# SEA MINE BURIAL PREDICTION FOR NAVAL MINE COUNTERMEASURES MISSION PLANNING

by

Rory J. O'Boyle

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Approved: ______________________________________________
Jack A. Puleo, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved: ______________________________________________
Sue McNeil, Ph.D.
Chair of the Department of Civil and Environmental Engineering

Approved: ______________________________________________
Levi Thompson, Ph.D.
Dean of the College of Engineering

Approved: ______________________________________________
Douglas J. Doren, Ph.D.
Interim Vice Provost for Graduate and Professional Education and
Dean of the Graduate College

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## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

## ABSTRACT

Sea mines have been used in every major conflict since the American Civil War and have sunk more combatant ships than all other means combined. Mines will continue to be a cheap, effective instrument, particularly for asymmetric forces. Consequently, all navies must possess a capability to counter enemy mining efforts to be successful. Most modern mines rest on the seabed and detect passing ships based on influence sensors, as opposed to older mines that floated in the water column and relied on enemy ship contact to detonate. Bottom mines can be difficult to detect with many of today's sonar systems, especially when they become partially or completely buried. Understanding bottom mine burial is critical to successful mine countermeasures mission planning, but burial prediction has historically contained large margins of error.

Sea mine burial has been studied intermittently since the end of World War II, with renewed interest and sustained efforts from 2000 through the present. The Office of Naval Research (ONR), in coordination with the U.S. Naval Research Laboratory (NRL), funded the Mine Burial Program (MBP) in 2000 with the goal of improving mine burial prediction models. The improved models were integrated into new mine burial programs, such as the Mine Burial Expert System (MBES) and the Deterministic Mine Burial Prediction (DMBP) program. The main output of both programs is time-dependent mine burial predictions. The scour model developed for DMBP was used to generate predictions of mine burial for specific wave conditions and sediment sizes. The data were analyzed to determine principles for burial prediction and the relative importance of environmental parameters in predicting mine burial.

In addition to the scour model burial prediction analysis, the full DMBP program was used to produce graphical burial prediction products which facilitated the development of a Burial Dominance Line (BDL). The BDL depicts the approximate offshore location where significant mine burial is expected to occur for specific geographic locations.

The results from the scour model data showed wave forcing conditions have a much stronger role in determining mine burial at a particular water depth than sediment grain size. Additionally, the range of possible burial percentages (0-100%) was skewed towards minimal burial (0-20%) or maximum burial (75%-100%). The number of depths experiencing 20%-75% burial was found to only occur for an average of 22% of the number of depths that experience greater than 75% burial. The finding of this narrow range of intermediate burial depths inferred confidence in the concept of a BDL predicting either no/minimal burial or significant/complete burial sections within a given area.

Analysis of the DMBP burial prediction results showed increased variability between annual averages than between month to month averages for a specific case. When plotting the BDL, there were pronounced differences in the offshore location of the seasonal BDL between summer and winter, sometimes tripling the BDL offshore distance in some locations.

The BDL was found to be a simple tool for quickly understanding the mine burial threat to improve the MCM planning process. Utilizing DMBP with additional scripts and functions developed during this research, graphical BDL products for specific areas can be quickly created and sent to forward operating MCM forces to be incorporated into mission planning.

# Chapter 1

# INTRODUCTION

## 1.1 Mine Warfare Overview

Mine warfare (MIW) is defined by the Department of Defense (DoD) Joint Publication 3-15 as: "The strategic, operational, and tactical use of mines and mine countermeasures, either by emplacing mines to degrade the enemy's capabilities to wage land, air, and maritime warfare or by countering of enemy-emplaced mines to permit friendly maneuver or use of selected land or sea areas." Mine warfare can be offensive (emplacing mines) or defensive (countering enemy mines, also known as mine countermeasures). Minefields can be used to protect harbors, cut off chokepoints and channels, or blockading an enemy in their port. Emplacing mines can be done by aircraft, minelaying vessels, fishing boats, and even submarines. Depending on the type of mine being employed and location, almost any surface ship can turn into a minelayer. Using commercial vessels of opportunity and submarines can make it difficult to identify covert enemy minelaying operations.

Mine Countermeasures (MCM), although protective in nature, can also be divided into offensive operations and defensive operations. Offensive MCM is preventing or eliminating the enemy's ability to lay mines, which can include destruction of mine stockpiles and minelaying vessels. Defensive MCM is reducing the effect of enemy mines after they have been laid. Defensive MCM consists of active and passive measures. Active defensive MCM is directly countering or neutralizing mines that have been deployed, either by mine hunting or mine sweeping, to remove the threat. Passive defensive MCM tactics are measures designed to reduce the effectiveness of mines without neutralizing them, such as area avoidance, magnetic signature reduction (degaussing procedures), and acoustic signature reduction (reduced speed, shutdown of non-essential machinery). Passive measures are typically used in conjunction with or following active defensive measures to minimize risk to forces.

Mines in use today can be classified by where they are located within the water column or by their method of actuation. Within the water column, mines can be floating or drifting on the surface; they can be moored to the bottom and floating somewhere in the water column; or they can be resting on the bottom. Actuation, or the way a mine is triggered, can either be through contact with a vessel, remotely detonated, or by physical influence. Remotely detonated mines can be physically connected to the firing device by a command wire or can receive an electromagnetic signal from a transmitter to actuate the mine. This actuation method is used for moored and bottom mines. Contact mines are becoming increasingly rare, as they are indiscriminate against friend or foe, and improvements in electronics have made remote detonation systems and influence sensors cheaper and more prevalent.

Influence sensors can be magnetic, pressure, acoustic, seismic, or a combination of the sensors. Influence sensors vary in complexity. They can be as simple as a single sensor that actuates on the first signal, or they can have multiple types of sensors that all need to be satisfied to trigger the mine. Influence sensors can also have “ship counters”, which are a pre-determined number of actuation times that need to happen before the mine explodes. Influence sensors can be found on some moored mines and most bottom mines.

MCM forces use either minehunting or minesweeping techniques to counter mines that have been emplaced. Minehunting is the use of sensor and neutralization systems to locate, identify, and dispose of mines in a minefield. The first step in minehunting is detection. Detection is the recognition by a sensor of a contact presenting a minelike echo (MILEC) or being minelike. After detection, the MILEC goes through classification where an operator determines if a MILEC is a minelike contact (MILCO) or a non-MILCO based upon the object's size, shape, shadow, features, sonar return strength, and/or aspect change (horizontal sonar angle). The next step is identification to determine the exact nature of an object detected and classified as minelike. It is the process of determining whether a MILCO is a mine or non-mine by visual, optical, tactile, or high-resolution sonar imagery. Identification can be accomplished by an Explosive Ordnance Disposal (EOD) diver, a remotely operated vehicle (ROV), or an additional unmanned underwater vehicle (UUV) sonar pass over the object. Once the MILCO is determined to be a mine, it needs to be located again (reacquired) and then neutralized. Neutralization is rendering the mine inoperable by either removing it, recovering it for exploitation purposes, or destroying it in place.

When mines are either too difficult to find or minehunting will take too long, minesweeping procedures are used. Minesweeping is the technique of clearing mines using either mechanical sweeping to remove, disturb, or otherwise neutralize the mine, or by influence sweeping to produce the acoustic or magnetic influence required to trigger and detonate the mine. Minesweeping indiscriminately tries to neutralize mines without taking the time to locate them first. It is typically faster than hunting, but almost always has increased residual post-mission risk compared to hunting. If there is uncertainty in the type of mines used or in the mine's actuation method (including ship count numbers), it may be ineffective. The U.S. Navy MCM force's mantra is "Hunt when you can, sweep when you must."

## 1.2 U.S. Navy Mine Hunting Systems Overview

The U.S. Navy has three types of systems used in MCM operations: surface, airborne, and underwater. These three are referred to as the "MCM Triad". Surface and airborne systems are used in both minehunting and minesweeping operations, while underwater systems are currently used only for minehunting. All three can complete the full detect to engage minehunting sequence on their own or used jointly during a mission to complement each other's efforts.

Surface mine countermeasure (SMCM) systems currently consist of the MCM "Avenger-class" minehunting ships. These ships were designed in the 1980's specifically for minehunting and minesweeping operations. They have a fiberglass hull, demagnetized engines to minimize their magnetic signature, and are specially designed to stream tow gear used in minesweeping. The Avenger class is equipped with the AN/SQQ-32 sonar system to detect and classify mines, the remotely operated Mine Neutralization Vehicle (MNV) to neutralize mines and sweep equipment to sweep moored or influence (acoustic and magnetic) mines. EOD MCM platoons can also embark onboard the ship to provide additional identification and neutralization capability.

Airborne Mine Countermeasures (AMCM) systems are utilized onboard the MH-53 "Sea Dragon" helicopter and MH-60 "Sea Hawk" helicopter. The larger MH-53 can conduct minehunting and minesweeping operations due to its larger towing capacity, while the MH-60 is only capable of conducting minehunting and neutralization with side-mounted equipment. As with the Avenger-class, the MH-53 can sweep for moored mines and influence mines (acoustic and magnetic) using towed sweep gear. The MH-60 utilizes two minehunting pieces of equipment; the Airborne Laser Mine Detection System (ALMDS) to detect near surface/in-volume mines and the Airborne Mine Neutralization System (AMNS), which is a tethered system to neutralize mines from the air.

Underwater Mine Countermeasures (UMCM) systems are the youngest of the MCM triad. Although EOD divers have been around since WWII, unmanned underwater vehicles (UUVs) are a recent development. UMCM uses the MK18 Mod 1 & Mod 2 UUVs (militarized version of the commercial Hydroid Remus systems) to search for and identify mines, and EOD divers and/or Seabotix ROVs to reacquire, ID, and neutralize mines. The UUVs are operated by sailors forming an Unmanned Systems Platoon (UMS), who are trained in small boat operations, UUV operations, and analysis of side-scan sonar imagery from the MK 18s. The UMS paired together with an EOD MCM platoon forms an Expeditionary MCM (ExMCM) company, capable of executing the full detect to engage mission based either afloat or ashore. The ExMCM company has a relatively small footprint when compared to SMCM or AMCM forces, making it much easier to rapidly deploy to a crisis.

### 1.3 Mine Warfare History

Mine warfare became an acceptable, commonplace mode of warfare following the American Civil War in 1865, but examples can be found throughout history prior to the war between the Confederacy and the Union. The brief history covers mine warfare globally, but focuses on the U.S.

As early as the Greeks, man began using floating devices to destroy enemy ships. They used a liquid called “Greek Fire” which burned ferociously and could be employed against enemy ships by either loading a "fire ship" and sailing that into the enemy fleet, or launching wooden barrels filled with Greek Fire via catapult. Following the Greeks, similar tactics were not seen again until 1585 when the Spanish Fleet was besieging the town of Antwerp. An Italian named Gianibelli developed a "fire ship" filled with gun powder, scrap iron, marble, and other stones to use against the Spanish. Gianibelli's ships were lit on fire and sent toward the Spanish Fleet, where they exploded with the scrap iron, marble, and other stones acting as shrapnel. Over 1,000 Spaniards were killed, and these ships were deemed to be such a cruel weapon that most military planners refused to use them.

The next occurrence in history of mines occurred in 1777 during the American Revolutionary War, when Daniel Bushnell placed his floating, tar-covered gunpowder barrels into the harbor with hopes of damaging the British Fleet. His attempt had little success, and he tried a second attempt in 1778. The second attempt involved towing the mines into a British ship, but before he could reach the ship the British disrupted his efforts and he had to cut the "mines" loose. The sailors aboard the British ship hauled the strange objects onto the deck to inspect them, when they exploded. Three sailors were killed, but the ship was undamaged. From both of Bushnell's attempts, 6 British crewmen were killed, and a small longboat destroyed. Despite his marginal success, his efforts inspired other American inventors to pursue mine development.

During the War of 1812, moored mines developed by Robert Fulton were used as defensive minefield to break the British blockade at New York Harbor. Mine use by the Americans in the war was effective enough that the British refused to moor in American ports and harbors, instead staying on patrol off the coast. Mine development continued following the war, and in 1843 Samuel Colt developed remote-detonated mines, allowing for friendly ships to pass over a defensive minefield. Mines could now be placed to protect a harbor and allow friendly traffic while denying enemy traffic. These defensive remote-detonated mines were utilized in warfare from that point on, with Russian use during the Crimean War in 1855, the Chinese using them against the British from 1857-1858, and use by both sides in the French-Austrian War of 1859.

Upon initiation of the American Civil War, a new era in mine warfare developed. The Confederacy needed to compete with the Union's maritime supremacy, and they developed several different types of mines (remote-controlled and contact) to counteract Union forces and minesweeping techniques. They also effectively utilized mines to protect their harbors against Union attacks.

Following the Civil War, two major inventions changed mine development. Dynamite was invented, allowing for three to five times more explosive power to be packed into mines as compared to gunpowder. The Hertz Horn was also developed in 1866 to ignite these new dynamite mines, which became the standard for contact mines for 70 years. In the Spanish-American War of 1898, defensive minefields used by the Spanish in Cuba and the Philippines drove the U.S. to begin investing in MIW/MCM, requiring all vessels to carry mines and minesweeping equipment.

The Russo-Japanese War from 1904-1905 marked a shift in how mines were employed, with the first use of offensive mining against an enemy to blockade them into their own port. The Japanese successfully used the technique against the Russians. Casualties from Japanese offensive mining included a highly respected Russian admiral, which led Russia to begin the development of new mine types and mine countermeasures systems. Russia's initiative drove other western powers to increase mine development between 1905 and WWI. Non-combatant commercial shipping casualties were also high during the Russo-Japanese War, to the outcry of the rest of the world. This led to the Hague Convention of 1907, part of which outlaws drifting mines and requires protective minefield locations to be announced to civilian mariners.

World War I and World War II saw large-scale, global offensive and defensive mining by both sides, followed by extensive post-war mine clearance operations. As is typical of U.S. Navy policy, the mine warfare force was severely diminished after WWII, only to be required a few short years later in the Korean War. During the Korean War, the U.S.-led United Nations force maintained a significant naval advantage over the minimal Communist fleet. What North Korea lacked in naval power, it made up for with Soviet-backed influence mines and minelaying capabilities.

Despite requests from MIW commanders within U.S. Navy in the Pacific at the outbreak of the war, additional support of MCM vessels was not provided. The dichotomy came to a head when the U.N. amphibious force went to assault Wonsan as part of a two-pronged land and sea assault. The approaches to the channel and landing area were mined, and a makeshift coalition MCM force struggled to clear a path for the landing force in the tight ten-day timeline. Underequipped and lacking enough vessels, the MCM force worked to clear two different approaches before succumbing to three vessels lost. By this time, the land-based prong had secured the port several days prior, and the MCM commander decided not to push forward with the landing but instead take the time and conduct a proper clearance. By the time the landing force made it ashore eight days later, Bob Hope and the USO were already in Wonsan performing for the troops. The Amphibious Task Force Commander Rear Adm. Allan

E. “Hoke” Smith informed his superior that “We have lost control of the seas to a nation without a Navy, using pre-World War I weapons, laid by vessels that were utilized at the time of the birth of Christ.”

The embarrassment for the Navy at Wonsan led to a renewed interest in mine warfare following the Korean War. Funding and resources were allocated to improving the U.S. MIW force by developing new MCM ships, new hunting and sweeping equipment, and developing a new Airborne Mine Countermeasures (AMCM) capability with helicopters. The U.S. Navy also reorganized its force structure to have a professional mine warfare community to retain MIW experience within the force and to improve command and control (C2). Despite the progress that was made, it was unfortunately a short-lived initiative. As memories of the Korean War faded and DoD budget constraints forced MIW programs to compete with higher visibility programs, investment in MIW plummeted.

The Vietnam War was a dynamic time period for U.S. MCM forces due to differing operational environments, MCM vessels reaching the end of their life cycle, and AMCM operations becoming an integrated part of the U.S. MCM force. The geography of Vietnam and guerilla-style warfare tactics of the Viet Cong led to riverine operations throughout the country. To combat U.S. patrol boat dominance of the waterways, the Viet Cong employed mines in the rivers, forcing U.S. mine warfare forces to develop “brown water” tactics to maintain their relative freedom of navigation of the waterways. Mine clearance in the rivers to support the patrol boats and inland assault forces became an additional duty for the small MCM force, which was already spread thin conducting more traditional “blue water” MCM clearance operations and patrols off the Vietnam coast.

Coinciding with the new operational requirement in riverine environment was that several of the major U.S. MCM vessel types were coming to the end of their life cycle. This brought about a modernization program in the late 1960s, with improvements in engines and sonar systems for some of these vessels. Despite the upgrades, additional MCM capacity was still required to meet all operational commitments. Helicopters conducting AMCM proved to be the answer. AMCM operations, tactics, and development continued throughout the war to support SMCM efforts, driven by CNO Adm. Elmo R. Zumwalt, Jr.'s airborne force modernization program implemented in the late 1960s. Achieving this operational capability led directly to the establishment of the first AMCM squadron, HM-12, consisting of CH-53A helicopters based in Norfolk, VA. Although the SMCM force welcomed the additional support and capacity, the focus on AMCM procurement, development, and modernization redirected funding from SMCM modernization, ultimately repeating the cycle of inconsistent and insufficient funding support of MCM vessels.

The U.S. also conducted offensive mining operations during the war, mining North Vietnam's major ports with surface and air craft to push the Viet Cong towards a peace agreement. Once both parties came to the negotiation table in Paris in 1972, clearance of the harbors was a major stipulation of the peace accords. The massive clearance operation was termed "End Sweep" and was developed over several months. The highest priorities of the operation were the safety of the U.S. personnel and equipment conducting the clearance operations. MCM commanders capitalized on the opportunity and acquired improved technology/systems they needed but never had the funding to get previously.

The cease-fire peace accords were signed in January 1973, with the requirement to clear/sanitize all mines from North Vietnamese harbors. Despite the long lead time in planning time and force preparation/staging, clearance took 6 months and cost $21 million (including two helicopters lost); this was double the cost of the minelaying operation. “End Sweep” was a success. It had the best possible circumstances for an MCM operation, which included high political visibility, exceptional staff work, large lead time, sufficient planning preparation, employment of all available AMCM assets and air-capable amphibious ships in 7$^{th}$ Fleet, and strong support from the Fleet Commander, shore facilities, and a community of exceptional officers.

As briefly mentioned above, the focus on AMCM during and after Vietnam had devastating effects on SMCM vessels; numbers dropped from 64 vessels in 1970 to 9 vessels in 1974, including the loss of many mine warfare community officer and enlisted billets. But as is the cyclic nature of big Navy interest in mine warfare, Soviet mine development in the 1970s and early 1980s, especially for deep ocean mining, led to renewed interest and investment in SMCM development (both vessel and sonar). The Navy committed to the development of the Avenger Class SMCM vessel in 1981. The Avenger Class is still in active use, and is the U.S. Navy’s only MCM-dedicated surface vessel.

In the 1980s, the U.S. MCM force dealt with two response incidents in the Middle East; mining activity in the Suez Canal in 1984 and the “Tanker Wars” in the Persian Gulf from 1986-1989. During the Tanker Wars, relic mines from the Iran-Iraq war and new mines laid by Iran against Kuwaiti oil tanker ships were a threat throughout the Gulf, and U.S. Navy ships escorted Kuwaiti tankers for protection. The regular Navy surface ships needed protection from the mine threat, driving the need for MCM forces to respond to the region. The Tanker War mine clearance operation lasted for almost two years, using AMCM and SMCM assets. One U.S. vessel was damaged during the conflict. The U.S.S. Samuel B. Roberts hit two mines in April 1988 while serving escort to a Kuwaiti tanker convoy, causing significant damage. The U.S. response was to destroy half of the Iranian Navy and two Iranian oil platforms.

Several years later, ahead of the U.S. invasion of Iraq during the Gulf War, the Iraqis seeded a large minefield in the anticipated amphibious landing area. Once Operation “Desert Shield” turned to Operation “Desert Storm”, U.S. and British SMCM forces and U.S. AMCM forces began work to clear a channel to Kuwait for the advancing amphibious assault force. MCM efforts to clear the minefield were slow, and an alternate invasion plan was developed. Two U.S. Navy ships were damaged by mines on February 18, 1991, the U.S.S. Princeton and U.S.S. Tripoli. The Princeton, a guided-missile cruiser, was providing anti-air warfare defense for the MCM force, and the Tripoli was serving as the flagship for the MCM force as well as serving as an AMCM operation platform. Tripoli was able to stay on station and remain mission capable, but the Princeton suffered over several million dollars in damage after it hit two mines. Princeton had to be towed out of the area and underwent emergency dry dock repairs. By the end of the operation, over 1,300 mines were destroyed by coalition MCM forces, with the MCM efforts supported by captured intelligence. Included in the 1,300 were over 200 acoustic/influence mines not seen by the West before, highlighting that enemy mine type is just one of the many uncertainties that can accompany MCM operations.

Since the American Civil War, mine warfare has been present in every major naval conflict across the globe. Despite this consistency, the cyclic nature of interest in mine warfare by navies and governments worldwide make it a challenge to maintain, let alone modernize, MCM forces for extended periods of time. George Santayana said, “Those who cannot remember the past are condemned to repeat it.” As can be seen throughout history, ill-prepared and/or ill-equipped MCM forces can cause significant operational delays and loss of life. Adversaries will continue to develop and employ increasingly sophisticated mines to prevent their opponent’s maritime superiority. Our MCM forces need consistent attention, investment, and support to be ready to counter an always evolving threat. The section above provided a short overview of mine warfare history; a thorough history can be found in (Morison, 2000) and (Hartmann, 1991).

### 1.4 Mine Burial Research

Mine warfare research in the U.S. was conducted in the 1950’s and early 1960’s following World War II and Korean War. A lull occurred during the Cold War, but MIW received renewed interest following the Gulf War. In 2000, the Office of Naval Research (ONR) and the U.S. Naval Research Laboratory (NRL) initiated a robust six year mine burial research program focused on mine burial prediction (MBP). The MBP program used field experiments, laboratory experiments, and computer modeling to improve the physical understanding of the burial processes and create state of the art mine burial probability models for use by the Navy’s MCM force. The research was broken into the two focus areas of initial impact burial and subsequent burial (Wilkens & Richardson, 2007).

Impact burial occurs at the initial deployment of the mine, when it first strikes the bottom. The amount of burial it experiences at that time is a function of the bearing strength of the sediment and the velocity, attitude, and shape of the mine when it hits the sediment. The impact models account for three phases of the process: falling through the air, falling through the water, and bottom penetration. At the start of the MBP program, several iterations of impact models had been developed through the 1980’s and early 1990’s as the impact burial prediction model (IBPM), IMPACT 25, and IMPACT 28; however, these models were found to overestimate the mine’s vertical velocity at the seafloor. The error caused over prediction of the amount of impact burial when compared to field studies.

Due to this recognized deficiency, the impact model improvements during the MBP program focused on better modeling the mine’s trajectory through the air /water interface and through the water column. A full 3-D hydrodynamic forcing model was developed to model the mine’s trajectory throughout the water column. Additional emphasis was put on the importance and measurement of sediment bearing strength. Several studies were conducted to measure the effectiveness and calibration of free-falling sediment penetrometers that can be used to quickly determine in situ sediment shear strength. The IMPACT 28 model was refined during the MBP program, and the upgraded version, the IMPACT 35 model, was completed and validated with field experiment data (Chu & Fan, 2007).

Subsequent burial of a bottom mine occurs from scour, liquefaction, and bedform migration. Scour and liquefaction are near-field, localized processes that occur on short length and time scales. Bedform migration is a far-field process occurring on long length and time scales, covering an entire littoral cell from the shoreline to the depth of closure offshore. Scour and bedform migration are the more dominant burial mechanisms, with liquefaction only occurring under specific site and environmental characteristics. Scour and bedform migration are sediment mobilization processes driven by oscillatory motion from orbital wave energy and/or currents at the seafloor. Scour processes affect all coastal structures, not just mine-like objects on the seafloor. Models to predict scour along coastal/offshore structures such as piers, jetties, bridges, oil platforms, and undersea pipelines have received continuous attention over the last few decades outside of the mine warfare community. Besides the external scour research, there are three mine burial prediction models that were developed for military application before the MBP program launched which are of note: the U.S. Wave-Induced Spread Sheet Prediction Model (WISSP), the German Nbury model, and the U.K.'s Defense Research Agency Mine Burial Environment (DRAMBUIE) model.

WISSP is a model to predict mine burial based on wave energy, water depth, and sediment grain size. It was developed by the U.S. Navy in the 1960s based on one set of empirical lab experiment results. WISSP does not include time dependence, nor does it account for currents. Its main use was to indicate whether burial may occur for a given location with given conditions.

Nbury was developed by the German Navy in the 1980s using the same empirical data that WISSP incorporated along with subsequent field observations. Additional functionality within Nbury is the inclusion of mine diameter and time dependence based on significant wave heights and bottom currents. With these additional parameters in the Nbury model, the improved bottom shear stress calculations (critical to determine sediment mobility) allowed for refined results, but since the empirical relationships were still based on limited observations, the applicability to all operational environments is minimal.

The DRAMBUIE model was the most recently developed prior to the start of the MBP program. It is the most advanced of the three, and directly fed into the final outputs of the MBP program. DRAMBUIE was developed by the United Kingdom in the 1990's and incorporated results from additional laboratory flume experiments. These experiments were able to gain a much deeper understanding of the physics behind the burial processes leading to the development of an additional empirical velocity multiplier to account for how the mine's shape/orientation in relation to the waves/current direction influences bottom shear stresses.

The DRAMBUIE model was used as the basis for wave-induced scour burial prediction for the MBP program, and a modified version of it was used as part of the final outputs of the program. Several other scour models, based on predictions of initiation of motion using Shield's parameter and/or Keulegan-Carpenter number were developed from laboratory flume experiments during the course of the program (Wilkens & Richardson, 2007). Lastly, the VORTEX model (Jenkins et al., 2007) was developed to simulate burial by both near-field scour processes and far-field bed migration processes for a sea mine. The VORTEX model was validated to reasonably depict horseshoe-shaped vortices caused by wave and current action coming from a mine, and the near-field ripples and depressions that develop surrounding a mine due to scour from these vortices. It was also found to be in reasonable agreement with large-scale, littoral cell sized bedform migration phenomena occurring on a long time scale from the coastal morphodynamics, which can cause burial and re-exposure of bottom mines. Unfortunately for operational MCM force use, the VORTEX model requires extensive input files and is computationally intensive (Jenkins et al., 2007).

The operational output from the ONR MBP program was two computer-based systems, the Mine Burial Expert System (MBES) and the Deterministic Mine Burial Prediction (DMBP) program. Both programs generate time-dependent mine burial predictions.  MBES utilizes a Bayesian network to determine the probability distribution function of various burial states for the mine, while DMBP provides a time-series graphical output of predicted mine burial for a given location. DMBP will be discussed in further detail in later sections.

# Chapter 2

# OVERVIEW OF U.S. NAVY MCM MISSION PLANNING

The general steps and considerations for planning active defensive MCM operations are described in the next section, followed by discussion of critical environmental parameters, their importance, and potential operational impact. Understanding both topics is instrumental in providing perspective for how different factors in MCM operations are interrelated and their relative importance to mission planning and execution.

