SANDIA REPORT
SAND2014-15239
Unlimited Release
Printed June 2014

Offshore Wind Guidance Document: Oceanography and Sediment Stability

(Version 1)

Development of a Conceptual Site Model

Jason Magalen, Craig Jones, and Jesse Roberts

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2014-15239
Unlimited Release
Printed June 2014

Offshore Wind Guidance Document: Oceanography and Sediment Stability

Jason Magalen and Craig Jones
Sea Engineering, Inc.
200 Washington Street, Suite 101
Santa Cruz, CA 95060

Jesse Roberts
Water Power Technologies
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS1124

Abstract

This guidance document provides the reader with an overview of the key environmental considerations for a typical offshore wind coastal location and the tools to help guide the reader through a thorough planning process. It will enable readers to identify the key coastal processes relevant to their offshore wind site and perform pertinent analysis to guide siting and layout design, with the goal of minimizing costs associated with planning, permitting, and long-term maintenance. The document highlights site characterization and assessment techniques for evaluating spatial patterns of sediment dynamics in the vicinity of a wind farm under typical, extreme, and storm conditions. Finally, the document describes the assimilation of all of this information into the conceptual site model (CSM) to aid the decision-making processes.

ACKNOWLEDGMENTS

The research and development described in this document was funded by the U.S. Department of Energy. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

This research was made possible by support from the Department of Energy's Wind and Water Power Technologies Office.

CONTENTS

1. Introduction 11
1.1. Background 11
1.2. Current Status in the United States 12
1.3. Using This Document 13

2. Guidance and recommendations 17
2.1. Lessons Learned and Existing Guidance 17
2.2. EIA General Guidance (CEFAS, 2004) 19
2.3. Oceanographic and Sediment Dynamic Specific Considerations 21
2.4. Modeling Considerations (Physical and/or Numerical) 22
2.5. Marine Spatial Planning 22
2.5.1. MSP in the U.S. 23

3. Sediment Transport Fundamentals 25
3.1. Introduction 25
3.2. Role of Hydrodynamic Processes 27
3.3. Physical Properties of Sediment 29
3.4. Sediment Erosion 30
3.5. Sediment Transport 32
3.5.1. Non-Cohesive Sediment Transport 33
3.5.2 Cohesive Sediment Transport 35
3.5.3 Sediment Deposition 37
3.6 Coastal Sediment Transport Processes 38
3.6.1 Near-Shore Coastal Zone 38
3.6.2. Offshore Coastal Zone 40

4. Erosion and scour fundamentals 43
4.1. Foundation Obstructions 43
4.2. Cable and Pipe Obstructions 46
4.3. Scour Potential – Single Pile 48
4.3.1. Horizontal Scour Extent 49
4.3.2. Vertical Scour Extent 49
4.3.3. Water Depth 50
4.3.4. Obstruction Shape 50
4.3.5. Sediment Gradation 51
4.3.6. Oscillatory Flow Influence 51
4.3.7. Resistant Bed Layer(s) 52
4.4. Scour Potential – Multiple Piles 52
4.4.1. Linear Pile Arrays 52
4.4.2. Pile Clusters 53
4.5. Scour Potential – Cables and Pipes 53
4.5.1. Sand Burial 53
4.5.2. Water Depth 54
4.5.3. Scour in Currents 54
4.5.4 Scour in Waves 55
4.5.5. Scour in Waves and Currents 56

4.5.6. Time Development of Scour 56
4.5.7. Pipe/Cable Roughness 57
4.5.8. Risers 57
4.5.9. Pipe Vibration 57
4.6. Scour Potential – Large Volume Structures 58
4.6.1. Water Depth 58
4.6.2. Scaling of Scour Depth 58
4.6.3. Scour Depth and Position 58
4.6.4. Scour in Waves 59
4.6.5. Scour in Wave-Current Flow 59
4.6.6. Shape 59
4.6.7. Angle of Attack 59

5. Site Evaluation 61
5.1. CSM - System Description, Classification and Evaluation 66
5.1.1 Coastal Characteristics 66
5.1.2. Coastal Forcing Mechanisms 73
5.1.3. Coastal Response to Forcing Mechanisms 76
5.1.4. Wind Farm Characteristics 80
5.2. Impact Assessment 85
5.2.1. Site Impacts 85
5.2.2. Environmental Impacts 86
5.2.3. Design Impacts 88
5.2.4. Define and Assess Near-Field Effects 90
5.2.5. Define and Assess Far-Field Effects 91
5.3. Impact Assessment and Prioritization 91
5.4. Monitoring Program 92

6. Summary 95

7. References 101

Appendix A: Example Coastal Hydrodynamics and Sediment Dynamics Model 109
A.1. Models 109
A.2. Setup and Validation 110
A.3. Simulating Offshore Wind Devices 114
A.4. Evaluating Sediment Risk 117

Distribution 122

FIGURES

Figure 1. Offshore wind specific CSM flowchart example. 15
Figure 2. Examples of offshore wind turbine foundation types (www.offshorewind.net). 26
Figure 3. Udden-Wentworth grain size scale for sediments. 28
Figure 4. Simplified diagram of sediment transport processes. 30
Figure 5. Simplified diagram of sediment transport processes. 31
Figure 6. Cohesive aggregates eroded from the bed may disaggregate downstream. 32

Figure 7. Shields curve for the initiation of motion for steady flow (from ASCE 1975). 34
Figure 8. Threshold of motion of sediments beneath waves and/or currents. The fitted curves of both Shields (1936) and Soulsby and Whitehouse (1997) are shown. 35
Figure 9. Illustration of longshore current generation and resultant sediment transport. 39
Figure 10. Diagram of the primary, cross-shore, wave driven current in the near shore. 40
Figure 11. Illustration of sediment transport processes interacting in the offshore coastal zone. 42
Figure 12. Hydrodynamics around a slender pile with scour. 44
Figure 13. Example of local (clearwater) and global scour around a structure 45
Figure 14. Tunnel scour causing erosion of sediments beneath pipe/cable (Sumer and Fredsoe, 2002). 47
Figure 15. Free-span showing the span shoulders supporting the pipe/cable. 47
Figure 16. Lee-wake vortex shedding in lee of a pipe/cable span (Sumer and Fredsoe, 2002). .. 47
Figure 17. Potential scour modes occurring in the vicinity of a transmission line. Scour can propagate longitudinally along the line causing large unsupported spans. 48
Figure 18. Illustration of the coastal zone as a component of the Conceptual Site Model. 67
Figure 19. Series of littoral cells along the California coast 68
Figure 20. Elements to consider in the near-shore sediment budget. 69
Figure 21. Map of shoreline stability assessment (NASA). 71
Figure 22. Illustration of single- (left) and multi-beam swath (right) survey technology bottom coverage (NOAA). 72
Figure 23. Contours of sediment grain size based on USGS sediment characterization activities. 72
Figure 24. Example meteorological and oceanographic data from the mouth of Chesapeake Bay (NOAA). 74
Figure 25. Example spectral wave data from a buoy coupled with a real time coastal wave model (CDIP) 75
Figure 26. Solid support systems used for offshore wind applications: (a) monopile structure; (b) suction caisson multi-foundation structure; (c) a suction caisson monopod structure. 82
Figure 27. Example gravity based foundation (http://www.eon-uk.com). 83
Figure 28. Top panel shows a general catenary moored platform where the tethers are arced. Bottom panel shows an exaggerated general tension leg moored platform where the tethers are drawn taut. 84
Figure 29. Pictorial representation of a moored floating wind turbine. The main components of the support system are the nacelle, platform, ballast and mooring system. 84
Figure 30. General CSM flowchart. 98
Figure 31. Offshore wind specific CSM flowchart example. 99
Figure 32.Monterey Bay model domain and bathymetry. NOAA NDBC buoys used for model validation are shown in green. 111
Figure 33.Model (line) representing the wave height (Hs), peak wave period (Tp) and mean wave direction (MWD) obtained from the Monterey Bay SWAN model. Measured data (dots) were obtained from the NOAA NDBC buoy 46236 in Monterey Bay. 112
Figure 34. Model (line) representing the current magnitude obtained from the nearshore Santa Cruz EFDC model. Measured data (dots) were obtained from a Teledyne RDI ADCP deployed during the field study. 112
Figure 35. Peak wave heights modeled using SWAN in the Santa Cruz, CA region. 113

Figure 36.Peak wave heights and velocity vectors in the model domain. Expanded view of the above region. 114
Figure 37. Monterey Bay model domain. 200 offshore wind turbine array. 115
Figure 38. Modeled wave heights before (top) and after (bottom) the inclusion of a wind turbine array. 116
Figure 39. Modeled seabed shear stresses before (top) and after (bottom) the inclusion of a wind turbine array. 119
Figure 40. Risk of sediment transport before (top) and after (bottom) the installation of a wind turbine array. 120
Figure 41.Flowchart of risk assessment methodology. 121

TABLES

Table 1. Shape factor, Ks, compiled by Melville and Sutherland (1988). 51
Table 2. Data needs to develop site characterization. 65
Table 3. Near-field processes and effects. 90
Table 4. Far-field processes and effects. 91
Table 5. Matrix to evaluate the relative importance of an impact. 93

NOMENCLATURE

ABS	Acoustic Backscatter
CDIP	Coastal Data and Information Program
CEFAS	Center for Environment, Fisheries, and Aquacultural Science
COWRIE	Collaborative Offshore Wind Research Into the Environment
CSM	Conceptual Site Model
DEM	Digital Elevation Model
DNV	Det Norske Veritas
DOE	Department of Energy
DOI	Department of Interior
EIA	Environmental Impact Assessment
ETSU	Energy Technology Support Unit
EWEA	European Wind Energy Association
GBF	Gravity Based Foundation
GIS	Geological Information System
GPS	Global Positioning System
GW	Gigawatts
KC	Keulegan Carpenter
MSP	Marine Spatial Planning
MW	Megawatts
NDBC	National Data Buoy Center
NGDC	National Geodetic Data Center
NOAA	National Ocean and Atmospheric Administration
NWS	National Weather Service
OSWinD	Offshore Wind Innovation and Demonstration
SEDFlume	Sediment Erosion at Depth Flume
SNL	Sandia National Laboratories
SSC	Suspended Sediment Concentration
UK	United Kingdom
US	United States
USACE	US Army Corp of Engineers
USGS	US Geological Survey
VIV	Vortex Induced Vibrations

1. INTRODUCTION

1.1. Background

Development of alternative energy production methods in the United States continues at a rapid pace, with significant public and private investment in recent years. Though some are proven energy-generating technologies that are being continually being improved upon (e.g. solar, hydropower, onshore wind), many new technologies are being developed to expand the possibilities of energy capture. Of these new methods (e.g. wave energy, water current (tidal) energy and offshore wind energy), the offshore wind energy development (herein referred to as offshore wind) market has made large strides globally and is presently proving its viability. As the technology improves and the ability to deploy offshore wind turbines in deeper waters and transmit that energy to shore becomes increasingly feasible, developers and agencies will likely continue to look to expand on the offshore wind market.

At present, the world leader in offshore wind development and power generation is Europe, which owns 90% of the installed capacity (EWEA, 2013). China and Japan are a distant second and third representing 9% and 1%, respectively. Within the European community, the UK has the largest amount of installed offshore wind capacity at 59%, followed by Denmark, Belgium, Germany, the Netherlands, Sweden, Finland, Ireland, Norway and Portugal. Further, Spain has recently deployed its first offshore wind turbine in 2013 (Dailyfusion, 2013). Much of the European offshore wind development is due to the European Council directive that sets a mandatory target of 20% share of energy (per country) by renewable sources by 2020.
As of the end of 2012, there were a total of 1,662 installed and grid-connected offshore wind turbines in Europe, with a potential to generate 4,995 MW of power. This is an increase of 31% from 2011 (EWEA, 2013). In the coming years, capacity is expected to continue to increase another 66% in Europe as the cumulative capacity approaches 8.3 GW by 2014.

In the U.S. there is more *onshore* wind capacity installed than any other country (DOE, 2012), but there is currently only one active *offshore* wind installation (though there are thirteen projects that are in various stages of permitting and development [Trabish, 2013]). In June, the VolturnUS 1:8 scale floating offshore wind turbine, designed and built at the University of Maine, was successfully connected to the US power grid (http://composites.umaine.edu).

States with other offshore wind projects in queue include Massachusetts (Cape Wind and Wind Energy Center), Rhode Island (Block Island and Wind Energy Center), Maine (Hywind Maine Pilot Project and Aqua Ventus), New Jersey (Atlantic City), Delaware (Mid-Atlantic Wind Park), New York (Long Island), Virginia (Virginia Beach), Ohio (Icebreaker project on Lake Erie), Texas (Gulf Offshore Wind and Rio Grande North and South Projects) and Oregon (WindFloat Pacific Demonstration Project).

The potential benefit of offshore wind energy in the U.S. is clear: according to the DOE, twenty-eight U.S. coastal and Great Lakes states use approximately 78% of the U.S.'s electricity (www.usoffshorewind.org). Further, it is believed that around 1/3 of all U.S power demand can be satisfied from offshore wind resources along just the East Coast, alone (Biron, 2013).

Offshore wind speeds tend to be larger and persist for longer durations during daytime peak energy consumption hours (compared to onshore wind resources); and, many urban centers are located near the coast and could benefit from offshore wind power generated locally (Black, 2013).

The U.S. is thought to have approximately 4,000 GW of offshore wind potential (Biron, 2013). Offshore wind energy is clean, domestic, and a renewable resource that can help the U.S. address its critical energy, environmental and economic challenges (DOE, 2012). By employing this technology, the U.S. can reduce its greenhouse gas emissions, diversify its energy supply, provide electricity to coastal regions and help revitalize the manufacturing market; though it is not without its costs.

1.2. Current Status in the United States

To make offshore wind a viable renewable energy source, the U.S. must overcome three critical hurdles: (a) reduce the cost of generating offshore wind energy, (b) accelerate the deployment and permitting process, and (c) integrate the new electrical source with the national grid (DOE, 2011; DOE 2012). At present, the U.S. DOE estimates that the cost of wind generated electricity is 2 to 3 times larger than coal- and natural gas-fired power sources (Goreham, 2013; Downing, 2013). Two of the primary reasons for this are the high costs of up-front development and permitting, and the increased engineering required for offshore installation (harsh installation environment, dynamic operational environment and other deployment considerations such as long distance transmission of energy to the shore). Current time estimates to receive project approvals to build offshore wind projects range from 7 to 10 years (DOE, 2012).

The U.S. DOE is presently undertaking numerous research activities that aim to overcome these challenges, including generation of a comprehensive guidance document to steer interested parties efficiently through the processes. The Offshore Wind Innovation and Demonstration (OSWinD) initiative was created in 2010 to consolidate and expand the DOE's efforts to promote and accelerate responsible commercial offshore wind development in the U.S. Also in 2010, the Department of Interior (DOI) announced the Smart from the Start initiative to speed up environmentally responsible offshore wind development along the Atlantic outer continental shelf by streamlining the approval process for projects, implementing a comprehensive expedited leasing framework, and processing offshore transmission applications concurrently (DOE, 2011). The OSWinD and Smart from the Start efforts are complementary and designed to reduce the offshore wind deployment timeline in the U.S.

Further initiatives have been developed to establish clear guidelines on marine development in order to foster a holistic approach. In 2009 the U.S. Executive Office signed a memorandum establishing the Interagency Ocean Policy Task Force, led by the White House Council on Environmental Quality. In 2010 the task force released a set of final recommendations that set a new direction for improved stewardship of the ocean, our coasts, and the Great Lakes. The recommendations provide for (1) the U.S.'s first ever national ocean policy; (2) a strengthened governance structure to provide sustained high-level and coordinated attention to ocean, coastal, and Great Lakes issues; (3) a targeted implementation strategy that identifies and prioritizes nine

categories for action that the United States should pursue; and (4) a framework for effective coastal and marine spatial planning (MSP) (www.cmsp.noaa.gov/).

1.3. Using This Document

To support the overall approach, the ensuing recommendations presented within this document support the nation's offshore wind strategy by providing the necessary information to:

a) Reduce time and costs associated with planning, development and permitting by enabling prediction of site-specific environmental (hydrodynamics and sediment dynamics) responses to offshore wind farm designs, and,

b) Reduce lifecycle installation and maintenance costs through informed offshore wind farm array design that considers the local installation environment and the near- and far-field environmental (hydrodynamics and sediment dynamics) impacts.

These tasks will be addressed in this document using focused, streamlined guidelines for comprehensive coastal assessments that consider the interrelationship between ocean waves, flow and seabed dynamics, the influence on subsea foundations and cables, and associated environmental effects of offshore wind installation. Specifically, this guidance will demonstrate the use and applicability of developing *Conceptual Site Models (CSMs)* as the framework for understanding the influence that offshore wind and other anthropogenic development activities have on the coastal zone. Impacts and considerations of environmental assessments not related to oceanographic and sediment stability guidance (e.g. visual impacts, navigation conflicts, ecological and/or biological effects) should also be considered by planners and managers, but are not addressed in this document.

This document is intended to be used by offshore wind developers, managers, scientists and regulators to guide development of a *CSM* framework for offshore wind site planning as it relates to oceanographic and sediment stability assessments. The CSM provides a qualitative and quantitative description of the system, describing all of the known physical processes, and their interactions, for the purposes of evaluation and decision making. It also provides the basis, throughout the entire project, for which data assimilation, collection and analysis is integrated into a single site description, ensuring that all information is both relevant and completely utilized in the decision making process. A comprehensive CSM will complement the overarching MSP procedure, allowing for straightforward decision-making of the intended development site in a holistic manner (considering other recreational and economical users, environmental impacts, ecological impacts and development impacts of the intended site). An example of a flowchart of oceanographic and sediment dynamics CSM development, specific to offshore wind impact assessment, is shown in Figure 1. The development of this flowchart and related CSM procedures will be described in further detail in the following sections.

