Modeling Brine Discharge Using a Lagrangian Approach

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Abstract
The U.S. Department of Energy (DOE) was tasked by the U.S. Congress to develop new crude oil storage sites in the Gulf of Mexico region to increase the capacity of the Strategic Petroleum Reserve (SPR). One of these proposed sites was located at Richton, MS and was designed to store 25.4 million m^3 of crude oil in underground caverns created within subsurface salt domes. The caverns are formed by controlled pumping of fresh water into the domes to dissolve the salt. The byproduct of this process is a high salinity (~263 psu) brine solution that would be discharged in the Gulf of Mexico. The concerns over discharging this high salinity brine solution included the possible impacts to fish, shellfish and other biota in coastal areas so it was important to develop reliable predictions of the fate of the brine plume.

The solution to the problem of determining the transport and fate of the high salinity discharge was solved using two modeling components, one to predict the currents in the area and a second to predict the transport of the brine as a result of the currents. A three-dimensional baroclinic hydrodynamic model (CH3D) was used to supply currents for the brine discharge modelling. The hydrodynamic model output data were used as input in the second modeling effort, which consisted of two models – a near-field model to predict the local dynamics and initial dilution of the brine plume as it exited the discharge structure, and a far-field Lagrangian model to predict the ultimate dilution as the plume was transported from the site.

The USEPA model UM3 was used to simulate near field dynamics of the discharge. A Lagrangian particle model was used to simulate the far field transport of the brine plume as it moved in response to ambient currents and differences in density between the discharge plume and the surrounding water. Lagrangian particle models do not sufficiently simulate brine discharge transport because the particle model does not account for the force of gravity acting on the density difference between the salty discharge plume and the surrounding ocean. This force can be greater than the force from ambient currents and drives the more dense brine fluid down slope into deeper water. An enhanced flow calculation was added to the Lagrangian model so that the motion of the plume responds to both ocean currents and local density differences.

There was generally good agreement between the far-field model results and observation data from a previously developed site. The modified particle model is an effective tool for predicting the fate of high density discharges with a reasonable modeling effort. This approach also shows that hydrodynamic model applications can be reused for different problems from what they were originally designed.

Keywords
Brine, modeling, Lagrangian, near field, far field, turbidity current

INTRODUCTION

The U.S. Department of Energy (DOE) has been evaluating the development of new storage sites in the Gulf of Mexico region to increase the capacity of the Strategic Petroleum Reserve (SPR) under congressional directive. One of these sites was located at Richton, MS and was designed to store 25.4 million m^3 (Mm^3) of petroleum (crude oil) in underground caverns (DOE, 2006). The caverns are formed by controlled pumping of fresh water into salt domes to dissolve the salt. The byproduct of this process is a high salinity (~263 psu) brine solution that would be discharged in the Gulf of Mexico. Being of higher density than the surrounding Gulf water, the brine remains near the bottom and moves down slope as it dilutes with the ambient water. The dense plume is also transported away by ambient currents and further diluted.

MODELING APPROACH

The solution to the problem of determining the transport fate of high salinity discharges was solved using two modeling components, one to predict the currents in the area and a second to predict the transport of the brine as a result of the currents. Currents were used from a previously applied hydrodynamic model of the area developed by the U.S. Army Corps of Engineers (USACE) (Bunch et al., 2003). The model output data were used as input in the second modeling effort. This effort consisted of two models – a near-field model to predict the local dynamics and initial dilution of the brine plume as it exited the discharge structure, and a far-field model to predict the ultimate dilution as the plume was transported from the site.

Hydrodynamic Model

The three-dimensional (3-D) baroclinic hydrodynamic model (CH3D) used to supply currents for the brine discharge modeling was originally developed by the U.S. Army Corps of Engineers (USACE) for the area surrounding and including Mississippi Sound to support a proposed project to deepen the channels and port area of Pascagoula, MS (Bunch, et al, 2003). The CH3D model was originally developed by Sheng (1986). Bunch et al. (2003) describe the Mississippi Sound model application and the model calibration to field data for the periods February to March 2001 and April through September 1997.