## 2.1 U.S. Navy MCM Planning Process

The U.S. Navy utilizes software to assist in mission planning. The legacy version is a software called the Mine Warfare and Environmental Decision Aids Library (MEDAL) and the latest version is web-enabled and called MineNET Tactical (MNT). Both the legacy and updated version provide the same types of functionality. For mission planning, this includes importing environmental and mine threat databases, developing tactical hunting/sweeping plans, computing MCM system performance against mine threats, and providing situational awareness and information visualization. During mission execution, the software allows for updates to MCM plans, calculations of progress and percentage clearance, contact management, and providing status update outputs to other units. These programs are critical in support of efficient and effective MCM planning. The MCM planning procedure outlined below is adapted from the Navy Tactics, Techniques, and Procedures 3-15.2 “Navy Mine Countermeasures” publication (NTTP 3-15.2) chapters 3, 4, and 5 and is edited to provide a general overview of the process for non-military readers.

1. Mission Analysis. This begins when an MCM unit receives an order to conduct a mine countermeasures operation from a higher authority (HHQ). Mission analysis is to review and analyze orders, guidance, intelligence, and other information to enable the Mine Countermeasures Commander (MCMC) and staff to gain an understanding of the situation, identify necessary tasks to accomplish the mission, and produce a mission statement. MCM operations will almost always be in support of a larger-scale operation, so the MCMC and MCM planning staff need to understand what higher authority has tasked them to do in addition to how the MCM operation fits into the larger mission.
    a. Mission Analysis Inputs:
        i. *Planning guidance from HHQ*: Mission statement, forces assigned, time available, where MCM is required, general threat information/intelligence, and acceptable risk to MCM forces/transiting vessels.
        ii. *Enemy Threat*: Examine the enemy's mine inventory, minelaying capabilities, and their objectives. Determine what their most likely and most dangerous mine employment plans could be. The mine employment plan includes location, type, and purpose of the mine.
        iii. *Historical MIW environmental database parameters for the area*: bathymetry, bottom type, predicted percentage of mine case burial, underwater visibility, tides, and the climatology data (average sea state/wind; sunrise/sunset)

iv. *MCM forces and MCM systems available, and their operational status; availability of MCM support platforms*

v. *Force Protection*

vi. *Logistics Requirements*

vii. *Communications Requirements*

b. Mission Analysis Outputs:

i. *MCMC Mission Statement*: Includes who, what, when, where, why, and the mission objectives.

ii. *MCMC Intent*: A concise statement of the purpose of MCM force activities, the desired results, and how actions will support that end state.

iii. *MCMC Planning Guidance*: The Commander's guidance to the staff to help with course of action development.

iv. *Identification of MCM tactics/techniques*. Based on the enemy's course of action, mine types expected, and the operating environment, the proper MCM gear is matched to counter each mine threat. This includes segmenting the MCM operations area for different systems and developing A/B worksheets for each MCM system. A/B worksheets are planning tools used to determine an MCM's system probability of successfully detecting and identifying a specific mine threat in a given operating environment.

2. Course of Action Development and Selection. A course of action (COA) is a scheme of maneuver to accomplish the mission objective that includes the forces and techniques to be utilized.
    a. COA Development: During the planning process, several different COAs will be developed with different force assignment, techniques, and maneuvers to be used.
    b. COA Analysis: The different COAs are then analyzed to ensure they meet mission objectives, are feasible, and are acceptable regarding risks vs. gains.
    c. COA Comparison: Once the COAs are determined to be valid options, each COA's relative merits are compared against each other for certain governing factors determined by the MCMC. Examples of governing factors are speed of accomplishing mission objectives, least dependent on weather, lowest risk to friendly forces, or easiest to logistically sustain. The governing factors are subjective and based on the MCMC's intent and priorities for the mission.
    d. COA Selection: The COAs are scored on their relative merits for each governing factor and the results are presented to the MCMC to decide on the appropriate COA for the mission. Once the COA is selected, it will be codified into a comprehensive plan describing detailed MCM force and system employment for the mission.
3. Review Plans and Scheme of Maneuver for Cohesion. This is a final review of the plan which requires prioritizing the order of systems used and priority of areas cleared, deconfliction of assets, reviewing the operational timeline,

reviewing the overall scheme of maneuver, and generating subordinate unit tasking.

4. Mission Execution: Once the MCM plan has been completed and execution begins, the staff's work is not done. They will monitor all operations, assign assets and prioritize areas as needed, track schedules for all subordinate units, keep track of area clearance, report status updates and found mines to higher headquarters, and update the MCM plan as required by the situation or the environment.

Table 1: Explanation of minehunting steps (adapted from NTTP 3-15.2).

| **Step** | **Description** |
|---|---|
| *Detection* | Recognition by a sensor of a contact presenting a minelike echo (MILEC) or being minelike. |
| *Classification* | Determination by an operator that a MILEC is a minelike contact (MILCO) or a non-MILCO based upon the object's size, shape, shadow, features/structure, sonar return, and/or aspect change (horizontal sonar angle). |
| *Identification* | The determination of the exact nature of an object detected and classified as minelike. It is the process of determining whether a MILCO is a mine or non-mine by visual, optical, tactile, or high-res sonar image. Can be done by an EOD diver, ROV, or additional UUV sonar pass. |
| *Re-Acquire* | Re-acquire the mine and prepare for neutralization. |
| *Neutralize* | Render the mine inoperable by either removing it, neutralizing it, recovering it for exploitation purposes, or destroying it in place. |

## 2.2 Environmental Parameters Affecting MCM Operations

An operational area's environmental characteristics are one of the most influential aspects on an MCM operation. Environmental parameters inform many commander's decisions and planning outcomes: to either conduct minehunting operations, minesweeping operations, or avoid an area entirely; determine which forces to employ where; the timeline of an operation; and even tactical decisions such as what the proper sensor settings are. Table 2 provides an overview of environmental categories, key factors, and major operation impacts they can have on military operations, particularly MCM operations.

### 2.2.1 Waves and Currents

Waves and currents have arguably the largest impact on MCM operations, as they affect not only the personnel and equipment operating on and below the surface, but also are the main driving force behind mine burial for most sediment types. Wave heights are used to determine sea state, which are tied to limits for certain types of actions. If a sea state limit exceeds the limit for a specific operation, the operation will be on hold until the sea state decreases below the limit threshold. For personnel and equipment, operational sea state limits exist for deploying small boats, divers, and UUVs, as well as MCM vessel operations. Below the surface, strong currents caused by waves or other oceanographic processes can limit or halt diver and UUV operations. Depending on the direction and magnitude of currents, they can cause UUV navigational errors and even distort sonar returns.

The forcing from waves and currents on the bottom can cause sediment transport leading to scour and bedform migration, which can bury mines. During storm conditions in sufficiently shallow water, objects on the bottom can become rapidly buried in a matter of hours. Wave and current conditions can be measured via in situ and remote sensors or modeled numerically. Given proper preparation time and access to resources, MCM forces can enter mission planning with a good estimate for historical and forecast wave/current conditions for their given operational area.

### 2.2.2 Bathymetric Features

Bathymetric features are elements and attributes found on the sea floor. On a large scale, these can describe major topographic features like undersea trenches, mid-ocean ridge systems, and sea mounts, but on the scale of mine countermeasures operations, it is used to describe small-scale features such as ripples, vegetation, and clutter. Bottom clutter are objects on the sea floor that resemble the size and shape of sea mines and can be anything from natural objects such as rocks and logs to manmade objects like oil drums or discarded appliances.

Bathymetric features affect mine detection and reacquisition. During detection, mines can be hidden from sensors by ripples, vegetation, or even depressions in the seafloor, and large amounts of clutter can lead to inordinate amounts of false contacts or missed mines due to oversaturation in the amount of returns on sonar. A similar problem occurs during re-identification, when it may be difficult to locate the contact due to it being obstructed from view or confused with other clutter items. Additionally, the presence of ripples suggests that forcing conditions are high enough for sediment transport and therefore can cause mine burial by scour and potentially bedform migration.

Bathymetric features are typically the most poorly estimated pre-mission parameter, as they, are not typically documented for new operational areas and can be subject to rapid change (e.g. sand ripples). Areas that have been previously surveyed can use techniques such as change detection to help quickly sort through clutter, but these surveys are not available for many areas. Change detection is where two sonar images for a location are examined by an algorithm to detect differences between the images. An item of clutter that is found in both images which may look like a mine, but was previously determined to be a log, will not register as a possible mine-like echo (MILEC), saving time and resources from having to re-identify the same item. Bathymetric features are best determined on site, and MCM planners need to use all available environmental data for a given site to make the best possible estimate during mission planning.

### 2.2.3 Seafloor Sediments

Seafloor sediment type is another important parameter in determining an MCM plan. In broad MIW doctrinal categories, sediment can be thought of as either mud, sand, or rock. In practicality, there is almost a boundless quantification of sediment type when considering the grain size distribution, shear strength, density, porosity, and other geotechnical parameters. Sediment type primarily affects mine burial and sonar acoustic properties. As a rule of thumb, a soft muddy bottom allows for significant impact burial, typically with little subsequent burial. Soft bottoms also absorb sonar energy while a mine case will reflect a significant amount. This allows mines to stand out more in these bottom types. Conversely for sandy bottoms, little impact burial is expected due to the increased shear strength of the sediment, but the cohesionless nature of sandy sediments leads to subsequent burial under sufficient forcing conditions. Sandy bottoms also reflect more sonar energy, reducing the contrast of the mine with the bottom. Rock bottoms experience no burial, either initial or subsequent, but the extreme hardness and typically rough bottom associated with rock make detecting mines difficult.

For high frequency sonar performance prediction (HF sonar is used by all current U.S. MCM systems), the Naval Oceanographic Office (NAVOCEANO) uses the "High-Frequency Environmental Acoustics" (HFEVA) classification database, with 23 sediment categories ranging from rough rock to clay. Six geoacoustic performance parameters are tied to these categories, and this information is imported into MNT when creating an MCM plan to determine sensor swath width and probability of detection (Fleischer et. al, 2017).

NAVOCEANO maintains worldwide sediment databases with varying levels of confidence that are used in MNT and other military applications. MCM forces can determine the sediment type on site by various methods, including dropping penetrometers, taking grab samples, UUV post-mission analysis, and even the "old fashioned" arm-thrust method, where a diver measures how far they can punch their fist into the seabed.

Table 2: Environmental Considerations for Mine Countermeasures (adapted from NTTP 3-15.2).

| CATEGORY | FACTORS | MAJOR OPERATIONAL IMPACTS |
|---|---|---|
| *Sea and surf* | Sea/swell conditions and surf characteristics | Operational limits for surface craft, EOD/VSW personnel, and MCM equipment; actuation probability for pressure mines; mine detection capability |
| *Currents* | Surface/subsurface current patterns, including tidal, surf, and riverine currents | Navigability/maneuverability of displacement craft and towed systems; navigational error, diver/ROV/UUV operational limitations; extent of mine burial; moored mine dip |
| *Acoustic environment* | Sound velocity profile, acoustic propagation and attenuation, acoustic scattering, and reverberation | Sonar settings, ranges, and effectiveness; acoustic sweep path and sweep safety; undetected contacts due to poor acoustic conditions; and sonar hunt efficiency |
| *Water column properties* | Water temperature, salinity, water clarity, and depth | Temperature effects on diver operations; ability to visually or optically locate mines; conductivity for magnetic sweeps; and operational depths for sonars |
| *Seabed characteristics* | Bottom roughness, bottom composition, bottom strength, uncharted bottom features | Minehunting techniques; mechanical sweep gear limitations; extent of mine burial; damage/grounding of MCM gear |
| *Magnetic environment* | Electrical conductivity, number of magnetic MILCOs, ambient magnetic background | Ability to employ EOD ordnance locator gear or open-electrode sweeps; extent and strength of the magnetic field established by magnetic sweep gear |
| *Pressure environment* | Natural pressure fluctuations due to wave action | Actuation probability for pressure mines |
| *Biological environment* | Biological growth, hazardous marine life | Ability to detect, classify, or identify mines visually or with sonar; marine life presenting potential hazards to divers |

## 2.3 Doctrinal Bottom Type (DBT) Classification

Doctrinal Bottom Type (DBT) is a classification system used by MCM planners to provide a simple alphanumeric label describing the suitability of the bottom for minehunting. There are four different parameters used to define DBT: bottom roughness, bottom composition, percentage of mine case burial, and clutter category. The first three parameters lead to the letter portion of the classification, which can be “A”, “B”, “C”, or “D”. The last parameter, clutter category, gives the numerical label of “1”, “2”, or “3”. Combined, there are 12 DBT categories: A1-A3, B1-B3, C1-C3, and D1- D3. For MCM mission planning, DBT is imported into the MEDAL/MNT software from the NAVOCEANO databases. Each parameter that makes up the DBT is described in Table 3. Note that clutter is typically the poorest assumption for uncharted areas, but it can be updated in MNT with in situ information once the first few sonar runs have been processed.

Table 3: Doctrinal Bottom Type parameter descriptions and categories.

| **Parameter** | **Description** | **Categories** | | | |
|---|---|---|---|---|---|
| *Bottom Roughness* | This describes the sand ridge height | Smooth<br>< 6” | Moderate<br>6” -12” | Rough<br>> 12” | |
| *Bottom Composition* | This describes the sediment type for a given location. | Mud | Sand | Rock | |
| *Clutter* | This describes how many mine-like contacts (MILCOs), either natural or manmade, are found on the bottom per square nautical mile. | 15 MILCOs/$nm^2$ | 15-40 MILCOs/$nm^2$ | 40 MILCOs/$nm^2$ | |
| *Percentage of Mine Case Burial* | Burial percentage gives the expected mine burial from impact, scour, and bedform migration based on a nominal mine case diameter of 23.6”. | <10% | 10-20% | 20-75% | > 75% |

DBT gives a general classification of the minehunting environment, and helps a MCMC determine whether minehunting, minesweeping, or avoidance is the best course of action. DBT also factors into the characteristic swath width “A” parameter and probability of detection “B” parameter used in mine hunting planning software to compute track width and optimal orientation for sonar paths.

There are several positive aspects to the Doctrinal Bottom Type system. First, it is a simple, easy to understand classification system that only has 12 variations, so experienced operators should have a good understanding of what a specific DBT will mean for their mission, as long as they understand what the values of the classification parameters are. Also, it is “corporate knowledge” across the MCM force and has been the doctrinal method for many years. Lastly, it would be difficult to implement a replacement classification system. A replacement system would need to be developed and based in “new” science; incorporated into the MCM planning process; incorporated into the NAVOCEANO databases that MNT imports planning information from; incorporated via software updates into the MNT planning system; added to MCM training curriculums; taught to current MCM operators by remedial training to understand the new system; and lastly, the new system would need to overcome the political resistance to change from the MCM community.

There are several arguments to be made against continuing with the current Doctrinal Bottom Type classification system. As mentioned before, there are only 12 categories for DBT, leading to reliance on large “bins” for site characteristics which do not provide detailed information about a site. These large bins can provide a false sense of confidence in a mission. For example, a type “B” bottom can be mud, sand, or rock, which have very different sediment properties and drastically change sonar performance. A type “B” bottom can also have anywhere from 0 to 75% estimated mine case burial depending on the sediment type and bottom roughness, which is a huge difference for sensor selection and for post-mission analysis work trying to identify mines.

With the continual advancement of sensors and automated target recognition (ATR) software, the coarse classification of the operating environment DBT provides will not prove sufficient to be used by all sensors. Due to differences in the development, operating frequencies, and software used by the various platforms, each system has its own unique sensitivities to different environmental parameters. A given minehunting system cannot accurately determine its probability of detection when given a DBT, unless additional details are known, such as the NAVOCEANO HFEVA sediment data. In the near future, there is a planned shift toward a “system of systems” using ATR to execute the full detect to engage sequence. For this to be attainable, systems will need detailed environmental data to properly compute their swath width, probability of detection, and percent clearance for a mission. The best way to achieve this is comprehensive pre-mission in situ environmental characterization either by the minehunting system itself or some of the methods described in section 2.2.

# Chapter 3

# MINE BURIAL MECHANISMS

## 3.1 Initial Burial

For all sediment types besides rock, some initial burial of a mine will occur when it impacts the seafloor. Cohesive sediments are clays and silts, and cohesionless sediments are sands and gravels (Soulsby, 1997). For cohesionless sediments, impact burial is typically low, while for cohesive sediments, a mine can be completely buried after impact. In cohesive sediments, the sediment particles are small enough (typically less than 0.06 mm) to be attracted to each other and stick together by biological and electromagnetic processes. Cohesionless sediments are where the grains are not attracted to each other. The shear strength and bearing capacity is typically lower in cohesive sediments.

Impact burial is a function of the bearing strength of the sediment and the velocity, attitude, and shape of the mine when it hits the sediment. Higher velocity of the mine when it reaches the seabed, a more vertical impact angle, and lower bearing strength of the sediment lead to higher impact rates. Impact models account for three phases of the process as the mine drops: falling through the air, falling through the water, and bottom penetration. The calculations tracking the mine’s trajectory through the air and water provide the velocity and angle when the mine reaches the seafloor, which is then used to calculate the bottom penetration and amount of burial.

## 3.2 Scour Burial

Following the initial impact with the seafloor, mines will experience further burial if the environmental conditions allow. Subsequent burial can occur from scour processes, bedform migration, or even liquefaction of the sediment.

When an object is on the seafloor, it disturbs the flow field occurring at that location. It will force the flow to travel over and around that obstacle, effectively shrinking the area the flow passes through, increasing the velocity and potentially the turbidity of the flow. This amplification of velocity and turbulence increases the shear stresses on the bed, which can lead to mobility of the local sediment around the object. On short time scales, sediment around an object on the seabed can erode or be deposited surrounding the object. These localized effects quickly dissipate with increasing distance from the object.

Sediment mobility can be predicted by calculating the critical Shields ($\theta_{cr}$) parameter for a given grain size and comparing it to the Shields parameter ($\theta$) for given wave/current forcing. The Shields parameter is a function of the water velocity at the bed, the sediment grain size, sediment density, and water density. If $\theta > \theta_{cr}$, the sediment will be mobilized. Variable forcing and direction of waves and currents produces a time variation in the amount and pattern of scour. Scour is termed a "near-field" process since it is dictated by and occurs directly surrounding an object on the seabed.

## 3.3 Bedform Migration

Bedform migration is the formation and movement of large-scale bathymetric features (sand ridges) within a littoral cell over long time periods. This can occur during a large storm but is typically associated with the long-term wave/current climate at a location. These large-scale features (1 m high, 100+m long) can travel long distances (several km) within a littoral cell, shoreward of the depth of closure. The migration can take months or even years. As these features move, they can bury and re-expose anything on the bottom.

The mechanics of bedform migration are similar to that of local scour, but affect the entire equilibrium beach profile of the area (Jenkins et al., 2007). Bedform migration is termed a “far-field” process since it occurs throughout a littoral cell, independent of influence by minelike objects on the bottom. Figure 1 shows the mechanisms and changing burial conditions for nearfield scour burial and farfield bedform migration burial and re-exposure (Inman & Jenkins, 2002). The extent of how far offshore the large scale bedform migration and bathymetry changes occur is tied to the idea of “depth of closure”. This depth of closure is the distance offshore where the beach profile no longer changes due to wave and current action.

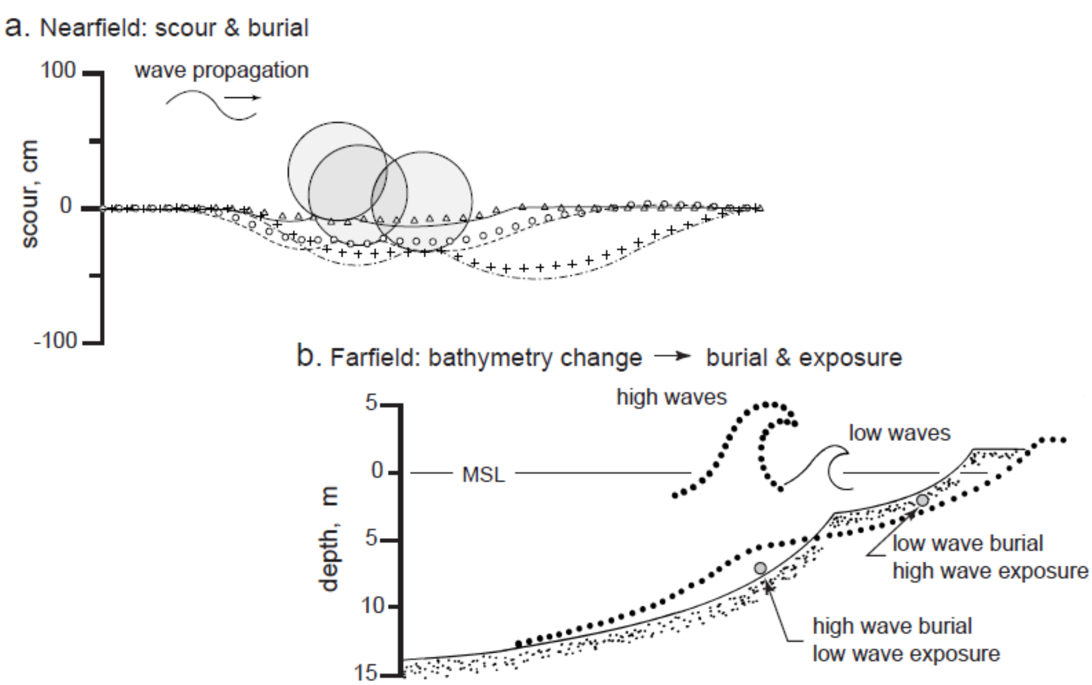


Figure 1: Schematic of nearfield scour burial and farfield bedform migration (from Inman & Jenkins, 2002, Figure 4.4).

### 3.4 Liquefaction

The seabed is in a liquefied stated when it has low or zero shear stress, meaning that the grains within the bed are unconstrained by neighboring grains. This eliminates the capacity of the bed to offset any vertical loads and increases grain mobility since there is reduced intergranular friction, decreasing the critical Shields parameter. Thus, a mine resting on top of the bed is likely to sink and can be much more easily covered with adjacent sediment grains. Liquefaction is mainly driven by steep storm waves that generate high pressure gradients at the bed. The high pressure gradients under the wave crests are followed by low pressure gradients under the wave troughs, and this cyclic pressure change in the pores can cause liquefaction behavior (Whitehouse, 1998).

# Chapter 4

# PREDICTING SCOUR BURIAL OF SEA MINES

Gaining a better understanding of subsequent burial of sea mines is the thrust of this research. Using established equations and methods, large data sets were generated covering various wave conditions, sediment sizes, and water depth to determine the interdependence of these variables and their relative importance to predicting mine burial.

## 4.1 Scour Burial Model

The time series scour burial procedure outlined by Trembanis et al. (2007) was used to generate data for several cases using varying wave conditions, water depths, and sediment grain sizes. Data were used to analyze scour around sea mines and to determine better predictive methods for use in MCM planning. The model was created in Matlab by modifying the scour burial model from the NRL's DMBP program (Elmore et al., 2007) to run time series analysis for specific wave conditions and sediment types. See Table 4 for the 36 different case perturbations. The scour model MATLAB script used is Appendix A.

Given wave height (*Hs*), wave period (*Tp*), median grain size (*d50*), and other constant parameters, the Matlab script calculated scour burial over a given time series ($t$) from 1 to 5000 time steps and for a range of water depths ($h$) from 1 m to 300 m. For each $h$, linear theory was used to calculate wavelength ($L$), accounting for the shoaling that occurs due to depth. Next, the orbital velocity ($U$), amplitude ($A$), and bottom friction factor (*fw*) were calculated by Equation 1, Equation 2, and Equation 3, respectively to determine the Shields parameter ($\theta$) (Equation 4) for the given case.

$$U = \pi * Hs \,/\, \left(\frac{Tp * \sinh(2\pi h}{L}\right) \quad (1)$$

$$A = {(U * Tp)}\big/{2\pi} \quad (2)$$

$$fw = \exp\left(5.213 * \left(\frac{d50}{A}\right)^{0.194} - 5.977\right) \quad (3)$$

$\theta = \frac{fw * U^2}{2 * g * d50 * \left(\frac{\rho_{sed}}{\rho_w} - 1\right)}$, where $\rho_{sed}$ is sediment density and $\rho_w$ is seawater density. (4)

Following the calculation of the Shields parameter, the critical Shields parameter ($\theta_{cr}$) was calculated from the dimensionless grain size ($D_*$) using conditional statements to check if the sediment is fine sediment (Whitehouse, 1998).

The procedure continues to determine the time series of scour burial. The dimensionless time scale of scour ($T_*$) is found using $\theta$ and two empirical coefficients determined from experimentation by Whitehouse (Whitehouse, 1998) (Trembanis et al., 2007). Next, the time scale for burial ($T$) is calculated from $T_*$, initial mine diameter ($D_o$), and *d50*. The specific ultimate scour pit depth (*Se*) equation to use is determined by the ratio of ($\theta/\theta_{cr}$). *Se* is then used to determine the amount of scour (*S*) at the given time step. Burial was assumed to be "burial by depth", meaning that the depth of the scour pit at a given time step is the depth of mine burial. The mine was assumed to stay buried (no re-exposure) once it experienced burial. At the end of the time series, the script begins again with the next water depth. Each time step *t* can be thought of as one period (*Tp*) of wave forcing.

The mine type used for this experiment was the Mk 57 mine with a diameter of 0.57 m (Morison, 2000). This is an intermediate size for many mines found throughout the world. See Table 5 for output variable descriptions and sizes.

Table 4: Input values for burial prediction.

| **Data Input Variables** | |
|---|---|
| ***Wave Parameters (Hs, Tp)*** | ***d50 (mm)*** |
| 1 m, 7 s | 0.1 |
| 2 m, 10 s | 0.2 |
| 3 m, 15 s | 0.3 |
| 4 m, 20 s | 0.5 |
| 5 m, 25 s | 0.7 |
| 6 m, 30 s | 1.0 |

Table 5: Scour burial output variables and their descriptions.

| **Data Output Variables** | | | |
|---|---|---|---|
| ***Variable*** | ***Size*** | ***Units*** | ***Description*** |
| Hs | 1 | m | Wave height |
| Tp | 1 | s | Wave period |
| d50 | 1 | m | Median grain diameter |
| h | 1xM | m | Vector of water depth values |
| t | 1xN | - | Vector of time step values |
| $D_o$ | 1 | m | Initial mine diameter |
| D | MxN | m | Matrix of changing mine diameter based on scour |
| deltaS | MxN | m | Matrix of scour amount for each time step |
| burialPct | MxN | % | Matrix of mine burial percentage |
| t_75 | Mx2 | - | Matrix denoting the time step of when burial reaches 75% |
| T | 1xM | - | Vector of the 63% equilibrium burial time scale |
| L | 1xM | m | Vector of wavelength values based on Tp and h |
| U | 1xm | m/s | Vector of bottom orbital velocity for each h |
| Re | 1xM | - | Vector of Reynolds number for each h |
| θ | 1xM | - | Vector of the Shields parameter for each h |
| $\theta_{cr}$ | 1 | - | Critical Shields parameter for given d50 value |
| ** Output scour variables are in an MxN matrix, with M rows of water depth and N columns of time steps.* | | | |

## 4.2 Scour Burial Data Analysis

In order to conduct data analysis, it was necessary to compile the case data into variables based on wave conditions. For example, *burialPct* was compiled into *Hs1_burialPct*, which became an MxNx6 variable, with the third dimension being the six different *d50* values. Due to the number of variables mine burial is affected by, data analysis becomes a 4D problem to consider all important variables at the same time (see Figure 2).