The oceanographic and seabed dynamics information discussed within this document represents examples of some of the leading scientific and engineering advances in physical processes understanding. The guidance and information within has been assimilated from available documentation on offshore wind development guidance and monitoring programs worldwide as well as existing physical processes literature. The methods and recommendations presented

herein, however, should not be construed as comprehensive. For one, the science is in a state of constant improvement, globally. As more wind farms are constructed, more laboratory and field data are obtained, more analyses are completed, and more analytical progress is made, new ideas, guidance and theories will be formed based upon lessons learned and the current state of the science; and, techniques may become available that are not discussed in this document. Therefore, this document is considered to be a 'living' document. As projects progress, additional data are collected and lessons are learned, the guidance within will be continually updated to reflect the state of the industry knowledge. Second, each planned development site is different from every other and should be evaluated based on site-specific information, data, and stakeholder's concerns. There is no conventional procedure to be applied universally to all sites as each has different physical, social and economic considerations.

The document is intended to provide the reader with a basic overview of the environmental considerations at a typical coastal location and the tools to help guide the reader through a thorough planning process. It will enable readers to identify the key coastal processes relevant to their offshore wind site and perform pertinent analysis to guide siting and layout design, with the goal of minimizing planning, permitting, and long-term maintenance costs. The document will highlight site characterization and assessment techniques for evaluating spatial patterns of sediment dynamics in the vicinity of a wind farm under typical, extreme, and storm conditions. Finally, the document will describe the assimilation of all of this information into the CSM to aid the decision-making processes.

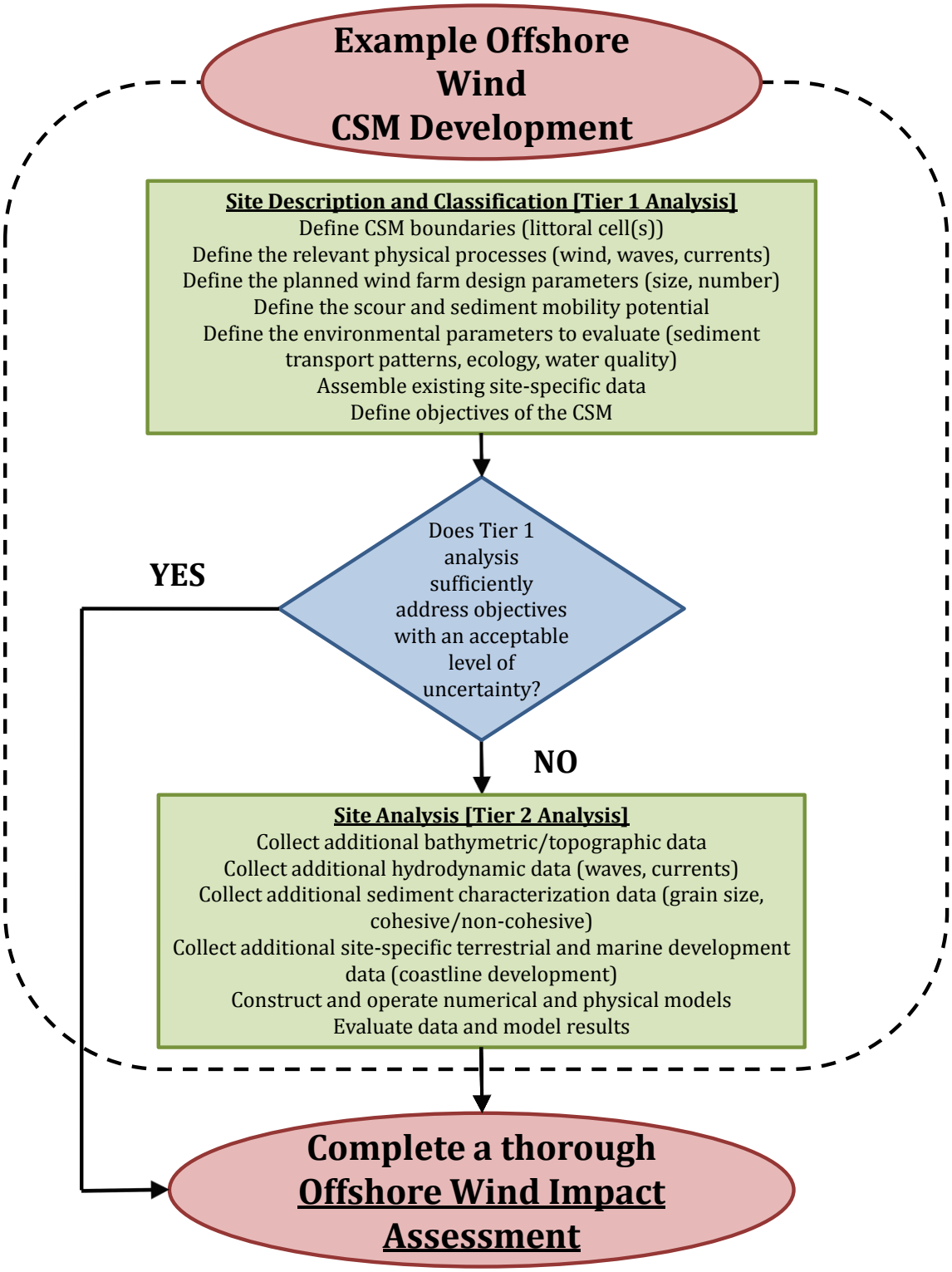

Figure 1. Offshore wind specific CSM flowchart example.

2. GUIDANCE AND RECOMMENDATIONS

2.1. Lessons Learned and Existing Guidance

Offshore wind farm development outside of the U.S. has, to date, progressed through several phases in some international locations, each acting as valuable knowledge basis for future development efforts. In the U.K., for example, the first development efforts (e.g. Rounds 1 and 2) focused on shallower water locations, where shallow water processes would dominate. Round 1 comprised a demonstration phase in order to first test many untested concepts on smaller scales. Eighteen (18) projects were contained within 10 km^2 of seabed and located within 12 nautical miles of the coast.

Guidance during this phase consisted of perceived issues of concern that potentially could lead to environmental risk (Lambkin et al., 2009). The environmental impact assessment (EIA) documents listed probable environmental risk issues and the types of data that should be collected; and described practical methods for modeling physical processes as part of site specific investigations (CEFAS, 2001; DTI, 2002; ETSU, 2002 (all references from COWRIE 2009). Little existing data or knowledge was available to make informed, accurate predictions of the environmental effects of offshore wind development.

The Round 1 projects progressed under these guidelines, tending to adopt a worst-case scenario in order to mitigate for any unknowns. Levels of uncertainty in EIA results were high during this initial phase since there was a lack of direct observational evidence to support the views expressed in the EIAs (Lambkin et al., 2009). Physical process monitoring programs were implemented in order to capture baseline and altered hydrodynamic and sediment dynamic states resulting from offshore wind development. These monitoring programs yielded valuable data to directly assess the impacts of offshore development and also to validate numerical modeling efforts. As a result of several studies (CEFAS, 2005 – sid5 ae1227; CEFAS, 2006 – ae0262), for example, certain aspects of study programs were refined and/or determined to be unnecessary for future efforts. In this manner, future efforts were more streamlined.

In the Round 2 efforts, development was opened to commercial scale projects. Exclusion zones were established to reduce visual impact and avoid shallow water bird feeding areas, and, as a result, projects were typically located in deeper water locations than the Round 1 counterparts. The move to deeper waters introduced additional issues of concern including designing for deeper waters, assessing the impacts of these alternative foundation designs on the environment, and the potential for cumulative impacts with other seabed users (Lambkin et al., 2009). Guidance documentation for Round 2 was similar to that used for Round 1 but was improved and enhanced based upon lessons learned (CEFAS, 2004).

Three key studies related to physical processes and construction that resulted from the Rounds 1 and 2 monitoring efforts included:

1) **Seabed and Coastal Processes Research report SED01 (ABPmer et al., 2008)**
    a. Evaluated the collective results of sediment monitoring activities (suspended sediment, seabed morphology and scour) from Round 1 sites and other European offshore wind farms, when available.
    b. Conclusions:
        i. Seabed morphology was only affected at local scales (e.g. scour) at all sites except for Scroby Sands, which has shown itself to be a very dynamic site.
        ii. Best practice method was recommended for suspended sediment monitoring activities (to include a specialist and a standardized method for inter-comparison)
        iii. Best practice method for repeated bathymetric surveys was recommended (for inter-comparison capabilities).

2) **Seabed and Coastal Processes Research report SED02: Dynamics of Scour Pits and Scour Protection (HR Wallingford et al., 2008)**
    a. Investigated in more detail the scour findings from SED01.
    b. Comparisons were made between scour measurements and predictions made in the preceding environmental assessments.
    c. Conclusions:
        i. The predicted maximum scour depths and extents compared well to the measured data, though some locations did not erode as much as predicted.
        ii. Concerns about secondary scour formation around scour protection were discussed
        iii. Site specific scour protection plans are now required for all locations.

3) **Review of cabling techniques and environmental effects (Royal Haskoning and BOMEL, 2008).**
    a. Studied the various options of cabling techniques in the marine environment.
    b. Provided a qualitative and quantitative assessment of the impacts of cabling operations.
    c. Conclusions:
        i. The increased suspended sediment concentrations as a result of cable laying are likely to be small in comparison to natural levels, that the effect will be limited temporally and localized spatially.

Round 3 efforts were subsequently announced and targeted even deeper water locations for development. Each development site still required a site specific environmental impact assessment in order to obtain the required development consent (Lambkin, 2009). Development in deeper waters required a renewed assessment of issues of concern. All previous development efforts were based on the potential impacts of shallow water processes and user interaction. With

movement into deeper waters, new perceived concerns required consideration including additional marine users, marine life and deep water physical process understanding, of which little existing data were at hand.

At this point, In the U.K., the Crown Estate (which owns the waters approximately 12 nautical miles offshore from the U.K. shoreline) took a more holistic approach to planning and approving development. They recognized that the coastal zone and continental shelf contains some of the U.K.'s most important conservation and protection areas, and that those needs needed to be balanced with the requirements for resource utilization, development, commercial and leisure activities. In 2008, they implemented a marine spatial planning tool, MaRS, which comprehensively assessed development zones under consideration. The MaRS tool was developed to facilitate a strategic, transparent and coherent approach to the decision making process and to foster a better understanding of, and agreement to, potential activity in the marine estate. According to the Crown Estate, the MaRS will improve the U.K.'s understanding of marine resource use, identify gaps in knowledge and underpin future development of the marine environment (www.coastms.co.uk/).

In recent years, several international agencies (DNV, ETSU, CEFAS, COWRIE, etc.) have prepared, published and subsequently updated recommendations and guidance pertaining to offshore wind development as a result installation of increasing numbers of offshore wind farms. As implied above, the guidance and recommendations have been developed initially from perceived issues of concern, and have evolved as negligible issues are omitted and/or important considerations are refined. The available guidance pertains to all facets of project planning and development from environmental impacts through post-construction monitoring, from navigation concerns and visual pollution to construction and decommissioning of the farms. Within the present document, the recommendations that pertain specifically to environmental (oceanographic and sediment dynamics) impacts are briefly discussed. The reader is referred to the specific references for additional detail.

2.2. EIA General Guidance (CEFAS, 2004)

As a result of previous projects, monitoring efforts and follow-on evaluations, general and specific guidance guidelines have been developed by agencies to assist in future project planning and assessment. In general, the guidance emphasizes that users should evaluate a project site for all direct and indirect impacts. From an oceanographic and sediment dynamics perspective, the following general recommendations are made:

1) All offshore wind farm developments should be assessed on a site-specific basis.
2) EIAs should include investigations into the anticipated direct impacts on hydrodynamics and sediment dynamics as a result of offshore wind farm installation.
3) EIAs should then include investigations into the potential indirect impacts of hydro- and sediment dynamics on other disciplines (e.g. benthos, fisheries, coastal protection, water quality, sediment quality, conservation designated sites)
4) At all offshore wind farm developments it is necessary to assess the magnitude and significance of anticipated changes to the:

a. Hydrodynamics (for both typical and extreme conditions)
b. Sedimentology (e.g. suspended sediment concentrations, composition, geochemistry, particle size distributions, contamination)
c. Sedimentary environment (re-suspension, sediment transport pathways, re-deposition, erosion, scour)
d. Geomorphology (e.g. channels, banks, canyons, bedforms, alteration rates/patterns, bioturbation, depth of mixed layers)

5) Offshore wind developments should be assessed for potential near- and far-field effects.
6) Offshore wind developments should be assessed with respect to:
    a. Baseline conditions
    b. Construction and post-construction scenarios
    c. Sedimentary recovery phase(s)
    d. Lifetime and operation phase(s)
    e. Decommissioning phase(s)
7) When describing the baseline conditions at a site:
    a. It is important to identify the processes that maintain the system, reasons for past changes to the system and the system's sensitivity to future changes.
    b. The relative importance of high energy/low frequency vs. low energy/high frequency events must be quantified and described as possible.
    c. The processes controlling temporal and spatial morphological change (e.g. longevity of bedforms) must be defined.
    d. The sediment budget must be defined (identify sediment sources, pathways, sinks, transport and fluxes).
    e. The ambient geological, geophysical, geotechnical and geochemical information of the site must be described.
    f. It is important to consider both the offshore and coastal regimes as each may be directly or indirectly altered by changes to the baseline scenario.
8) When considering the impacts to a project site after development:
    a. The potential for foundation scour should be assessed, including justification and requirements for scour protection.
    b. The potential for scour to occur around supply cables and other associated structures, including the potential for suspended sediment concentration changes and/or development of free spans in cables.
    c. It is important to consider the spatial design of the turbine grid array and offshore substations and the subsequent potential for impacts to the wave patterns, tidal flows and sedimentary regime.
    d. The non-linear interactions of waves and currents, and the quantification of the extent to which the seabed sediment becomes mobilized, should be investigated.

e. The potential for sediment mobility and negative impacts on turbine foundation strength and stability should be investigated in determining proper foundation design.
f. It is important to evaluate the effect of development of the seabed, foundation installation and cable laying on suspended sediment concentrations (SSCs).
g. It is important to assess the scales and magnitudes of processes that control the ambient and altered sediment transport pathways and rates.
h. It is important to consider the effects of climate change on hydrodynamic, sedimentological and geomorphological regimes.

2.3. Oceanographic and Sediment Dynamic Specific Considerations

When specifically assessing the coastal and seabed impacts at a planned offshore wind array site, some example key issues to consider are listed below. It is important to note that this list is representative, but not all-inclusive, of the issues of concern at offshore wind development sites. As mentioned above, each project should be assessed on a site-specific basis since each location is subject to different physical, chemical, biological and ecological influences and considerations.

1) The wave energy dissipation and/or focusing that may negatively impact shorelines when the offshore wind array is less than 5 km from shore.
    - *Relevance: investigating the receptors sensitive to changes in coastline morphology*
2) The wave and/or current processes that control the shallow water morphology, especially for dense turbine arrays and/or less understood foundations.
    - *Relevance: investigating the ecological or navigation receptors that are sensitive to changing bed morphology, scour or channel migration*
3) The SSCs and deposition patterns that may result from foundation and/or cable installation, operation and decommissioning (Lambkin et al., 2009).
    - *Relevance: investigating any receptors that may be sensitive to specific changes in burial depth, SSC loads or sediment seabed textural changes*
4) The potential changes in coastal morphology due to cable landfall installation, operation and maintenance.
    - *Relevance: investigating receptors sensitive to erosion/accretion including habitat, property, recreation and landscape*
5) The potential for scour to occur and the need for scour protection.
    - *Relevance: investigating receptors sensitive to the introduction of a new substrate*
6) Foundation types, array densities and geometries that are considered more likely to alter the incident wave parameters.
    - *Relevance: investigating the receptors sensitive to changes in coastline morphology*

2.4. Modeling Considerations (Physical and/or Numerical)

Physical or numerical modeling may not always be necessary or appropriate. If the impacts on the receptors cannot be quantified reliably and categorized as significant or not significant, then little additional benefit may be obtained by undertaking costly and complex modeling. Therefore, modeling shall be recommended and utilized when professional opinion indicates a likely increased value to the project. Some guidelines to follow when considering a modeling effort:

1) Whether physical or numerical, choose a model that will allow assessment of baseline and alternative schemes.
2) Ensure that the model provides for sufficient resolution and quantification of data and quality results.
3) Ensure that the model results can be expressed confidently through model calibration and validation efforts.
4) Utilize the model to compare the alternative development schemes to the baseline scheme.
5) When appropriate, use realistic worst-case scenario modeling conditions to reduce uncertainty.
    a. In this way, all other less intrusive design options can be accounted for.

2.5. Marine Spatial Planning

Marine spatial planning began as a planning tool in Europe and Asia to achieve economic and environmental objectives. It is a practical decision-making approach that moves toward ecosystem-based management of marine areas (Ehler and Douvere, 2009). MSP is a practical way to create and establish a more rational organization of the use of marine space and the interactions between its uses; to balance demands for development with the need to protect marine ecosystems; and to achieve social and economic objectives in an open and planned way.
It offers countries an operational framework to maintain the value of their marine biodiversity while also allowing sustainable use of economic potential of their oceans and coasts.
Marine spatial planning is similar to CSM development in that the steps involved are, generally:

- Organize the process through pre-planning
- Define and analyze the existing conditions
- Define and analyze the future conditions
- Prepare and approve the plan
- Monitor and evaluate the project
- Evaluate and adapt as necessary

Conceptual site models can be as small or large-scale as needed (e.g. local or regional scale oceanographic and sediment dynamics CSM), whereas MSP is typically a holistic, large-scale approach. Characteristics of MSP include:

- Being eco-system based

- Integration with all stakeholders
- Being place-based or area-based
- Being adaptive
- Being strategic and anticipatory
- Being participatory

An MSP is a living plan that learns and adapts over time.

2.5.1. MSP in the U.S.

The U.S. has adopted a MSP program to assist with managing marine uses and activities at the regional level (http://www.csmp.noaa.gov/). Marine planning places sound science and the best available information at the heart of decision-making and brings federal, state, tribal and other partners together to cooperatively develop coastal and marine spatial plans. As in other international MSPs, this process is designed to decrease user conflict, improve planning and regulatory efficiencies, decrease associated costs and delays, engage affected communities and stakeholders, and preserve critical ecosystem functions and services. In short, it is a tool developed to improve collaboration and coordination among all coastal and ocean interested, and to better inform and guide decision-making that affects the economic, environmental, security and social and cultural interests of all involved.