Near Field Discharge Model

A near-field model simulates the movement of the brine plume based on the dynamics of the discharge itself. Output from a near-field model provides an estimate of the evolving dimensions of the brine jet as it exits the diffuser port, rises into the water column, descends back down and encounters the bottom. The near field model also calculates the dilution achieved within the near-field area, typically a few meters to tens of meters from the discharge device. In the near-field the effluent discharged through nozzles or diffuser ports is dominated by both the momentum of the discharge flow and by buoyancy forces resulting from difference in density between the discharge and the surrounding water. The U.S. Environmental Protection Agency (USEPA) model UM3 (Visual Plumes model framework) (Frick et al., 2003) is a near field model based on the UM model described by Baumgartner, et al. (1994).

Far Field Brine Transport Model

The far field model simulates the flow of the discharge plume as it spreads in response to ambient currents and differences in density between the brine plume and surrounding water. A Lagrangian particle model is used in the far field simulation of plume dilution and movement. The model predicts the movement of particles which, in aggregate, represent the plume. However, Lagrangian particle models do not sufficiently simulate brine discharge transport because the particle model does not account for the force of gravity acting on the density difference between the salty discharge plume and the surrounding ocean. This force can be greater than the force of ambient currents and drives the more dense brine fluid down slope into deeper water. For this application an enhanced flow calculation was added so that the motion of the plume responds to both ambient ocean currents and local density differences.

Dynamics of Dense Plumes. The dissolved salt in the brine plume significantly increases the density of the plume relative to ambient ocean water so that the plume cannot be adequately simulated by the advection and diffusion processes alone. The density difference between the discharge and the ambient waters will exert forces on the discharged brine which tend to reduce the potential energy of the system. These baroclinic forces (due to sloping pressure surfaces) reduce the potential energy by lowering the center of mass of the water column. Just as water on land seeks the lowest level, the brine discharge will flow down slope displacing less dense ambient fluid.

The model of dense brine discharge from an oceanic bottom diffuser developed by ASA started from a review of the model literature and analysis from other dense plume studies. Determining which of these was most applicable was a critical step in the analysis. Starting from observations in the early 1980s of a brine discharge similar to that proposed for the Richton site (Hann and Randall, 1982; Randall, 1982), key characteristics of the flow were identified. The brine plume was observed to form a layer on the bottom a few meters thick. The water column remained highly stratified in all the observed profiles. The lateral extent of the plume spread up to 3 km from the discharge site. The direction of the plume reflected the integrated current history at the discharge site.

The bottom slope was identified by a scaling analysis as an important term which drives bottom plumes over long distances. Parker et al., (1986) developed a vertically integrated set of equations for the dynamics of a dense plume in a rotated reference frame relative to the sloping bottom. While the bottom slope at the proposed Richton site is small, these equations are equally valid as the bottom slope goes to zero (with a flat bottom the original equations of motion are recovered). From Parker's analysis it was clear that a wide range of dynamics is still possible. Depending on the conditions at the discharge, baroclinic forces due to either the bottom slope or the shape of the plume could force the plume. Parker's theory has been applied to both turbidity currents and dense overflows.

Turbidity currents occur in the ocean where the load of suspended sediment in the water column is so large that the density is significantly higher than the surrounding water. These currents often occur where strong currents, breaking waves or a river outflow create large turbulently suspended sediment loads which can travel several kilometers due to the baroclinic forces acting on the dense plume. Wright (1985) and Wright, et al. (2001) identified many instances where turbulent gravity currents have been observed. Turbidity currents have a complex interaction with the sea floor below and the ambient water above. To keep sediment in suspension the turbidity current must move fast and remain highly turbulent within the plume to counteract the sinking rate of the sediment particles. The plume can accelerate if the turbulence is strong enough to resuspend sediment as it passes over the sea floor. However, the more turbulent the plume is the more energy is lost to bottom drag, which slows the plume. The entrainment of ambient water from above is another consideration which also depends on the speed of the current and the strength of the turbulence in the plume. The basic equations for the momentum of the plume described by Parker et al. (1986) still apply to these complex systems. It is the boundary conditions and conservation equations for the mass of sediment that become complex when considering turbidity currents.