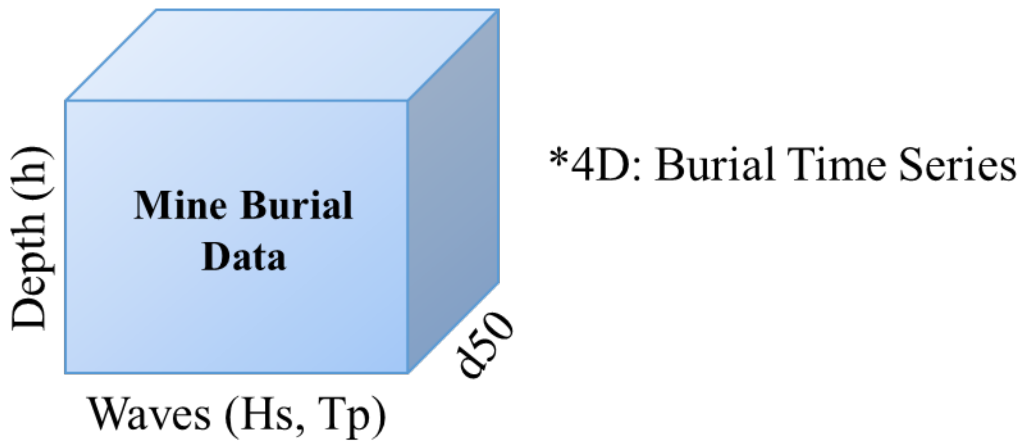


Figure 2: Mine burial results depend on four variables, making analysis 4D.

The same can be done to examine what happens for a given *d50* value over the range of wave parameter cases, creating MxNx6 variables now with the six different wave parameter cases being the third dimension. The focus of analysis was placed on examining the results for values of *d50* = 0.2 mm and *d50* = 0.7 mm, as these represent the typical range of grain sizes found in the nearshore and farshore in areas with non-cohesive sediment bottoms.

## 4.3 Scour Burial Results

Time dependent scour burial results were found for all wave conditions, grain sizes, and water depths. Simulations indicate that, as expected, mine burial increases for: shallower water depth, increased wave height, or smaller grain size (for non-cohesive sediments). Understanding the relative importance of each variable and quantifying its impact is the key to improving scour burial processes and prediction.

Contour plots were used to show time series of burial for the water depth range using a given wave case and sediment size. Figures 3 and 4 show results for all wave cases and two different sediment sizes for each wave case (*d50* = 0.2 mm and 0.7 mm). The contour plots are arranged in descending wave case order (*Hs* = 1 m to *Hs* = 6 m), with *d50* = 0.2 mm in the left column and *d50* = 0.7 mm in the right column. Wave conditions are constant for each row (e.g. *Hs* = 1 m for (a) and (b)), and grain size is constant for each column (e.g. *d50* = 0.2 mm for (a), (c), and (e)). The scale of water depth from 1 m to 300 m is constant on the y-axis and the time scale from t = 1 to 5000 is constant on the x-axis. Burial percentage is denoted by the color bar and is divided into 10% contours and allows direct comparison of burial percentage results for the various cases.

Consistently for all cases, burial percentage for a given water depth decreases with an increase in grain size (up to a certain shallowness, where burial remains 100%). Increasing the wave forcing has an almost twofold increase in the depth predicted to have complete (100%) burial, as seen by the “jump” of the dark red color in descending plots. The relative rate of burial can be inferred from the slope of the contour lines. The rate of burial increases with larger wave heights, denoted by the increasing slope of the contour lines in the first portion of the plot (t = 0 to 2000). Smaller grain size also generates a slight increase in the rate of burial.

For all plots besides *Hs* = 6 m the contours approach a horizontal asymptote; this asymptote is the equilibrium burial percentage for a particular depth under the given forcing conditions. The asymptotic equilibrium burial percentage takes longer to achieve for larger burial percentage values since it takes the repeated forcing more time steps to reach that amount of burial. The amount of time steps to reach a chosen equilibrium burial percentage (e.g. 20%) is approximately the same for a given grain size, regardless of the wave forcing. More time is required for equilibrium burial for smaller grain sizes than larger grain sizes. This difference in time steps to equilibrium burial is likely due to burial in smaller grains being more sensitive to forcing conditions.

The results also show relatively wide and evenly dispersed contour intervals for the first 1500 time steps; at this point the contours begin to transition toward their asymptotic values. Upon transitioning to the asymptotic burial, the curves tend to concentrate around a narrow band of water depth, leaving two large areas above and below. Above the narrow band, in dark blue, denotes depths where no burial will occur, and below the band, the dark red denotes 100% burial. Given sufficient time under the forcing conditions, with mines evenly distributed across the range of water depths, most mines will either experience complete burial or no burial, with only a small fraction experiencing partial burial. Thus, instead of trying to determine an exact burial percentage expected at a given depth, it may be more appropriate to identify a bathymetric contour differentiating burial or no burial. This idea will be examined further with the concept of a "Burial Dominance Line" (BDL) in section 5.

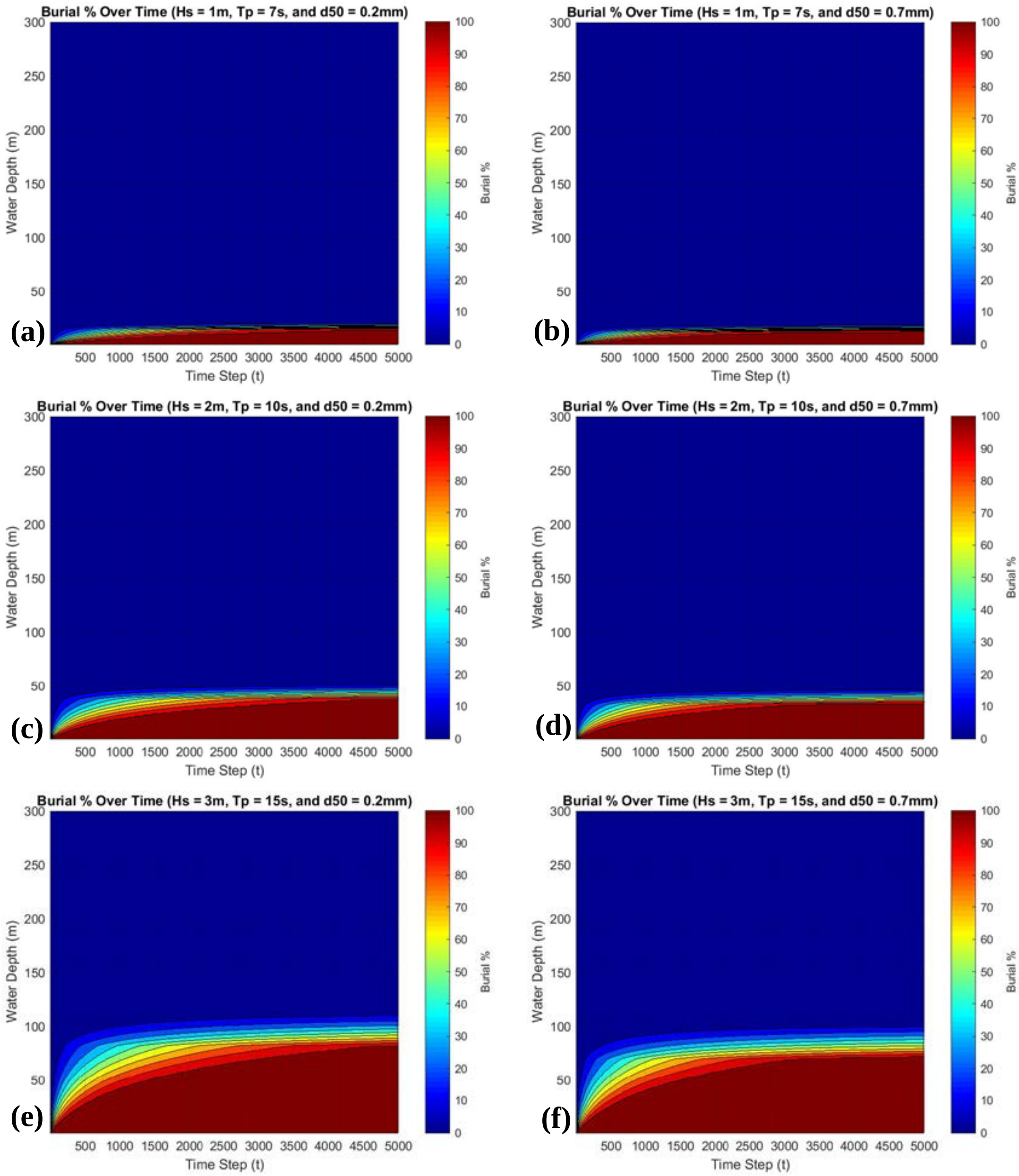


Figure 3: Burial percentage over time for *Hs* = 1 to 3 m and *d50* = 0.2 and 0.7 mm.

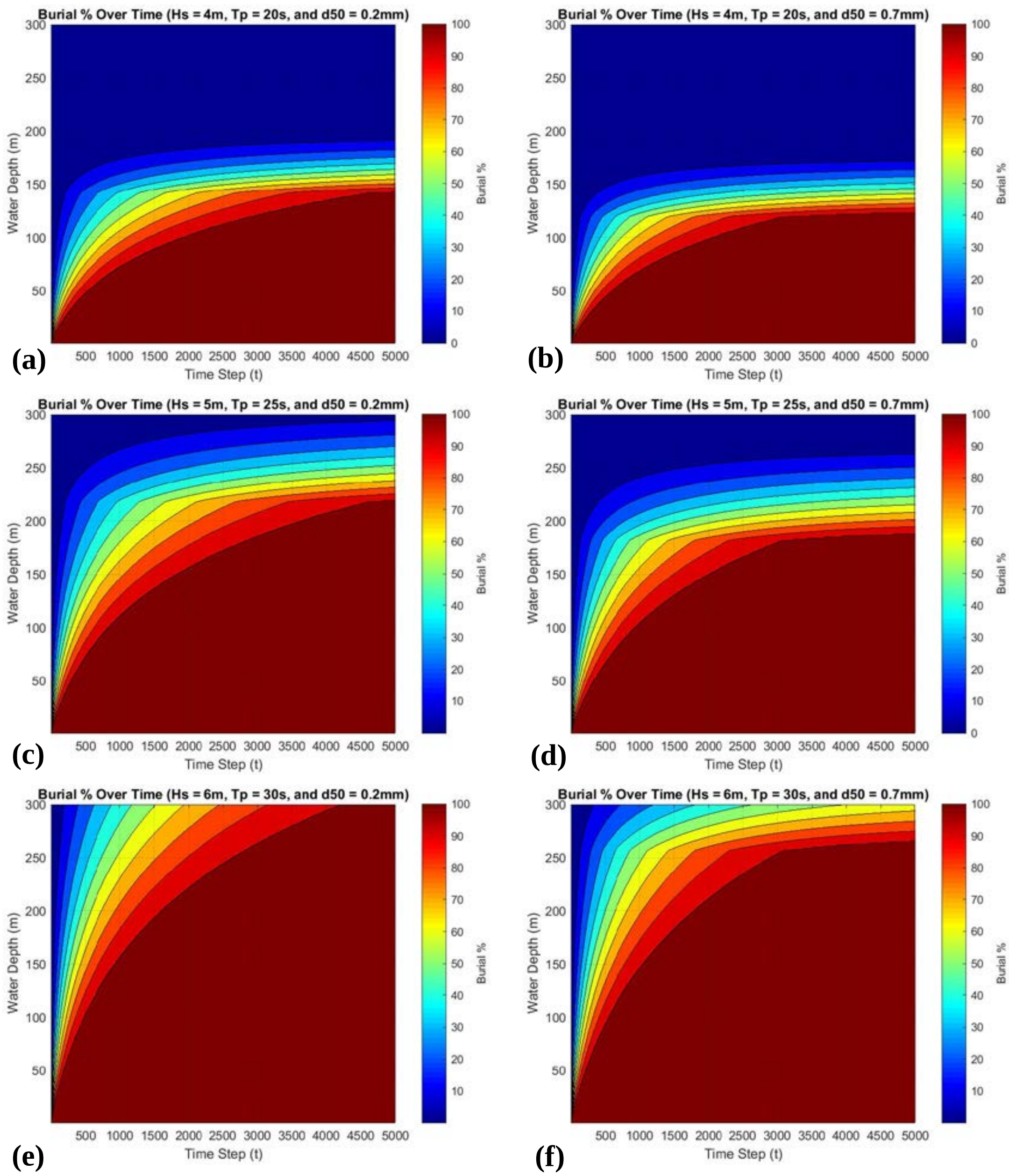


Figure 4: Burial percentage over time for *Hs* = 4 to 6 m and *d50* = 0.2 and 0.7 mm.

A relatively narrow band of burial outputs covering the range of 10%-75% was found for all results. To explore this narrow burial band further and to tie the burial percentages to MCM doctrine, the contour plots were recreated to place contours at the levels of the DBT burial percentage categories (0-10%, 10-20%, 20-75%, and > 75%). Figures 5 and 6 use the same data and scale of Figures 3 and 4, with the only change being the contour intervals and colors.

Table 6 shows the asymptotic water depth values for each DBT burial percentage category for wave conditions of *Hs* = 1 m to *Hs* = 5 m and for *d50* = 0.2 mm and 0.7 mm. Results were not obtained for *Hs* = 6 m since equilibrium burial states were not reached for the range of depth values (significant burial was predicted for depths greater than *h* = 300 m). Each DBT burial category can be considered by a "band" of given depths where that amount of burial percentage can be found. The ranges of each band (depth values covered) were compared to each other for a given case to determine their relative size compared to each other. Since the band for burial of less than 10% will extend from the edge of the 10% to 20% to the ultimate water depth, which is variable, that proportionality was not considered. The key comparisons were between the 10%-20% band, the 20%-75% band, and the greater than 75% band.

The size of the 10%-20% band was found to be an average of 27% of the 20%-75% band, the size of the 20-75% band was found to be an average of 22% of the greater than 75% band, and the combined 10%-75% band was found to be an average of 28% of the greater than 75% band. This finding confirms that even though the burial percentage band of 10%-75% covers 65% of given burial states, it is relatively small compared to the greater than 75% burial band. The size of the 10%-75% band can thus be found by Equation 5 and size of the 20%-75% band found by Equation 6.

$$10\%\ to\ 75\%\ Burial\ Band\ = 0.28 * \ > 75\%\ Burial\ Band \quad (5)$$

$$20\%\ to\ 75\%\ Burial\ Band\ = 0.22 * \ > 75\%\ Burial\ Band \quad (6)$$

As an example, the wave case for *Hs* = 1 m is only predicted to have 10%-75% burial at 5 values of water depth (*h* = 16 m to *h* = 21 m), while greater than 75% burial is expected between 1 m and 15 m depths. Deeper than 21 m, burial is predicted to be less than 10%. Depending on the operational area, there could be large areas that comprise the 16 m to 21 m water depths, but it is important for MCM operators to understand the partially buried state is only a small portion of potential burial states.

Table 6: Depth of occurrence of DBT burial categories for given wave conditions.

| | Hs=1m, d50=0.2mm | Hs=1m, d50=0.7mm | Hs=2m, d50=0.2mm | Hs=2m, d50=0.7mm | Hs=3m, d50=0.2mm | Hs=3m, d50=0.7mm | Hs=4m, d50=0.2mm | Hs=4m, d50=0.7mm | Hs=5m, d50=0.2mm | Hs=5m, d50=0.7mm |
|---|---|---|---|---|---|---|---|---|---|---|
| **Transition depth (m) from <10% burial (Green to Yellow)** | 21 | 19 | 50 | 46 | 110 | 100 | 191 | 172 | 294 | 263 |
| **Transition depth (m) from <20% burial (Yellow to Red)** | 20 | 18 | 48 | 44 | 105 | 95 | 183 | 164 | 281 | 251 |
| **Transition depth (m) from <75% burial (Red to Black)** | 16 | 14 | 40 | 36 | 88 | 78 | 153 | 134 | 235 | 205 |
| | | | | | | | | | | |
| **10%-20% burial depth band (m) (Yellow)** | 1 | 1 | 2 | 2 | 5 | 5 | 8 | 8 | 13 | 12 |
| **20%-75% burial depth band (m) (Red)** | 4 | 4 | 8 | 8 | 17 | 17 | 30 | 30 | 46 | 46 |
| **Combined burial depth band (m) for 10%-75% (Yellow and Red)** | 5 | 5 | 10 | 10 | 22 | 22 | 38 | 38 | 59 | 58 |
| **10%-20% Band (Yellow) Compared to 20%-75% Band (Red)** | 25% | 25% | 25% | 25% | 29% | 29% | 27% | 27% | 28% | 26% |
| **20%-75% Band (Red) compared to depth of >75% burial (Black)** | 25% | 29% | 20% | 22% | 19% | 22% | 20% | 22% | 20% | 22% |
| **Combined 10%-75% burial band (Yellow and Red) compared to depth of > 75% burial (Black)** | 31% | 36% | 25% | 28% | 25% | 28% | 25% | 28% | 25% | 28% |

| | Avgerage for d50=0.2mm | Avgerage for d50=0.7mm | OVERALL AVERAGE |
|---|---|---|---|
| **10%-20% Band (Yellow) Compared to 20%-75% Band (Red)** | **27%** | **26%** | **27%** |
| **20%-75% Band (Red) compared to depth of >75% burial (Black)** | **21%** | **23%** | **22%** |
| **Combined 10%-75% burial band (Yellow and Red) compared to depth of > 75% burial (Black)** | **26%** | **30%** | **28%** |

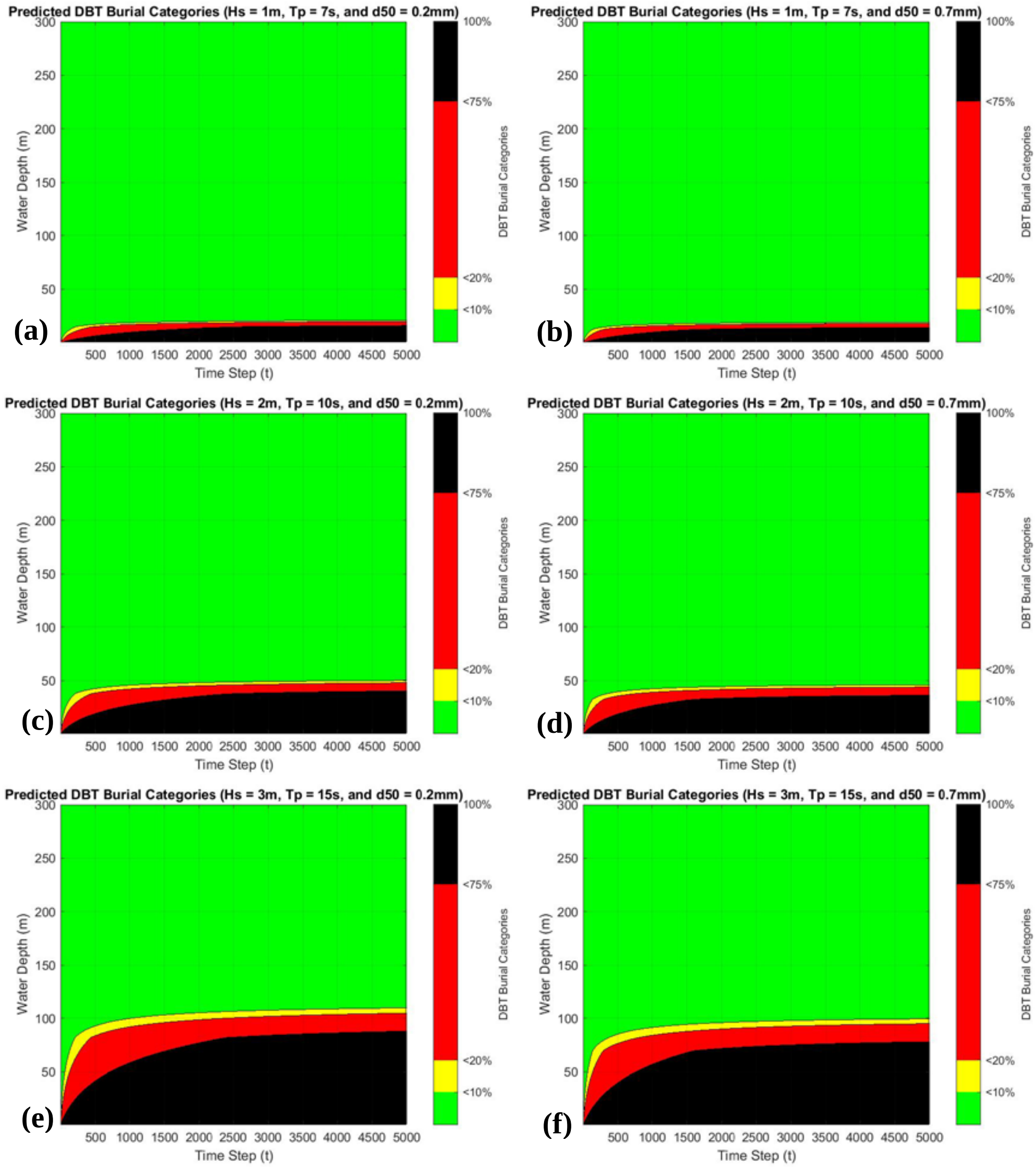


Figure 5: Burial percentage over time with contours of DBT burial categories for *Hs* = 1 to 3 m and *d50* = 0.2 and 0.7 mm.

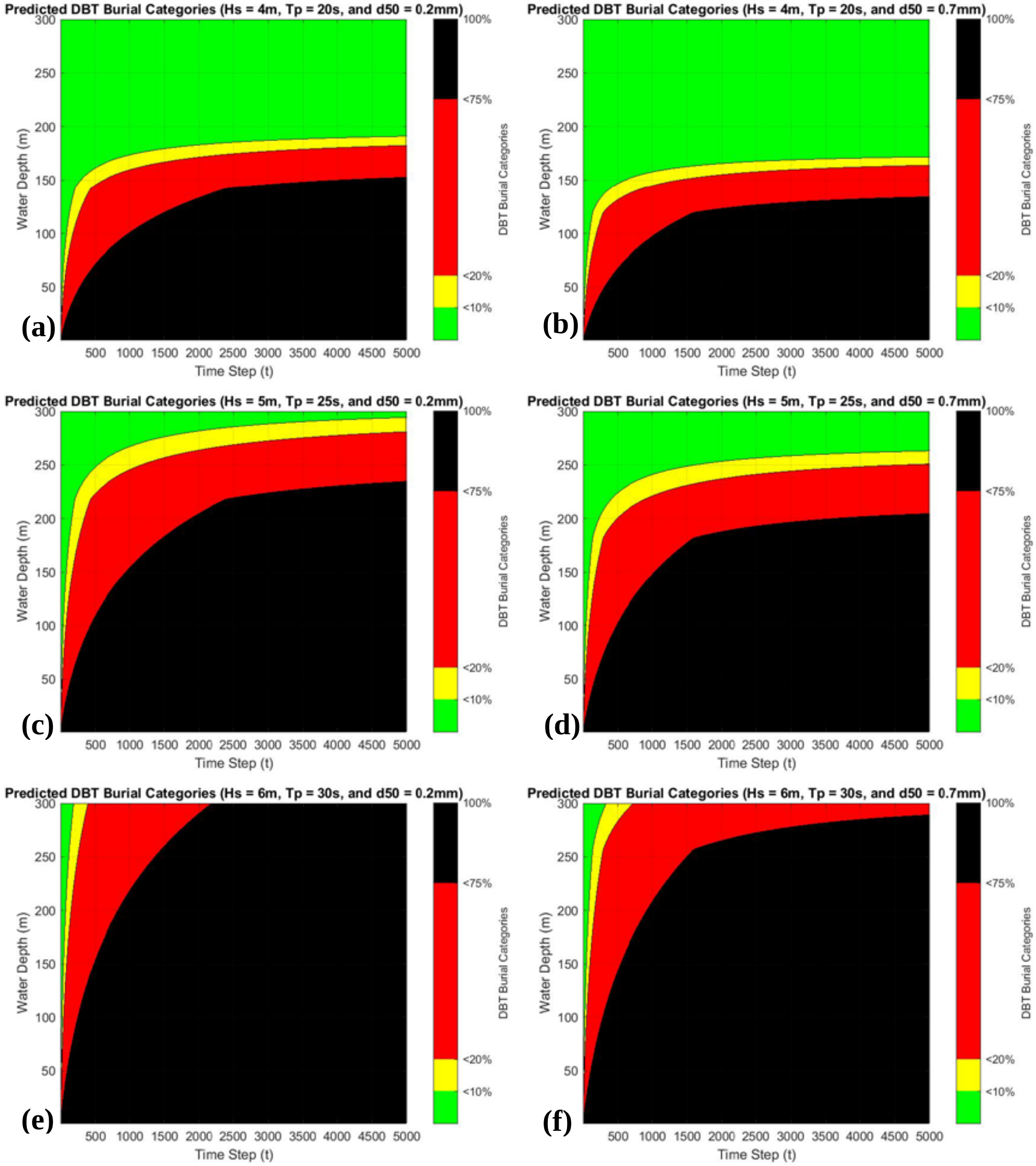


Figure 6: Burial percentage over time with contours of DBT burial categories for *Hs* = 4 to 6 m and *d50* = 0.2 and 0.7 mm.

An important parameter to analyze is the time it takes for a mine to reach 75% burial and the maximum depth to expect 75% burial for given wave conditions due to DBT burial categories from U.S. Navy MCM doctrine. Mine burial greater than 75% is the doctrinal cutoff for a DBT characterization for a type "D" bottom. A "D" bottom determination will usually result in the MCMC's decision to either switch from minehunting to minesweeping, or to avoid the area entirely. Figure 7 shows the number of time steps required to reach 75% burial for all values of *d50* and two sets of wave conditions, *Hs* = 1 m (lower curve) and *Hs* = 2 m (upper curve). Water depth on the y-axis shows the respective depths where the burial occurs. The time to burial increases with depth and grain size; burial occurs deeper and more rapidly for increased wave forcing, and that time to 75% burial is minimally dependent on grain size for depths up to 10 m (*Hs* = 1m) and 30 m (*Hs* = 2 m). Figure 7 also shows the cutoff depth for 75% burial where the data sets taper off.

Further analysis of the data investigated the relationship between *Hs/h* and comparing that to the final predicted burial value and to the time steps required to reach the critical burial value of 75%. Figure 8 and Figure 9 show the predicted final burial percentage based on *Hs/h* for *d50* = 0.2 mm and *d50* = 0.7 mm respectively. Of note is that a larger value of *Hs/h* indicates a shallower depth compared to the wave height, so depth *decreases* with an increase along the y-axis. The results for both cases show nearly horizontally sloping lines for all values of *Hs*. These slopes indicate that there are few values of water depth for a given *Hs* value that have between 0% and 100% burial, which affirms the earlier findings that most of the final predicted burial states are no burial or full burial.