In the U.S. the National Ocean and Atmospheric Administration (NOAA) is the nation's primary ocean agency. Therefore, to support the MSP mission of considering the ecosystem as a whole, NOAA will assist with the establishment of science-based decision-making in marine planning activities by engaging the federal government, states, tribes, non-governmental agencies, academia and other stakeholders to develop scientific support tools to for the purposes of marine planning (http://www.csmp.noaa.gov/role/).

3. SEDIMENT TRANSPORT FUNDAMENTALS

3.1. Introduction

There are many commercial and recreational users of U.S. coastal waters; and, offshore wind development will need to seamlessly co-exist with these stakeholders. Also, the coastal environment can be harsh and for the offshore wind industry to succeed, offshore wind structures and infrastructure (foundations and cables) must not only survive, but thrive, with minimal maintenance requirements.

With offshore wind foundation and cable stability of primary importance to turbine lifetime longevity, scour, the net erosion of sediments around these structures, has become a highly studied phenomenon. Laboratory and field experiments have resulted in empirical and semi-empirical equations to determine the breadth and depth of scour holes that will form near a flow obstruction, evaluations of which have provided some valuable guidance for future offshore wind development (Cooper and Beiboer, 2002; den Boon et al., 2004; OSPAR, 2004; CEFAS, 2004; CEFAS, 2008a; CEFAS, 2008b; OSPAR, 2008; Stahlmann and Schlurmann, 2010; Yang et al., 2010; DNV, 2011; among others).

These investigations have comprised mostly of scaled laboratory investigations, though, and applications of the empirical equations to prototype scales have yielded mixed results. However, the offshore wind development that has taken place in recent years has led to the accumulation of field data (through established post-construction monitoring programs) and to the creation of guidance frameworks that incorporate the latest advances in site planning and understanding. These recommendations can be used by developers to streamline the permitting, planning, design and development processes. Due to the infancy of offshore wind in the U.S., little is known about either (a) the short- and long-term, and near- and far-field, environmental effects associated with offshore wind installation, operation, and maintenance activities, or, conversely, (b) the effect the environment has on the sub-aqueous wind turbine components during typical and extreme (storm) conditions. Therefore, it is critical for the project planners to review all available guidance literature, to be able to reasonably predict the ocean's impacts on the wind turbine structures, and to predict the wind turbine structure's influence on the coastal processes, in order to support efficient siting, planning and permitting efforts.

The motion of the ocean is largely driven by waves and tides. These processes will generate forces throughout the water column that are important for foundation and cable structural stability design. Moreover the near bottom currents generated by these coastal processes impart stresses on the ocean floor sediments and are directly responsible for the erosion, transport and deposition of these sediments.

Shallow water offshore wind technologies often require foundations systems that are anchored through the ocean floor and/or resting on the seafloor surface, with transmission cables laid upon or buried in the sediments. Transitional and deepwater offshore wind technologies often do not involve traditional supports in or on the seafloor; however they tend to require additional anchorage, stabilizing structures, or may comprise floating platforms that are anchored to the

seabed (Figure 2). The presence of each of these structures, their anchorages and their cables will change local flow patterns in different manners, which may, in turn, alter local seabed dynamics.

Scour occurs where the sediment is eroded from an area of the seabed in response to the forcing by waves and/or currents (Whitehouse, 1998). It has the potential to negatively affect offshore wind foundation stability, cable installations, and critical attachment points (e.g. j-tubes), requiring costly maintenance or repair. If a large number of offshore wind structures are placed offshore of a coastline, near-shore wave energy and current circulation patterns may also be adversely affected. Consequently, the way sediments are mobilized and distributed along the coast and the manner in which wave action is imparted on a shoreline may be altered. Potential consequences include generation of erosional "hot spots" and/or depositional "shoaling" locations, disruption of natural littoral sediment transport, water quality alterations and ecological consequences.

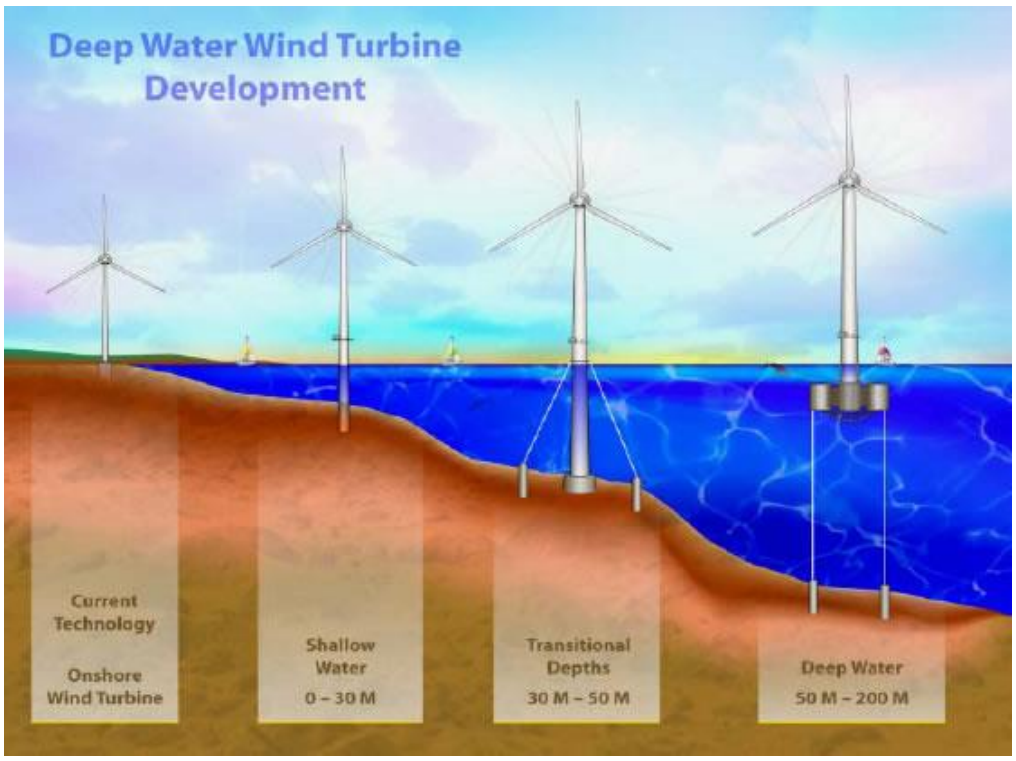

Figure 2. Examples of offshore wind turbine foundation types (www.offshorewind.net).

As mentioned, sediment in the coastal zone is primarily mobilized and transported by the action of waves and currents. The overall sediment transport of a region is quantified in a sediment budget, which describes the rate and amount of sediment being transported into and out of that region. In a broad sense, regions may comprise large sections of a coastline and continental shelf or a small embayment between two promontory headlands. A sediment budget, once defined, can determine the type(s) and magnitude(s) of regional transport taking place and whether a coastal region is ultimately eroding or accreting.

The sediment transport type is commonly categorized into cross-shore (perpendicular to shore) and alongshore (parallel to shore) components and is directly dependent upon the direction of the incident waves and currents. The sediment transport magnitude, therefore, is the amount of sediment that is eroded, mobilized and re-deposited, and is dependent upon the strength and duration of the incident waves and currents.

The key to understanding sediment transport is the identification, description, and quantification of the dominant physical processes involved in moving sediments, and understanding how the processes interact at a site. Although other seabed properties and characteristics may affect sediment transport, an understanding of these fundamental physical processes is critical to the overall quantification of transport. In the sections below the properties of site hydrodynamics (waves and currents) and sediment characteristics that have the greatest influence on sediment transport are established and their relative importance described.

3.2. Role of Hydrodynamic Processes

Waves are typically generated by strong winds imparting stresses on the water surface over long distances. The larger the wind stress (i.e. wind speed), and the longer that wind stress is applied to the wave surface, the larger the wave height generated. The wave height that is generated is typically limited by the duration for which the wind blows, the local water depth (depth-limited), or the distance over which the wave has to grow (fetch-limited). Swell waves are generated by winds that blow for long durations and over large fetches (distances). Sea waves are generated by winds that blow for short durations or over short-fetches. Swell waves are generally created by a distant storm and travel for long-distances. Sea waves are created by local storms and travel for relatively shorter distances. Swell wave frequency and direction spectra tend to be narrow-peaked and approach from a more focused direction; sea wave frequency and direction spectra tend to be broad-peaked and may approach from multiple directions. Finally, waves are also generated by other physical processes such as storm pressure gradients, storm surges, tide fluctuations, seismic events (e.g. tsunamis) and transiting marine vessels.

Needless to say, wave motion is very complex. The combination of all wave-generating processes mentioned above may create waves that are well-focused in a particular direction or waves that are broadly spread in a wide direction (or multiple directions), which has a direct effect on the resultant wave energy and sediment transport at a particular location. As deepwater waves approach the coast, they are transformed by additional processes including refraction (as they pass over changing bottom contours), diffraction (as they propagate around solid objects such as headlands and breakwaters), shoaling (wave height increases as the depth decreases), and energy dissipation (due to sea surface white-capping, seabed bottom friction, seabed vegetation, and, ultimately, by wave breaking).

Combine these effects with the impacts of near-shore circulation (upwelling, lunar tide and/or Coriolis effect), local flow and water level effects such as wind setup, storm surge and river discharge, and long-term effects such as sea level rise, and the equation becomes increasingly more complex. Though the prediction of hydrodynamic conditions may be difficult, the long-term measurement and subsequent analyses of these data allows statistical assessment of many of these processes at a particular site. It is the duty of the prudent engineer to determine the most

important hydrodynamic processes to evaluate at a site to describe the local wave regime with the highest confidence level possible.

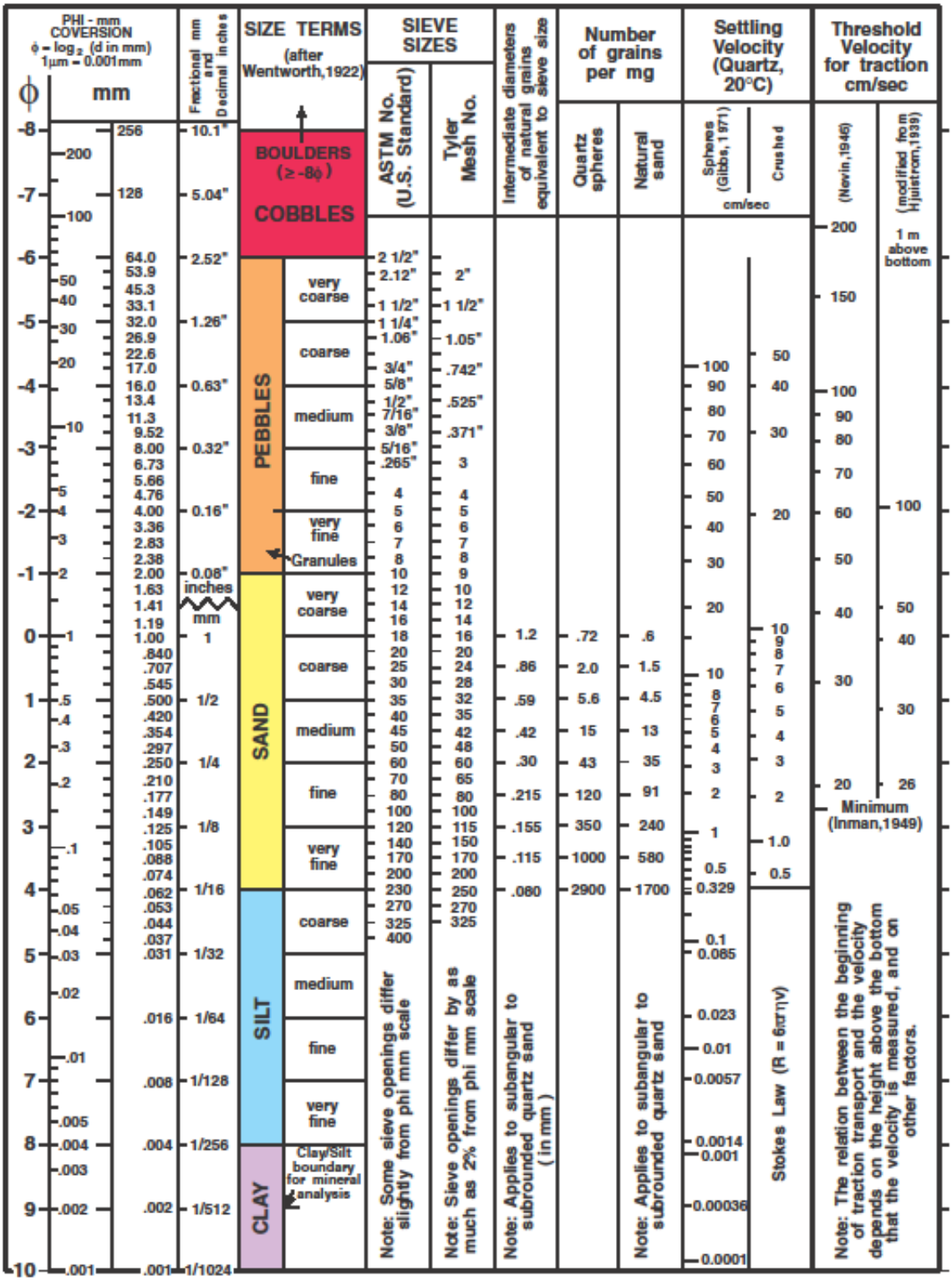

Figure 3. Udden-Wentworth grain size scale for sediments.

3.3. Physical Properties of Sediment

For most systems, knowledge of particle size distribution and bulk density are instrumental to the understanding of local sediment transport processes. Particle size (or grain size) distribution is the most widely used property in engineering and environmental studies for the characterization of the sediment bed. Sediment particle sizes are classed from very fine clays with a particle diameter of 0.24 μm (.000 000 24 m) to boulders larger than 0.25 m in diameter. In between these extremes are particle sizes that make up the sediment beds of common aquatic systems: sands and silts. Figure 3 describes the typical ranges of particle (or grain) size associated with each classification, along with a corresponding phi (Φ) classification that is also used in many engineering and environmental classifications. The classification system shown here is commonly referred to as the Udden–Wentworth classification system.

Sediments are generally classified as cohesive (fine grain-sized silts and clays) or non-cohesive (coarse grain-sized sands and gravels). Cohesive sediments are sediments in which inter-particle forces are significant, creating an attraction or cohesion between particles. Though there may be some variation in definition, cohesive sediments are generally defined as those with particle sizes less than 200 μm in diameter. The smaller ranges of cohesive particles (<62μm) are silts and clays, and the larger sizes (62 to 200 μm) are fine sands. Non-cohesive sediments are those in which inter-particle forces are insignificant, and are generally defined as those with particle diameters larger than 200 μm. These size ranges typically include, at the smallest diameters, fine to medium sands, and at the largest diameters, gravels.

Most often, natural sediments consist of a mixture of these sediment grain sizes, and samples are often qualitatively described based on the relative proportions of each sediment type. For example, a mixture of a small amount of sand with clay can be called sandy clay; and a smaller amount of silt with larger amount of sand might be called a silty sand. As intuition suggests, sediment mixtures will, therefore, have varying amounts of cohesiveness. This is an important distinction because the cohesiveness of a sediment sample directly affects its susceptibility to erosion, transport and deposition.

Bulk density is another basic property of a sediment bed that is useful for classifying sediments and quantifying transport properties. The bulk density, ρ_b, of a sediment bed describes the overall degree of packing or consolidation of the sediments, and can be described as the dry bulk density or saturated (wet) bulk density. It is defined as the ratio of the mass of dry sediment to the total sample volume (dry bulk density) or the total sample mass (sediment plus water) to the total sample volume (wet bulk density).

The approximate particle density of the quartz and clay minerals that make up the majority of sediment particles in the natural world is about 2.65 g/cm^3, though some variation exists where other sediment types and organic materials are encountered. The sediment bed, as mentioned, is often composed of a mixture of different types and sizes of sediment particles packed into a porous bed. In non-cohesive sediments, bulk density may not vary much with depth, as non-cohesive particles typically do not readily compact over time. In cohesive sediments, though, bulk density generally increases with depth into the sediment because the deeper sediments are typically more consolidated; containing less porous space between individual particles. Cohesive

sediment beds will consolidate over time due to the weight of overlying sediment, expelling pore water to the surface and bringing the particles closer together in the absence of the expelled water. This causes an increase in the bulk density at increasing depth into the sediments. As the bulk density increases due to consolidation, the potential for scour or erosion of the sediment generally decreases as a larger shear stress is required to mobilize the compacted sediments (Jepsen and Lick, 1997; Mehta and McAnally, 1998).

3.4. Sediment Erosion

Erosion, water column transport, and deposition are the sediment transport processes that occur in aquatic systems (illustrated in Figure 4). Erosion is defined as the flux (i.e. movement) of particles from the sediment bed into the overlying water column. Deposition is the settlement of particles out of the water column. Sediments that are in motion travel as bedload (bouncing along the bottom), suspended load (up in the water column supported by turbulent mixing), or as wash load (very fine particles dispersed throughout the water column that travel with the mean flow).

