time of the lake when exposed to these chemical loads. In the uncertainty analysis, we have selected a subset of all the uncertain parameters used in the study following a sensitivity analysis of all parameters that characterize the model.

METHOD

All chemicals behave differently in the nature; they partition into different pathways when introduced into a surface water system such as a lake. Fugacity, F is the escaping tendency of a chemical from a medium. Fugacity has the units of pressure and it is equal to the partial pressure in ideal gases, it is logarithmically related to chemical potential, and thus linearly related to concentration.

In this study, lake has three compartments, water, air, and sediment. Each compartment is assumed to be well-mixed.

$$\begin{aligned} V_w Z_{bw}\frac{dF_W}{dt} &= S + (K_{aw}A_w Z_w + Q_{dry}Z_{aerosol} + \\ &Q_{wet}Z_{aerosol})F_A + (Q_{res}Z_s + K_{sw}A_s Z_w)F_S \\ &-(k_w V_w Z_w + Q_{dep}Z_p + Q_{out}Z_{bw} + K_{aw}A_w Z_w)F_W \end{aligned} \tag{1}$$

$$\begin{aligned} V_a Z_{aw}\frac{dF_A}{dt} &= (K_{aw}A_w Z_w)F_W - (Q_{dry}Z_{aerosol} + k_a V_a Z_a \\ &+Q_{wet}Z_{aerosol} + Q_{air}Z_{ba} + K_{aw}A_w Z_w)F_A \end{aligned} \tag{2}$$

$$\begin{aligned} V_s Z_{bs}\frac{dF_S}{dt} &= (Q_{dep}Z_p + K_{sw}A_s Z_w)F_W - \\ &(k_s V_s Z_s + Q_{res}Z_s + K_{sw}A_s Z_w + Q_{bury}Z_s)F_S \end{aligned} \tag{3}$$

in which F_W is the fugacity of the water compartment, F_A is the fugacity of the air compartment, and F_S is the fugacity of the sediment compartment. S is the source rate of contaminant in the water phase. V_w, V_a, and V_s represent the volumes of water, air, and sediment compartments, respectively. Similarly, A_w and A_s represent the surface areas of water and sediment. Q_{dry} is dry deposition rate from air, Q_{wet} is the rate of wet deposition from air, Q_{res} is the resuspension rate of sediments, Q_{dep} is the deposition rate of suspended particles in the water column, Q_{air} is the wind induced air flowrate on the lake, Q_{out} is the rate of water flowing out of the lake, and Q_{bury} is the burial rate of bottom sediments. Z_w is the fugacity capacity of water, Z_a is the fugacity capacity of air, Z_s is the fugacity capacity of sediments, Z_p is the fugacity capacity of water particles (suspended solids), $Z_{aerosol}$ is the fugacity capacity of aerosols (particulate matter in air), Z_{bw} is the bulk water fugacity capacity, Z_{ba} is the bulk air fugacity capacity, and Z_{bs} is the bulk sediment fugacity capacity. K_{aw} is the mass transfer coefficient between air and water whereas K_{sw} is the mass transfer coefficient between sediments and water. k_w, k_a, and k_s are the first order decay rate constants in water, air and sediment compartments, respectively. The processes considered are shown in Figure 1.

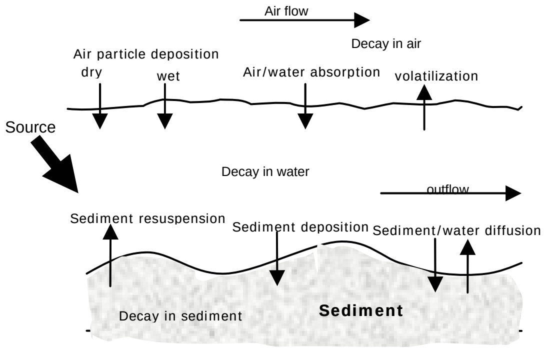

Figure 1. Schematic View of the Natural Processes Considered in the Fugacity Model