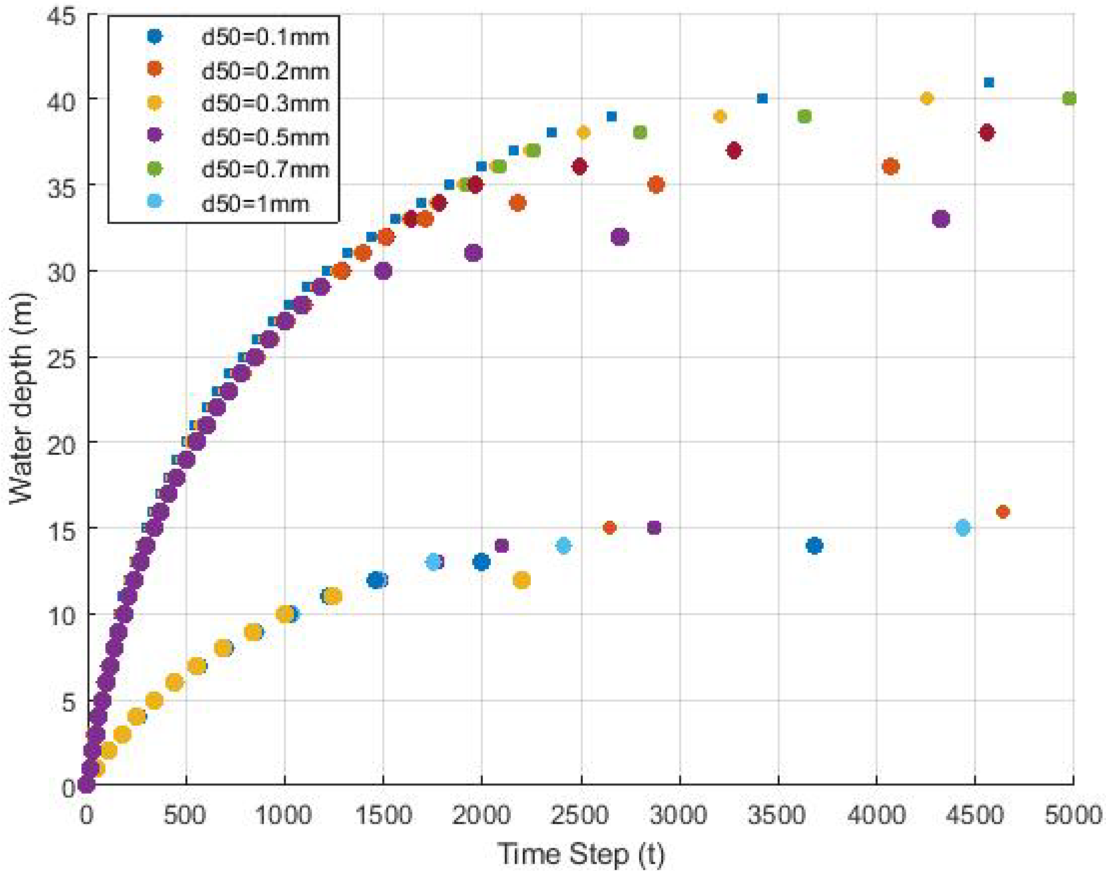


Figure 7: Time steps required to reach 75% mine case burial for all values of *d50* for *Hs* = 1 m and *Hs* = 2 m.

In Figure 8, the green line for *Hs* = 5 m starts at approximately 7% final burial, and the light blue line for *Hs* = 6 m is only seen along the right side at 100% burial, revealing that the minimum final burial for the given water depth (1 m – 300 m) is approximately 8% for *Hs* = 5 m and that there will be complete burial (100%) for all depths for *Hs* = 6 m. Figure 9 shows a similar phenomenon for *Hs* = 6 m, with a minimum burial of approximately 64% at the greatest depth. Both figures also show similar trends with increased wave height increasing the burial amount for a given depth, even for dimensionless *Hs/h*. The change in slope that can be seen approaching

100% final burial in the results for *Hs* = 1 m in Figure 8 and for *Hs* = 2 m in Figure 9 is a function of the relatively rapid change of burial percentage and *Hs/h* on this scale. The burial values for *Hs* = 1 m (Figure 8) transition over three water depths from 100% at *Hs/h* = 0.071 (*h* = 14 m) to 98% at *Hs/h* = 0.067 (*h* = 15 m) and to 77% at *Hs/h* = 0.063 (*h* = 16 m). The trend is not as drastic in Figure 9 for *Hs* = 2 m, but it does follow a similar fast decent from 100% burial at *Hs/h* = 0.061 (*h* = 33 m) to 98% at *Hs/h* = 0.059 (*h* = 34 m) and to 88% at *Hs/h* = 0.057 (*h* = 35 m). For larger wave heights, the transition from 100% burial to less than 100% burial occurs at deeper depths, where a 1 m change in *h* corresponds to a small change in *Hs/h*, and the trend line becomes more of a cut off than the sloped transition.

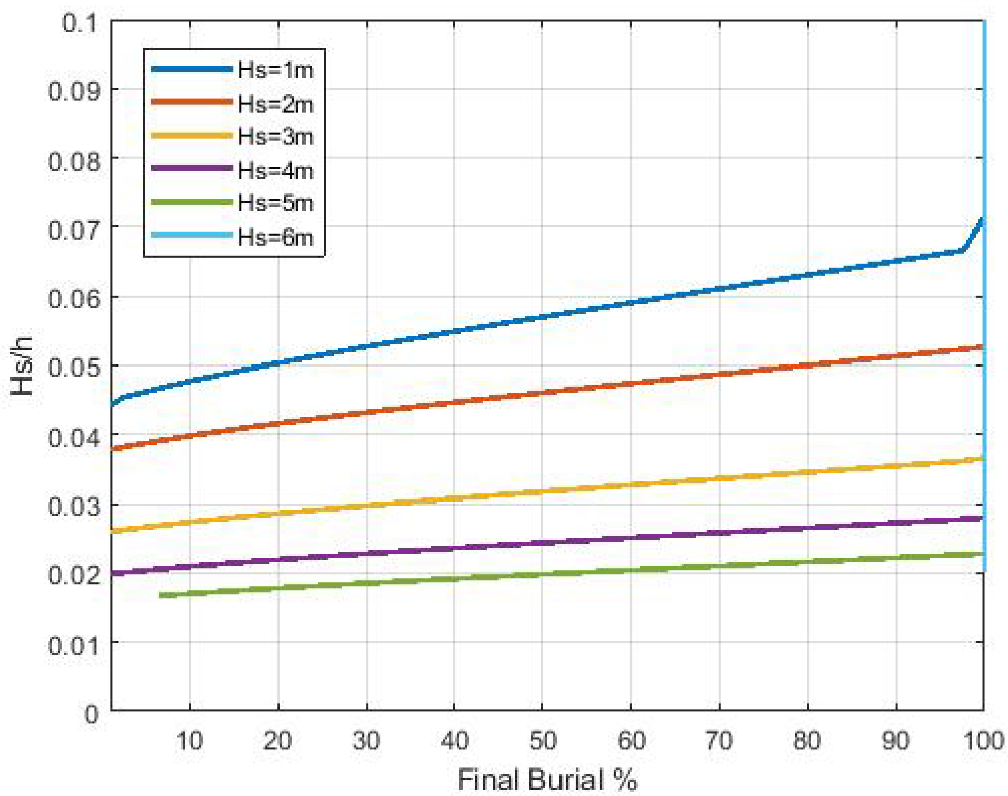


Figure 8: Predicted final burial percentage based on *Hs/h* for *d50* = 0.2 mm.

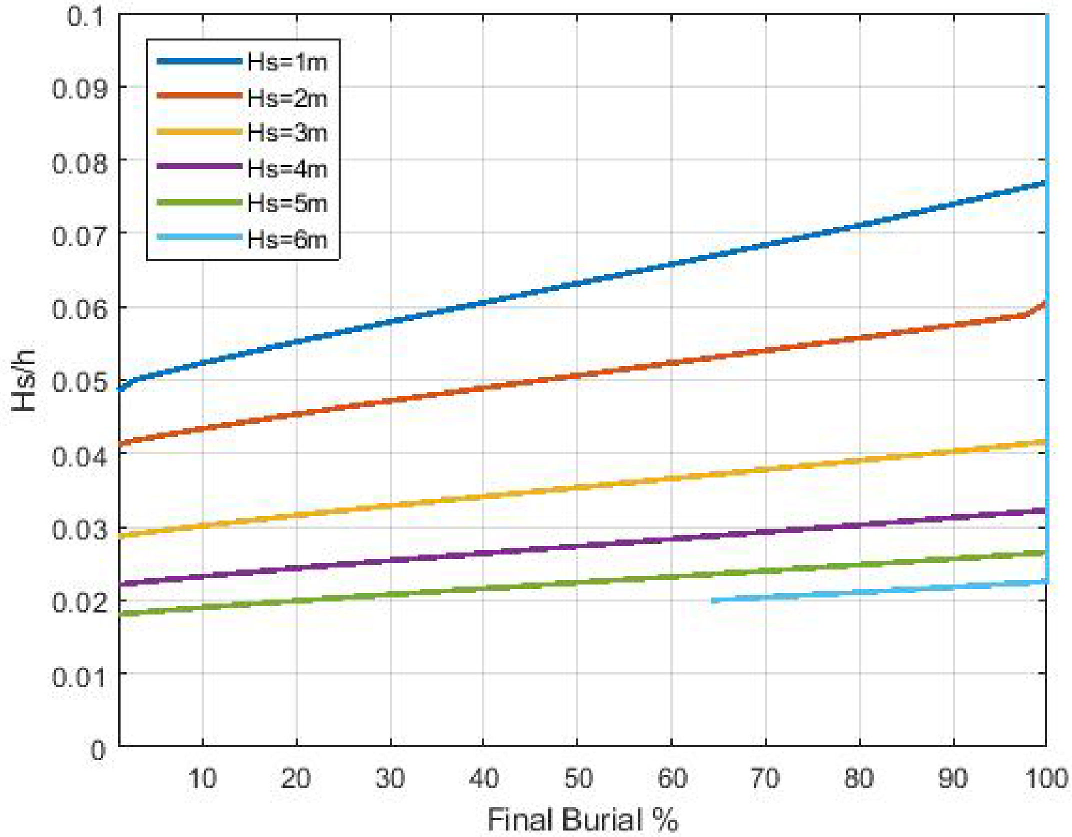


Figure 9: Predicted final burial percentage based on *Hs/h* for *d50* = 0.7 mm.

Insight is gained from analyzing individual cases and comparing findings. However, a more comprehensive visualization is required to summarize the results. The results for *d50* = 0.2 mm and 0.7 mm were assumed to provide an adequate range of cohesionless sediment sizes and all wave cases were compiled. As previously discussed, 75% burial represents a critical value for DBT classification and MCM operational decision making, so that value was used as the target burial percentage.

The results for the depth and time step when 75% burial is reached for all wave cases are shown in Figure 10. Sediment sizes between 0.2 mm and 0.7 mm are identified in the filled areas, providing a range of depths for the range of sediment sizes. The filled curves represent a given wave case where the top curve boundary represents 75% burial for *d50* = 0.2 mm and the bottom curve boundary represents 75% burial for *d50* = 0.7 mm. Any depth below the bottom boundary curve for a given wave case is predicted to have greater than 75% burial for that time step.

All of the curves show similar trends to the contours in Figures 3 and 4 with an exponential start that tapers toward an asymptotic value as time increases. Depth where burial reaches 75% increases with wave height, as does the height (range) of the filled area of the 75% burial depth.

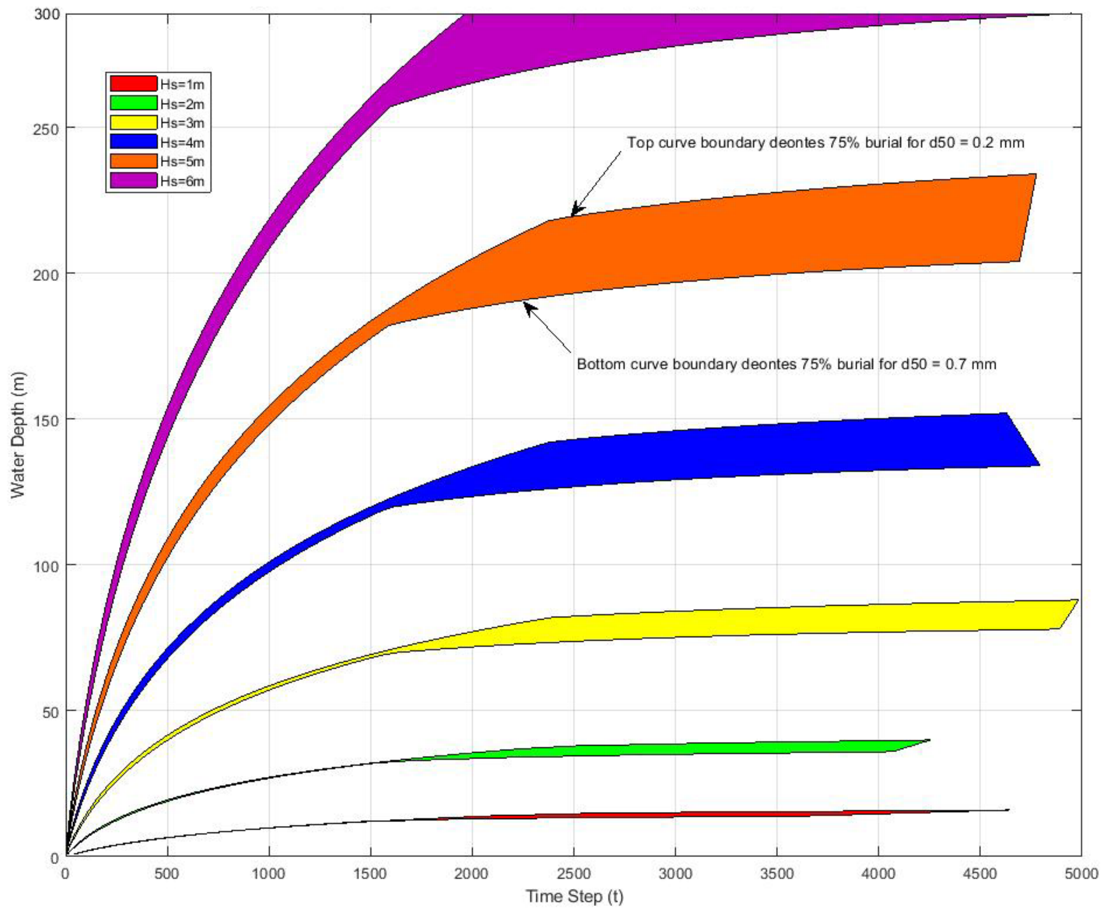


Figure 10: Depth and time step of 75% mine burial for all wave conditions and a range of *d50* values between 0.2 mm and 0.7 mm.

# Chapter 5

# THE DETERMINISTIC MINE BURIAL PREDICTION (DMBP) SYSTEM

## 5.1 DMBP Overview

The Deterministic Mine Burial Prediction (DMBP) system is a MATLAB-based graphical user interface (GUI) that provides time series of mine burial prediction for a given geographic location. The program requires inputs for bathymetry, sediment type, mine parameters, and a time series of wave and/or currents. Input files for bathymetry and sediment for the location of interest are extracted from NAVOCEANO databases, and wave conditions can easily be incorporated from NOAA Wavewatch III data files or SWAN wave modeling results. The user then determines the number of calculation locations to be placed on the map by choosing the number of mines to seed, and then can either have MATLAB randomly place the mines or can choose to seed all grid points. Calculations occur at these specific points, and results are interpolated between the points to provide full coverage of the area. DMBP first calculates burial due to the initial impact with the seabed, and then subsequent burial by scour (Elmore et al., 2009).

Data input files can be saved at any stage of the process (.mat), and data output files can also be saved to allow for further analysis or manipulation of results. Input files save the information the user has entered into the GUI, allowing for consistency between cases (including the random mine locations) and time savings from not having to re-enter the same data when running each case. The DMBP user guide provides clear step-by-step procedures to operate the program (Elmore et al., 2009).

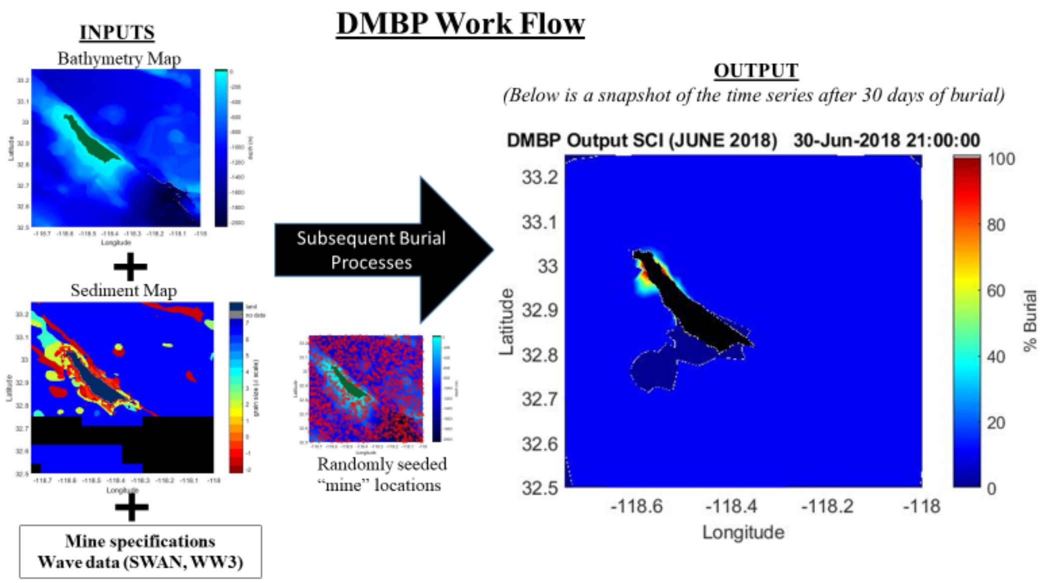


Figure 11: Workflow process for DMBP.

Following its development, DMBP was tested using field experiment data from several studies to ensure proper functionality and accuracy of both the impact and scour burial modules. Findings from the scour model validation showed that variations in wave height prediction were more significant in determining the accuracy of scour burial than uncertainty of grain size (Elmore et al., 2007), which matches the findings from the data generated by the scour model and discussed in section 4.

### 5.2 DMBP Experimentation

Experiments were conducted with the NRL's Deterministic Mine Burial Prediction System (DMBP) to develop a procedure for future analysts to conduct a burial assessment for a given area, which can then be used by MIW and MCM planning staffs to understand mine burial mechanisms for a given operating area. The focus when developing the procedures was on determining which output products to use from the program and providing recommendations for how MIW/MCM planners should use them in the established planning process.

Multiple case studies were run to determine seasonal mine burial and average that into a “Burial Dominance Line” (BDL) contour on the map to show where scour burial processes or impact burial processes dominate in a given area. The underlying assumption of the BDL is that there exists a distance offshore from each coast where the beach profile no longer changes due to typical wave and current action. Coastal scientists/engineers call this the “depth of closure”.  Shoreward of the depth of closure, an object on the seafloor will typically experience burial due to scour, bedform migration, and liquefaction caused by waves and currents. Seaward of that depth, an object dropped to the seafloor will experience impact burial, but typical wave and current forces will not be strong enough to cause subsequent burial.

The offshore distance of this “line” is a function of local bathymetry, wave climate, sediment type, tide, and currents. We propose that depth of closure can be delineated by a line off any coast to provide a visual representation of where bottom change occurs. Since this line denotes where initial burial processes or subsequent burial processes dominate, it is called the “Burial Dominance Line”.

For an area consisting solely of non-cohesive sediment, the BDL can delineate areas where either no/minimal burial or complete burial occurs. As found by analyzing the data output from the scour model, the depths where partial burial (20%-75%) occurs is only a small portion of water depths compared to greater than 75% burial. The BDL can thus identify the water depths of partial burial and delineate between no/minimal burial and pronounced/complete burial.

Two experiment locations were chosen to provide a range of different wave climates and bathymetry. Location 1 is off the coast of southern California, with a high energy wave climate and narrow continental shelf causing varied bathymetry. The area was created with a wider range of longitude to incorporate both the southern California coast and San Clemente Island off the coast. Location 2 is around the entrance to Delaware Bay, off the coast of Delaware and southern New Jersey; this is an area with a typically low energy wave climate and relatively shallow bathymetry due to the wide continental shelf on the U.S. east coast.

The experiment methodology was to cover two seasons (summer and winter) over five years of historical data for each site. An example summer case covered the months of June, July, and August for years 2014-2018, creating 15 data sets for each case. Summer and winter cases were run for each location to show site specific differences from relative high energy winter waves and low energy summer waves. Table 7 provides an overview of the cases run and Figures 12 and 13 show the bathymetry and sediment grain sizes for each case.

For each case, 3000 "mines" were seeded in the area, and an initial burial of 10% was assumed from the mine's impact with the seafloor. The impact burial portion of DMBP was not run in these simulations. Wave height and wave period data from NOAA's Wavewatch III model were used, which have 4-minute resolution. The site bathymetry was extracted from the NAVOCEANO DBDBV version 5.2 tool that accompanies DMBP, providing 0.05-minute resolution, and the sediment types were extracted from NAVOCEANO's Sediments2.0 database, which also accompanies DMBP.

Table 7: Overview of DMBP cases.

| Case # | Location | Wave Climate | Months of WW3 Data | Years of WW3 Data | Geographic Grid (degrees) | | | | Area Height (km) | Area Width (km) | Total Area (km^2) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Top (N) | Bottom (N) | Left (W) | Right (W) | | | |
| 1 | Southern California | Low Energy | JUN/JUL/AUG | 2014-2018 | 33.25 | 32.5 | 118.75 | 117.25 | 83.48 | 139.62 | 11654.61 |
| 2 | | High Energy | JAN/FEB/MAR | 2015-2019 | | | | | | | |
| 3 | Delaware Bay Entrance (Southern NJ & DE) | Low Energy | JAN/FEB/MAR | 2015-2019 | 39.25 | 38.25 | 75.25 | 74.5 | 111.30 | 64.64 | 7194.70 |
| 4 | | High Energy | JUN/JUL/AUG | 2014-2018 | | | | | | | |

The DMBP model was run for all annual and monthly instances for each case, for a total of 15 sets of results per case. The data outputs were both graphical maps of time series burial and time series data of burial percentage for each "mine" location. These data allowed for visual and numerical analysis of the results. Burial data for each month for each of the five years were averaged to determine a monthly average, and the three months of each season were averaged to provide a yearly seasonal average. Table 8 shows how the results were compiled.

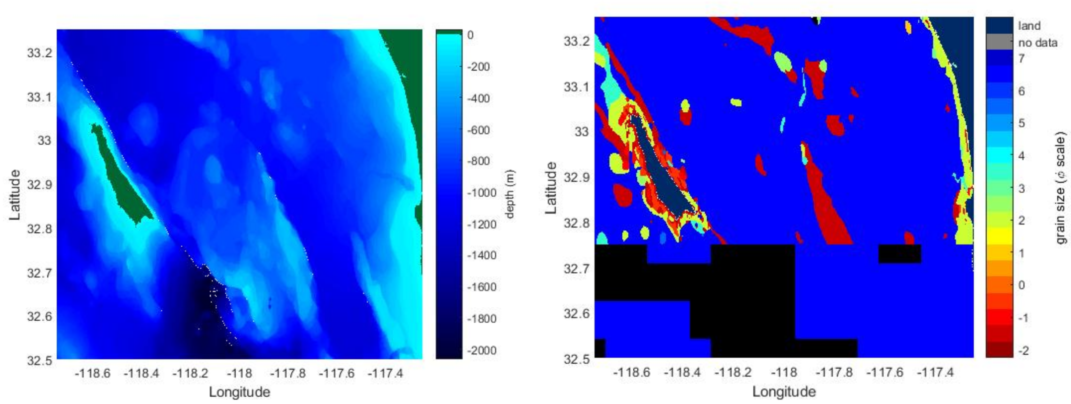


Figure 12: Bathymetry (left) and sediment size (right) for Case 1 and Case 2.

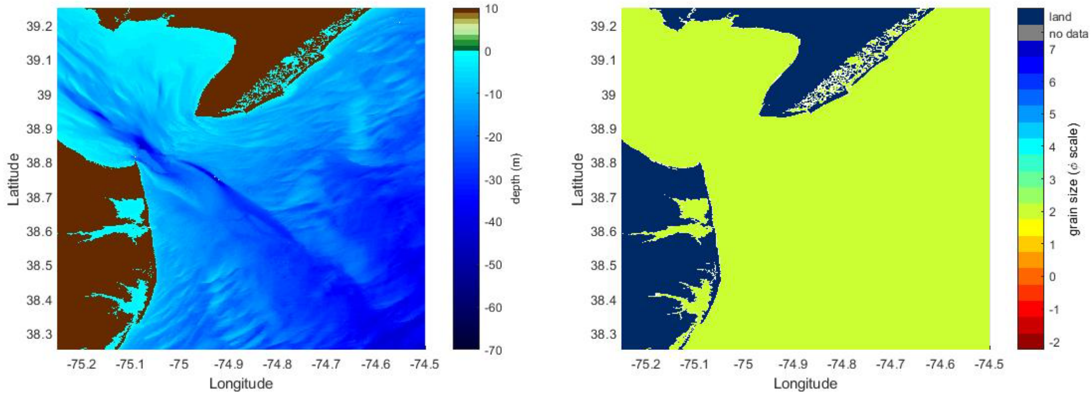


Figure 13: Bathymetry (left) and sediment size (right) for Case 3 and Case 4.

To create the BDL, the averaged subsequent burial data were used to generate a contour plot to show where minimal change has been predicted to happen over the time series. Seasonal cases were compared (Case 1 vs. Case 2; Case 3 vs. Case 4) to see how the BDL changes temporally for a site.

Table 8: An example of DMBP experiment results.

| ***Example Case #1 Experiment and Outputs*** | | | | |
|---|---|---|---|---|
| ***Month/Yr*** | ***JUNE*** | ***JULY*** | ***AUGUST*** | ***Yearly Average*** |
| ***2019*** | JUN19 Results | JUL19 Results | AUG19 Results | **2019-AVG** |
| ***2018*** | JUN18 Results | JUL18 Results | AUG18 Results | **2018-AVG** |
| ***2017*** | JUN17 Results | JUL17 Results | AUG17 Results | **2017-AVG** |
| ***2016*** | JUN16 Results | JUL16 Results | AUG16 Results | **2016-AVG** |
| ***2015*** | JUN15 Results | JUL15 Results | AUG15 Results | **2015-AVG** |
| ***Monthly Avg*** | **JUN AVG Results** | **JUL AVG Results** | **AUG AVG Results** | **Seasonal Avg** |

## 5.3 DMBP and BDL Results

The results from DMBP showed the variability of burial due to the wave forcing conditions, bathymetry, and sediment type. See Appendix B for all DMBP case outputs. Seasonal variation was evident in all cases, as was temporal variations between months of a season and between years for a given month. Location 1 off of Southern California for Case 1 and Case 2 proved more challenging to identify differences between individual results due to the high amounts of deep bathymetry at that location (rapid increase in depth with offshore distance) and the substantial area analyzed, which was over 1.5 times the size of the Location 2. For comparison, the maximum depth found in Location 1 is over 2000 m, while the maximum depth found at Location 2 is approximately 50 m.

Overall, trends showed increased burial during high energy winter months for all cases and increased burial at shallower depths. Areas that were constantly predicted to have burial occur were identifiable, as well as areas that could change from month to month or year to year depending on the wave forcing. Figures 14 and 15 show examples of wave forcing changing from year to year for a given month for Case 1 and Case 2 respectively, as well as seasonal differences between cases. Figure 14 shows reduced burial from 2014 (a) to 2015 (b), particularly along the northern and eastern sides of San Clemente Island (on the left side of the figure) and along the California coast (top right of the figure). Figure 15 shows reduced burial from 2017 (a) to 2018 (b), as well as the disappearance of a bar-like feature of approximately 40% burial off the California coast denoted by a white rectangle. The disappearance of this feature is significant, as overlooking an area of higher mine burial creates unidentified risk for operational forces transiting that area following mine clearance operations.

Also of note, the predicted burial for August 2014 (Figure 14 (a)) and January 2018 (Figure 15 (b)) show that the wave climate season is not always an accurate representation of burial. The disappearance of this predicted burial feature and the similarity of burial for August 2014 compared to January 2018 highlights both the annual variability of burial and reinforces the importance of understanding/predicting the wave climate to accurately predict burial.