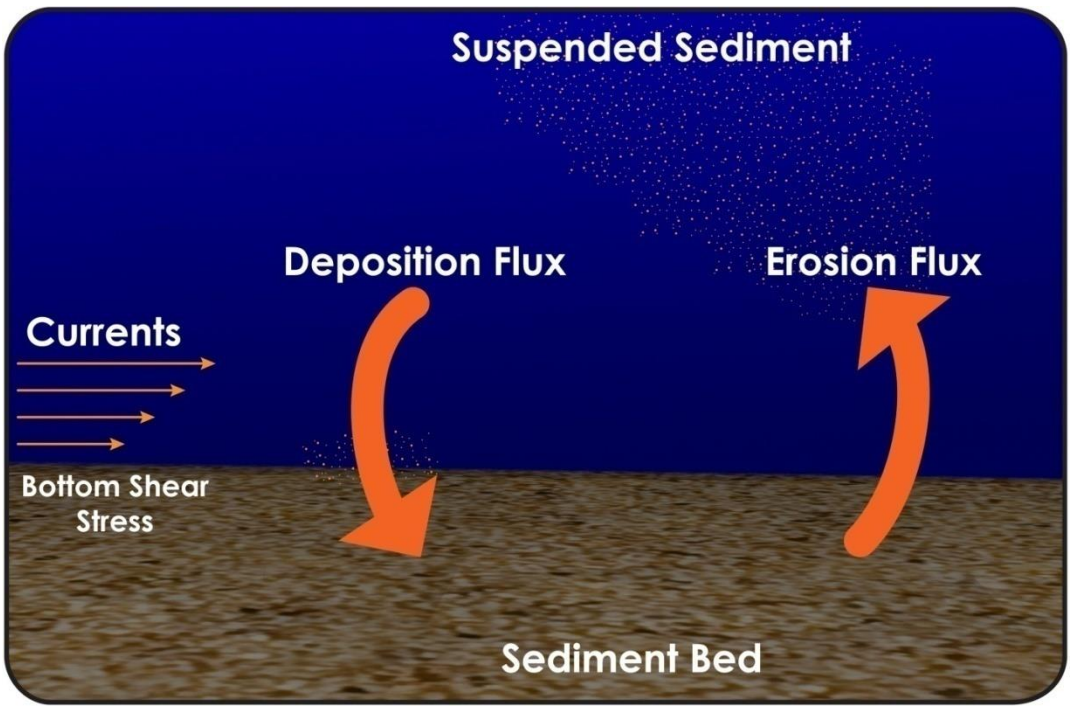

Figure 4. Simplified diagram of sediment transport processes.

Resting sediment bed particles are in equilibrium between the drag forces from fluid shear, the lift forces from flow over the particles, gravitational pull on the particles, particle to particle contact forces and cohesive inter-particle forces. At a certain velocity, though, the combined drag and lift forces on the uppermost particles of the sediment bed are great enough to dislodge them from their equilibrium positions. This velocity is termed the critical velocity and is proportional to the critical shear stress for erosion, τ_{ce} (measured in units of force per unit area (N/m^2), which is the shear stress at which sediment motion is initiated. This motion initially tends to occur only at a few isolated spots, but, as the shear stress increases with increasing flow velocity, the

movement of particles becomes more widespread, causing a net erosive flux from the sediment bed.

The flow velocity near the bottom can be modeled as a logarithmic profile in its simplest sense: At the sediment bed, the velocity is zero (following standard pipe flow theory). Velocity increases logarithmically above the bed until a distance is reached where the bottom friction no longer affects the flow. The layer between the bed and this elevation, where the shear stresses (e.g. friction) are the highest, is called the boundary layer (Figure 5).

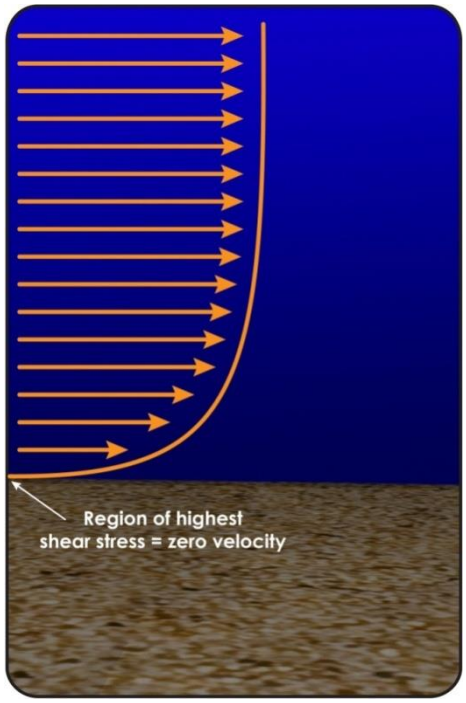

Figure 5. Simplified diagram of sediment transport processes.

In riverine systems a unidirectional current is generally responsible for the shear stresses imparted on the sediment bed. In coastal regions and estuaries, though, a combination of oscillatory waves, currents, and fluctuating tides are responsible. Determination of the processes responsible for imparting shear stresses on the sediment bed is important in characterizing a sediment transport regime. Shear stress can be measured directly and/or indirectly in the laboratory or in the field. It has been studied in detail for currents and waves, and can be defined and quantified mathematically if given sufficient information about the hydrodynamics of the system.

Finally, in addition to ambient forcing mechanisms (background wave and current forces), erosion may also be induced due to enhancements of each of these phenomena. For example, as flows encounter waterway constrictions and obstacles, the local flow speed typically increases in proximity to these impediments. The localized flow increases may cause corresponding increases in near-bottom shear stresses, which, if larger than the critical shear stress of the bed sediments, may induce additional erosion.

If significant enough, the localized erosion (also known as scour) may cause structural degradation or failure of the obstacle. In particular, erosion around wind turbine foundations, cables, and other infrastructure has the potential to eventually undermine foundations and lead to unexpected maintenance and system failure if left unchecked.

Scour around underwater structures subsequently becomes a sediment source as the sediment becomes suspended in the water column, is transported away from its resting location, and is re-deposited elsewhere. Net erosion occurs if, over time, the amount of sediment removed from the bed in an area exceeds the amount that is episodically deposited.

3.5. Sediment Transport

Once sediment has been mobilized, the subsequent transport mechanisms are divided into two general modes: bedload transport and suspended load (which also includes wash load) transport. Coarser particles and aggregates (or particles subjected to shear stresses similar to the critical shear stresses) move along the bed by rolling and/or saltation (i.e., bouncing) in a thin layer as bedload, whereas finer particles (or particles subjected to large enough shear stresses) are suspended into the water column and move as suspended load. The mode of transport for a given particle is largely affected by the sediment properties and flow regime of the region.

Bedload can account for a significant amount of sediment transport in systems comprised of coarse-grained sediments (sands and larger), where the flow is high enough to cause rolling motion but not strong enough to lift particles off of the sediment bed. Although bedload transport may be dominant in coarse-grained rivers and near-shore coastal regions, it may or may not be of significance in fine-grained (fine sands and smaller) regions such as estuaries, lakes or deeper coastal waters. In fine-grained sediment systems, both individual particles and aggregates will erode and move along the bed as bedload or suspended load depending upon the flow regime. Individual particles may flocculate (cohere) during transport, increasing their likelihood and/or rate of deposition; or the larger aggregates may break up into smaller aggregates or individual particles during transport, making them more likely to travel as suspended load for a longer period of time (Figure 6).

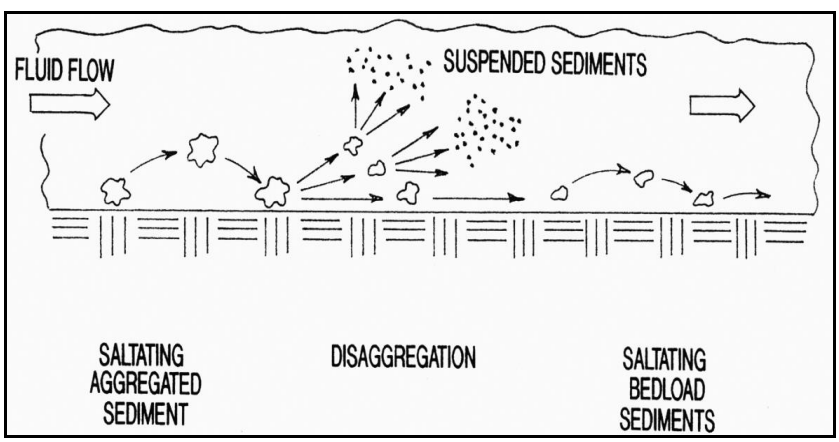

Figure 6. Cohesive aggregates eroded from the bed may disaggregate downstream.

Sediment particles transported as suspended load tend to move at, or very close to, the mean velocity of the fluid. In a steady-state situation, upward turbulent transport of a sediment particle by the fluid is balanced by the gravitational particle settling. This balance keeps the sediments suspended in the water column. As long as the flow remains sufficiently turbulent, sediments will be transported as suspended load. As current velocity decreases, suspended sediment concentrations generally increase near the bed as heavier particles begin to settle out of suspension. Vertical profiles of suspended sediment concentrations can be calculated based on particle size, a reference suspended sediment concentration near the sediment bed, and the ambient fluid velocity (Rouse, 1938; van Rijn, 1993). They can also be measured and estimated with acoustic and/or optical instrumentation. This can be useful in determining overall sediment flux of a region.

Within the water column, two processes generally dominate the movement and net transport of particles: advection and turbulent diffusion. Advection is the transport of particles caused by the motion or velocity of the fluid (i.e. mean current velocity). Turbulent diffusion is the dispersal of particles in the water column due to random turbulent motion within the fluid. An accurate characterization of these processes in any aquatic system will yield a good quantitative description.

3.5.1. Non-Cohesive Sediment Transport

The mobilization of *non-cohesive* sediment (e.g. sands) is presently fairly well understood and accepted by the scientific community. It is a function of the individual sediment particle grain size diameter and the lift and drag forces (from the overlying current) being imparted on the particle. In the simplest sense, when the lift and drag forces exceed the particle weight, the particle will mobilize and begin to roll along the bottom (bedload transport). As higher flow rates are imparted upon the sediment bed, the increasingly turbulent flows may cause sediment to be suspended and transported in the water column (suspended load transport) before falling out of suspension in another location (deposition).

The shear stress force imparted by the flow on the particle at the moment the particle mobilizes is the critical bed shear stress. Shields (1936) developed an approach to relate the threshold of non-cohesive sediment motion to the bed shear stress. It was a ratio of the force exerted by the bed shear stress acting to move a grain on the bed, to the submerged weight of the grain counteracting this (Soulsby, 1997):

Eqn. 1

$$\theta_{cr} = \frac{\tau_{cr}}{g \cdot (\rho_s - \rho) \cdot d}$$

where,

Θ_{cr} = the Shields parameter (dimensionless)
τ_{cr} = the threshold bed shear stress (Pa or N/m^2)
g = the acceleration due to gravity (9.81 m/s)
ρ_s = grain density (kg/m^3)
ρ = water density (kg/m^3)
d = grain diameter (m).

Shields found an empirical relationship between the dimensionless Shields parameter and the Reynolds number:

Eqn. 2

$$\mathrm{Re} = \frac{u_* d}{v}$$

where,

v = kinematic viscosity
u_* = the shear velocity defined as

Eqn. 3

$$u_* = \left(\frac{\tau_b}{\rho}\right)^{1/2}$$

and τ_b is the bed shear stress applied by the flow.

The oft-referenced Shields diagram (Figure 7) is a plot of the Shields parameter versus the Reynolds number. The curve was hand-drawn by Shields using all available sediment data at the time, which only considered sediment under the influence of current shear forces. Using the diagram, a user can infer whether a particular sized <u>non-cohesive</u> particle will be susceptible to mobilization and transport given a specific flow regime.

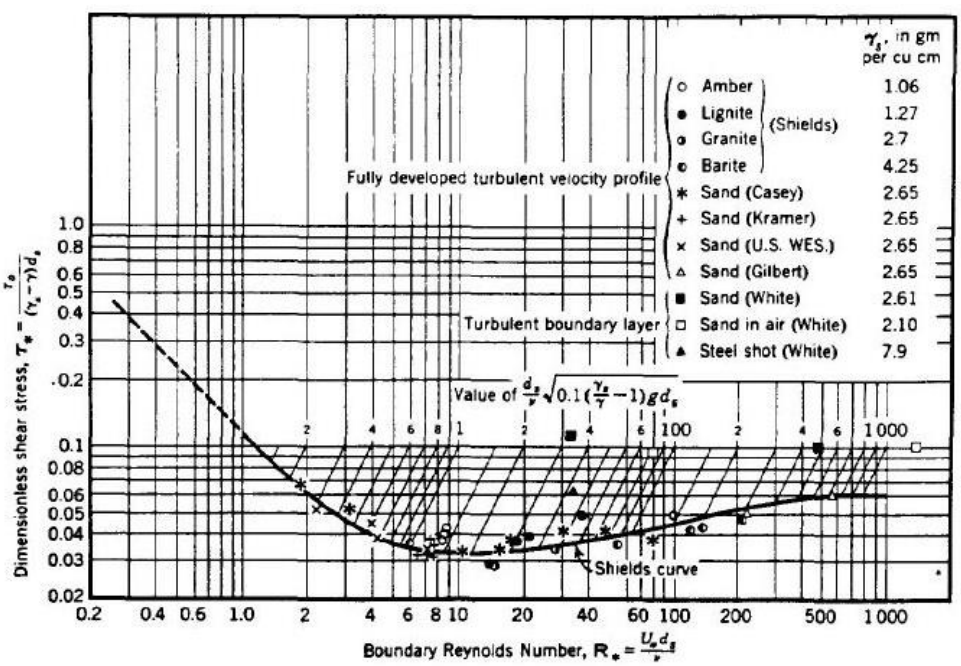

Figure 7. Shields curve for the initiation of motion for steady flow (from ASCE 1975).

This theory has been further researched by Soulsby (1997) who, instead, plotted the Shields parameter against the non-dimensional grain size, D (Figure 8). This procedure simplified the solution process by avoiding the iterative process required by Shields' method (i.e. where u^* appears in both axes). He also expanded the plotted dataset to include shear stresses imparted on

particles by waves, currents and the combined action of waves and currents. Soulsby and Whitehouse (1997) then created an analytical solution (e.g. an equation) that mimicked Shields' (hand-drawn) curve. When plotted with their additional data points, though, their equation (i.e. the Shields curve) over-predicted the shear stress parameter values for very fine grain sizes (see lower D* values in Figure 8).

Subsequently, Soulsby and Whitehouse altered the equation to account for the deviation at fine grain sizes to yield an improved formula for predicting the threshold bed shear stress. As seen below this curve is equivalent to their original formulation (i.e. Shields' curve) at D* greater than 10, but more closely follows the data points for fine grained sediments.

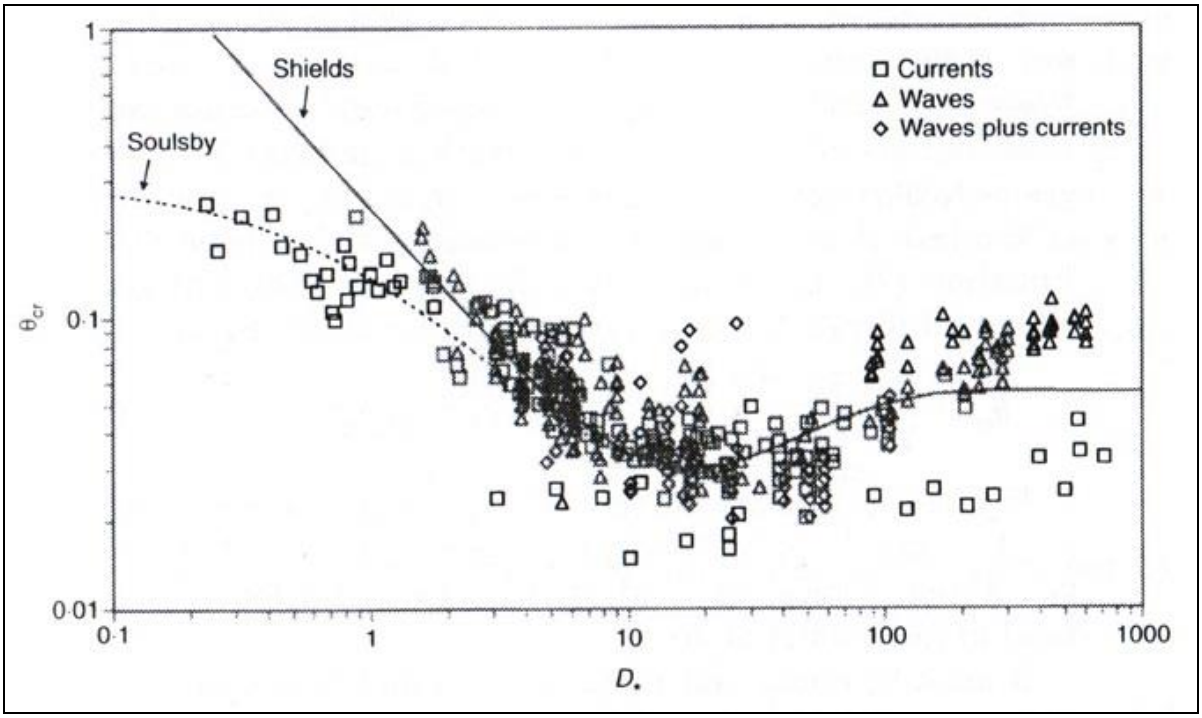

Figure 8. Threshold of motion of sediments beneath waves and/or currents. The fitted curves of both Shields (1936) and Soulsby and Whitehouse (1997) are shown.

3.5.2 Cohesive Sediment Transport

Though studies on non-cohesive sediments have shown a strong correlation between particle size and sediment transport rates, this observation does not hold for cohesive sediments, where particle size alone cannot be used to predict transport rates (van Rijn, 1993; Roberts, et al., 1998; Mehta and McAnally, 1998; Mehta, Hayter, Parker, Krone, and Teeter, 1989). The transport of cohesive sediments (very fine sands, silts and clays) is also dependent upon properties and characteristics such as the sediment bulk density, the organic vs. inorganic content in the sediment, electrostatic and electrochemical forces, ambient water quality (e.g. salinity) and the bioturbation activity. Cohesive particles tend to erode in aggregates made up of individual sediment grains and/or flocculate during transport, both of which make the accurate prediction of their erosion, transport and deposition characteristics difficult to predict. Further, the cohesiveness and susceptibility of mobilization of a cohesive sediment source is site-specific,

requiring local knowledge and insight to evaluate the transport likelihood. Without the benefit of empirical relations that can be applied universally to cohesive sediments, scientists and engineers have resorted to collection of site-specific erosion data when needed.

There are presently several methods of directly measuring surface sediment erosion rates (McNeil et al., 1996; Briaud et al., 2001; Roberts and Jepsen, 2001; Jepsen et al., 2002; Roberts et al., 2003; Black, 2010; Rutgers, 2011). Some characteristics of these methods include in-situ and ex-situ erosion rate measurements; measurement of bedload and suspended load fractions; and erosion rate with depth below the sediment surface. Each has its own advantages depending upon the overall project objective.