Table 1. Physicochemical Characteristics of Selected Contaminants

Parameter	**C_6H_6 - Benzene**	**$C_8H_{14}ClN_5$ - Atrazine**	**Total PCBs**
Molecular Weight (g/mol)	78.11	215.75	326
Log Kow	2.13	2.75	6.66
Henry's Law Constant (atm. m^3/mol	5.55×10^{-3}	2.88×10^{-4}	2.9×10^{-5}
Z_{water} (mol/m^3.Pa)	1.78×10^{-3}	3480	0.0818
Z_{air} (mol/m^3.Pa)	4.04×10^{-4}	4.04×10^{-4}	4.04×10^{-4}
$Z_{sediment}$ (mol/m^3.Pa)	1.41×10^{-2}	77000	11500
$Z_{bulk\ water}$ (mol/m^3.Pa)	1.8×10^{-3}	3480	0.0951
$Z_{bulk\ air}$ (mol/m^3.Pa)	4.04×10^{-4}	1.62×10^{-3}	4.58×10^{-4}
$Z_{bulk\ sediment}$ (mol/m^3.Pa)	2.96×10^{-3}	14500	1730
Half life in water	1700 hrs	17000 hrs	139000 hrs
Half life in air	170 hrs	5 hrs	693 hrs
Half life in sediment	17000 hrs	1700 hrs	347000 hrs

These three equations are solved with finite difference method. For the time derivative, forward difference is used and for fugacity terms, time average value is used. After implementing finite difference approach, we have three linear equations with three unknowns. They are, then, written and solved in a matrix form, with LU decomposition.

The amount of floodwaters pumped into Lake Pontchartrain is about 10% of the lake volume, and the draining of floodwaters took about one week. The loading into the lake is calculated using this information. 10% of the lake volume in one week corresponds to a pumping rate of 3.5×10^6 m^3/h. Using this pumping rate, a source rate term is estimated, which becomes the key input to the model.There are no measurements prior to the pumping of floodwaters into Lake Pontchartrain. Any kind of source rate calculation would be uncertain. To reflect the uncertainty in the source rate, a uniform distribution is assigned to the source rate term. A source rate of 0.01% (by volume) of the inflow floodwaters is used as the lower limit and a source rate of 1% (by volume) of the floodwaters is used as the upper limit of the distribution. Any source rate between these values is given an equal probability of occurrence.

The time to recover from the contaminant load is calculated as the time to reach allowable concentrations given in Environmental Protection Agency's (EPA) 2004 Edition of the Drinking Water Standards and Health Advisories (EPA, 2004).The standards or regulated values for the aforementioned chemicals are 0.005 mg/L for benzene, 0.003 mg/L for atrazine, and 0.0005 mg/L for total PCBs.

Also needed are transport and transformation parameters such as deposition, resuspension, water outflow, and wind-induced air flow rate. The water outflow value is the total water output via tributaries from the system. This value is given as 1,565000 m^3/h (USGS, 2002). Rates from another fugacity based lake model are used as guidelines to calculate the deposition and resuspension rates in Lake Pontchartrain (Mackay, 2001). Using these suggested values and surface area of the lake, 816m^3/h of deposition and 1000 m^3/h resuspension rates are selected.

For the air flow calculations, the annual average wind velocity is used (USGS, 2002). An average of 19900 m/h wind is expected above Lake Pontchartrain in the predominant SE-NW direction. The volumetric air flow rate is calculated using the cross-sectional area of the air compartment in SW-NE direction. The thickness of air compartment is taken to be 50 cm in this study as the mixing zone. The air flow rate is calculated to be 3.2×10^7 m^3/h.

A sensitivity analysis of the values representing the transport and transformation processes in the lake enabled us to observe what parameters have the most significant effect on the self cleaning capacity of Lake Pontchartrain. As a result of the sensitivity analysis, we concluded that the most sensitive parameters are the source rate, mass transfer coefficients and decay rate constants. Decay rate constants directly affect the persistence of a chemical in the lake system. The faster the decay in a specific phase, quicker the chemical is removed from the system. Mass transfer coefficients are also very important in the recovery time of the system. If the chemical passes to sediments faster, it stays longer in the system. On the other hand, if it passes to the air phase faster it is removed from the system more rapidly due to wind induced advection. Monte Carlo Simulation was applied to all the sensitive parameters. As mentioned before source rate is sampled from a uniform distribution. In the literature, mass transfer coefficients and decay rate constants have been given lognormal distributions (Citra, 2004; MacLeod, Fraser, & Mackay, 2002). Choice of lognormal distribution for many fate and transport model parameters is advantageous as lognormal distribution has a positive state space. The lognormal distribution has two parameters; standard deviation and mean which are related to a corresponding normal distribution.