Burial prediction changes were more pronounced in Cases 3 and 4 since the bathymetry was shallower, therefore smaller changes in the wave climate generate larger burial prediction changes. Figure 16 displays variations month to month within a given season during a single year. This year (2018) showed the most pronounced monthly burial prediction changes for Case 3, but similar monthly fluctuations can be seen for all years and all cases.

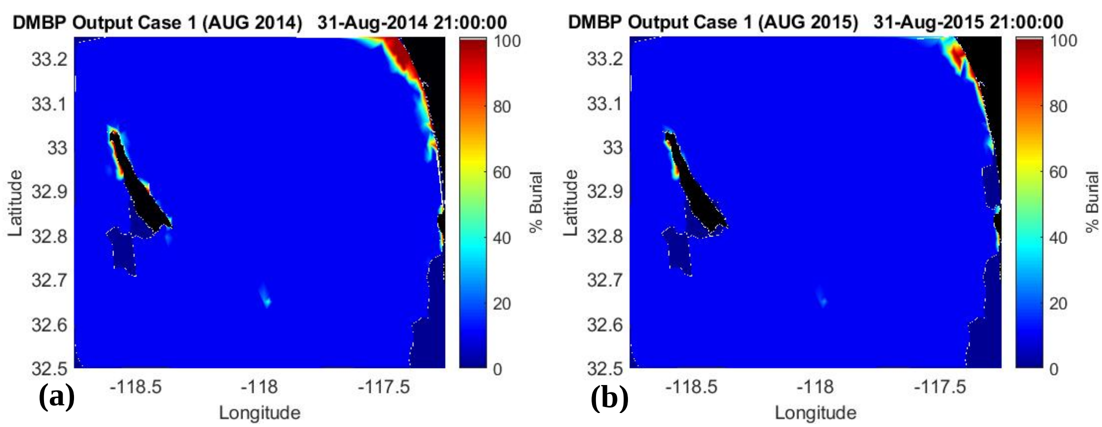


Figure 14: Difference in predicted burial from 2014 to 2015 for August.

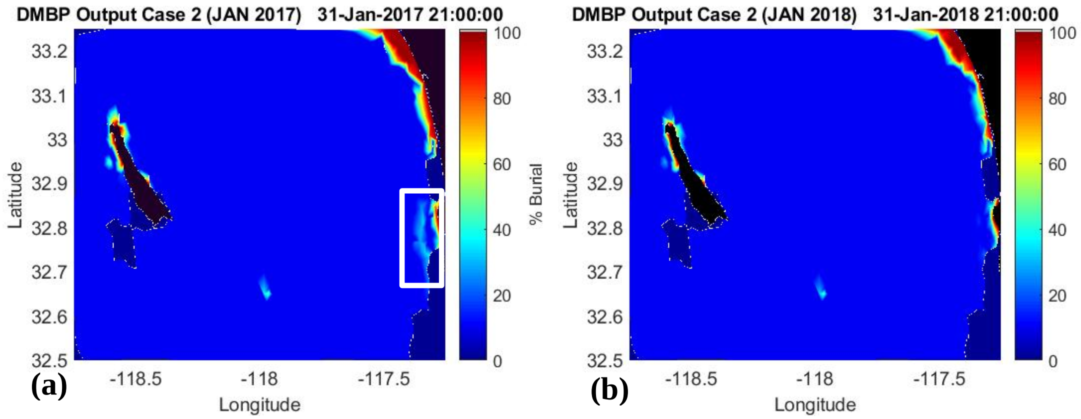


Figure 15: Difference in predicted burial from 2017 to 2018 for January.

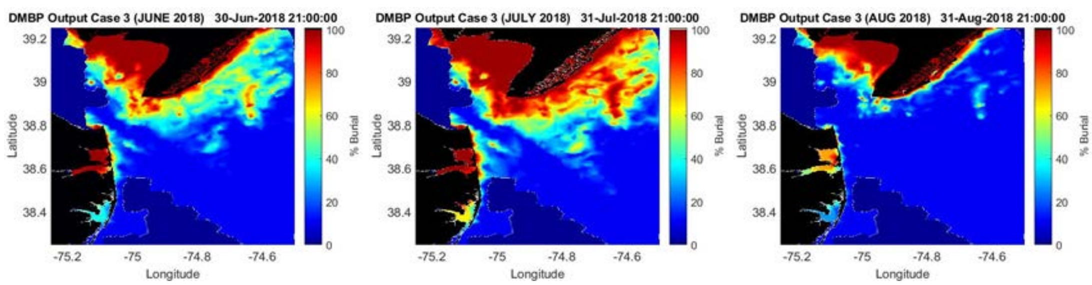


Figure 16: Variation in predicted monthly burial for one season (June to August 2018).

During several instances in Case 3 and Case 4, rapid burial was seen to occur over several time steps, between 24 and 72 hours. This can likely be attributed to storm events passing through a given location and serve as a reminder that burial does not have to be a slow process. Figure 17 shows an example from Case 4, from March 14, 2017 to March 16, 2017. Over the course of two days, much of the area off the coast of New Jersey (top right portion of the map) went from approximately 30%-40% burial to complete burial.

There is a six-hour time lapse between Figure 14 (a) and (b) to illustrate how rapidly the burial changes occurred, 24 hours between (a) and (c) to show the daily change, and 24 hours between (c) and (d) showing the establishment of a steady-state final equilibrium burial percentage.

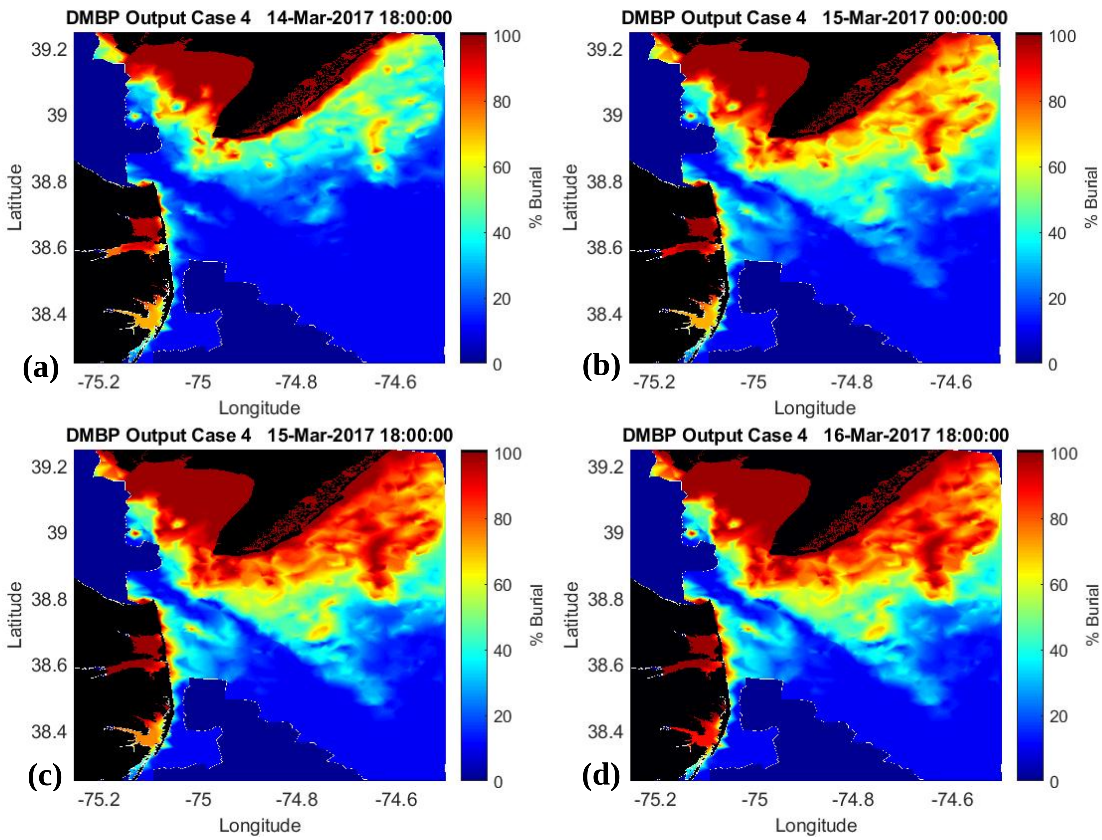


Figure 17: Example of a rapid burial event during one of the Case 4 scenarios.

After computing the monthly predicted burial for all of the cases, the results within each case were averaged to find monthly averages, yearly averages, and a seasonal average for the entire case (see the yellow boxes in Table 8). The seasonal average was generated by averaging the monthly and yearly averages all together, compiling all scenarios run for each case (15 scenarios). Plots of all results can be found in Appendix C; the BDL is the thick black line separating the blue and yellow areas.

When analyzing the data outputs and creating the BDLs, key concepts to understand were how the wave climate affects the location of the predicted BDL; how the BDL can change temporally for a specific location; and the effect of sediment grain size on the predicted BDL. Because there may be uncertainty in the wave climate predictions and sediment grain size, the BDL was plotted at 20% predicted burial, which accounted for initial impact burial (10%) and a minimal amount of scour burial. Of note, there were some areas where the WavewatchIII data were unavailable; those are the gray areas found on the BDL plots and dark blue areas on the DMBP output plots. Missing wave data creates some gaps in the predictions but by using predictions for similar bathymetry close to the area of no data, an educated guess can be made as to whether or not burial will occur.

For any given case, the BDL was found to show more variability from year to year than month to month, specifically for Case 3 and Case 4 where burial is more responsive to smaller changes in wave climate. Seasonal variability was also observed for Location 2 with the BDL shifting offshore significantly during the winter. Figure 18 shows the comparison between the seasonal BDL average for Cases 3 (summer) and 4 (winter). The areas of significant change are denoted by the red outline, which comprises areas of water depth between 15 m and 30 m. For reference, the two white triangles on Figure 18 are 20 km apart, showing a large increase in BDL shift offshore from summer to winter. The shift off the eastern coast of Delaware (left side of the figure) was approximately 15 km, also a significant shift. The no data area at the bottom of Figure 18 consists of water depths between 10 m to 25 m, so this area would more than likely experience burial as well. The area of no/minimal burial predicted for both seasons at the entrance to Delaware Bay averages between 35 m and 45 m depth; burial was not predicted here during any of the simulations.

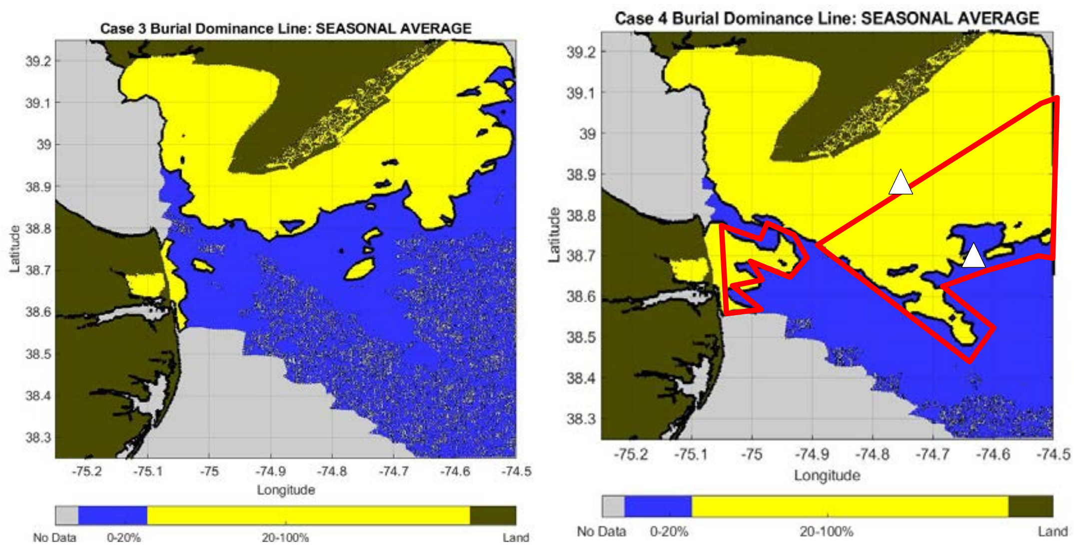


Figure 18: Seasonal BDL comparison for Location 2 (Case 3 and Case 4).

### 5.4 Applications of BDL to MCM Operations

The BDL denotes the approximate location for where the scour or impact dominated regions exist, or areas of minimal or complete burial for areas of non-cohesive sediment. Understanding where these processes occur in the MCM operational area can inform many aspects of the planning process and provide increased confidence in MCMC decision making. For operational decisions, the BDL can increase confidence in the determination between minehunting, minesweeping, or area avoidance, it can inform segmentation of the OPAREA and sequencing of clearance operations, how quickly re-acquire/ID needs to happen (due to changing bottom conditions in certain areas), and the types of equipment to use (e.g. low frequency sonar systems to better detect buried mines). From an environmental perspective, the BDL can inform an in situ environmental sampling plan and where to focus detailed environmental data collection (waves, currents, winds, sediment type) for improved burial calculations.

Figure 19 shows an example of how a BDL plot can be used to inform OPAREA placement and geometry for an example amphibious assault mission requiring mine clearance beforehand. The original OPAREA, comprised of the red rectangles, provides ideal placement for the two boat lanes (the two rectangles perpendicular to the shore) to reach the objective ashore. By overlaying the original area on the map with BDL plotted shows those areas are predicted to experience significant mine burial in almost the entire area. Hunting buried mines takes significantly longer and leaves increased residual risk compared to hunting minimally buried mines.

By examining the BDL and knowing the sediment type is predicted to be the same throughout this region (non-cohesive, so no impact burial concerns), a MCMC can make an informed decision to shift to the revised OPAREA (denoted by the green rectangles). There is still mine burial predicted in portions of this revised area, but it is predicted in considerably less of the area, therefore mine clearance can be expected to take less time and leave less risk. Even though this is farther from the objective, Marines are typically faster and safer traveling ashore to an objective than traveling through a mine-threat area onboard a ship.

There are of course many factors that go into determining the location of a military operation (e.g. the enemy threat, proximity of support forces, etc.), but the BDL provides the commander a better understanding of the operational environment to help balance the mine burial threat against these other factors.

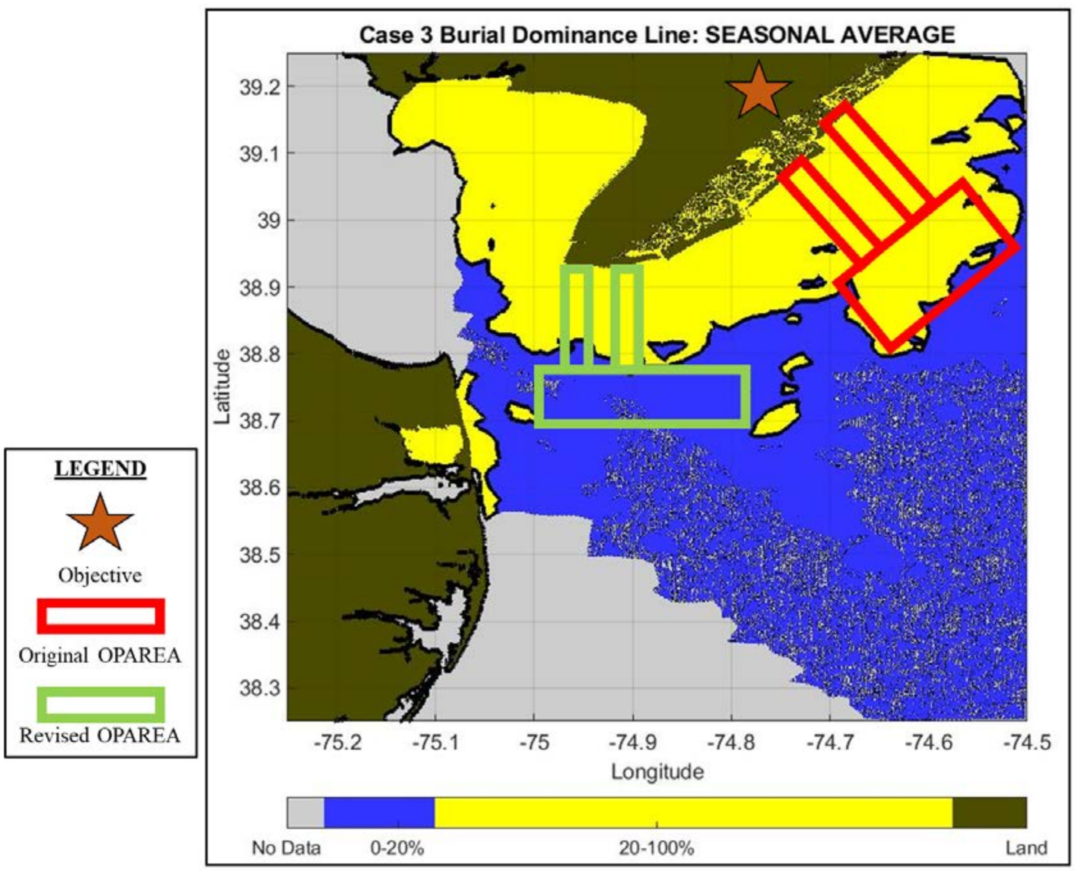


Figure 19: Use of a BDL plot to inform MCM decision making.

# Chapter 6

# CONCLUSIONS

## 6.1 Summary of Results

A scour burial model with varying wave conditions and sediment sizes was used to generate time series mine of burial data for a range of water depths. The data showed that wave height is a more significant variable than sediment size in predicting burial for a given depth. The number of time steps for a mine to experience a given burial percentage was approximately the same for a given grain size, regardless of the wave forcing. Additionally, the range of possible burial percentages (0-100%) was skewed towards minimal burial (0-20%) or maximum burial (75%-100%). The number of depths experiencing 20%-75% burial was found to only occur for an average of 22% of the number of depths that experience greater than 75% burial. The finding of this narrow range of intermediate burial depths inferred confidence in the concept of a BDL predicting either no/minimal burial or significant/complete burial sections within a given area.

The Deterministic Mine Burial Prediction program was used to calculate time series of mine burial for four cases covering two seasons (summer and winter) over the course of five years at two locations; the coast of southern California and around the entrance to the Delaware Bay. Analysis of the DMBP results showed variation from month to month, year to year, and season to season, as expected.

These findings were compiled into averages and plotted as a BDL to characterize mine burial for a given location and season. The wave climate averages showed more fluctuation in annual seasonal outcomes than in month to month averages for a specific case. The Delaware case showed pronounced differences in the offshore location of the seasonal BDL between the summer and winter, sometimes tripling the BDL offshore distance in some locations. This shift highlights how areas of shallower bathymetry may be very sensitive to wave climate fluctuations.

### 6.2 Mine Burial Prediction Importance for MCM Operations

Mine burial prediction is incorporated into the MCM planning process during the mission analysis phase when planners are characterizing the environment, and again during COA analysis when developing the MCM plan in MNT. Mine burial is a main factor of the DBT classification, which is one of the major considerations in determining whether to conduct minehunting or minesweeping operations; this makes burial prediction extremely important.

A key concept to predicting the expected burial for an MCM operation is how long the mines have been deployed, which is important in both the initial hunting and in the re-acquire/ID phase. Where conditions allow, local burial happens quickly while larger scale bedform migration takes longer to occur. Mines can be buried/unburied by the bedform migration, and sheet-flow conditions at the bed during large wave events can completely change the bottom picture by rapid burial or object mobility. For sandy bottoms where mines have been on the seafloor for more than two weeks, impact burial is essentially irrelevant; subsequent burial processes have taken over.

To help MCM planners better understand mine burial for their given environment, a BDL plot can be generated and used during the Mission Analysis phase to quickly determine the feasibility of minehunting in that location, increasing confidence in the determination between minehunting, minesweeping, or area avoidance. During the COA Analysis phase of mission planning, the BDL can inform segmentation of the OPAREA and sequencing of clearance operations, how quickly re-acquire/ID needs to happen (due to changing bottom conditions in certain areas), and the types of equipment to use (e.g. low frequency sonar systems to better detect buried mines). From an environmental perspective, the BDL can inform an in situ environmental sampling plan and where to focus detailed environmental data collection (waves, currents, winds, sediment type) for improved burial calculations OPAREA geometry, environmental prediction data required, and MCM equipment/techniques to use.

Utilizing DMBP with additional MATLAB scripts and functions developed during this research, graphical BDL products for specific operational areas can be quickly created and sent to forward operating MCM forces to be incorporated into their MCM mission planning process. This is a strategic-level, reach-back type support that can be generated at an organization like NAVOCEANO and sent forward to operational/tactical MCM forces.

### 6.3 Recommendations for Mine Burial Prediction Improvements

Although a robust amount of data were generated and analyzed during this research using models based in extensive experimentation and science, there is always room for improvement. One of the key findings from data analysis is that wave height plays a significant role in predicting mine burial. Current NOAA Wavewatch III (WW3) model data has 4-minute latitude/longitude resolution for the U.S., with most of the rest of the world at 30-minute resolution. Having higher resolution global forecast/hindcast data or the ability to model/measure waves for a mission-specific location is critical for accurate mine burial predictions.

Additional work needs to be done to understand and predict burial of non-cylindrical mine shapes. The scour model was developed and tested using cylindrical mine shapes with minimal diameter variations. There are mine shapes in inventories worldwide that do not fit this description; for example the Manta mine from Italy is a truncated cone shape and the Swedish Rockan mine is wedge-shaped (*Oceanography and Mine Warfare*, 2000). To provide increased end-user confidence for burial prediction of all mine types, scour models need to be developed or existing models validated to ensure acceptable burial prediction of these mine types and other non-cylindrical mine shapes.

Further analysis can be done with the Burial Dominance Line concept by expanding the hindcast wave data set used to create a longer historical seasonal average (e.g. 10 years, 20 years) for a given location and by considering additional locations outside of the U.S. The BDL can be compared to calculations of the depth of closure for a specific area to see how closely they are aligned. Month-long burial averages were used the BDL in this research, but further analysis can overlay one-week, two-week, three-week, and month-long BDL predictions over a given location to clearly show how burial changes over time.

The DMBP program was written in MATLAB in the early 2000s, and there were several compatibility issues when running it with a newer version of MATLAB. There are several features that were prone to errors or were not functional, including the bathymetry/sediment data base import tools and the burial movie feature. NOAA has also changed the format of their WW3 files, which is not compatible with DMBP's import WW3 function. Some of these challenges were overcome by generating separate scripts (e.g. for importing the new version of WW3 files), but additional efforts need to be made to update the program to facilitate ease of use. Lastly with DMBP, there are placeholders for burial prediction by bedform migration and liquefaction when calculating subsequent burial; these models need to be added into the code to provide increased confidence in burial prediction by factoring in these other important processes.

There are many considerations that go into military planning. A commander's operational and tactical decisions, especially regarding risk to forces, is always a compromise filled with uncertain planning factors. Mine burial is a small but extremely important parameter to consider in any naval operation due to the level of uncertainty in prediction and the high risk mines pose to personnel and assets. The BDL provides a commander a simple tool for better understanding of the operational environment to help them balance the mine burial threat against these other factors; the more accurate BDL prediction can be, the more confidence our military can have in their operational MCM decisions.

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# Appendix A

## SCOUR BURIAL MODEL SCRIPT

```
%% Scour burial time series for mines under various wave conditions
% Rory O'Boyle, U of Delaware, Center for Applied Coastal Research
(CACR). Code modified from the Naval Research Laboratory (NRL)
Deterministic Mine Burial Prediction Program (DMBP). This is based on
Paul Elmore's version, which was a version of DRAMBUIE based on Carl
Friedrich's version from the Virginia Institute of Marine Science
(VIMS) and later refined by Trembanis, et al. 2007.

clear; clc;

% Define Wave/Current Parameters
h = 1:300; % Water depth (m)
Hs = 1; % Wave height (m)
Tp = 7; % Wave period (sec)
t = 1:5000; % Time series length

% Define Environmental Parameters
d50 = 0.7; % d50 is sediment grain size in mm
d50 = d50/1000; % Sediment grain size converted to meters
zo = d50/12; % Bed roughness length
g = 9.81; % Gravitational acceleration (m/s)
nu = 1.36e-6; % Kinematic viscosity of sea water ((m^2)/s)
p = 0.6; % Used to calculate scour. Dependent on mine geometry.
rho = 1027; % Sea water density at 10 deg C (kg/m^3)
rho_s = 2650; % Sediment density (kg/m^3)
s = rho_s/rho; % Ratio of the sediment density to seawater density

% Define Mine Parameters
As = 0.095; Bs = -2.02; % Used to calculate scour time constant,
based on mine geometry in Whitehouse Eq 5a. Values from Trembanis.
D0 = 0.57; % Initial diameter of exposed mine (m) Mk 57
% End parameters definitions.

%% Begin Calculations
for i=1:length(h) % For loop to calculate along water depth vector

% Calculate Wave Length (L) based on water depth:
WL = h(i)*2; y = 0; % Seed values for iteration calculation
while abs(WL-y) > 0.01 % Value for allowable error in the iteration
y = WL;
WL = g*Tp^2/(2*pi)*tanh(2*pi*h(i)/WL);
end
L(i)=WL;

% Bottom horizontal orbital velocity (U)
U(i)=pi*Hs/(Tp*sinh(2*pi*h(i)/L(i)));
```

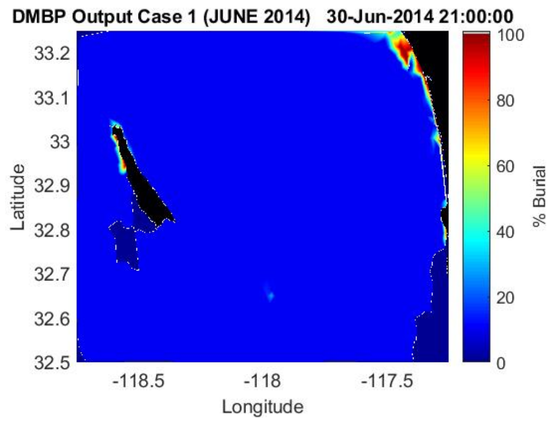
```
% Amplitude of Orbital Wave Motion (A) (Whitehouse Eq 70)
A(i) = U(i)*Tp/(2*pi);

%% Calculate Stresses from Waves (for waves only)
% Reynolds Number (Re)
Re(i) = U(i)*A(i)/nu;

% fw (Trembanis et al Eq 10)
fw(i) = exp(5.213*(d50/A(i))^(0.194)-5.977);

% Shields Parameter for Waves Only (Trembanis et al Eq3 )
theta(i) = fw(i)*U(i)^2/(2*g*d50*(s-1));

% Calculate Critical Shield's parameter (theta_cr) from the
% dimensionless grain size (D_star)
D_star = d50*((s-1)*g/(nu^2))^(1/3); % Dimensionless grain size
(Soulsby Eq 75)

% Check if D_star is for fine sediment
if D_star >= 10 % Whitehouse Eq 75b
theta_cr = (0.24/D_star)+0.055*(1-exp(-0.02*D_star));
else % Whitehouse Eq 75a
theta_cr = 0.3/(1+1.2*D_star) + 0.055*(1-exp(-0.02*D_star));
end

flag = 0; % Flag to mark burial percent greater than 75% to get t_75

%% Calculate scour over time scale length "T", at intervals of "t"
for j = 1:length(t) % For loop to calculate scour time series

% Dimensionless time scale of scour (T_star) (Whitehouse Eq 5a)
T_star(i) = As*(theta(i)^Bs);

% Time Scale T is time after which scour depth has developed 63% of
% equilibrium value (Whitehouse Eq 4), based on initial diameter (D0)
T(i) = (D0^2)*T_star(i)/sqrt(g*(s-1)*d50^3);

% Obtain Ultimate Scour depth (Se) (Trembanis, et al 2007)
if sqrt(theta(i)/theta_cr) < 0.75
Se(i) = 0;
elseif sqrt(theta(i)/theta_cr) > 1.25
Se(i) = 1.15*D0;
else % sqrt(theta/theta_cr) between 0.75 and 1.25
Se(i) = 1.15*D0*(2*sqrt(theta(i)/(theta_cr)) - 1.5);
end

% Total scour (S) after this time step t(j) (Whitehouse Eq 3)
S(i,j) = (Se(i)*(1-exp(-t(j)/T(i)^p)));
%% Calculate the burial percentage, assuming "burial by depth"
if S(i,j) <= D0
burialPct(i,j) = 100*(S(i,j)/D0); % Percentage of mine burial
elseif S(i,j) > D0
```