One method that has been employed frequently for the purpose of evaluating sediment erosion rates below the surface is the Sediment Erosion at Depth Flume (SEDFlume; McNeil et al., 1996). One distinct advantage of the SEDFlume is that it provides a means to directly measure and quantify the erosion rates at distinct depths within a sediment core and for various applied shear stresses. Using the measured data, engineers can then evaluate the likelihood of a site's sediments to erode given typical and extreme flow conditions. An example of how these data can be utilized is briefly described here.
Following the methods of Roberts et al. (1998), the erosion rates of all natural sediments can be approximated by:

Eqn. 4

$$E = A\tau^n \rho^m$$

where,

E = erosion rate (cm/s)
τ = bed shear stress (Pa)
ρ = sediment wet bulk density (g/cm^3)
A, n and m = experimentally determined constants that depend on the sediment characteristics.

The constant, n, is always positive, implying that as the shear stress force increases, the corresponding erosion rate of the sediments will increase. The constant, m, is always negative, indicating that as bulk density increases (e.g. as a result of higher compaction at greater depths into the sediment core), the erosion rate of the sediments decreases (i.e. sediments become more difficult to erode). This holds true as long as all other sediment properties remain the same in the core, which is an assumption that may not always be true in natural settings.

For large negative values of the constant, m, the sediments comprise of a large amount of cohesiveness. The converse is also true: for small negative values of the constant, m, the cohesive forces are weaker (i.e. the sediment is more non-cohesive). At a value of m = 0, the sediments are non-cohesive.

Through direct measurement, the bulk density and erosion rate for a given shear stress can be estimated. A least squares regression solution will yield the constant parameters A and n for that sediment sample. Then, using a user-defined critical erosion rate threshold (e.g. 10^{-4} cm/s), the corresponding critical shear stress can be determined. Conversely, when presented with a

specific shear stress or a time series of shear stresses, the erosion rate(s) of that sediment sample can also be estimated.

3.5.3 Sediment Deposition

Deposition is the process by which sediment particles settle out of suspension onto the sediment bed, causing an accretion of particles. As suspended and bedload sediments are transported, they will encounter areas of lower fluid velocity. When sufficiently low velocity fluid is encountered, turbulent eddies may be insufficient to keep the particles suspended or in motion as bedload and the particles will settle to the sediment bed and motion will be halted.

The shear stress at which settlement begins is termed the critical shear stress for suspension, τ_{cs}, and is also measured in units of force per unit area (N/m^2). In a non-moving fluid, where no shear stress is present, deposition rate is dependent solely on the settling speed of the sediment particles and the sediment concentration in the overlying water. In flowing water, however, deposition is affected by the fluid turbulence and near-bottom shear stresses which makes its estimation difficult.

To quantitatively determine deposition rates at a specific location, one method incorporates a probability of deposition, P, into the formulation to account for effects of the near-bottom shear stresses:

Eqn. 5

$$D = P \cdot w_s \cdot C$$

where D is the deposition to the sediment bed ($g/cm^2/s$), C is the sediment:water concentration (mg/L), w_s is the particle settling speed described by Cheng (1997) as:

Eqn. 6

$$w_s = \frac{v}{d}\left(\sqrt{25 + 1.2d^{*2}} - 5\right)^{1.5}$$

and d* is the dimensionless particle diameter described by Blake et al. (2007):

Eqn. 7

$$d^* = d \cdot \left[\left(\rho_s - 1\right) \cdot \frac{g}{\upsilon^2}\right]^{1/3} .$$

In this formulation, which estimates the settling speed of the particles based on the sediment diameter, d is the median particle diameter (cm), ρ_s is the density of the particles (generally assumed to be 2.65 g/cm^3), g is the acceleration due to gravity (980 cm/s) and υ_s is the kinematic fluid viscosity (cm^2/s).

The probability of deposition, P, would be unity (i.e. 1) in the case of zero flow, and would decrease as the shear stress increases. This formulation accounts for the decreased chance for deposition as the shear stress increases. For sediment particles, Krone (1962) found that the probability of deposition varied approximately as:

Eqn. 8

$$P = \begin{cases} 0 & \tau > \tau_{cs} \\ \left(1 - \dfrac{\tau}{\tau_{cs}}\right) & \tau \le \tau_{cs} \end{cases} .$$

When the shear stress is larger than the critical shear stress for suspension, τ_{cs}, no deposition will take place. When the shear stress near the sediment bed is lower than τ_{cs}, particles will begin to deposit onto the sediment bed proportionally (Blake et. al, 2007). As the shear stress decreases, the probability of a particle settling onto the sediment bed and remaining there increases. At a shear stress of zero, the probability of deposition is one (i.e. 100%).

Significant deposition can occur in deeper and/or less energetic coastal or lake environments, where fluid velocity is very low or negligible. Furthermore, as fine-grained particles interact in the water column, they may flocculate to form larger clumps that will settle out of suspension faster than individual particles. This process is dependent on sediment type, suspended sediment concentration, fluid velocity, ambient shear stresses, and water chemistry.

As the shear stress fluctuates in a natural system, the sediment bed may be subjected to episodic erosion, deposition, and re-suspension. Net deposition occurs if, over time, the amount of sediment deposited on the bed exceeds the amount that is episodically eroded.

3.6 Coastal Sediment Transport Processes

As previously mentioned, coastal sediment transport can be separated into alongshore and cross-shore (or offshore) components. These processes can be differentiated one step further to reflect the nature of the coastal zone in the near-shore (inside the wave breaking zone) and offshore (outside the wave breaking zone). Although offshore wind farms are, by design, typically installed outside the breaker zone, their potential effects extend to the near-shore and shoreline and, therefore, warrant a discussion of the full coastal environment.

3.6.1 Near-Shore Coastal Zone

As waves approach shallow water regions cross-shore (shore-perpendicular) and alongshore (shore-parallel) mass flux (and, therefore sediment transport) is induced by the breaking waves and currents. The turbulence generated by the breaking waves suspends sediments into the water column that are then transported by the ambient near-shore currents (which may be driven by tidal currents, wave mass flux or other forcing mechanisms such as river discharge).

The cross-shore component of the mass flux will cause flow and sediment transport in an onshore/offshore direction. The alongshore component of the mass flux will generate near-shore currents parallel to shore, forcing sediment transport along the shoreline (Figure 9). Standard coastal engineering methods can be implemented for determining the rate of cross-shore and alongshore (a.k.a. littoral) sediment transport, which will be dependent on the size of the incident waves (i.e. energy dissipation), direction of the waves, local shoreline configuration, near-shore bathymetry and the sediment characteristics, among other properties.

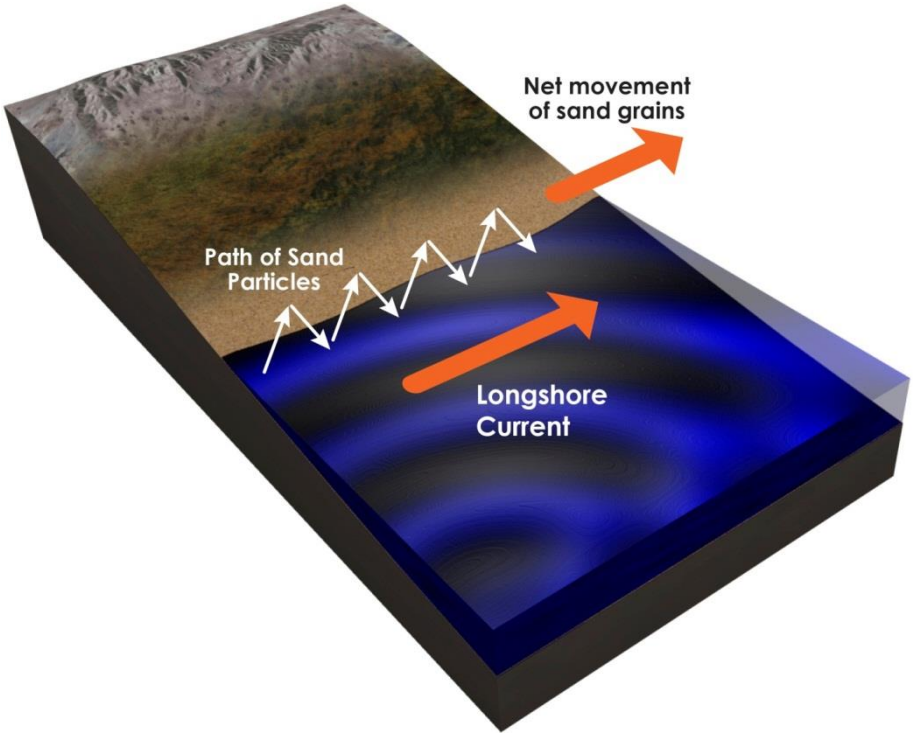

Figure 9. Illustration of longshore current generation and resultant sediment transport.

Figure 10 illustrates the interaction of processes that cause one form of cross-shore flow, a rip current, which is a localized region of offshore flow at a shoreline. The onshore flow (termed "return flow" in the diagram) of water generated by the mass flux of breaking waves causes a build-up (wave setup) of water mass on the shoreline. The imbalanced wave setup results in a flow of water (rip current) that heads offshore in distinct locations. These rip currents are capable of transporting mobilized sediment from the near-shore to outside the breaker zone; the stronger the waves (i.e. larger mass flux), the more intense this process.

Typically, coastal regions experience a net onshore transport of sediment during low energy periods (e.g. milder, summer conditions) and then a net offshore movement of sediment during the higher intensity wave periods (e.g. strong, winter storms), which cause strong rip currents and undertow currents. This is often reflected in larger beach widths observed during low energy summer months; and, conversely, smaller beach widths observed during higher energy winter months.

If there is a sufficient understanding of the typical wave and current conditions for a particular region an overall net transport rate can be approximated. The balance of the sediment transport due to cross-shore currents, alongshore currents, rip currents, and sediment exchange at the boundaries characterizes the near-shore zone sediment transport for the location of interest.

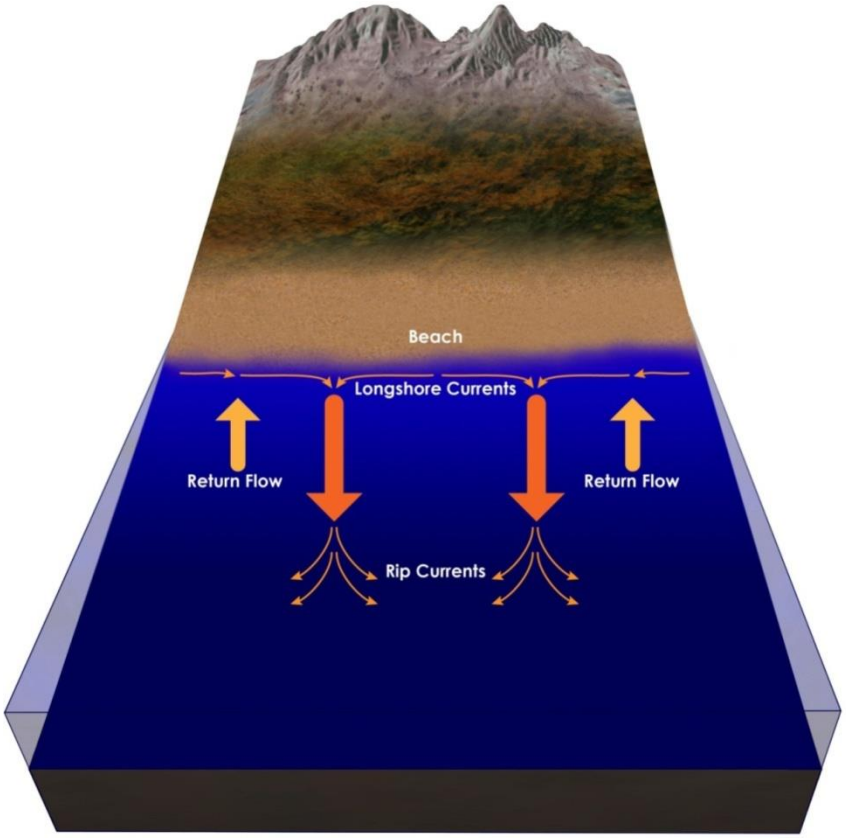

Figure 10. Diagram of the primary, cross-shore, wave driven current in the near shore.

3.6.2. Offshore Coastal Zone

The offshore coastal zone, outside of the breaking wave zone, is typically where most offshore wind farms will be deployed. The three largest coastal regions of the United States are the Pacific, Gulf, and Atlantic Coasts (though the Great Lakes are also under consideration for offshore wind development). When defining the regional boundaries for a planned project site, the offshore boundary of these regions is generally considered to be the continental shelf. Particularly on the Pacific Coast where the continental shelf is relatively close to the shore, the boundary of the area of study is easy to define as the continental shelf. The Gulf of Mexico offshore boundary is more difficult to define, though, as the shelf break may be much further offshore of a planned development site than practical for consideration of transport processes. In these cases, the offshore boundary should be located some logical distance where transport processes can be assumed to have negligible impact on the offshore wind array. These distances must be considered on a site-specific basis and may require iteration. The Atlantic Coast is a mix of the two, where the shelf is both near and far from the shoreline, depending upon location. Sound engineering judgment must be used on a site-specific basis for selection of these boundaries.

As discussed, near-shore coastal surface waves are frequently a combination of wind-generated sea waves and storm-generated swell waves that drive the near-shore circulation. In the deeper offshore waters, the surface waves continue to have an impact on sediment transport; however, this impact diminishes as the water depth increases. Typically, an offshore wind farm should be located far outside the depth of closure, the depth at which sediment motion as a result of near-shore wave and current forcing is negligible. Doing so will minimize mitigation measures associated with wave-forcing mobilized sediment. But it will not eliminate all concerns: cable installation costs increase with distance from shore and power transmission lines that cross the near-shore region will still likely require engineering mitigation in order to minimize risk of damage to the lines.

Circulation, as a result of surface waves and tidal circulation, is another forcing mechanism that requires consideration offshore of the breaking wave zone. Tidal circulation results from the movement of water due to the propagation of the tide through a region. The typical dominant period of astronomical tides is 12.42 hours, yet the tidal range and variation are highly variable, temporally and spatially. Coriolis forces (due to Earth's rotation), storm surges and other local meteorological weather patterns (e.g. variable pressure systems) may cause additional fluctuations to the ambient circulation.

Furthermore, in the vicinity of large estuaries and rivers the offshore region may experience local high-flow currents particularly during ebbing tides and large rainfall runoff events. Seasonal cycles of temperature changes, fresh water input, and large scale winds can also substantially affect the resulting offshore current circulation and wave climate. The interaction of the tides and other processes result in a current structure that oftentimes dominates sediment transport in the offshore.

Unlike near-shore sediment transport, which varies significantly on both short- and long-term time scales, the sediment transport patterns on the continental shelf are generally in long-term equilibrium with the prevailing wave and current climate. While there are still temporal and spatial variations at all time scales, the sediment tends to organize into regular patterns (e.g. bedforms) that are indicative of the long-term dominant configuration. These patterns can develop and fade on short time scales in the near-shore (e.g. seasonal sandbars). Typically the dominant spring tidal currents will develop a net movement of sediment along the shelf that is periodically interrupted by storms that generate large waves and currents and direct large sediment loads to the shelf. The disruption in the pattern by these events is quickly incorporated back into the long-term dominant pattern. Figure 11 illustrates the range of processes that interact in the offshore coastal zone.

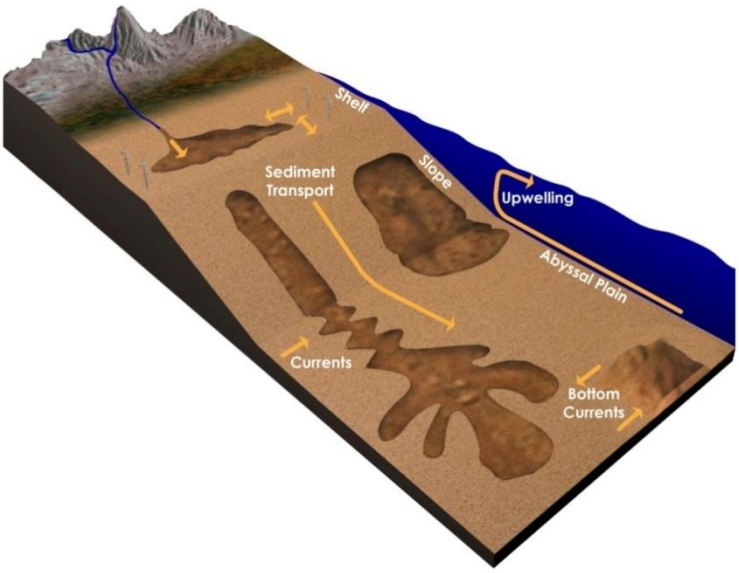

Figure 11. Illustration of sediment transport processes interacting in the offshore coastal zone.

4. EROSION AND SCOUR FUNDAMENTALS

4.1. Foundation Obstructions

Oftentimes the primary risk to an offshore wind structure (and its peripheral components) placed in a natural flow regime will be the risk to structural stability created by localized erosion or scour. Scour is the net removal of sediment from the vicinity of the structure foundation (or components) that increases susceptibility of structure (or component) failure. Scour may have an impact on the geotechnical capacity of a foundation and thereby on the structural response that governs the ultimate and fatigue load effects in structural components (DNV, 2011). Most foundations are generally oriented perpendicular (vertical) to the seabed and are known as 'vertical obstructions' as they obstruct the flow regime vertically through the water column. As a result, flow streamlines much transition horizontally around the object.

Scour is a consequence of flow obstruction caused by the structure; the very presence of the structure alters the ambient wave and current flow streamlines (i.e. flow must alter direction around the structure), creates wake vortices, and leads to an increase both in the speed of the flow in the vicinity of the structure, and in the turbulent intensity of the flow (Whitehouse, 1998; DNV 2011). The increase in flow speed near the structure is a result of the conservation of mass (Continuity Theory): the flow is being constricted and must accelerate around the obstruction. The increase in near-bed turbulent intensity is a consequence of the generation of flow vortices around the structure. Both velocity and turbulent intensity amplifications create intensifications in near-bottom shear stresses, ultimately increasing the likelihood of sediment erosion and mobilization.