Dense overflows are a critical area of study in physical oceanography. Much of the water mass in the ocean interior originates in high latitude marginal seas (Cenedese et al., 2004; Ozgokmen et al., 2002). The cold, high saline water which forms at the sea surface sinks to the bottom and fills the marginal sea until it overflows via sills on the bottom into the deeper ocean basin to form the water which occupies most of the ocean interior. These dense overflow plumes may travel hundreds of kilometers as they move down the slope into the deep ocean, slowly entraining ocean water as they go. In spite of the entrainment the net buoyancy forcing is fixed at the sill as the water leaves the marginal sea. There is no other source or sink for density as the flow moves down slope. Entrainment of ambient water into the plume reduces the average density but also makes it proportionally thicker. There is no change in the density anomaly integrated over the plume thickness. The dense overflow plume shares this trait with the brine discharge plume where the forcing is set at the discharge diffuser.

The single source of buoyancy forcing for the brine discharge plume greatly simplifies the dynamics of the plume relative to studies of turbidity currents. The highly turbulent turbidity currents which can self accelerate are much more complex than the brine plume problem. The interaction with the upper boundary and entrainment of overlying fluid in the brine discharge is dynamically less complicated and ideally suited to a Lagrangian approach. There is still a critical value for the speed of the plume above which it will entrain fluid quickly due to shear instability and below which entrainment of water into the plume is slow. However entrainment of fluid from above is not a first order forcing term because the buoyancy anomaly of the plume is fixed at the source.

The primary force driving the brine plume is the baroclinic force due to horizontal differences in density and the sloping ocean bottom. An Eulerian model of the brine discharge was considered but that approach was found to be impractical. Standard ocean models used to simulate coastal ocean circulation do a poor job of calculating the baroclinic forces in a thin plume and require an extraordinarily high (~2 cm) vertical resolution for this kind of application (Hodges et. al., 2006). Only a fully unstructured (tetrahedral) finite element approach would correctly resolve the plume flow in an Eulerian model. While models such as the Imperial College Ocean Model (ICOM) are under development they are not publicly available, nor have they been rigorously tested and reviewed (Piggott, 2009). Further, an application of the ICOM model to the Richton brine discharge site would require computational resources only available at a national supercomputing center and would constitute a major research project. In contrast the Lagrangian approach was found to handle the baroclinic forces accurately and efficiently because they are applied to each particle using a parameterization derived in the local rotated reference frame. The Lagrangian model is ideally suited to modeling the plume salinity as an anomaly with a single source at the diffuser and exact mass conservation. Given these considerations the Lagrangian model described here provides the best available scientific estimate of the brine plume motion at the proposed Richton site.

Enhanced Plume Velocity Equation. The equilibrium velocity is defined in terms of the down slope (v) and across slope (u) components. The down slope component is a balance among the Coriolis force, the bottom drag and an additional term that is the product of the reduced gravity, plume thickness and bottom slope. The across component is a balance between the Coriolis force and the bottom drag. For specific formulations see Swanson et al. (2009). The dynamic effects of entrainment on the plume velocity are fully described by these equations, changing the local velocity as entrainment thickens the plume. The thickness of the plume is determined from the vertical distribution of particles. The entrainment process is modeled by the vertical diffusivity of the Lagrangian particles.

APPLICATION OF MODELING APPROACH

The focus of this section will be on the application of the Lagrangian model alone due to space limitations. The model system was successfully calibrated to monitoring data acquired during brine disposal at another site, Bryan Mound, off the coast of Texas (Randall 1982; Hann and Randall, 1982). The interested reader will find additional information on the calibration and the results of the CH3D modelling in Bunch et al. (2003) and the UM near field modeling in Swanson et al. (2009).