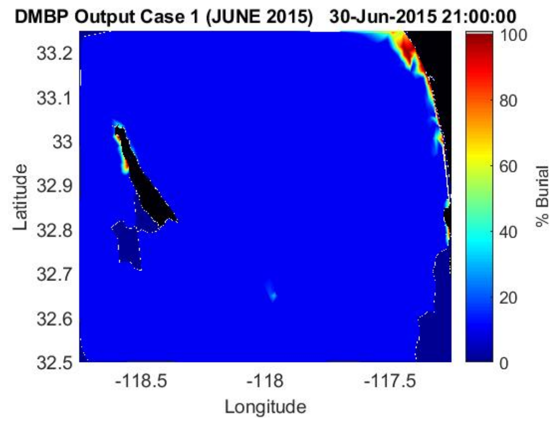
```
burialPct(i,j) = 100;
end

% Record time step when burial reaches 75% (t_75)
if flag == 0 && burialPct (i,j) > 75
flag = 1;
t_75(i,1) = h(i); t_75(i,2) = j;
elseif flag == 0
t_75(i,1) = 0; t_75(i,2) = 0;
end

% Adjust mine diameter D due to the total scour burial (S)
if j >= 2
D(i,1) = D0;
D(i,j) = D(i,j-1)-(S(i,j)-S(i,j-1));
deltaS(i,j) = S(i,j)-S(i,j-1); % Amount of burial for each time step
end
end % j loop for scour (based on length of t)
end % i loop for water depth (length of h)

%% Build and Save Data Structure of the Case
data.Title=['Burial for Hs=',num2str(Hs),'m, Tp=',num2str(Tp),'s, &
d50=',num2str(d50),'m'];
data.info.Description='Variables that are MxN matrices have M indices
of depth (h) and N indices of time step (t) value. M is the length of
h and N is the length of t.';
data.Hs=Hs; data.info.Hs='Wave Height (m)';
data.Tp=Tp; data.info.Tp='Wave period (s)';
data.d50=d50; data.info.d50='Median Grain Size (m)';
data.h=h; data.info.h='Water depth (m)';
data.t=t; data.info.t='Time series vector';
data.D0=D0; data.info.D0='Initial Mine Diameter';
data.D=D; data.info.D='Mine diameter change over time due to burial';
data.deltaS=deltaS; data.info.deltaS='Incremental scour burial depth
(m) for each time step';
data.S=S; data.info.S='Scour pit depth (m)';
data.burialPct=burialPct;
data.info.burialPct='Burial Percent over time';
data.t_75=t_75;
data.info.t_75='Time step where burial percent reaches 75%';
data.T=T; data.info.T='Time scale for 63% equilibrium burial';
data.L=L; data.info.L='Wave length (m) for each depth';
data.U=U; data.info.U='Wave orbital velocity at the bed (m/s)';
data.Re=Re; data.info.Re='Reynolds number for each depth';
data.theta_cr=theta_cr;
data.info.theta_cr='Critical Shields Parameter';
data.theta=theta;
data.info.theta='Shields Parameter for each water depth';
save(['Burial_Hs=',num2str(Hs),'_Tp=',num2str(Tp),'_d50=',num2str(d50
),'.mat'],'data');
% END SCRIPT
```

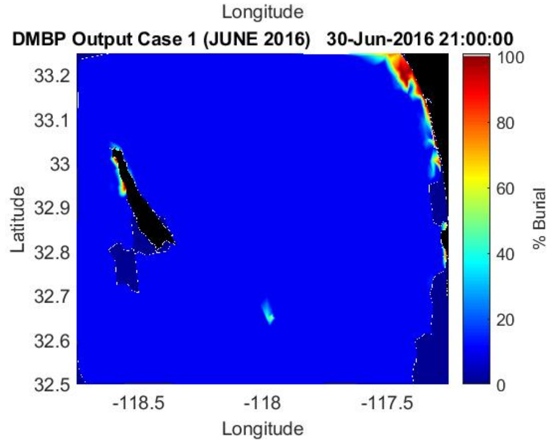
# Appendix B

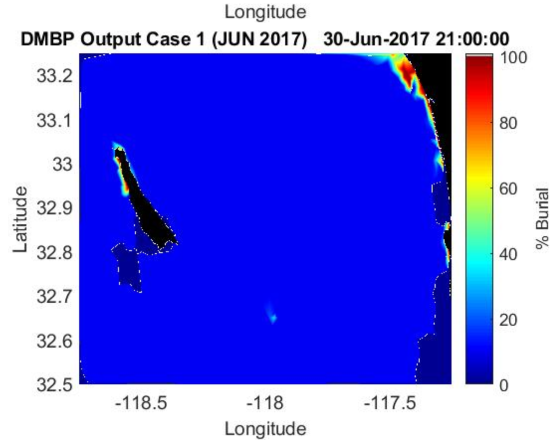
## DMBP CASE OUTPUTS

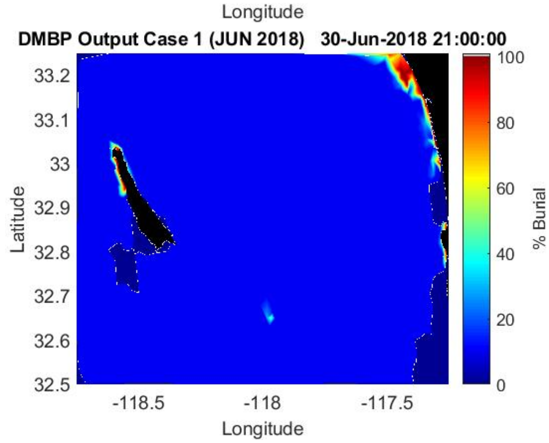
### CASE 1: June 2014-2018 output results.



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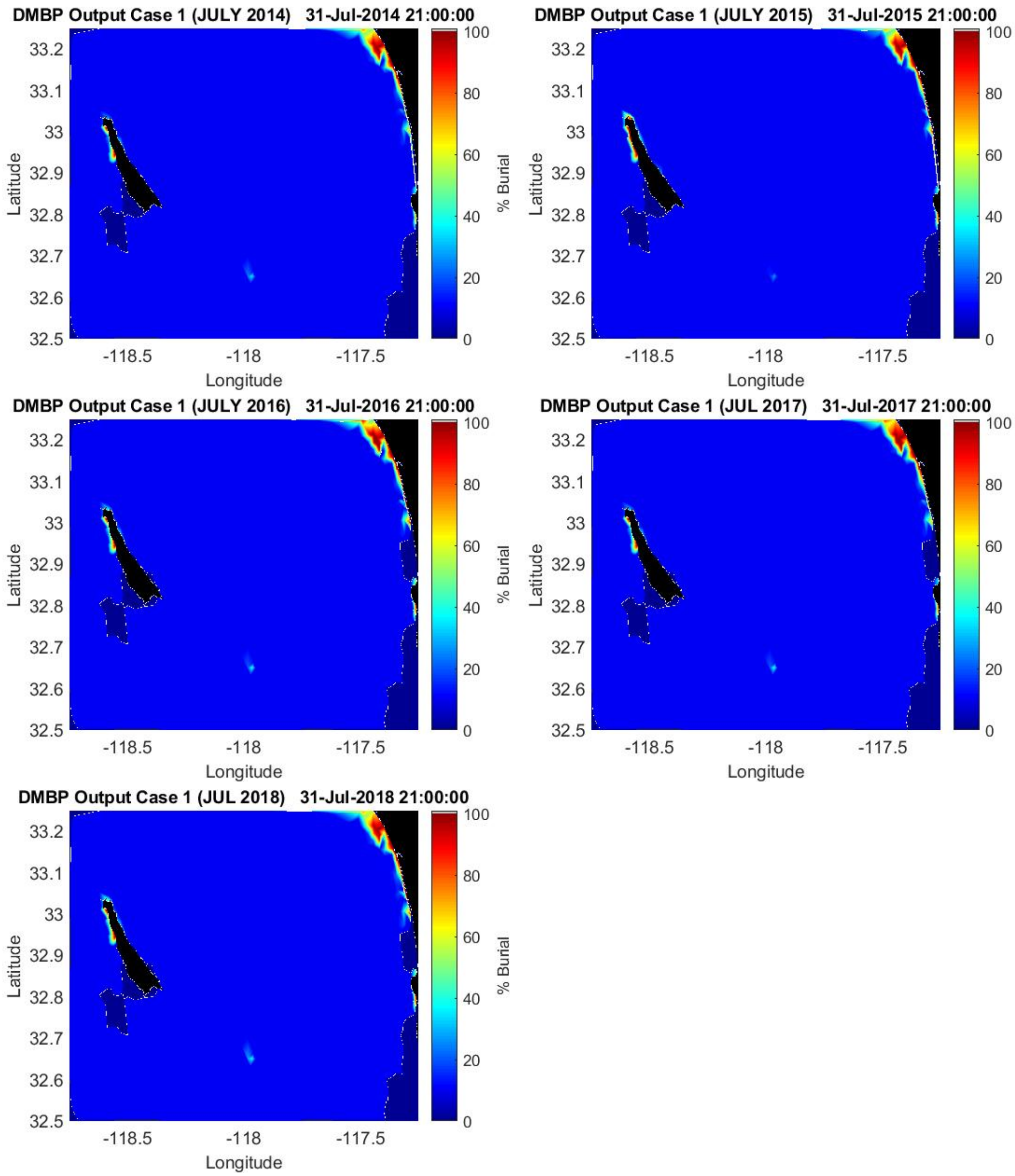

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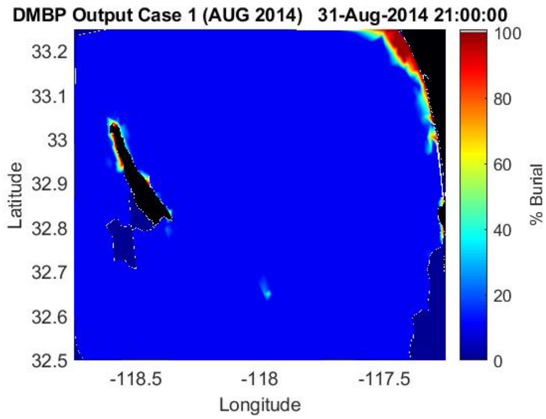
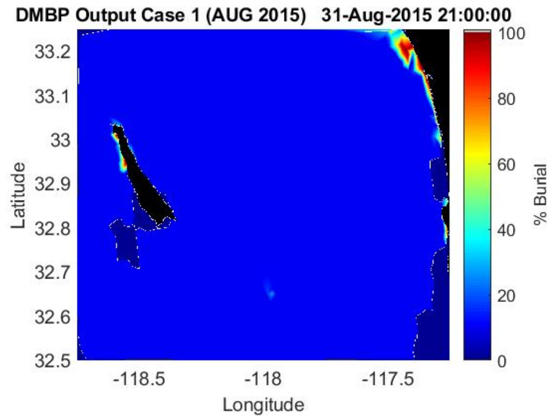
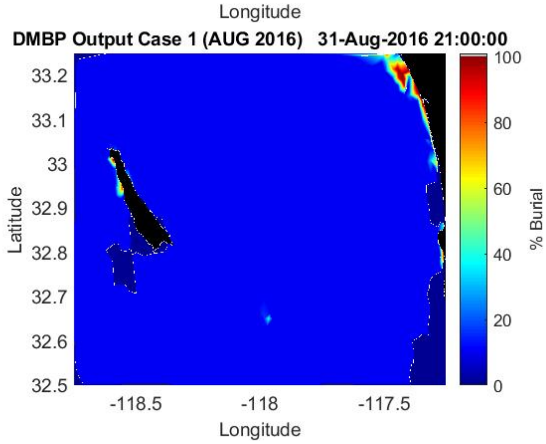
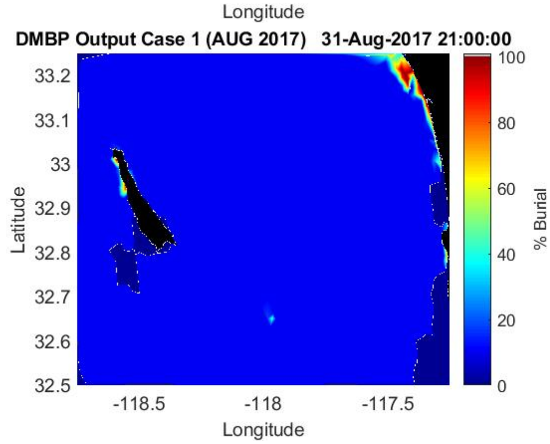
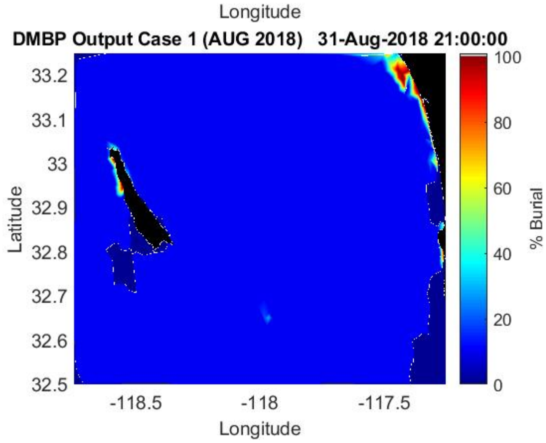


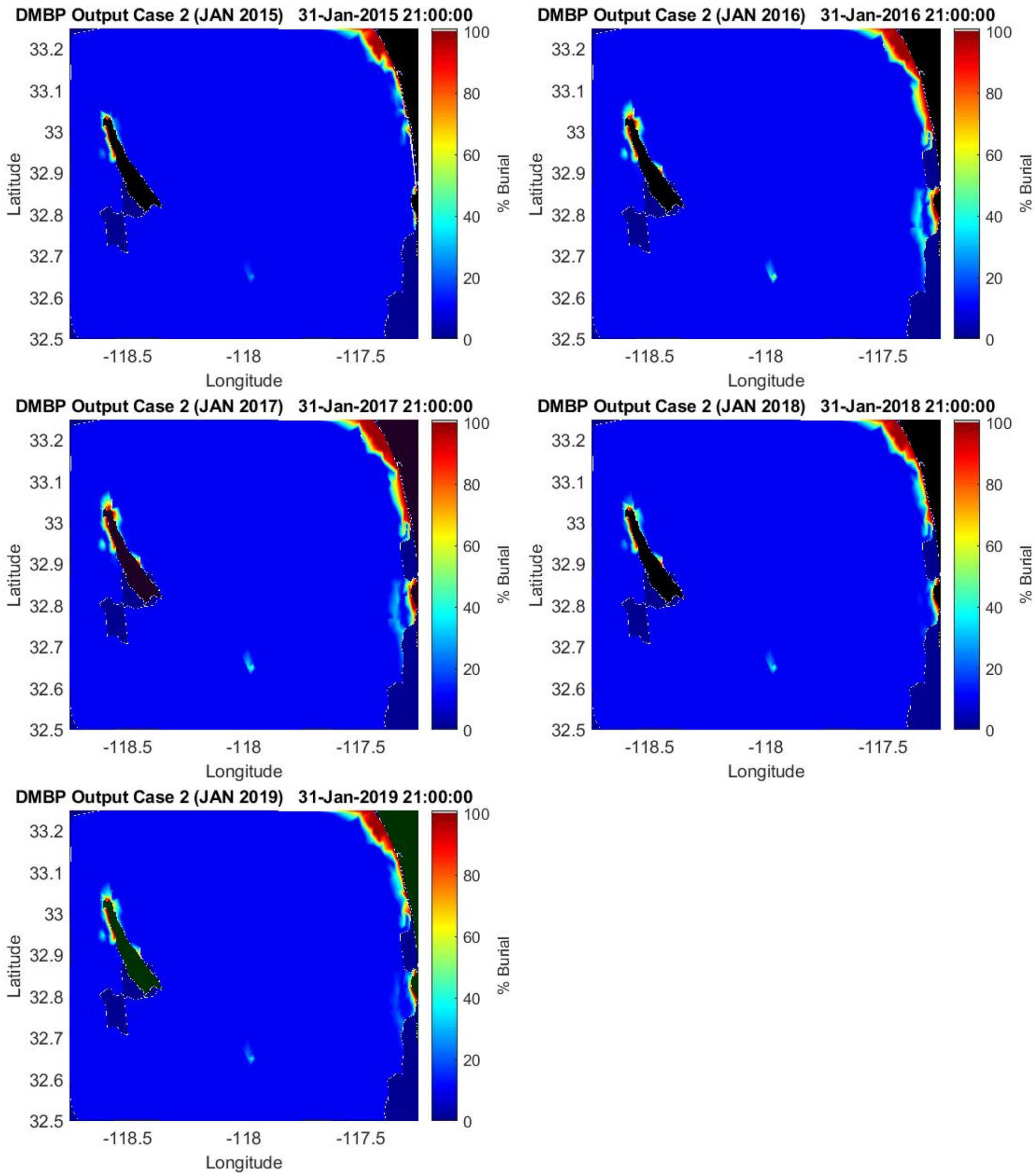



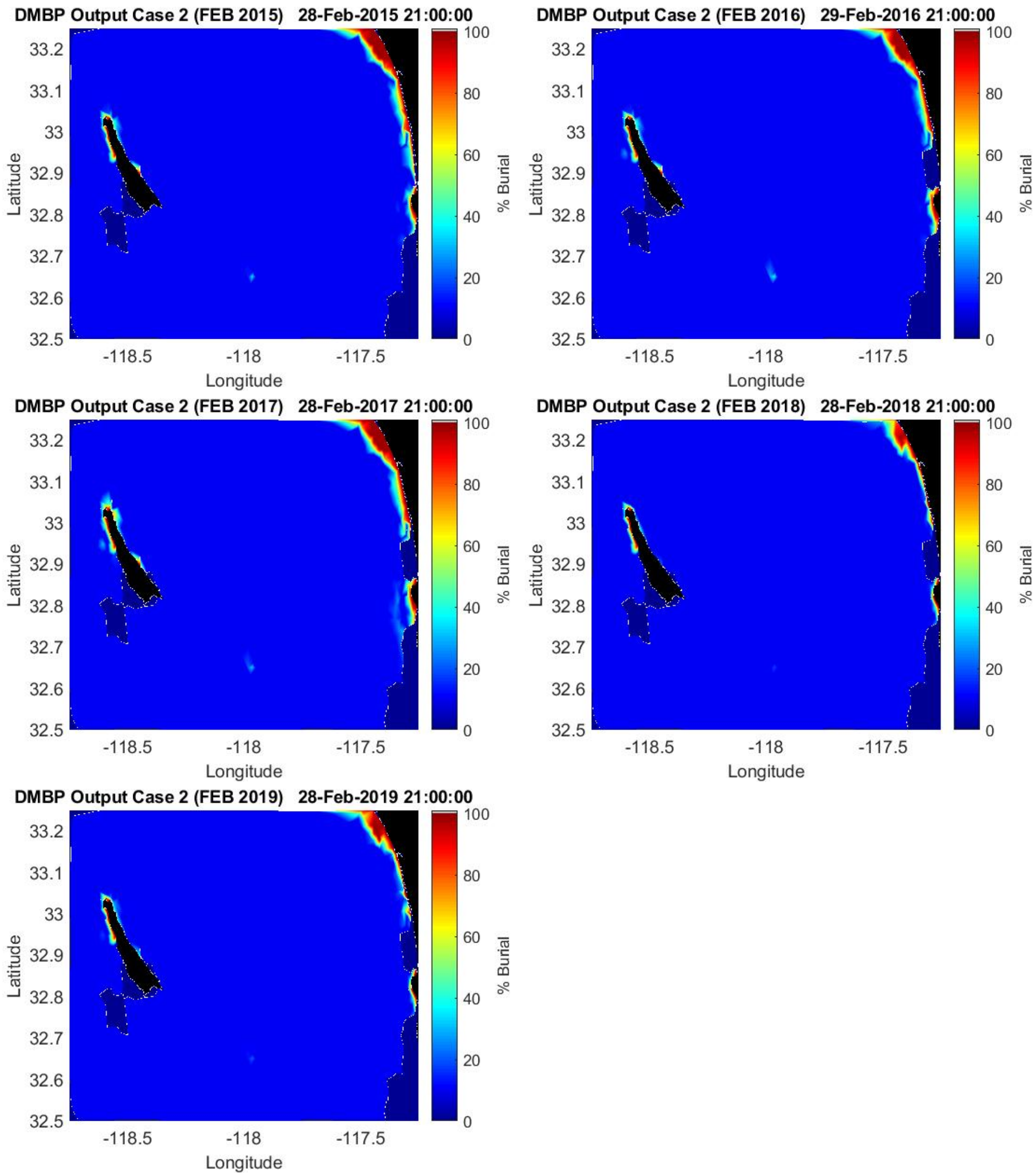



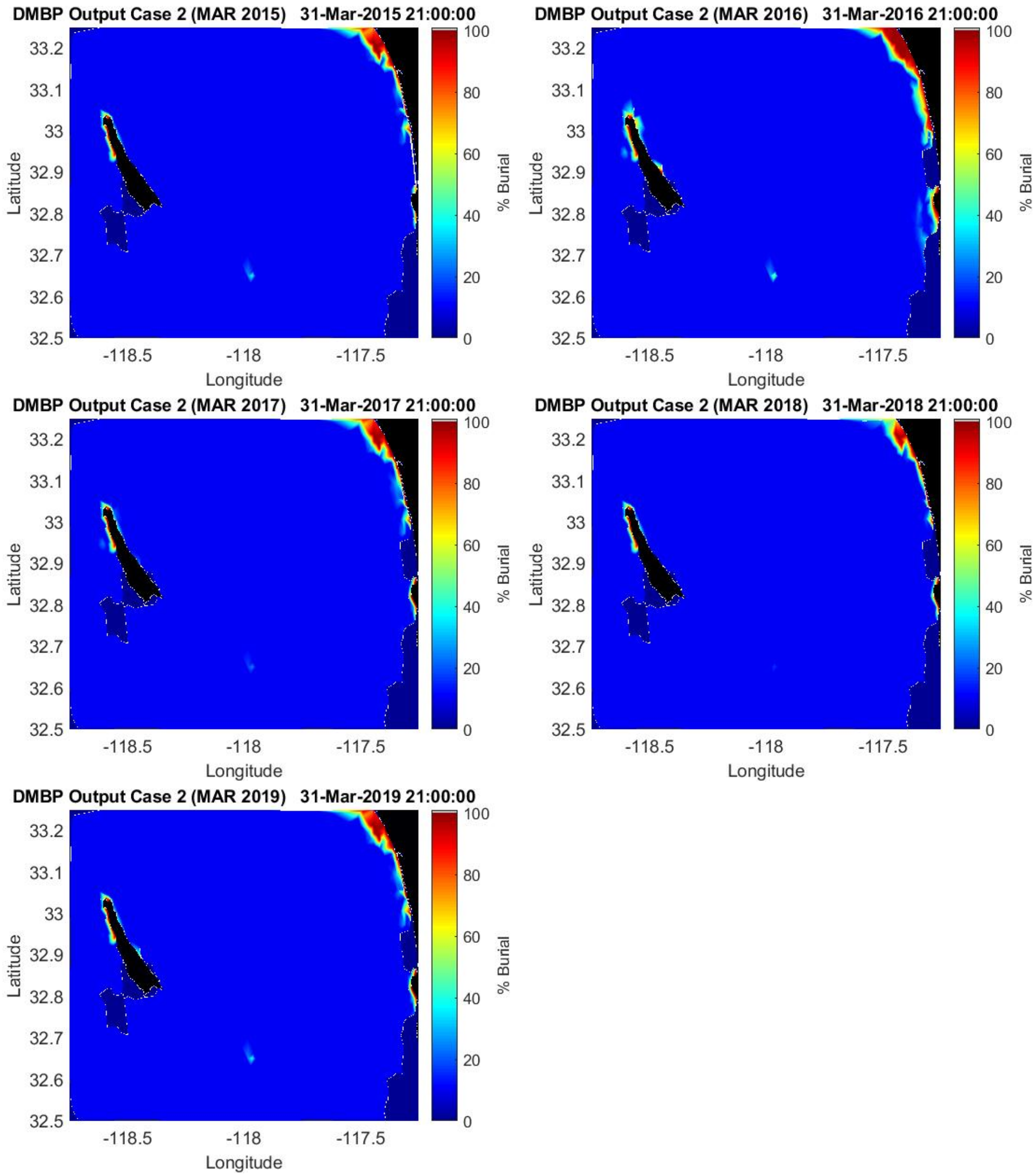
## CASE 2: January 2015-2019 output results.