In the case of solidly supported offshore wind structures (e.g. monopoles, jacket structures and/or gravity based foundations) scour may erode sediment that is providing vertical and lateral support; the loss of which may lead to an increase in bending stresses unless remedial action is taken (Watson, 1979, from Whitehouse, 1998). Scouring typically produces seabed depressions adjacent to the structures, reduces the effective depth of pile penetration, and may expose suspended risers, anchors, or other components to hydrodynamic loading that exceeds design limits. For suction caissons or mat foundations, scour may reduce the weight of sediment acting against the overturning moment of the structure and lead to overturning instability. Scour effects dissipate with increasing distance from the structure as the flow becomes less affected.

Scour is commonly classified as <u>live-bed</u> or <u>clearwater</u> scour. Live-bed scour occurs when the threshold necessary to mobilize sediment is exceeded everywhere on the bed (e.g. a high-flow river regime causing universal sediment movement); sediment transport proceeds from upstream to downstream and through scour depressions, if any exist. It is overall seabed movement; regional, large-scale erosion, deposition and bedform movement through a region; and ambient morphology. Oftentimes, there is no net erosion or deposition as a result.

Clearwater scour occurs when the upstream, ambient flow is *insufficient* to mobilize sediment; yet, flow speed amplifications resulting from the structural obstruction *are sufficient* to cause nearby sediment mobilization and erosion. The presence of the structure causes a sufficient increase in flow velocity and shear stress to facilitate erosion. Clearwater scour may occur adjacent to bridge piers at a river crossing during typical river flow regimes.

Clearwater scour results from the flow disturbances directly generated by the flow obstruction. The seabed boundary layer flow approaching a vertical cylinder (e.g. pile), for example, creates a pressure gradient on the upstream face of the cylinder between the low pressure in the near-bed flow and the high pressure in the flow above. This drives a flow downward at the face of the pile. A primary vortex is formed at the upstream face of the pile during this stage as the downward flow impinges with the seabed. The vortex then wraps around the cylinder creating the secondary horseshoe vortex, and trails off downstream (Whitehouse, 1998). Secondary vortices are periodically shed from either side of the cylinder as the flow diverges around the obstruction (Figure 12).

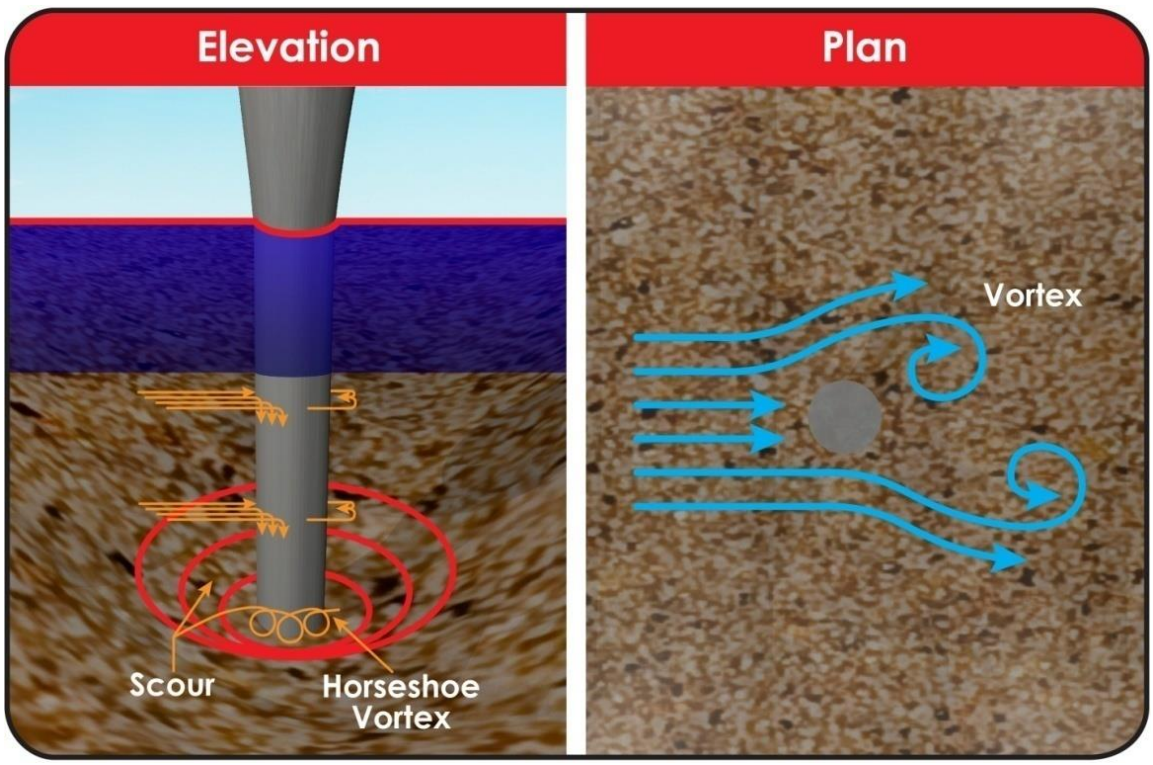

Figure 12. Hydrodynamics around a slender pile with scour.

Clearwater scour may be further characterized as:

- *Local scour* – where steep-sided scour pits form adjacent to individual piles or slender obstructions, or

- *Global (or dishpan) scour* – where shallow, wide depressions form under and around individual or groups of structures and obstructions such as jacket foundations (
- Figure 13).

In addition to near-bed turbulence from the vortices, the cross-sectional area of flow around the cylinder is constricted, resulting in a corresponding increase in flow speed around and near to the structure (adhering to the definition of Continuity Theory). Therefore, sediment particles are likely mobilized by the increase in turbulence and then transported downstream by the increase in flow speeds. From a sediment transport perspective, the primary and secondary horseshoe vortices (and increased velocities) are the major mechanisms leading to the scouring of sediment from around the base of a cylinder (Whitehouse, 1998). Similar vortices are generated and shed by alternatively-shaped obstructions (e.g. square piles, rectangular, diamond, oval). The obstruction shape and orientation to the incident flow have a direct effect on the manner in which vortices, and resultant scour patterns, are generated.

Furthermore, the vortex generation and resultant scour processes described above also pertain to multiple-piled structures (such as that illustrated in
Figure 13) and large-scale offshore flow obstructions (e.g. wind farm deployments). Each of these types of obstructions acts to disrupt the ambient flow to varying degrees, possibly resulting in varying magnitudes of clearwater and global (dishpan) scour near the structure. The magnitude of scour will depend upon several factors such as ambient current speed, incident current direction, amount of flow that is obstructed, the total size of the obstructing structure and the proximity of multiple piles formulating the total obstructed area.

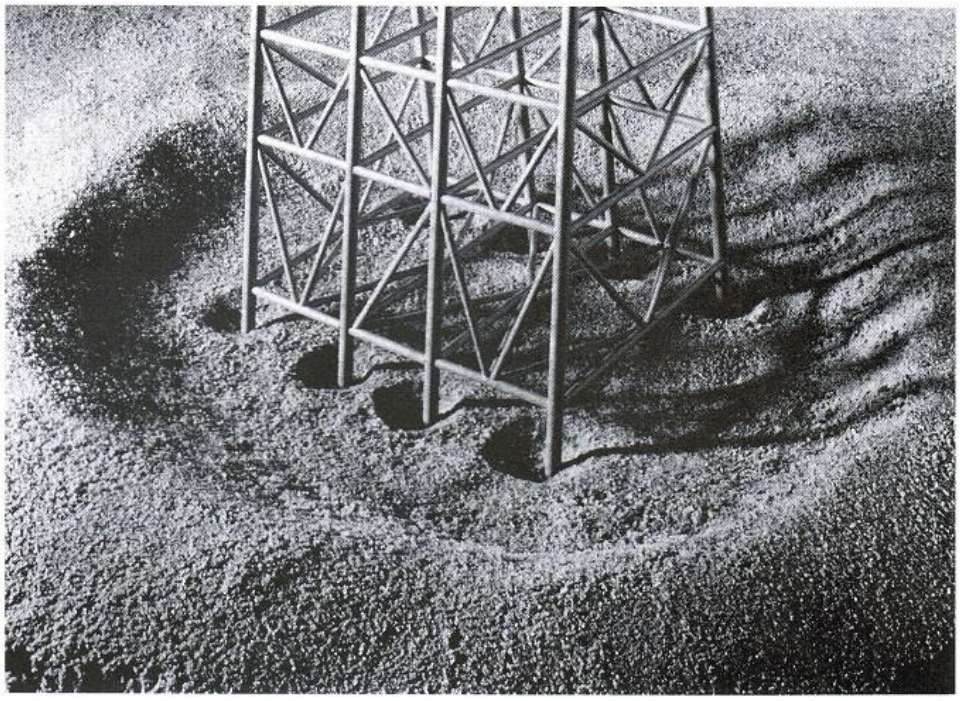

Figure 13. Example of local (clearwater) and global scour around a structure (from Whitehouse, 1998; reproduced from Angus and Moore, 1982).

4.2. Cable and Pipe Obstructions

Similarly to large structural obstructions, pipelines laid along the seabed, pipes extending short distances horizontally from subaqueous offshore wind structures (generally parallel to the seabed) and the corresponding cables protruding from them that are laid along the seabed also act as flow obstructions, and may experience adverse effects of scouring. If extender pipes (sometimes termed J-pipes) and cables are not sufficiently buried in the seabed, or become exposed due to clearwater scour, flow separation will occur in flows passing over the pipeline as flow passes above and below the obstruction. This results in an area of re-circulating flow being produced in lee of the obstruction.

Eddies may be shed from the pipeline and cause fluctuating shear stress (and erosion) in lee of the pipeline. Since extender pipes extend only short distances from the infrastructure to which they are connected, they, and the cable they support, are within the zone susceptible to scour pit formation caused by the larger vertical obstruction (e.g. monopile), and are more likely to be exposed to the scour processes described here. If J-tubes are exposed to ambient flow, the cable within may be allowed to freely move with the local currents. Overtime, the cable can wear against the end of the J-tube (and the sediment that can accumulate there), abrading the cable, potentially leading to failure.

Pressure gradients between the upstream and downstream sides of pipes and/or cables (as a result of flow divergence and separation) resting on the seafloor may induce a seepage flow in the sand bed underneath the pipe/cable, called the ‘onset of scour’ (Sumer and Fredsoe, 2002). Eventually, the seepage flow may cause a mixture of sediment and water to “break-through” the space beneath the pipe/cable in a process termed ‘piping’. Piping proceeds rapidly to ‘tunnel erosion’ as the flow begins to diverge beneath the pipe/cable and scour additional sediments (Figure 14). As a result of the Continuity Theory, very high flow velocities beneath the pipe/cable will exist initially due to the small cross-sectional area of space through which the flow can proceed. As more sediment erodes, the void beneath the pipe/cable will continue to grow (both in depth and width). If the tunnel erosion beneath the pipe/cable is sustained, eventually a free span will be formed which may leave the pipe/cable susceptible to altered hydrodynamic loading, higher flow speeds, cross-flow vortex induced vibration, sagging, and/or lateral movement of the line, all potential causes of structural instability and failure (DNV, 2010). Figure 15 illustrates an example of a free span.

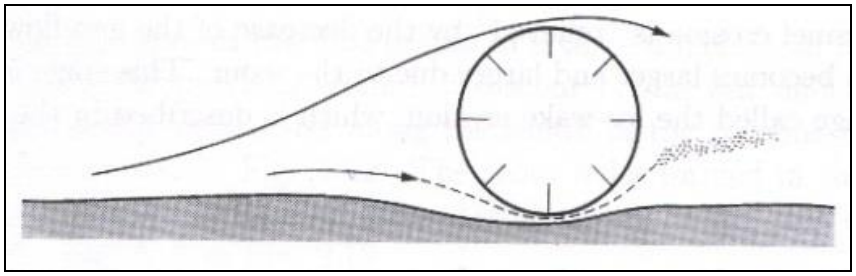

Figure 14. Tunnel scour causing erosion of sediments beneath pipe/cable (Sumer and Fredsoe, 2002).

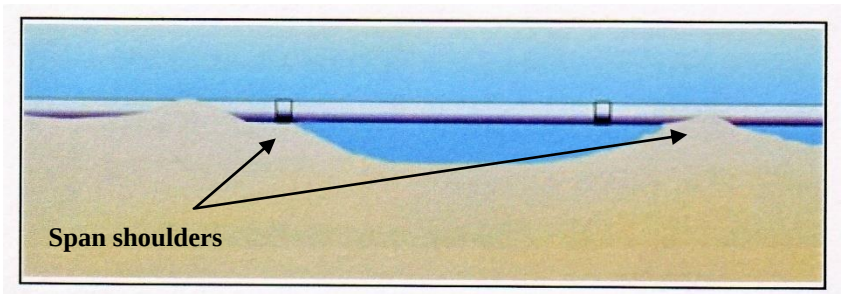

Figure 15. Free-span showing the span shoulders supporting the pipe/cable.

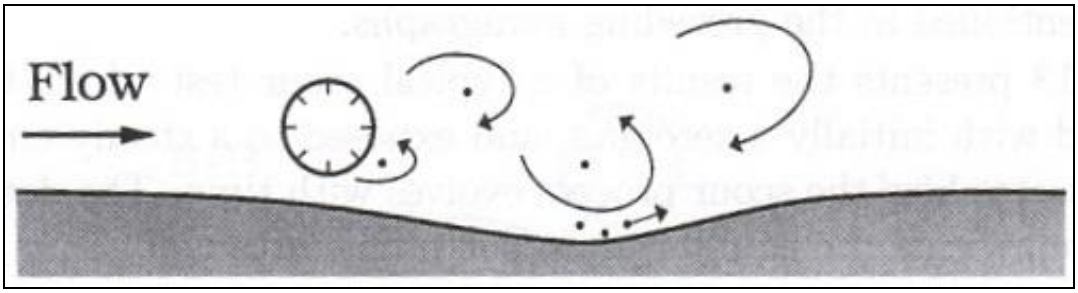

Figure 16. Lee-wake vortex shedding in lee of a pipe/cable span (Sumer and Fredsoe, 2002).

The onset of scour and tunnel erosion phases are followed by a stage called lee-wake erosion, where flow diverges around, and horseshoe vortices are shed from, above and below the pipe/cable (Figure 16). Vortices shed from the seabed side of the pipe/cable will pass near the bed, momentarily increasing near-bed shear stresses and causing downstream erosion. Scour in lee of the pipeline will persist as a result of the turbulence generated until the seabed equilibrium is reached (Sumer and Fredsoe, 2002).

Scour below pipes/cables occurs in three-dimensions (Figure 17) and is directly dependent upon the localized velocities (and near-bed shear stresses) below the pipe/cable. As the scour magnitude increases directly beneath (depth of scour) the pipe/cable, the erosion also continues parallel to the pipe/cable axis. The pipe/cable continues to be supported by the span shoulders, but the free span grows in length until equilibrium is reached between the amplified flow and the seabed erosion susceptibility (Sumer and Fredsoe, 2002).

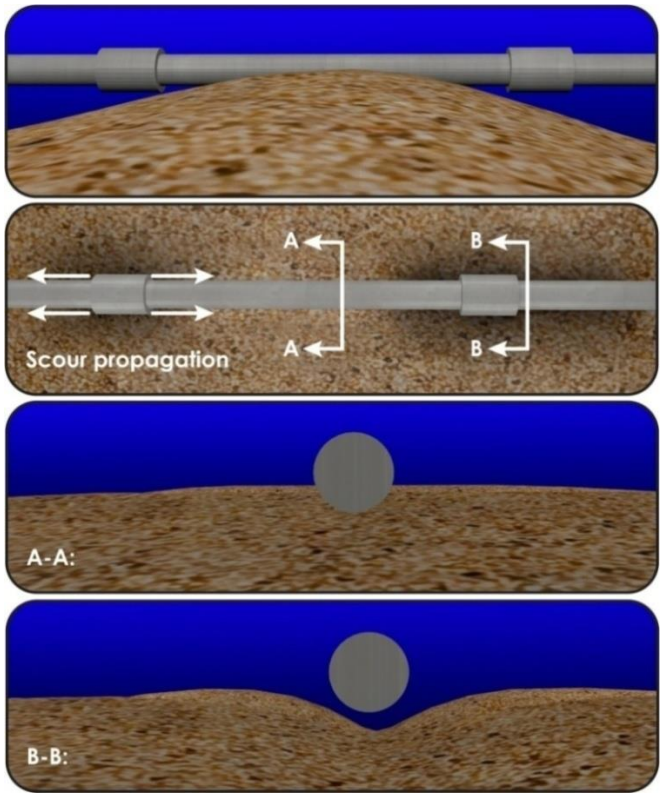

Figure 17. Potential scour modes occurring in the vicinity of a transmission line. Scour can propagate longitudinally along the line causing large unsupported spans.

In order to assess (quantitatively or qualitatively) the potential for scour to occur, the surrounding sediment material must be initially characterized (e.g. hard vs. soft; sandy vs. silty vs. mixed sizes; cohesive vs. non-cohesive) and then the overall transport processes must be quantified (e.g. magnitudes of near-bottom effects from tidal currents and waves). Local field studies, if any exist, can be used as a starting point to better characterize the dynamic conditions at the site and estimate potential structural scour extents. The following sections detail some specific considerations, and quantification methods, when considering small scale scour near subaqueous obstructions such as offshore wind foundations.

4.3. Scour Potential – Single Pile

Investigating scour around a single, slender pile (e.g. monopole) is a simple, initial step that can be used as a basis from which to augment complexity (e.g. multiple pile configurations such as

jacket structures or non-cylindrical shapes). A pile is generally considered to be slender when the pile diameter (D) to water depth (h) ratio D/h < 0.5 (Whitehouse, 1998).

4.3.1. Horizontal Scour Extent

Laboratory investigations indicate that initial scouring takes place at 45° to either side of the pile centerline. Eventually, the scour holes morph to form a truncated conical shape around the entire perimeter of the pile (when viewed in plan). Sediment that has been scoured from near the pile is typically re-deposited in the lee of the pile, at the downstream extent of the wake vortex system. The final horizontal extent of the scour pit away from the pile is primarily a function of the sediment type (that defines the sediments angle of repose) and flow velocity amplification (increased flow and turbulence observed as flow passes around the foundation), among other factors. The overall scour pit diameter (including the pile geometry) may be as large as six pile diameters (6*D).