Description of Study Area

The proposed Richton brine discharge area is located on the inner continental shelf in the northern Gulf of Mexico east of Chandeleur Sound and south of Mississippi Sound. Figure 1 shows the bathymetry of the region with the locations of the two proposed discharge sites shown. The sites (shown as diamonds in the figure) are located in an area with a gently sloping offshore gradient. Further offshore the gradient reorients towards the east into deeper water. The north brine discharge diffuser site was located 6 km south of Horn Island in 14 m water depth. The south brine discharge diffuser site was approximately 15 km south of Horn Island in a water depth of 16.8 m. The proposed diffuser at the Richton discharge sites consisted of a 1060 m long pipeline section with 53 ports extending vertically to a height of 1.2 m above the bottom. Each port had a 7.6 cm diameter opening with a 20 m horizontal spacing. The brine would be discharged from the diffuser 24 hours per day from all 53 ports.

Currents at the proposed discharge sites are typically dominated by tides, but tidal currents are periodically overridden by wind generated currents from passing tropical storms and hurricanes (Johnson, 2008). The tide is diurnal with an average range of 0.43 m and an average period of 24.84 hours. Tidal currents are generally oriented east-west offshore from the barrier islands separating the shelf form Mississippi Sound with a strong north-south component near the inlets. Winds are predominantly from the south during the summer season, changing over to a westerly direction during the fall and winter.

Lagrangian Model Application

The Lagrangian particle model was applied at the Richton north and Richton south discharge sites using the CH3D hydrodynamic model results of Bunch, et al., (2003) to describe the ambient environmental parameters. The far field brine transport model was used to simulate the summer and winter periods based on the period covered by the CH3D hydrodynamic data provided.

The far field model simulated the discharge of the brine from the diffuser by releasing a mass of salt at a constant rate equal to the known discharge rate. The salt was represented by particles of equal mass. Consistent with the specification of the proposed discharge at the Richton sites, the initial salt particle release in the far field model occurred within a volume of water 1060 m long (53 ports x 20 m spacing), 3 m high and 100 m wide. One thousand particles were released each day.

The far-field model used a concentration grid to calculate the resulting brine salinity from the Lagrangian particles that each represents the same mass of salt. The concentrations were used in the particle transport calculation to define the spatial extent of the brine plume. Calculations encompassed the water column from the surface to a variable depth across the grid in layers 1 m thick. Particles moving through the three open (water) boundaries (edges of the grid) were assumed not to return.

MODEL RESULTS

A number of model runs were performed to investigate the dynamics of the enhanced gravity flow and bound the uncertainty of the model. The results presented here are for three conditions: using ambient currents only, using the gravity enhanced flow only, and using the full enhanced velocity model. By deconstructing the components of the flow in this way it is more easily seen how each contributes to the solution. Figure 2a shows the model predicted excess salinity of the brine discharge from the Richton north site under ambient flow only and Figure 2b shows the model predicted excess salinity under enhanced flow only. Figure 2c shows the model predicted excess salinity combined ambient and enhanced flow. Contours enclose areas of excess salinity at the indicated concentration. Results for the south site are not presented here due to space limitations but are documented in Swanson et al. (2009).