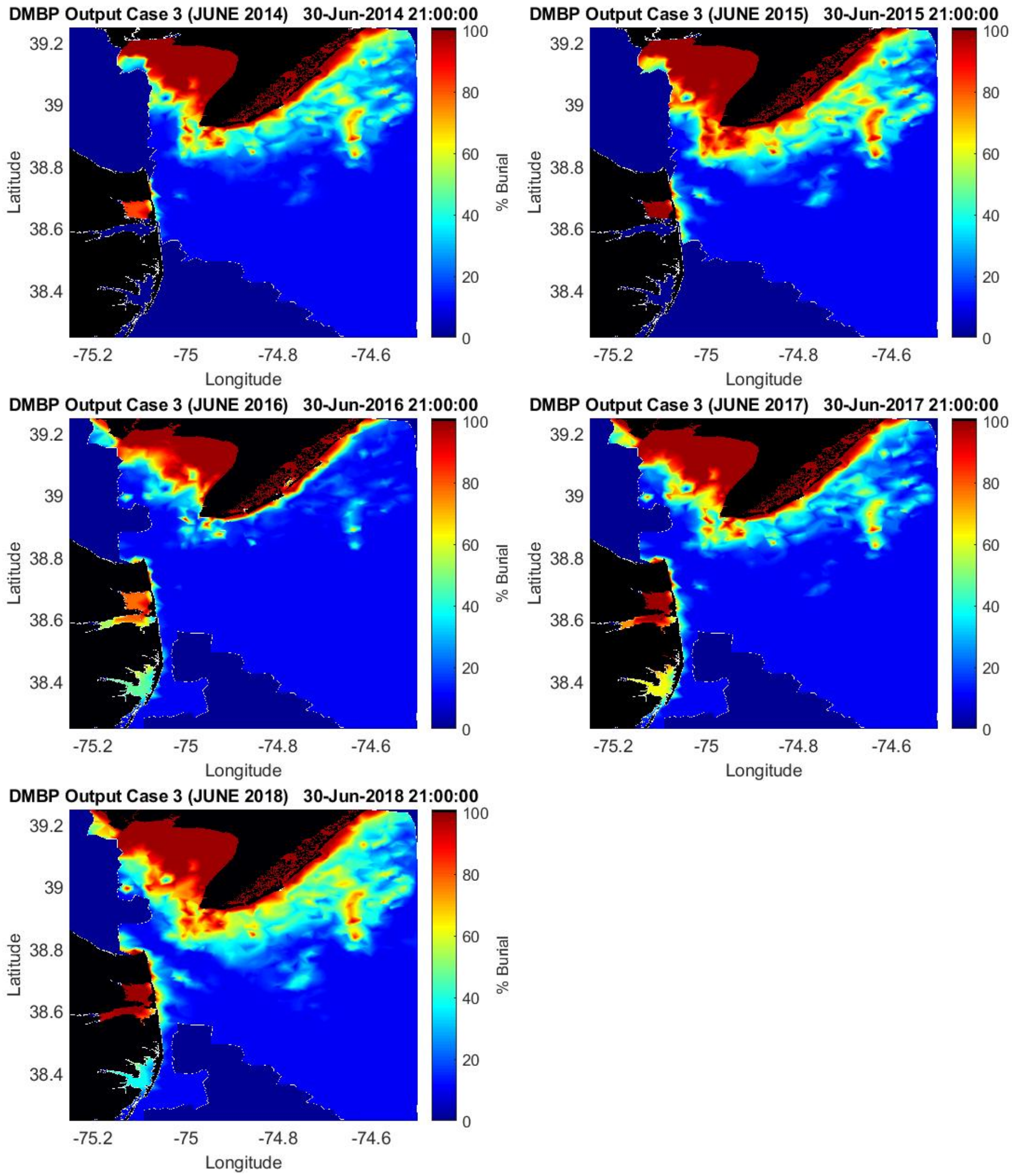
**CASE 2: February 2015-2019 output results.**



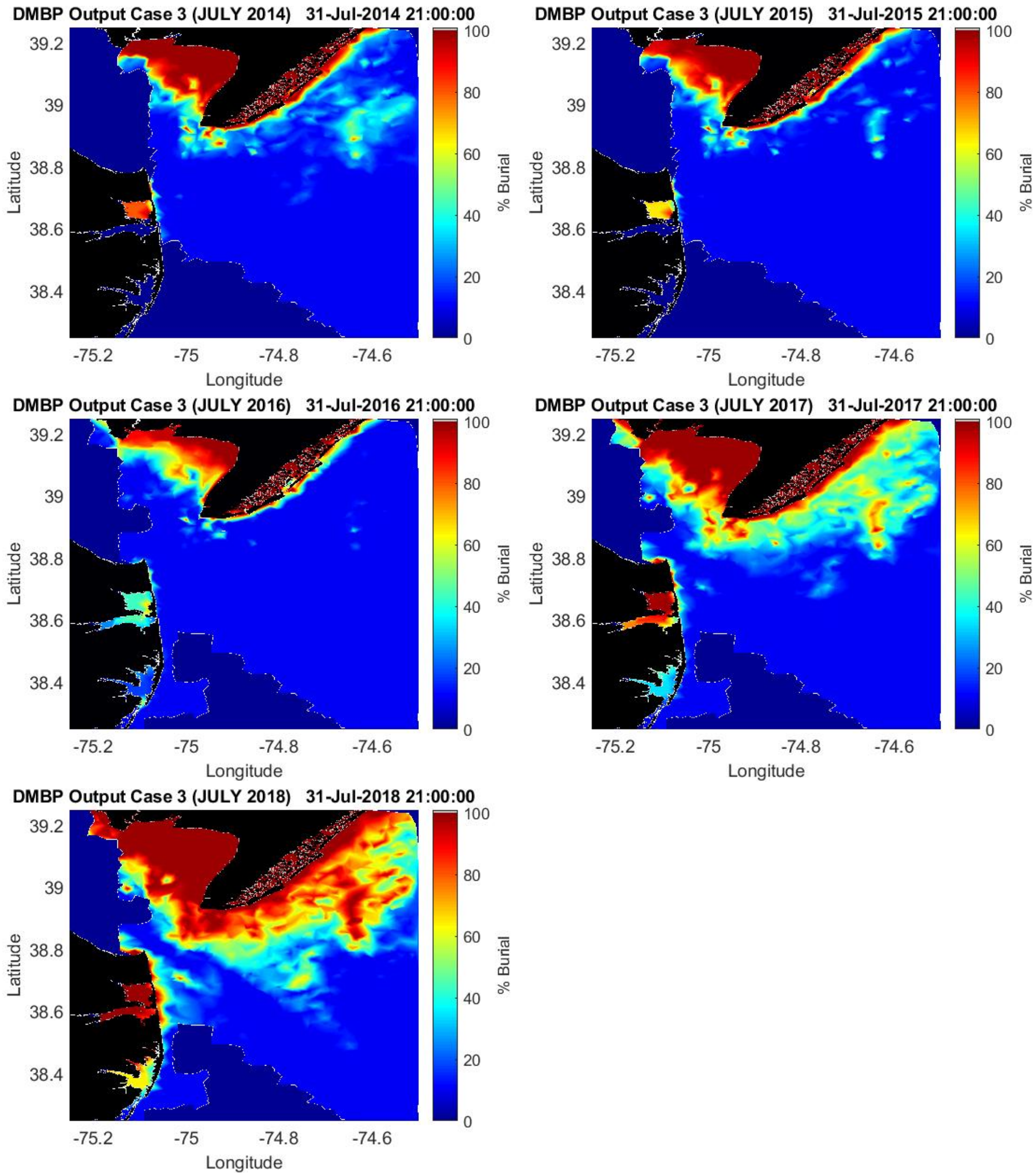
**CASE 2: March 2015-2019 output results.**



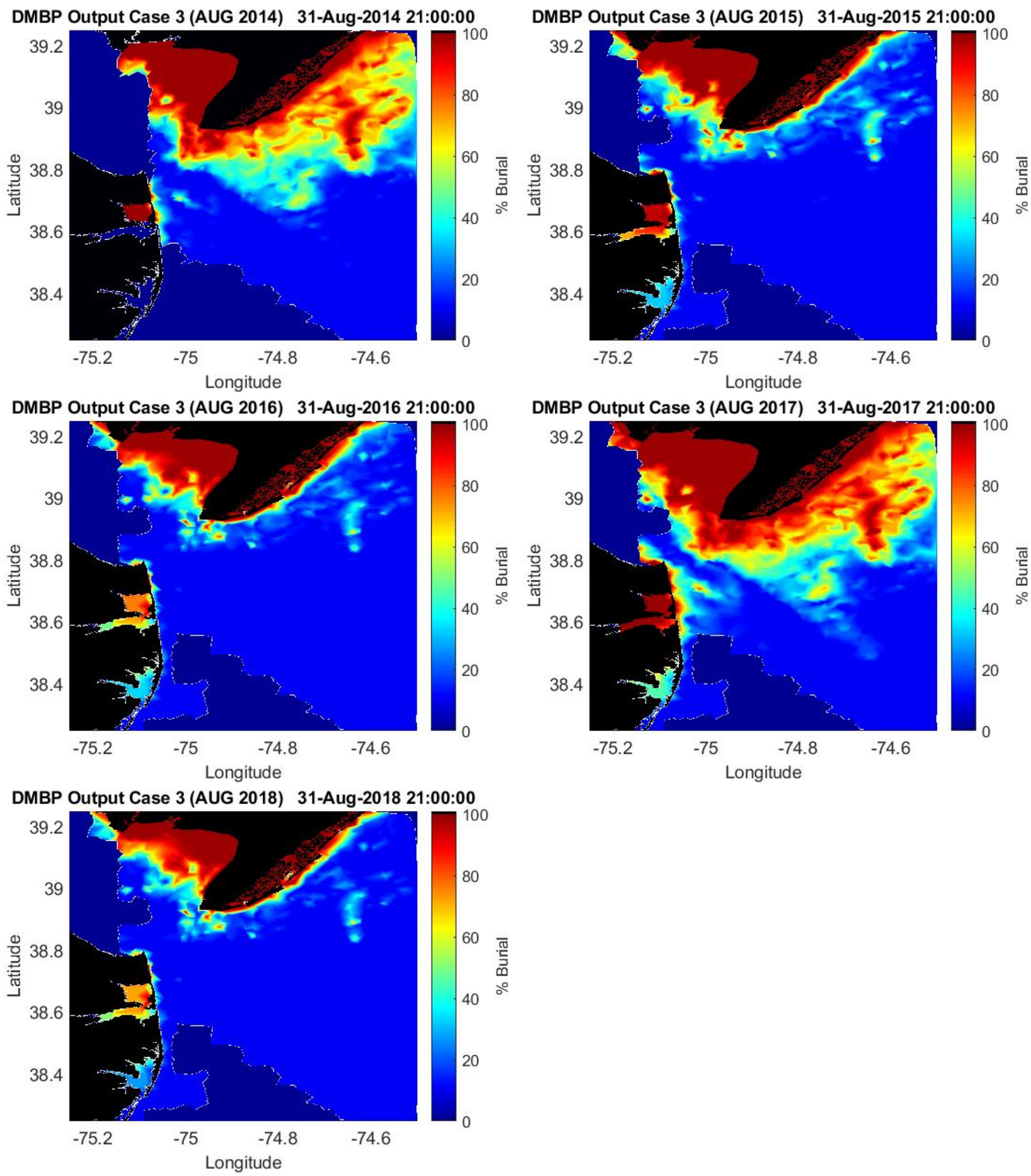
## CASE 3: June 2014-2018 output results.



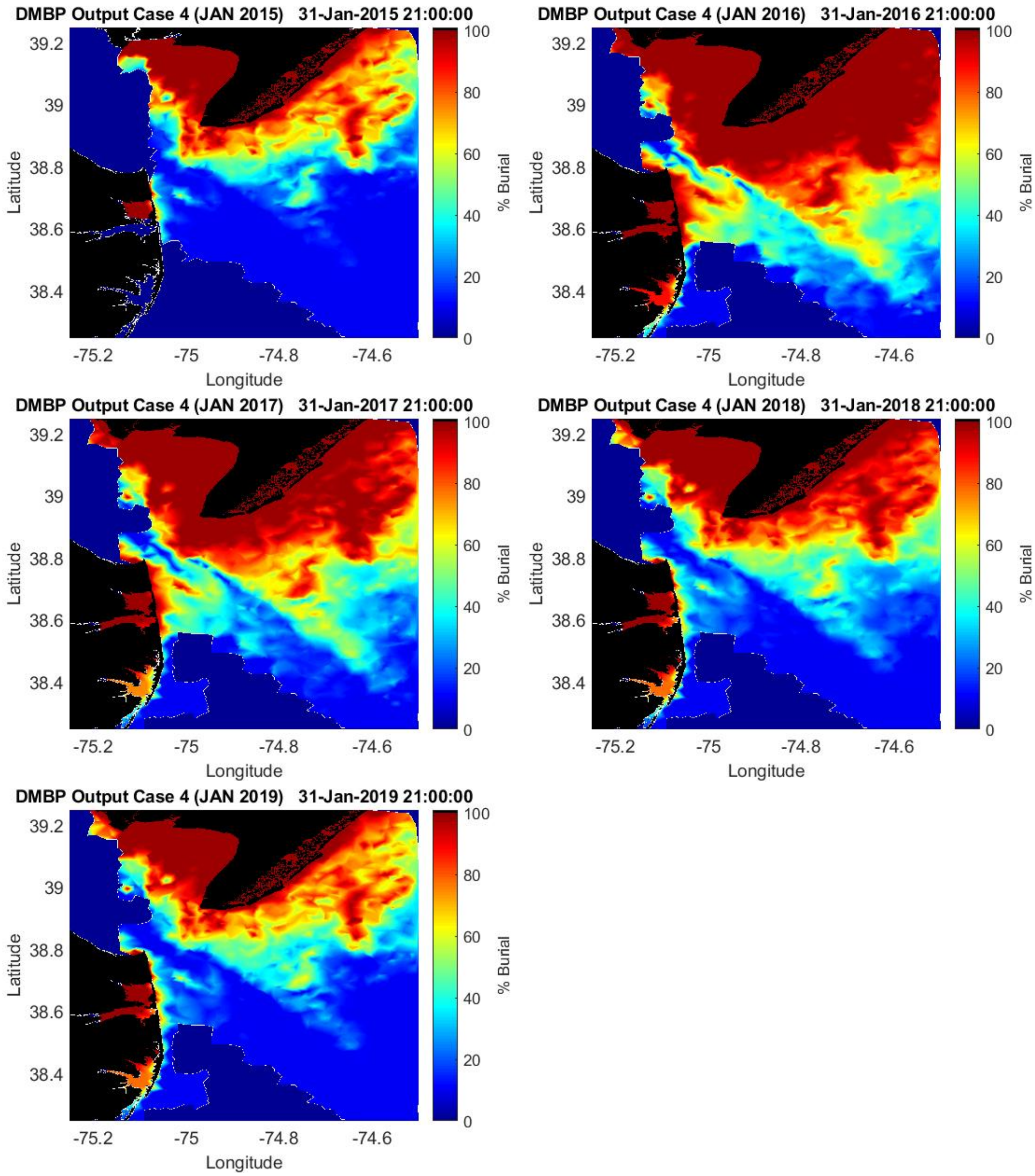
**CASE 3: July 2014-2018 output results.**



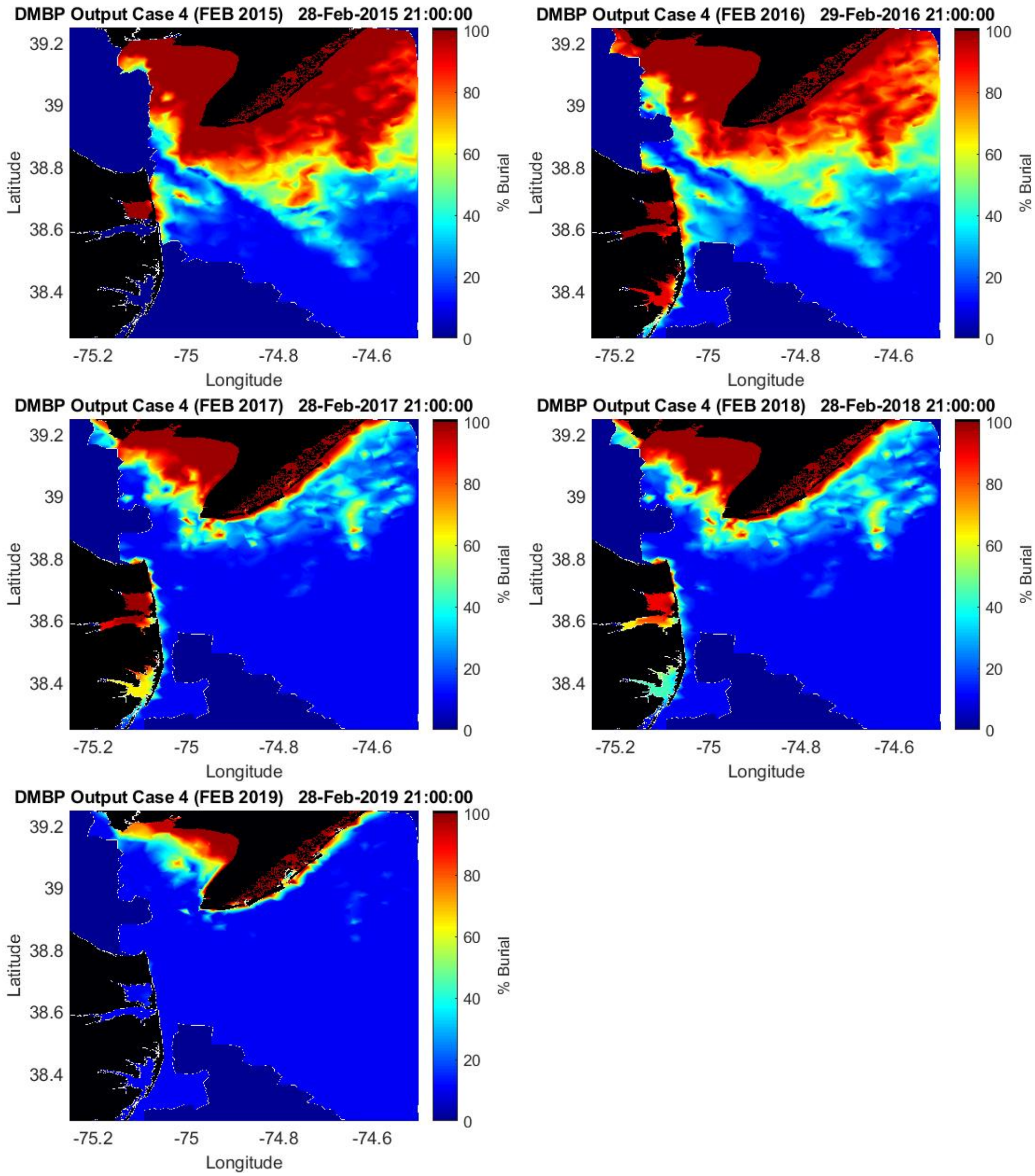
**CASE 3: August 2014-2018 output results.**



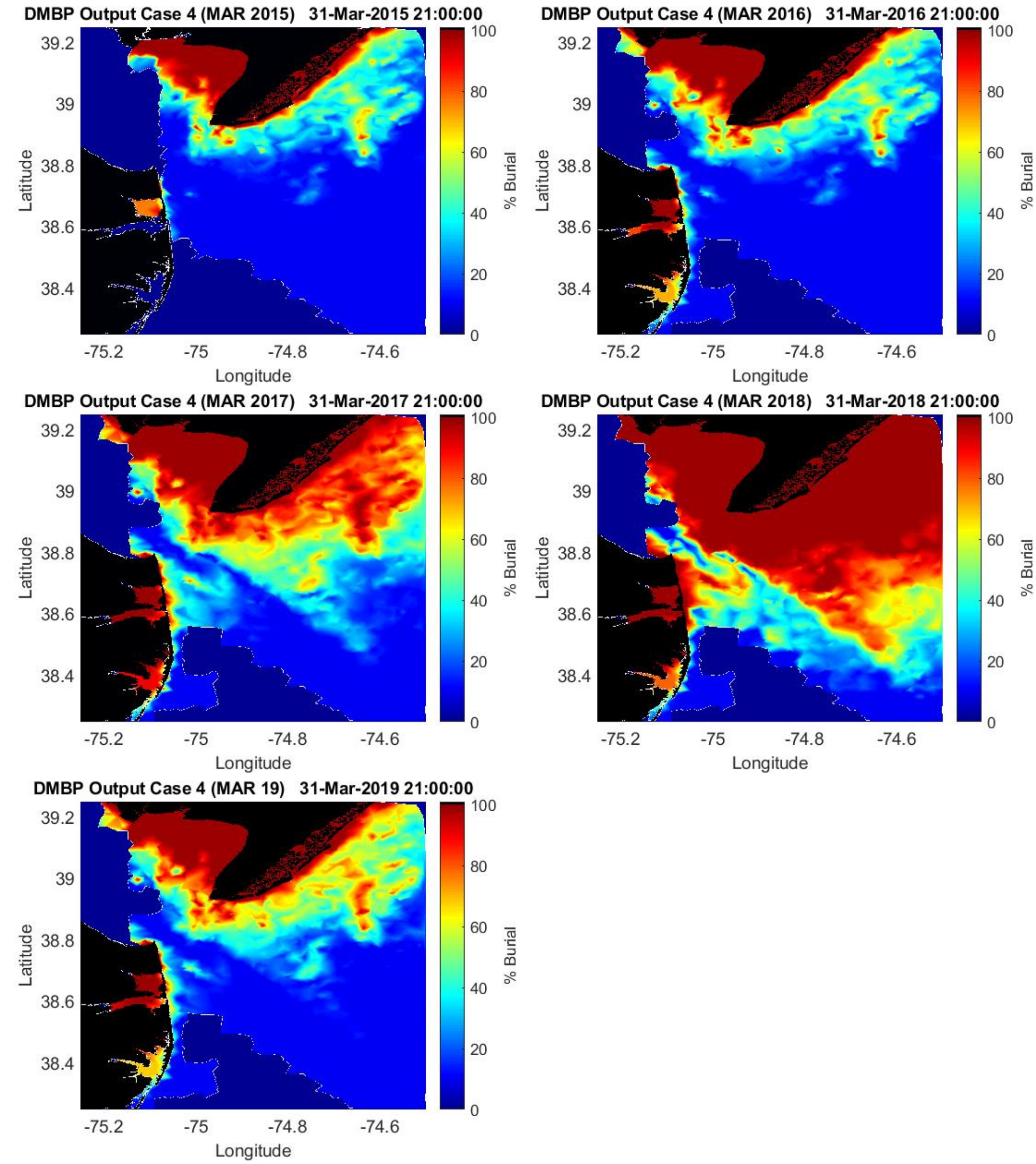
**CASE 4: January 2015-2019 output results.**



**CASE 4: February 2015-2019 output results.**



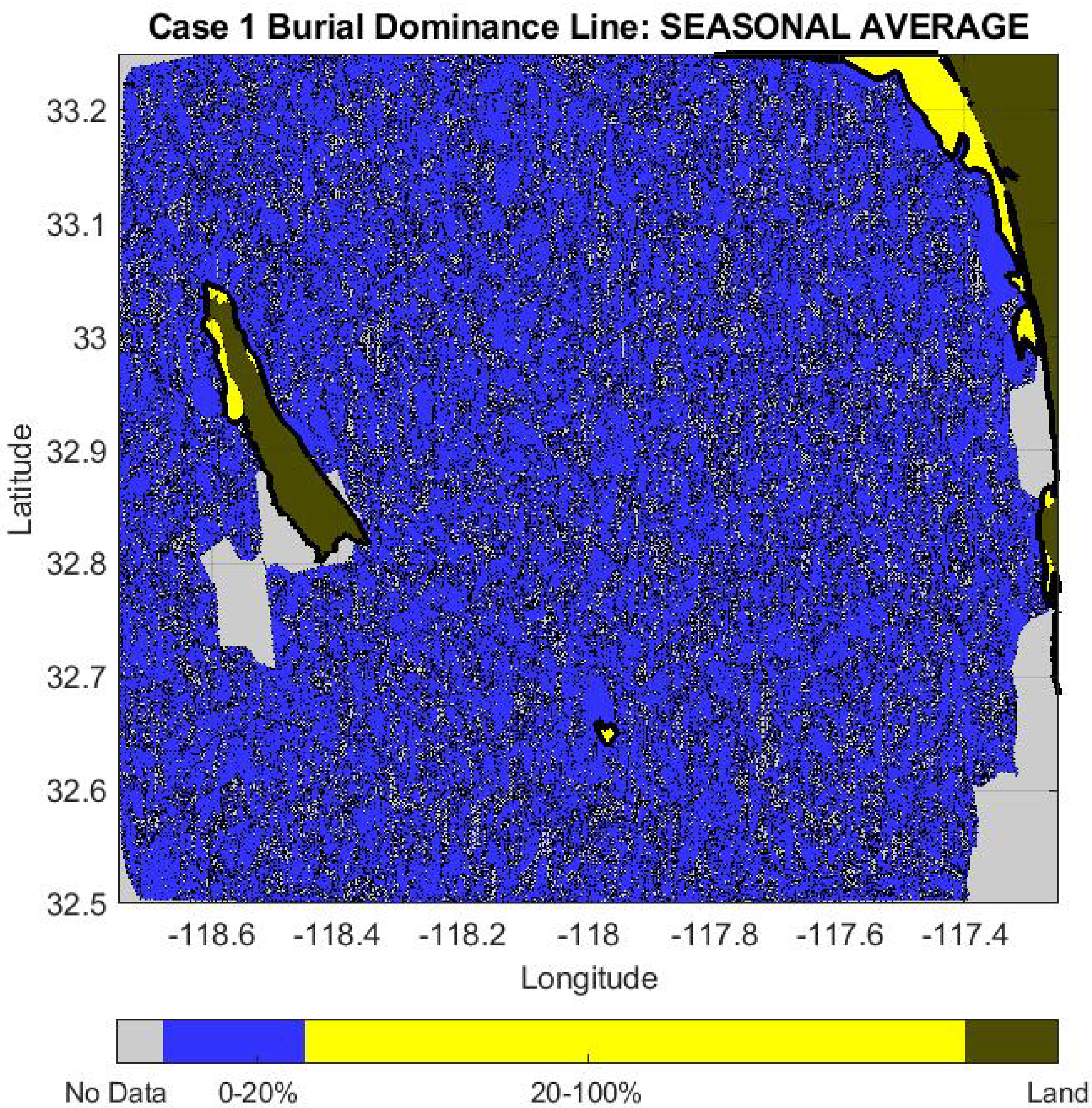
**CASE 4: March 2015-2019 output results.**



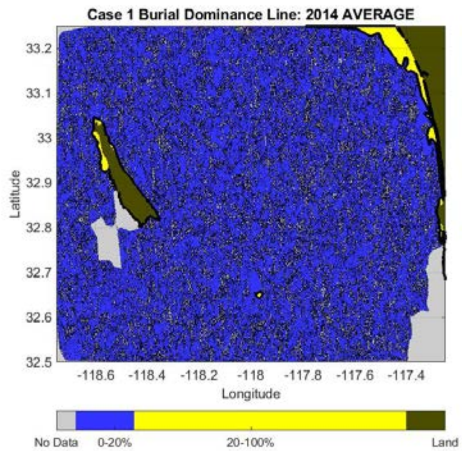
# Appendix C

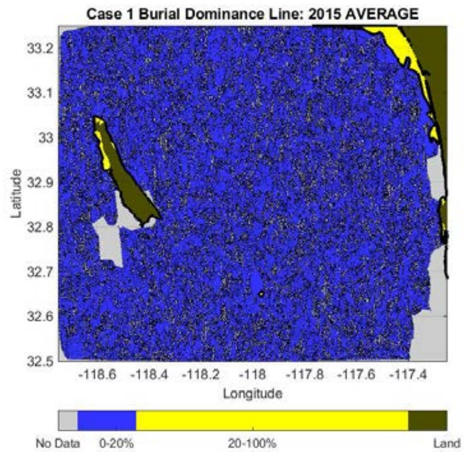
## BURIAL DOMINANCE LINE OUTPUTS

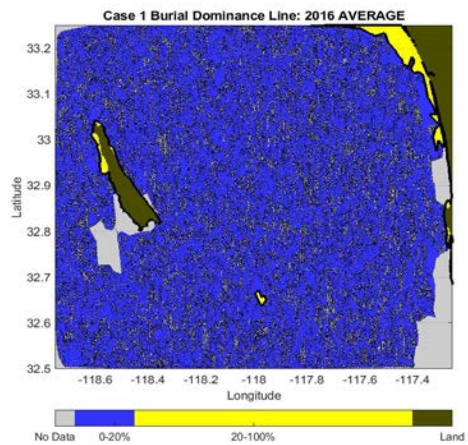
**CASE 1: Burial Domiance Line Seasonal Result.**

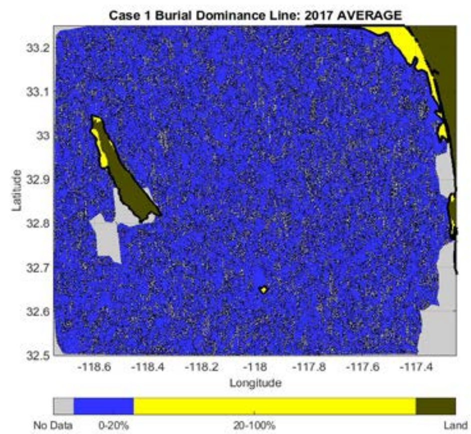


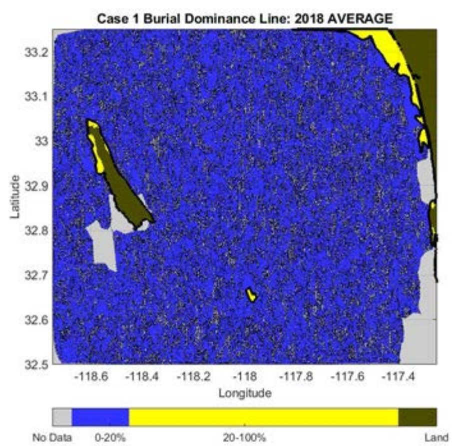
**CASE 1: Burial Domiance Line Yearly Results.**