4.3.2. Vertical Scour Extent

The depth of a scour pit, as well, is generally assumed to be a function of the pile diameter. The equilibrium value of the scour depth scales linearly with the magnitude of near-bed shear stresses and may vary up to 2.3*D. Brussers et al. (1977), from compilation and evaluation of laboratory data, obtained a maximum value of:

Eqn. 9

$$\frac{S_e}{D} = 1.5$$

Where S_e is the equilibrium scour pit depth and 1.5 is a design value constant. However, they recommended a conservative value of 2.0 be used for the design value constant in actual designs. Further studies have recommended a larger value of 2.4 for the design constant (Ettema, 1990), especially when sufficient supporting data does not exist. The DNV offshore wind guidance suggests a value of 1.3*D when estimating equilibrium scour depth (DNV, 2011).

In their laboratory investigation, den Boon et al. (2004) found that the average maximum scour depth with no scour protection present was 1.75*D. Yang et al.'s (2010) laboratory experiment found that 1.5*D was sufficient as a general rule of thumb. Furthermore, Yang et al. (2010) discuss De Bruyn's (1998) findings that the equilibrium scour depth in currents alone can be approximated by 1.3*D, in currents and non-breaking waves it is 1.0*D, and in currents and breaking wave conditions can be as much as 1.9*D. Of noteworthy importance is that local scour depths in larger scale experiments have been found to be as much as 50% larger than in smaller scale experiments (Stahlmann and Schlurman, 2010). Again, it is the responsibility of the prudent engineer to make the best professional judgment based on all available site-specific information.

If sediment and flow speed data are available, the following formula can also be used to estimate equilibrium scour depth (Whitehouse, 1998):

Eqn. 10

$$\frac{S_e}{D} = c_1 \cdot c_2 \cdot c_3 \cdot c_4$$

where,

$c_1 = 0$ if $U/U_{cr} < 0.5$
$c_1 = 2*U/(U_{cr} - 1)$ if $0.5 < U/Ucr < 1.0$
$c_1 = 1$ if $U/U_{cr} > 1.0$
$c_2 = 2.0 * \tanh(h/D)$, *where 2.0 is the value of the design constant described in Eqn. 9*
c_3 *= a coefficient pertaining to the pile cross-sectional shape(discussed below)*
c_4 *= a coefficient pertaining to the length:breadth diameter of rectangular piles (Hoffmans and Verheij, 1997)*
U = flow velocity;
U_{cr} *= flow velocity at sediment particle incipient motion*

4.3.3. Water Depth

The effect of water depth on the scour depth around cylindrical piles is generally considered negligible when h/D>3 (Whitehouse, 1998); however, pile structures in water depths where h/D>3 should still be evaluated for scour potential.

4.3.4. Obstruction Shape

Based on results of laboratory experiments, the effects of pile shape on flow disturbance and scour generation have been quantified. The equilibrium scour depth factor for a square pile, for example, has been found to be 1.3 [S_e (square) = 1.3*S_e (cylinder)], using a cylindrical pile as reference (Whitehouse, 1998). Sumer, Christiansen and Fredsoe (1993) have estimated that S_e/D = 1.3 for a circular pile and 2.0 for a square pile oriented normally to the incident flow. Sumer and Fredsoe (2002) also provide representative shape factors for various pile shapes found by various researchers (Table 1):

Table 1. Shape factor, Ks, compiled by Melville and Sutherland (1988).

Shape in plan	Length/Width	I*	II	III	IV
Circular	**1.0**	1.0	1.0	1.0	1.0
Lenticular	**2.0**	-	0.97	-	-
Lenticular	**3.0**	-	0.76	-	-
Lenticular	**4.0**	0.67	-	0.73	-
Lenticular	**7.0**	0.41	-	-	-
Parabolic Nose	**-**	-	-	-	0.56
Triangular Nose (60°)	**-**	-	-	-	0.75
Triangular Nose (90°)	**-**	-	-	-	1.25
Elliptic	**2.0**	-	0.91	-	-
Elliptic	**3.0**	-	0.83	-	-
Ogival	**4.0**	0.86	-	0.92	-
Joukowski	**4.0**	-	-	0.86	-
Joukowski	**4.1**	0.76	-	-	-
Rectangular	**2.0**	-	1.11	-	-
Rectangular	**4.0**	1.4	-	1.11	-
Rectangular	**6.0**	-	1.11	-	-

I: Corresponds to study by Tison (1940)
II: Corresponds to study by Laursen and Toch (1956)
III: Corresponds to study by Chabert and Engeldinger (1956)
IV: Corresponds to study by Venkartadri at al. (1965)

4.3.5. Sediment Gradation

The scour depth will not be limited by the grain size provided the pile diameter, D, is larger than 50 median grain size diameters ($D > 50*d_{50}$). In the offshore environment, where the grain size diameters are likely to be much smaller than the offshore wind pile diameters, the limiting influence of grain size and grading on scour is likely negligible (Whitehouse, 1998). However, it is still recommended to estimate the critical shear stress of the local sediments with depth into the sediment bed, if possible.

4.3.6. Oscillatory Flow Influence

Most researchers agree that local scour around a pile due to waves is smaller than that achieved in steady current flow (Whitehouse, 1998). This is likely a result of sediment re-deposition as the wave orbital velocities switch directions. Sumer et al. (1992) correlated the equilibrium scour depth with the Shields parameter and the Keulegan Carpenter (KC) number. The KC number can be computed as (Whitehouse, 1998; DNV, 2011):

Eqn. 11

$$KC = U_w \frac{T_w}{D}$$

Where U_w is the bottom orbital velocity and T_w is the period associated with U_w. A *KC* value >= 6 is necessary to generate horseshoe vortices around obstructions. Sumer et al.'s (1992) research demonstrated good correlation between scour depth and KC number. Scour depths are negligible for *KC* <6 and approach the scour predictions of a steady stream current when *KC* >> 100.

4.3.7. Resistant Bed Layer(s)

If piles are installed in regions with stiffer bed material (more difficult-to-erode) layers, either on the surface or beneath the surface, the depth of scouring may be limited accordingly.

4.4. Scour Potential – Multiple Piles

When the environmental effects of multiple piles (clusters, tripods, jacket foundations) are considered, the combined flow interference effects of the cluster become important and are directly proportional to the angle of orientation of the cluster to the incident waves and prevailing currents. The main factor to consider is flow interference on a larger scale, leading to enhanced flow speeds or turbulence being imparted from individual piles on other individual piles. In some cases, sheltering or shadowing effects may also need to be considered (Whitehouse, 1998). The assumptions and methods described in the previous section can be applied to multiple pile scenarios and then augmented to correspond to specific settings. Some considerations of multiple pile arrays are discussed below; however, it is a complex scenario dictated by the project-specific pile cluster orientation and configuration. It is recommended that computer numerical simulations and/or physical scaled models be created to quantify the effects of a planned installation configuration.

4.4.1. Linear Pile Arrays

From laboratory experiments, it was found that scour depths at individual cylindrical piles in a cross-flow array were the same as for a single pile, provided that the pile-pile spacing was greater than or equal to 6*D (Breusers, 1972; Hirai and Kurata, 1982 – from Whitehouse, 1998).

Hirai and Kurata (1982) showed that scour depth increased as the spacing of 2 piles perpendicular to the flow direction was reduced from 6*D to 2*D (as their altered flows began to interfere with each other). For pile spacings of 2*D, the scour depths at the sides of the cylinders increased as much as 40% from that of a single pile value, and continued to increase as the pile spacing decreased, eventually exceeding a scour depth of twice that of a single pile (i.e. proportional to the projected area of 2 piles).

For piles arranged parallel to the flow direction, experiments have shown that the scour depth around the upstream pile may increase 10-20% for pile spacings in the range of 1.5*D to 4*D. When pile spacing was increased to 6*D, the scour depth of the downstream cylinder was reduced to 60% of the single cylinder value. This was likely a result of sediment that had been scoured from the upstream cylinder location and deposited at the downstream cylinder location (Hirai and Kurata, 1982).

4.4.2. Pile Clusters

Scour potential as a result of pile clusters (tripods, jacket structures) can be rudimentarily investigated through a literature search of laboratory investigations. Mann (1991) evaluated scour magnitudes around varying pile cluster orientations (cluster numbers and geometry) and pile cross-sectional shapes (octagonal and hexagonal). He reported results in terms of a scour ratio, which was defined as the ratio of a scoured area of bed to the group area of the pile array. Mann found that the scour ratio varied with the pile center-to-center spacing (scour ratio was larger for closer spaced piles). This is expected as closer spacing inhibits the ambient flow more than coarse spacing of the obstructions. Furthermore, he found the scour ratio tended to be larger when the pile cluster was oriented 45° to the incident flow.

Vittal et al. (1994) found that the scour depth at a pile group with pile spacing 2*D was approximately 40% smaller than the scour depth measured around one single pile with the same diameter as the cluster (i.e. single pile with a diameter equal to the diameter of a circle circumscribing the pile cluster). They found that scour depth only varied 6% with variations in incident flow direction.

4.5. Scour Potential – Cables and Pipes

Cables and pipes installed on the sea bed (or under the seabed and later exposed) are susceptible to damage arising from wave and current forcing, cross-flow induced vibration of the pipe/cable, sagging, lateral movement of the cable and sediment loading, among other environmental concerns (Whitehouse, 1998; DNV, 2010). In order to minimize or mitigate for these concerns, the potential for scouring needs to be evaluated. The oil and gas industry has, and remains strongly interested in, pipeline scour. As such, that industry has developed a lot of knowledge on pipeline scour. The sections below describe typical considerations to evaluate the potential for pipe scour to occur; however, the theories may be applied to any pipeline-like structure placed on a seabed (e.g. wind farm J-tubes, transmission cables).

4.5.1. Sand Burial

The optimal consequence of cable/pipe scour (to most stakeholders) is natural cable/pipe burial, during which the cable/pipe settles into the seabed as adjacent sediment erodes. This process protects the cable/pipe from further structural vulnerability and may act as a cost savings mechanism that negates the need to "trench-in" cables/pipes. In regions of highly mobile sandy sediment, pipelines have been known to settle into the substrate within several months. Kroezen et al. (1982) observed a pipeline that was 100% buried along 70% of its length within 7 months in a sandy substrate.

Other studies from areas subjected to sand wave migrations have indicated significant temporal and spatial variations in pipeline exposure. Detailed repeated surveys of a particular pipeline length (2 km length of 30-inch pipe) in the North Sea indicated the following percentages of exposed pipe for each of the five years investigated: 45%, 81%, 47%, 43% and 35%. Only 8% of the length of pipeline surveyed remained consistently buried throughout the five year duration (Whitehouse, 1998; excerpt from Langhorne, 1980).

4.5.2. Water Depth

Chiew (1991) found that when the upstream water depth exceeds four (4) times the pipe diameter, the effect of the flow field on the pipe (and resultant scour development) was insignificant. This conclusion was a result of studies that indicated the altered flow field was not sufficient to mobilize sediment. In other words, the flow rate and turbulent intensity of the flow adjacent to the structure did not increase sufficiently to cause sediment erosion. Further, HR Wallingford determined that deep water conditions (i.e. where the water depth was negligible) existed in an intertidal estuarine site when the upstream flow depth exceeded three (3) times the pipe diameter (1972).

However, each site should be investigated separately as there are known deepwater regions where near-bottom currents are large enough to mobilize sediment (Clukey et al., 2007) and leave pipelines vulnerable. Further, cables and pipelines that cross the intertidal zone should be evaluated for scour potential, as well, because they will transect a highly energetic environment of waves and currents.

4.5.3. Scour in Currents

Kjeldsen et al. (1974) used an empirical formula to describe the equilibrium tunnel scour depth under a fixed pipeline resting initially on the bed:

Eqn. 12

$$S_e = 0.972 \cdot \left(\frac{U^2}{2g} \right)^{0.20} \cdot D^{0.80}$$

where the formula is valid in the Reynold's number range of $9.84 \times 10^3 < Re_{pipe} < 2.05 \times 10^5$. The Reynold's number is calculated as in Eqn. 2.

The formula was modified to include a dependence upon sediment grain size as (Bijker and Leeuwenstein, 1984):

Eqn. 13

$$S_e = 0.929 \cdot \left(\frac{U^2}{2g}\right)^{0.26} \cdot D^{0.78} \cdot d_{50}^{-0.04}.$$

These formulae indicate that the pipe diameter is the primary parameter of importance. Sumer and Fredsoe (1990) compiled previous data to arrive at the conclusion that the average scour depth beneath a pipeline initially resting on the bed was approximately $S_e/D = 0.6$ (with a standard deviation of 0.1). As the initial gap between pipeline and seabed increases (gap distance), the magnitude of equilibrium scour depth, S_e, decreases (Mao, 1986). This is an expected result based on the Continuity Theory as velocities (i.e. shear stresses) will decrease as gap distance increases and vice a versa.

4.5.4 Scour in Waves

Sumer and Fredsoe (1991) examined the onset of scour in the presence of wave oscillatory flow. They presented an empirical expression that describes the critical burial depth of a pipeline, e_{cr}, beneath which no additional scouring is expected to occur. The parameter e_{cr} is the distance of the bottom of the pipe below the sediment surface:

Eqn. 14

$$\frac{e_{cr}}{D} = 0.1 \cdot \ln(KC)$$

where *ln* is the natural logarithm. This expression is valid for *KC* values between 2 and 1000. It implies that pipelines buried deeper than e_{cr} will not be affected by scour.

Sumer and Fredsoe (1990) also proposed an equation of the form:

Eqn. 15

$$\frac{S_e}{D} = 0.1 \cdot \sqrt{KC}$$

where the scour depth was equivalent to the steady flow current case when $KC = 30$ and increased towards $S_e/D = 2.4$ for *KC* values up to 600.

Mao (1986) and Grass and Hosseinzadeh-Dalir (1995) have found that a nearly symmetrical scour pattern forms for a fixed pipe in tidal flow; that the lee-wake scour holes tend to be very wide (larger than 50 pipeline diameters) and deep. Grass and Hosseinzadeh-Dalir found good correlation between scour hole width, *W*, and depth, *D*, for fixed pipes:

1) For W/D = 100, S_e/D = 1.8-2.0;
2) For W/D = 50, S_e/D = 1.6, approximately.

4.5.5. Scour in Waves and Currents

The effects of waves and currents combined on scour depths are variable and uncertain. Conclusions support both enhanced and reduced total scour. Bijker (1986) noted that for the same bottom shear stress, the scour depth under steady unidirectional flow was always larger than under oscillatory flow or combined wave and current forcing. Experimental findings by Lucassen (1984), though, indicate that combined wave and current forcing increased the scour depth by approximately 30% when compared to that attained by current forcing alone. Further investigations are, therefore, warranted, and the design engineer should err on the side of conservativeness.

4.5.6. Time Development of Scour

Staub and Bijker (1990), from field observations, reported that the tunnel erosion, when it occurs, takes place immediately after pipeline installation, but that lee-wake erosion can take weeks or months to reach equilibrium. Kroezen et al. (1982) indicate rapid scouring and burial can occur within a few months of pipeline installation. The time development of scour in a steady current and waves has been well described by the following equation:

Eqn. 16

$$S(t) = S_e\left[1 - \exp\left(\frac{-t}{T}\right)^p\right]$$

where *t* is the time since installment, *T* is the characteristic time scale for scour, and *p* is a fitting coefficient that is typically unity (1.0). The time scale, *T*, is defined as the time after which the scour depth has developed to 63% of the equilibrium value (Sumer et al., 1992). By assuming that the dimensions of the scour pit scale geometrically with the dimensions of the obstructing structure, a formula for the dimensionless time scale is (Sumer et al., 1992; Fredsoe et al., 1992; Whitehouse, 1998):

Eqn. 17

$$T^* = T \cdot \left[g(s-1)d_{50}^3\right]^{0.5} \cdot D^{-2}$$

Where s is the sediment specific density (ρ_s/ρ) and D is the diameter or other significant dimension of the structure.

Further, Fredsoe et al. (1992) found that the time-scale for scour in waves and currents was correlated with the non-dimensional shear stress (i.e. Shields parameter), θ *as:*

Eqn. 18

$$T^* = 0.02 \cdot \theta_{cr}^{-5/3} \quad .$$

Where T^* is the non-dimensional time scale described by Sumer et al. (1992):

Eqn. 19

$$T^* = A\theta_{cr}^{B} .$$

The larger the Shields parameter, the smaller the time scale. A and B were determined to be 0.014 and -1.29, respectively by Fredsoe et al (1992). The shear stress in θ_{cr} is based on the steady flow (current) or maximum orbital velocity (waves).

4.5.7. Pipe/Cable Roughness

Results of investigations indicate that pipe roughness has a negligible influence on scour depth (Sumer and Fredsoe, 1990).

4.5.8. Risers

Scour around vertical rising members, or combination horizontal and vertical members, can be treated as a composite problem. Vertical portions of the member can be considered a single, slender pile. Horizontal portions of the member can be considered a pipeline. This is particularly important for horizontal and vertical members that may be initially buried. Scour along a vertical section of a member may unbury a horizontal section, causing structural instability and/or vulnerability overall.

4.5.9. Pipe Vibration

Flow proceeding past a pipeline, under certain conditions, can cause shedding of vortices from the lee side of the pipe. This can result in vibrations of the free-spanning pipeline. Aside from potentially causing pipeline structural instabilities, vortex induced vibrations (VIVs) can also cause increases in equilibrium flow depth, particularly when the pipeline is able to impact the bed (Mao, 1986). Cross-flow vibrations have been shown to be the cause of a 20-50% increase in equilibrium scour depth (Sumer et al., 1988).

4.6. Scour Potential – Large Volume Structures

For the purposes of scour evaluation, a structure not meeting the criteria of being considered a slender pile (or multiple piles) may fit the criteria of being a large volume structure. Examples of large volume structures include coffer dams, bridge piers that do not constitute slender piles and large, offshore tidal current energy or wave energy conversion devices, amongst other structures. These larger obstructions alter the flow dynamics in different manners than slender piles. Horseshoe vortices and vortex shedding may not be the dominant processes like in the slender pile case. Therefore, they require slightly different considerations when assessing scour magnitude.