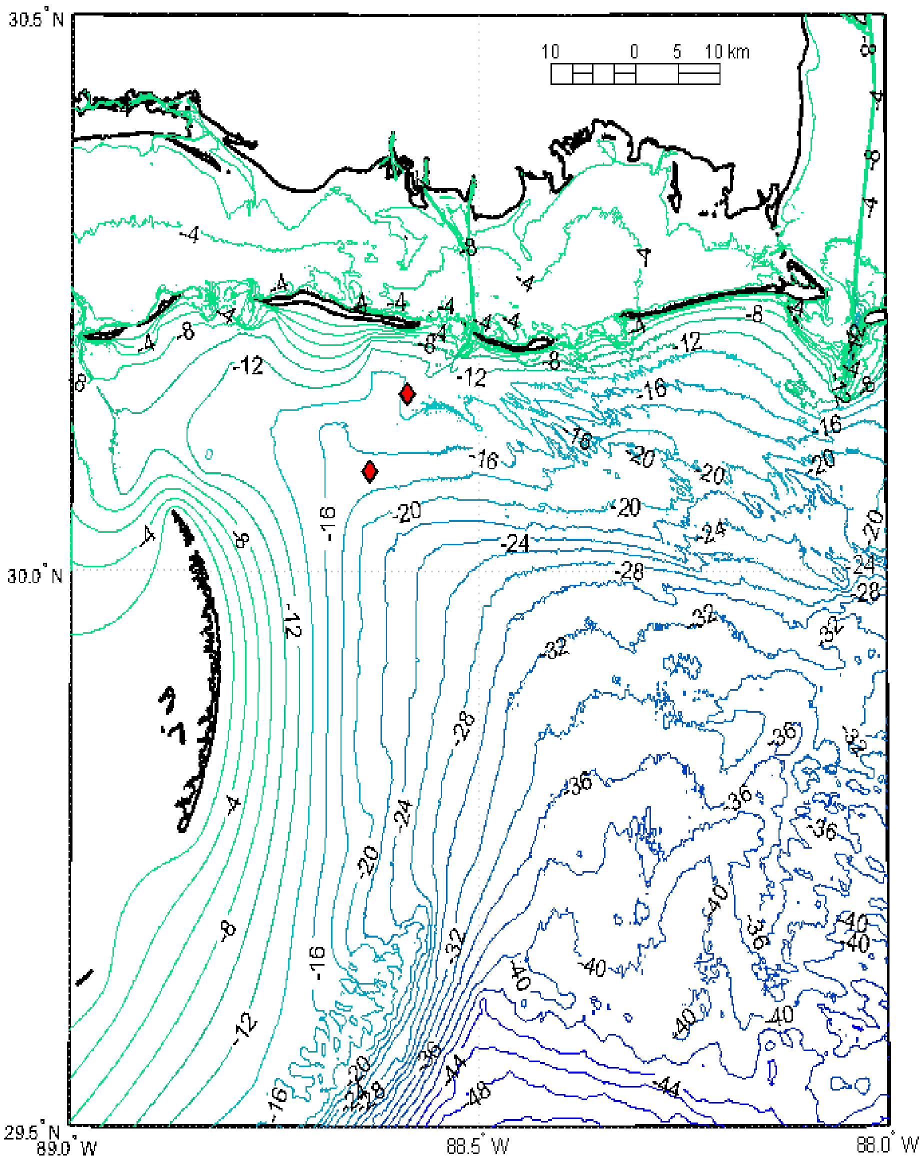

Figure 1. Bathymetric contours in the vicinity of the two proposed Richton sites.

Richton is a relatively low energy site with low ambient tidal velocities (i.e., bottom current mostly less than 5 cm/s. The ambient only (Figure 2-top) and enhanced velocity only results (Figure 2-middle) showed very different behavior compared to each other while the combined model result (Figure 2-bottom) clearly showed elements of both. In the ambient only case the plume moved east with the current. There is significant build up of salinity at the diffuser site as there was very little mean flow in the ambient currents. With mostly small periodic tidal currents to advect the plume, the salinity concentration around the diffuser tended to build up. The enhanced flow only result showed the down slope trajectory of the plume and the associated entrainment as the plume dilutes. When combined with the baroclinic physics of the enhanced flow case, there was still a strong build up around the diffuser, but the enhanced velocity flow transported the plume away from the diffuser where entrainment and other processes diluted the plume in deeper water.