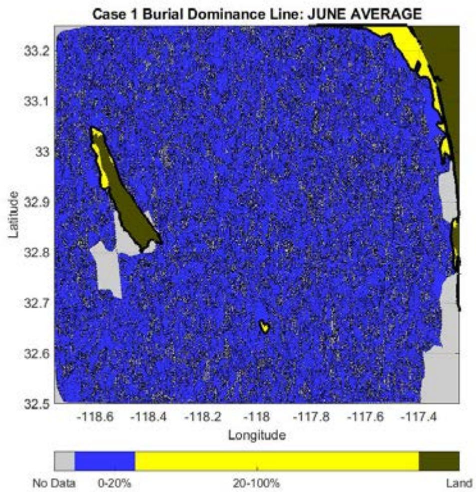



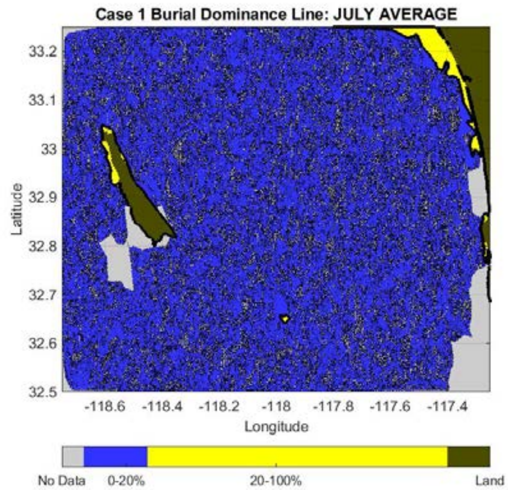



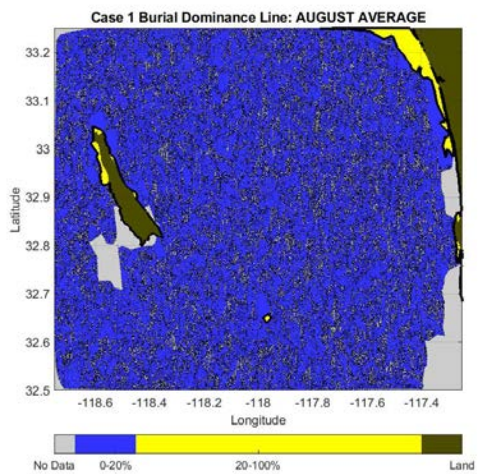



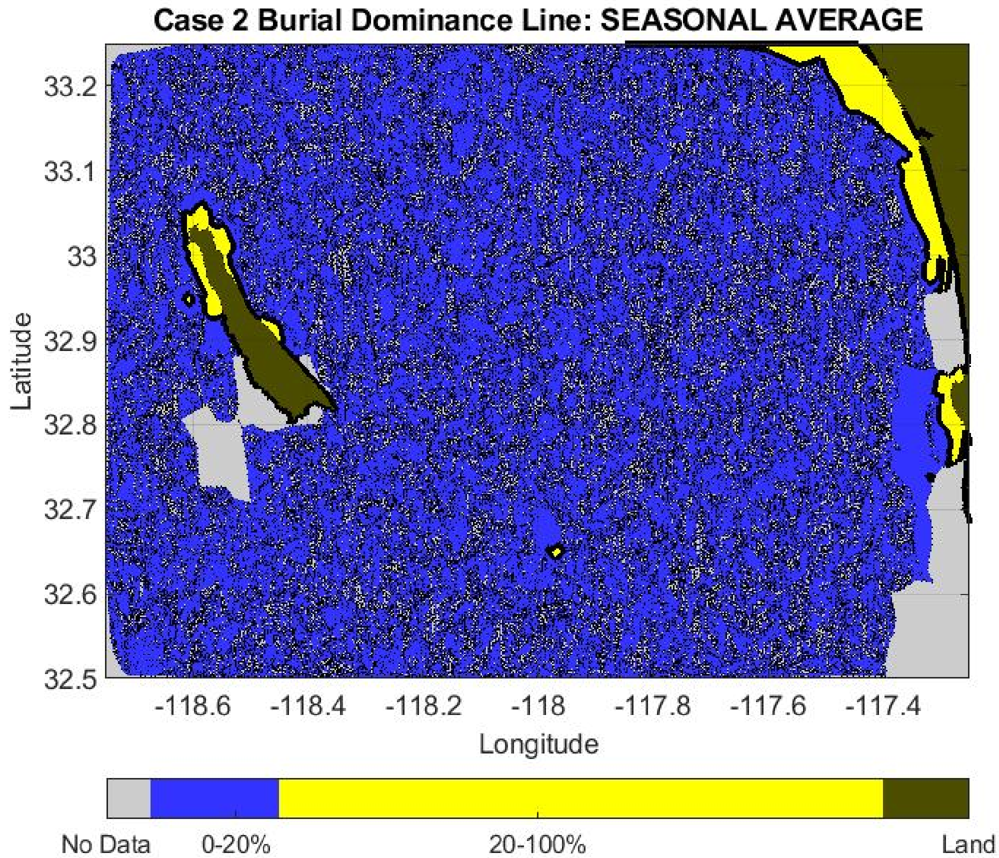
**CASE 1: Burial Domiance Line Monthly Results.**



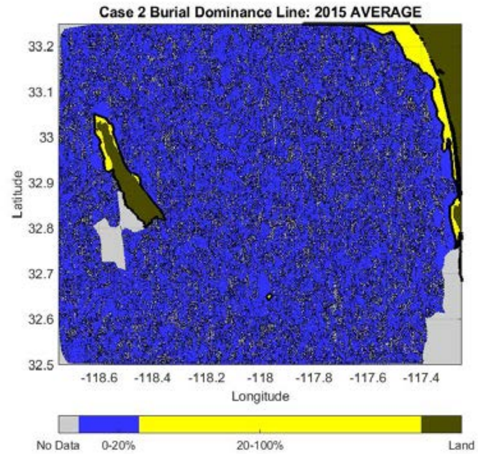



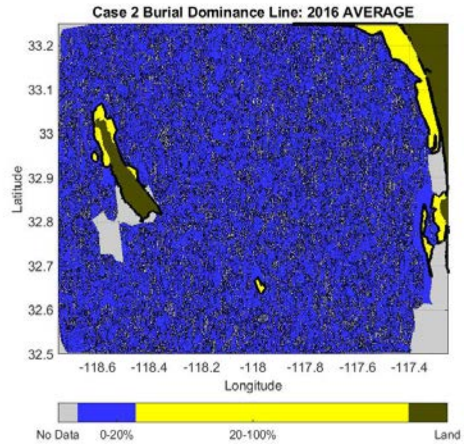



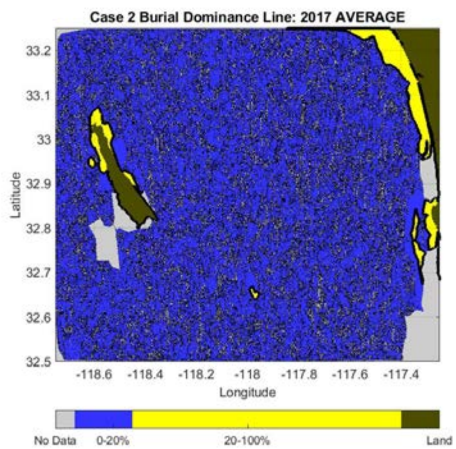
**CASE 2: Burial Dominance Line Seasonal Result.**

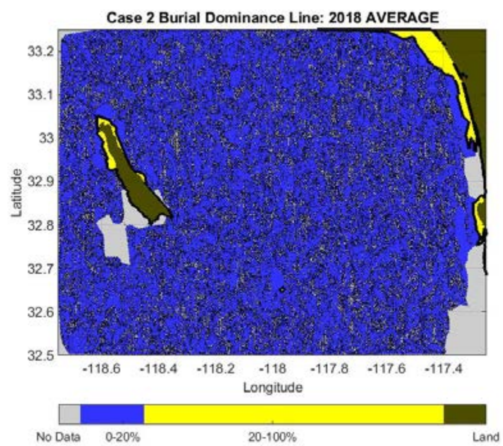


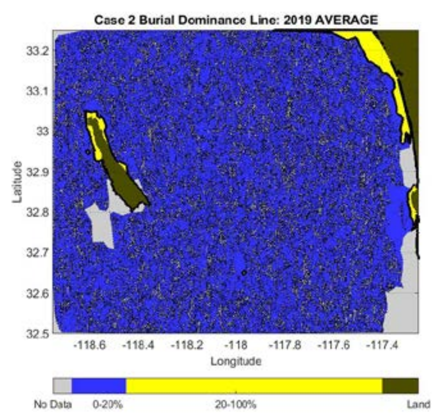
## CASE 2 : Burial Domiance Line Yearly Results.



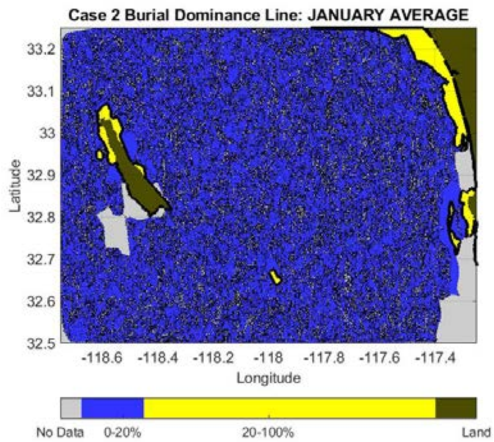



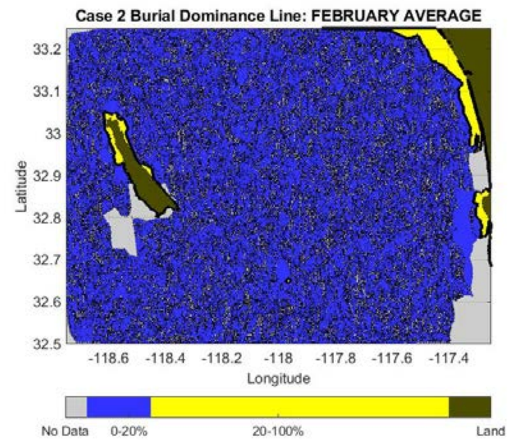



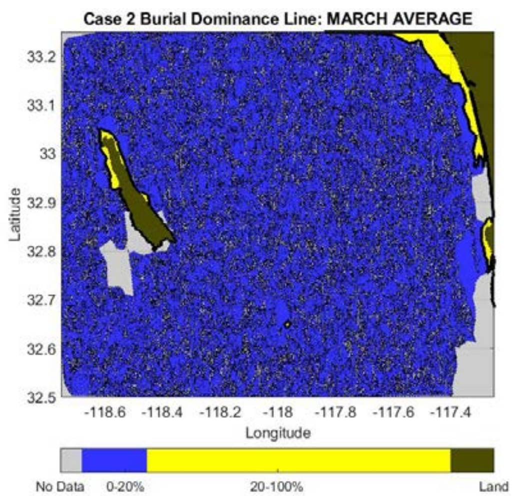



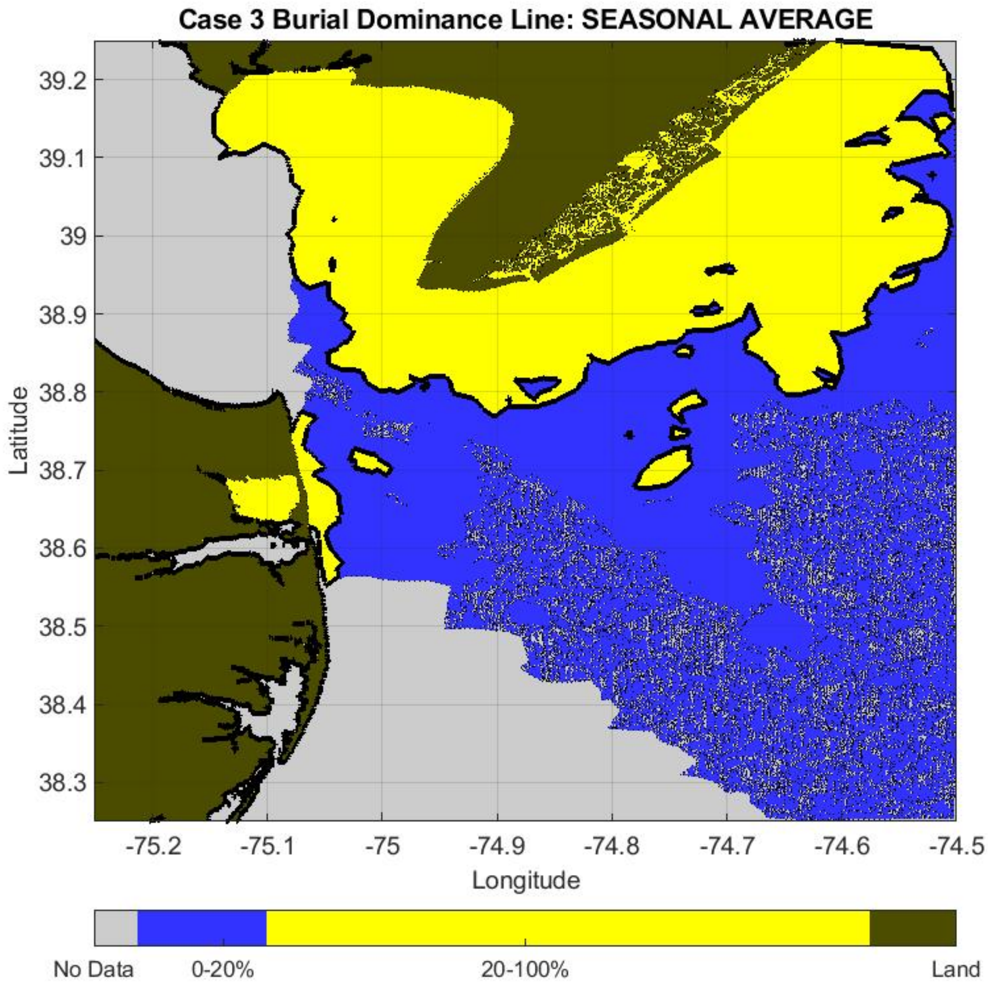
## CASE 2: Burial Dominance Line Monthly Results:



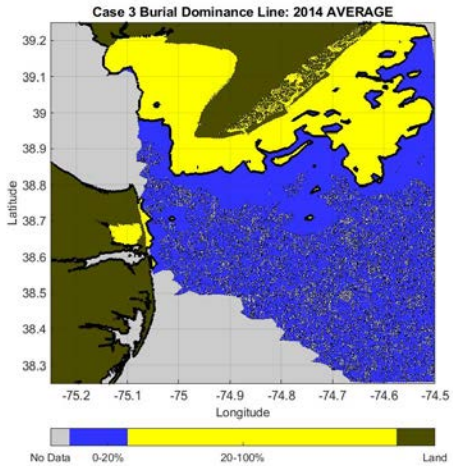



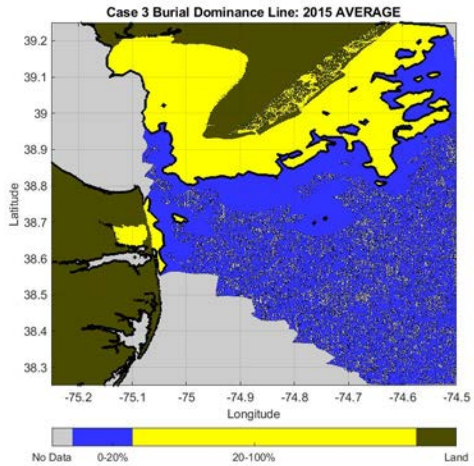



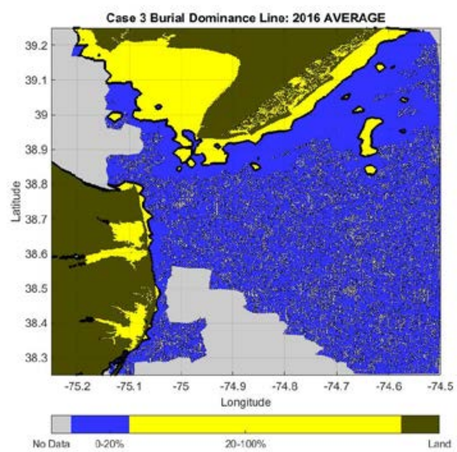
**CASE 3 Burial Dominance Line Seasonal Result.**

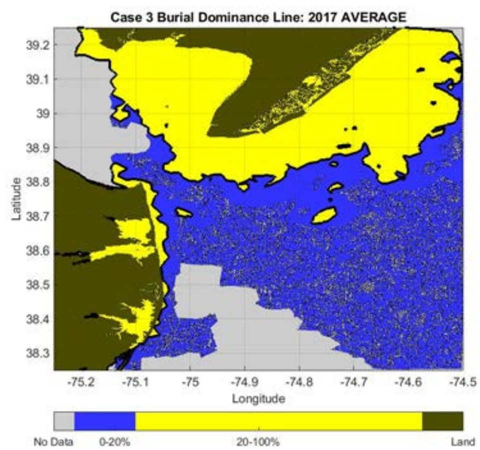


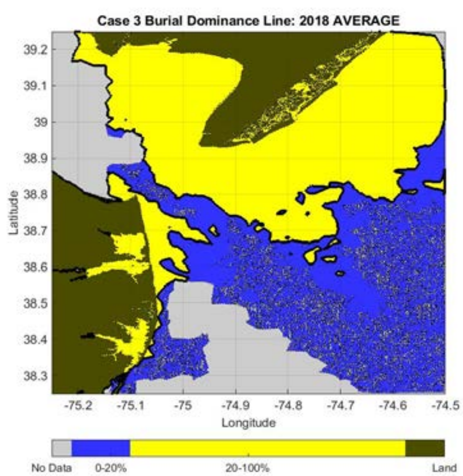
**CASE 3: Burial Dominance Line Yearly Results.**



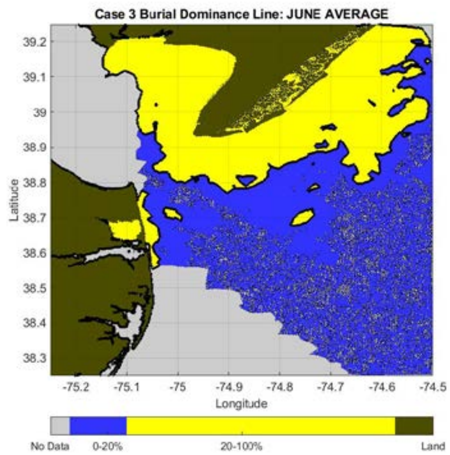



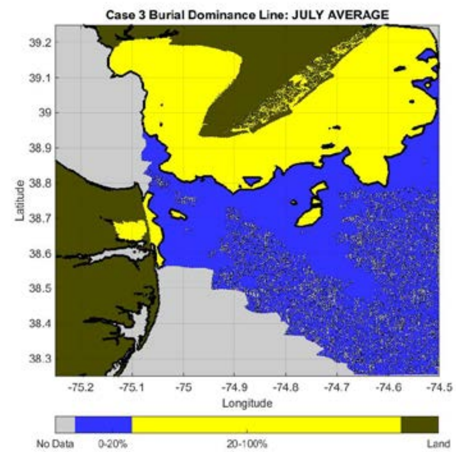



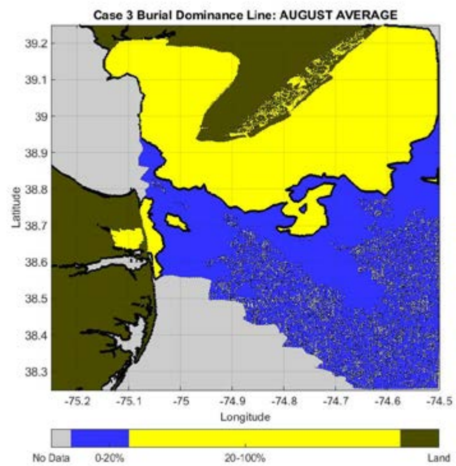



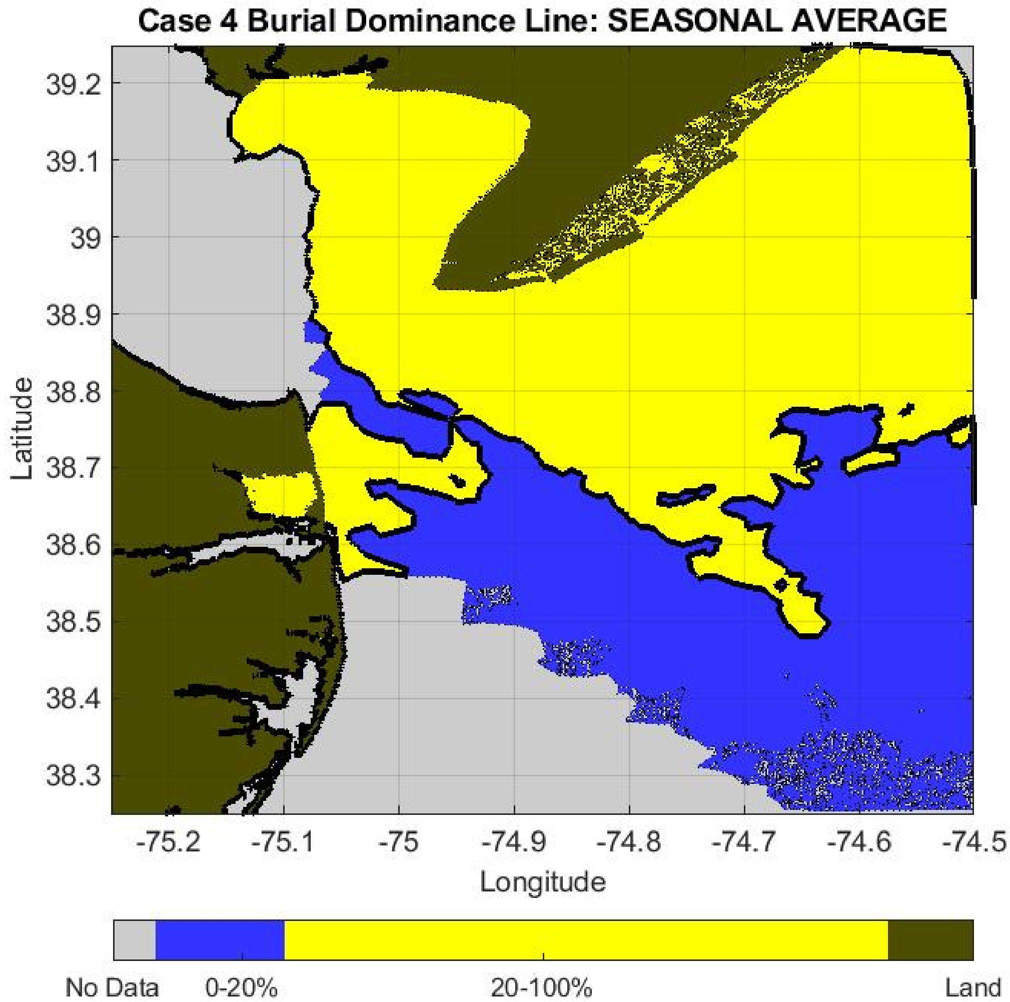
**CASE 3: Burial Dominance Line Monthly Results.**



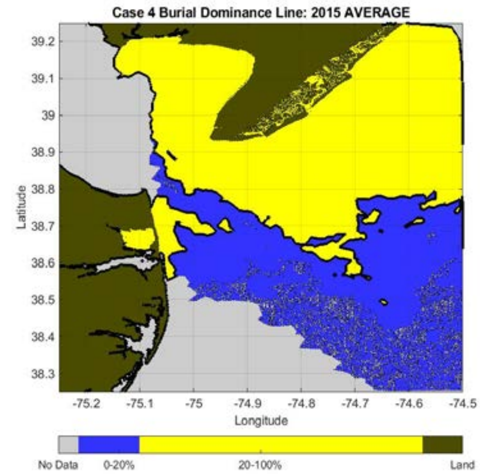



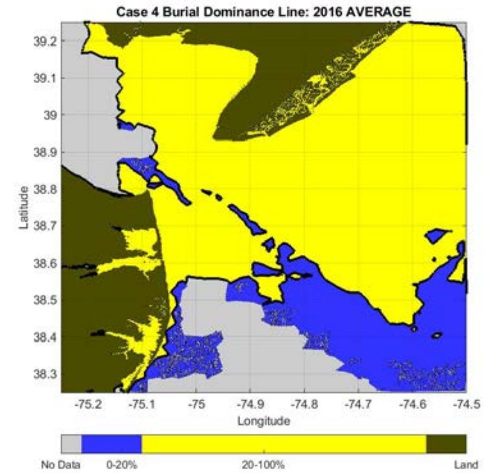



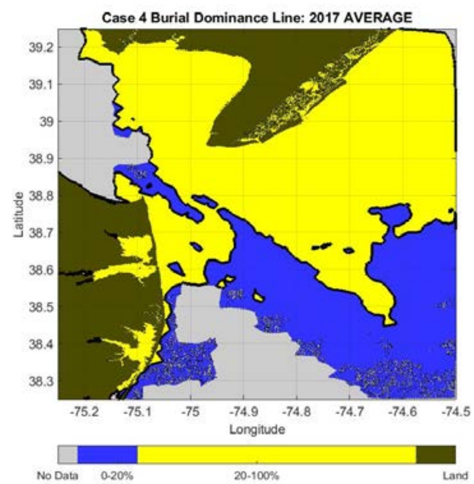
**CASE 4: Burial Dominance Line Seasonal Result.**

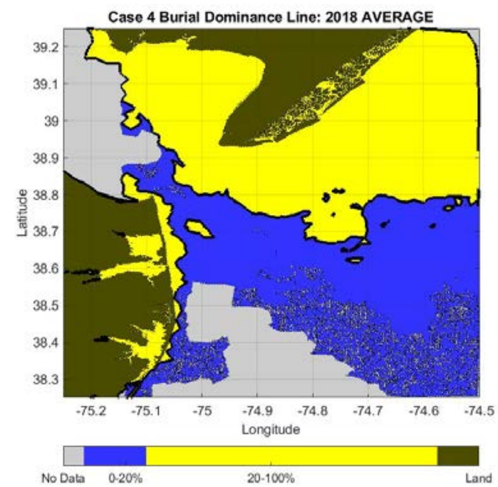


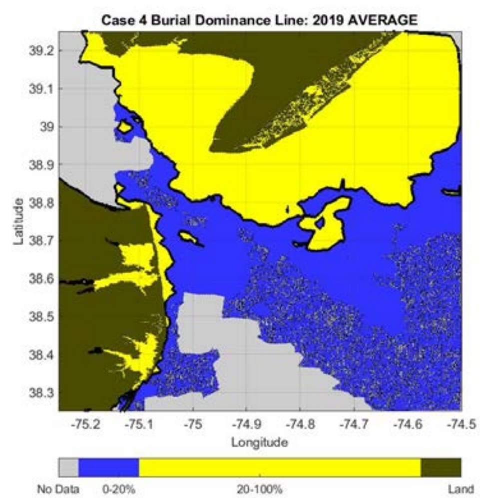
## CASE 4: Burial Dominance Line Yearly Results.



## CASE 4: Burial Dominance Line Monthly Results.