A total of 10 000 trials are performed for Monte Carlo runs. 10 000 random variables are created for overall air-water mass transfer coefficient, water-sediment mass transfer coefficient, water decay rate constant, air decay rate constant, sediment decay rate constant and source rate. Box-Muller algorithm is used (Gentle, 2003) to generate random values from a lognormal distribution. The values found in chemical handbooks for these parameters are used as means for mass transfer coefficients and decay rate constants. For all the mass transfer coefficients and decay rate constants a standard deviation of 0.5 is used. This value gives a confidence factor of about 2.7 (MacLeod, Fraser, & Mackay, 2002), which implies that about 95% of all random values lie between $1/2.7$ and 2.7 times the median. The inverse of the cumulative density function of a uniform distribution is used to generate random variables for the source rate.

DISCUSSION

For each set of randomly selected group of mass transfer coefficients, decay rate coefficients and source rate, the time to reach MCL values is recorded. This value reflects the duration of time required for Lake Pontchartrain to recover from contaminant load by natural processes. In other words, this value is the self-cleansing time of the lake.

The resulting set of 10 000 time values are represented within three plots. The first plot is the frequency of occurrence of a time value. Then cumulative and complementary cumulative probability plots are shown. The complementary cumulative probability plot can be very useful in interpreting the results. It tells us the probability of exceeding a certain amount of time to recover from a contaminant load.

The results for each contaminant is given in the figures below.

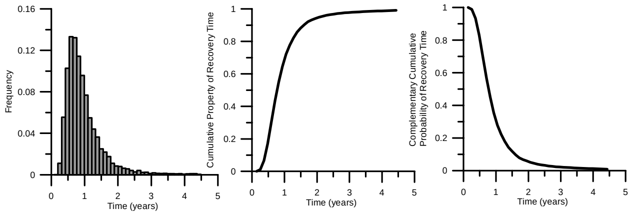

Figure 2. Analysis Results for Recovery of Lake Pontchartrain from Atrazine Load

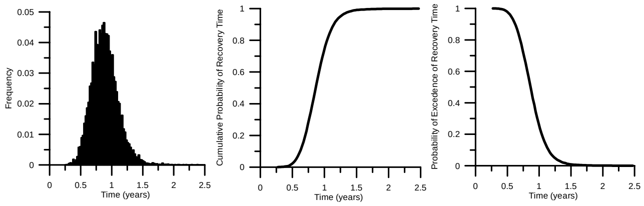

Figure 3. Analysis Results for Recovery of Lake Pontchartrain from Benzene Load

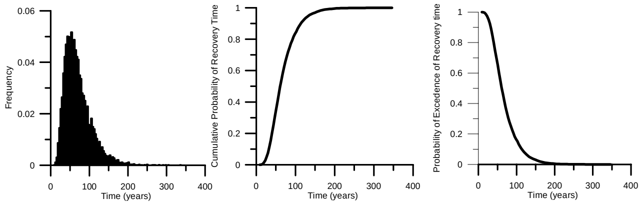

Figure 4. Analysis Results for Recovery of Lake Pontchartrain from PCB Load

Atrazine is the most soluble chemical I water among the three representative contaminants selected for this study. Decay within the relatively larger volume of water compartment and outflow with the tributaries enables the rapid removal of atrazine. Atrazine has an average recovery time of 0.9 years. In the application of second case, source value can take lower of higher values with equal probability. The probability of exceeding one year for self-cleansing has a higher value of 0.3 for this case. The cumulative probability plot shows that atrazine will reach MCL values within three years.

Benzene is the most volatile among the three contaminants. It is rapidly removed from Lake Pontchartrain system. Lake Pontchartrain would recover from benzene loading of magnitude calculated in this study within two years at the latest. Average time of recovery is 0.8 years for benzene as shown in figure 6. The probability that benzene concentrations will still be higher than MCL values after the first year is 0.25.

PCB is the most hydrophobic and expected to stay longest in the system. Figure 4 shows that PCBs indeed are very persistent in nature. the average time of recovery drops to 65 years. However, the probability of recovery in more than 100 years is still high with a value of 0.2

This study is designed to be tool to understand the behavior of Lake Pontchartrain after Hurricane Katrina. The model, developed here, can also be used to study the effect of any contaminant load on any shallow lake system. As expected, if the contaminant is more hydrophobic it will resist longer in the system, while if it is volatile, it will stay shorter. The amount of contaminant load introduced into the system is a crucial parameter determining the time of recovery. In evaluating the terms that are uncertain, use of Monte Carlo Simulation is an effective tool.

The model developed in this study offer a very simple yet effective procedure to assess environmental response in surface water systems. It would make a great tool in designing emergency response scenarios and the potential effects of each scenario on the environment The model is very general, thus it can be used for any chemical compound. The results would be very informative for decision makers who are forced to find solutions in very short time during emergencies.

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