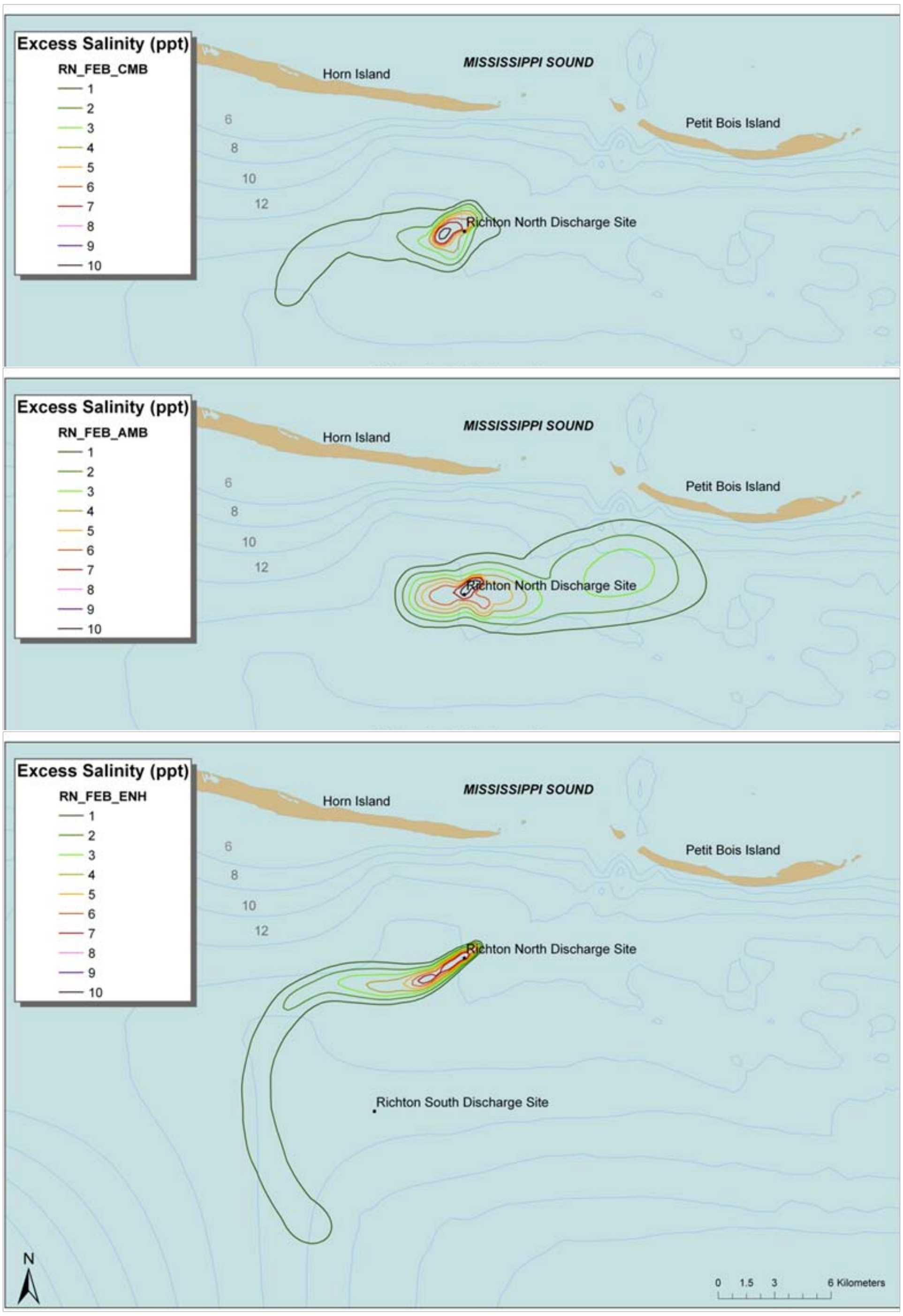

Figure 2. Model predicted excess salinity of the brine discharge plume from the Richton north discharge site under (top), ambient flow alone; (middle), under enhanced velocity flow alone; and (bottom), under combined ambient and enhanced velocity flow.

CONCLUSIONS

A modified Lagrangian model of the far field evolution of a dense plume of brine on the coastal shelf was developed by adding a velocity term that was directly induced by the dense plume that enhanced the original hydrodynamic model results. The approach was successfully compared to a monitoring data set collected at one of the brine discharges from construction of an earlier storage facility at Bryan Mound, Texas (Swanson et al., 2009).

The model was run to simulate the movement of the brine plume away from the proposed Richton north and south discharge sites. The results presented here (for the north site only) were for three conditions: using ambient currents only, using the gravity enhanced flow only, and using the full enhanced velocity model, By deconstructing the components of the flow in this way it is more easily seen how each contributes to the solution. The ambient flow only and enhanced flow only results showed very different behaviors compared to each other while the combined model result clearly showed elements of both. These distinctive results are indicative of the importance of using the enhanced approach to best estimate the location and extent of the plume.

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