4.6.1. Water Depth

When the relative diameter of the structure is larger (D/h >0.5), where h is water depth, the scour pattern is different from that of the slender pile case (Whitehouse, 1998). Furthermore, wave diffraction begins to become important when the structure diameter to wavelength ratio D/L > 0.2 (Rance, 1980). When D/L > 1.0, where L is the wavelength of the incident waves, wave reflection begins to be the dominant force imparted on the incident wave energy by the device.

4.6.2. Scaling of Scour Depth

The same formulations as used for estimating scour around slender piles typically cannot be scaled up to account for a larger diameter structure. In fact, due to the larger dimensions of the structure, scour and siltation may occur simultaneously around the periphery (Rance, 1980; Katsui and Toue, 1992). Physical model results have indicated that scour depths around a large cylinder approached 0.032*D in the presence of just waves, and 0.064*D in the presence of collinear waves and currents. In addition, accretions of as much as 0.028*D were observed in some areas adjacent to the structure.

Results were also reported for the same wave and current conditions for a square-shaped structure, with the corner oriented toward the incident wave and current flows. The maximum scour depth for the wave-only case was 0.08*D and maximum deposition was 0.066*D. The maximum scour depth for the wave *and* current case was 0.18*D; the maximum deposition was 0.128*D (Rance, 1980).

4.6.3. Scour Depth and Position

Alternative physical model tests have determined that, contrary to that which occurs around slender piles in a steady current (maximum scour depth is at upstream face of the cylinder), the maximum scour around a large cylinder occurs at approximately 45-degrees from the axis of oncoming flow. Further, the actual scour depths were found to be dependent upon the ratio of water depth to structure diameter and actual pile diameter (Torsethaugen, 1975; May and

Willoughby, 1990). Both reports indicated that the maximum scour would occur at the corners of a square structure and after long exposure to a steady, unidirectional flow.

Breusers (1972) estimated equivalent prototype scour depths of 6.0-9.0 meters on tests of a gravity structure with rectangular rafts at a 1:50 laboratory scale. May and Willoughby (1990), however, measured scour depths significantly smaller than those predicted by the Breusers et al. formula (Eqn. 10), in the range of $0.1 < h/D < 3.0$ (Whitehouse, 1998). Dahlberg (1981) reported maximum scour depths of 2.0 meters at the corners of structures observed in the North Sea and the numerical findings of O'Riordan and Clare (1990) compare similarly.

4.6.4. Scour in Waves

In the physical model tests reported by Rance (1980), the scour pits around square and hexagonal structures were slightly larger than those reported around circular cylinders. Further, the scour pits extended one-half diameter from the edge of the circular cylinder structure and 1 full dimension from the edge of the square structure. Wave action produced alternating scour and accretion patterns around the structures (Whitehouse, 1998).

4.6.5. Scour in Wave-Current Flow

In Rance's (1980) experiments, the equilibrium scour depth in the waves and currents scenario was deeper than for just currents alone; however, it should be noted that only one wave and current scenario was tested. The horizontal scour extent was approximately 1*D from the edge of the structure.

4.6.6. Shape

Dahlberg (1981) concluded that square-shaped structures were more sensitive to scour than circular ones. May and Willoughby (1990) found that the scour depth for large square-shaped structures was, on average, 1.3 times larger than for an equivalent dimension circular cylinder structure.

4.6.7. Angle of Attack

The angle of attack of the wave and current flows were found to have a direct impact on the velocity amplification near a square-shaped structure (O'Riordian and Clare, 1990; Hebsgaard et al., 1994). Therefore, the scour and backfill processes will also have varying results as the direction of waves and currents varies. Rance (1980) also illustrates examples of varying wave and current directions on scour patterns.

5. SITE EVALUATION

As previously discussed, the primary goals of the guidance in this document are twofold:

1) reduce time and costs associated with planning, development and permitting of offshore wind structures by considering site-specific oceanographic and sediment dynamic responses to offshore wind farm designs
2) provide information to help reduce lifecycle installation and maintenance costs through informed offshore wind farm array design.

To address the interaction of offshore wind farms with the environment requires, first, a holistic understanding of the characteristics of the coastal areas in which the development is proposed. One manner of approach is a comprehensive MSP-type of project assessment; a second is a more focused, CSM-type of approach. Any documented guidance from national or international agencies should be reviewed for relevance and assistance, as well. All available *relevant* knowledge and data of the region of interest then needs to be assimilated in order to evaluate collectively.

In this document, since the ultimate objective is a more focused (i.e. does not consider all potential issues of concern) oceanographic and sediment dynamics understanding, a CSM is the chosen framework for assessment (though any similar spatial planning platform will suffice). A CSM, in this sense, is the framework of any comprehensive understanding of the physical, environmental, and human interaction in the coastal zone. It is a qualitative and quantitative description of the system describing all of the known physical processes, and their interactions, for the purposes of evaluation and decision making. The CSM provides the basis, throughout the entire project, for which data collection and analysis is integrated into a single site description, ensuring that all information is both relevant and completely utilized in the decision making process. Particular to offshore wind development (or any offshore alternative energy development) in the coastal zone, the information areas that require description are the site-specific physical, chemical, ecological and biological processes, and the offshore wind farm (or other structure) design parameters.

Generally, the initial CSM begins with assembly of all existing qualitative and quantitative site characterization data. Often referred to as a ‘Tier 1 Analysis’, this first step will indicate if there are missing pieces of beneficial data (i.e. important data gaps) necessary for system characterization.

With the general understanding of the site conceptually developed, potential negative impacts related to offshore wind farms and their interaction with the environment can be outlined. Subsequent tiers of a CSM study may involve additional data collection, modeling and/or analysis, focusing on addressing unresolved questions and filling data gaps. This will persist,

iteratively, until the uncertainty is reduced or questions are resolved to the satisfaction of the site managers.

An example of the primary components to consider when evaluating a site for offshore wind development is identified below. Italicized items are suggestions for specific characteristics to define within the CSM for each category, but this list may not be comprehensive for a particular site. Fundamental questions to be answered in characterizing the site are included as sub-bulleted items.

1. **Site Evaluation**
    a. **CSM - System Description, Classification and Evaluation**
        i. Coastal Characteristics – *Describe natural (ambient) sediment characteristics, seabed morphology, water quality, ecology, biology*
            1. What is the bathymetry of the system?
            2. Are there submarine canyons or other features that would act to focus or de-focus wave propagation?
            3. What are the sediment characteristics?
            4. What are the dominant geologic features?
            5. Is the system dynamic (e.g. sand wave propagation)
            6. What is (are) the regional sediment transport pattern(s)?
            7. What ecological/biological activity exists in the near-field and far-field of the proposed development?
            8. Are there environmental restrictions (e.g. endangered animals, established work windows, contaminated sediment concerns)?
            9. What are the potential sensitive receptors by category/species?

        ii. Coastal Forcing Mechanisms – *Describe the prevailing wave, current, and wind velocities (both typical and extreme)*
            1. What is the typical wave energy environment?
            2. What extreme wave/wind events are possible (large storms, hurricanes, tsunamis)?
            3. What is the tidal current and circulation environment?
            4. Is there a river/estuary that contributes to local forcing?
            5. What are the potential combined effects of interactions of forcing mechanisms?

        iii. Coastal Response to Forcing Mechanisms – *Describe natural sediment erosion, transport, and deposition*
            1. What is the short- and long-term evolution of the coastal region (shoreline, near-shore and offshore)?

2. Are there erosional/depositional trends along the shoreline or in other areas?
3. What are the short-term (storm) responses?
4. Does the area recover rapidly to equilibrium when altered?

iv. Wind Farm Characteristics – *Describe planned number of units, installation water depth, and size of flow obstruction*
1. What does the system design and layout look like?
2. What is (are) the water depth(s)?
3. What is the orientation of the device/array?
4. What is the vertical obstruction (full water column monopole or floating platform)?

b. Impact Assessment

i. Site and Environmental Impacts – *Analyze potential site/environmental concerns based on the CSM information at hand*
1. Define typical and extreme forcing events
2. Quantitatively evaluate the local coastal forcing mechanisms and response to installation of an offshore wind farm
3. Quantitatively evaluate the local morphological reaction to installation of an offshore wind farm.
    a. Does the analysis suggest that the planned offshore wind farm array could significantly alter wave propagation or coastal circulation?
    b. Does the analysis suggest that the offshore wind farm array could significantly alter seabed shear stress and sediment transport patterns in the near- or far-fields?
    c. Would alteration of the hydrodynamics and/or sediment transport patterns affect (negatively or positively) the local biology or ecology?
4. Estimate expected far-field scour (if any) resulting from alteration of the lee hydrodynamics.
5. Estimate all anticipated environmental effects such as alteration of sediment transport patterns and harmful changes to important aquatic habitat
    a. What is the potential for local and global seabed instability?
    b. Define the magnitude of the small- and large-scale ongoing seabed and shoreline changes

c. What are the potential effects on the hydrodynamics, water quality, biology and ecology?

ii. <u>Design Impacts</u> – *Analyze the potential Offshore Wind array concerns based on the CSM information at hand*

1. Estimate expected local (near-field) forcing alterations and scour that may occur (if any) around foundations
2. Estimate the expected forcing and scour impacts on associated pipes and cables.
3. Estimate all anticipated environmental effects such as alteration of sediment transport patterns and harmful changes to important aquatic habitat for all alternative design scenarios.
    a. What is the potential for local and global seabed instability?
    b. Define the magnitude of the small- and large-scale ongoing seabed and shoreline changes
    c. What are the potential effects on the hydrodynamics, water quality, biology and ecology?

As each question is addressed a database will be developed to assimilate and describe the known and unknown information. If no data (or insufficient data) is available to answer a particular question, the need for additional site-specific data collection should be assessed for the improvement and/or augmentation of the existing datasets. *For example, if only sparse NOAA bathymetric datasets are available, there may not be sufficient information to evaluate the wave propagation, current circulation, and, therefore, scour potential at (or in lee of) the wind-farm site. A site-specific bathymetric survey may be required to more accurately define and analyze the site.*

Many times data to initially consider the CSM questions are already available from public and/or private sources. Assimilating this data is typically the first step in development of a CSM. Table 2 lists the data needs for addressing some of the CSM questions from above. Shoreline, bathymetry, seabed properties, waves and currents, and water column properties are typically required to define the physical system. Historical information on each of these characteristics can be used to develop past and present patterns at the site that will assist in the impact assessment.

Table 2. Data needs to develop site characterization.

Site Characteristic	Data Need	Sources
Shoreline configuration	Provides a basic boundary for the system. The location of the shoreline and any historical evolution of the shoreline can lead to critical information on the long term geomorphology of the system and yield information on rates of change.	Aerial photography, Sattelite imagery, NOAA maps, USGS maps, Local GIS databases often available online
Bathymetry	Bathymetric data provides the basic underwater configuration of the system that is used to bound the conceptual site model and provide data for enivronmental and engineering analsysis. High resolution bathymetric data can provide critical information on the system geomorphology.	Single- and multi-beam survey data, NOAA data sources, specific surveys may need to be conducted to collect high resolustion data at the site.
Site History	Information on human activities at the site (e.g. dredging, shipping, fishing) provide the potential impacts a wind farm may have on these operations through modification of the system.	USACE and NOAA maintain records on the navigation and commericial fishing activities throughout the coastal United States. State agencies also maintain information on public site usage.
Seabed Properties	Grain size distributions, water content/sediment density, total organic carbon, sediment erosion properties, benthic characteristics, and other geophysical data provide basic information on the horizontal and vertical distribution of sediment in a region and its potential for mobility.	Site specific data is often available through local research organizations. The USGS often maintains larger databases of general coastal sediment characteristics for the region. Specific coring and surveying trips will often need to be designed to collect this data for a wind farm area.
Waves and Currents	The dominant hydrodynamic forces at the site must be identified to determine impacts of the wind farm on the system. Magnitudes and directions of the prevailing conditions as well as conditions during lower probability storm or seasonal events must be considered.	NOAA and USGS often maintain large databases of site specific measurements, but also conduct real-time measurements of waves and currents throughout the coastal United States. Site specific measurements may be required in complex regions.
Water Column Properties	Information on the temperature, salinity, and suspended solids are required to understand the horizontal and vertical structure of the water column. The three-dimensional distribution of these characteristics offers insight into how the system presently behaves and how a wind farm may effect this behavior.	NOAA and USGS often maintain large databases of site specific measurements, but also conduct real-time measurements throughout the coastal United States. Site specific measurements may be required in complex regions.

5.1. CSM - System Description, Classification and Evaluation

Characterizing a coastal system first involves the description of the natural setting. Important considerations include evaluating the long- and short-term evolution of a shoreline and near-shore coastal environment, determining the offshore and near-shore bathymetry structure, and defining the sediment budget and transport constraints (sediment sinks, sources and transport boundaries).

The ultimate objective is to forecast changes in the coastal region associated with offshore wind installation and quantitatively assess environmental or design impacts associated with these changes. Establishing the baseline scenario is a key requirement. When the baseline scenario is defined, changes relative to that baseline (from offshore wind installation) can be quantified and risk can be evaluated.

5.1.1 Coastal Characteristics

5.1.1.1. Define CSM Boundaries

River sediments are the source of 80% to 90% of the sand existing in coastal regions. In general, coastal areas aggrade, or grow, during times of rising sea level provided sediment delivery (from all sources) is sufficient. The available sediment in the coastal regions is directly linked to the sources (e.g. watersheds, rivers, up-coast sediment delivery, coastal erosion) and sinks (e.g. down-coast sediment loss, offshore canyons, shoreline deposition) of sediment. The general interaction of these processes is illustrated in

Figure 18. The region that bounds these sources and sinks is termed a littoral cell. A littoral cell comprises the circulation patterns of sediments transported in and through a region, often bounded by distinct geologic features (e.g. headlands, points, inlets, rivers, offshore canyons). Littoral cells, by definition, do not exchange sediment.

Figure 19 illustrates examples of known littoral cells along the California coast. The first step in defining the CSM is to identify the littoral cell bounds (or the appropriate regional boundaries for the CSM) and develop a sediment budget. Fundamentally, a sediment budget establishes the mass balance (sediment input - sediment output) of an area over time. In many natural systems this balance is not zero, meaning the system is either eroding or accreting sediment over time. The magnitude of these changes provides information on the rate of sediment transport within, as well as into and out of, the system. Additionally, the magnitude of these changes may be reflective of the nearby geologic shoreline trends (i.e. is the local shoreline eroding or accreting over time?).

The sediment budget establishes the large-scale natural sediment transport patterns within the cell. It provides a basis for the eventual quantification of the sediment transport, delivery, storage, and output and is a means of linking up-coast erosion and down-coast accumulation, and

long-term sediment transport trends. The site-specific sediment budget can be developed using measurements of sediment delivery pathways to quantify the sediment capacity of the system; which, in turn, will define the ambient stability of the seabed in the vicinity of a proposed wind farm. This will allow for an assessment of the future impacts on these processes due to the presence of the offshore wind farm. Figure 20 shows the common elements that must be considered in developing a complete near-shore sediment budget.

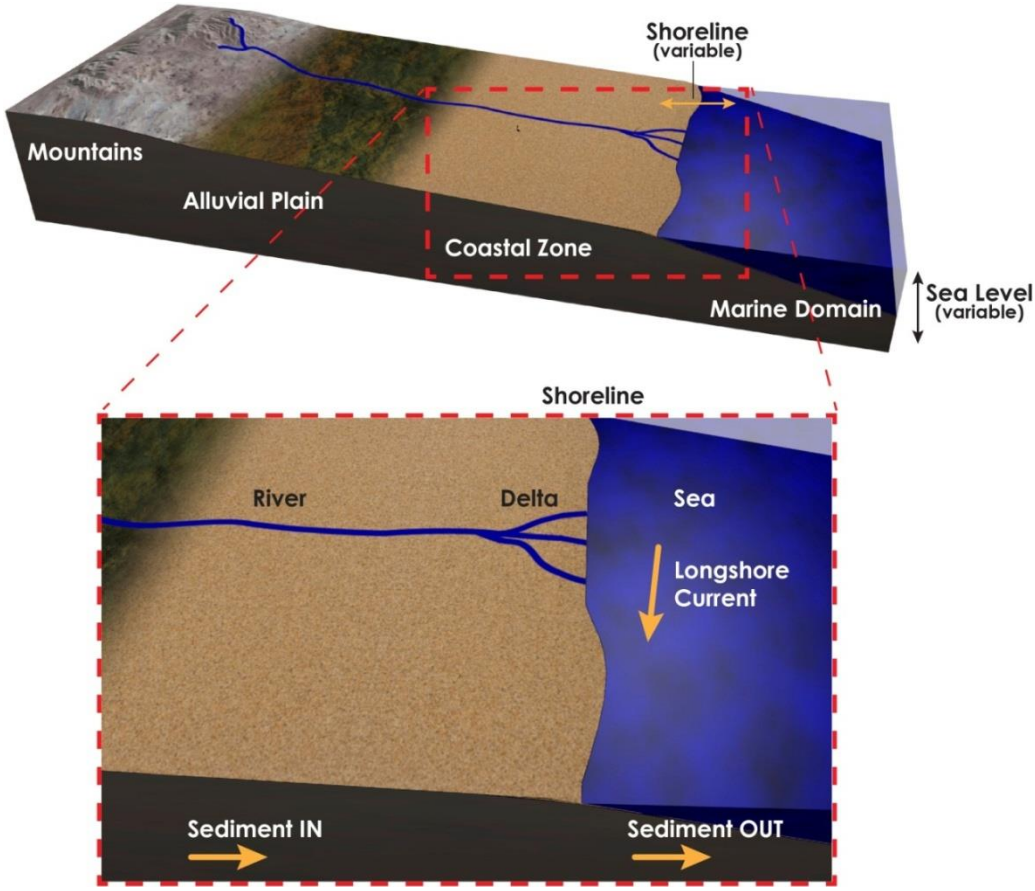

Figure 18. Illustration of the coastal zone as a component of the Conceptual Site Model.

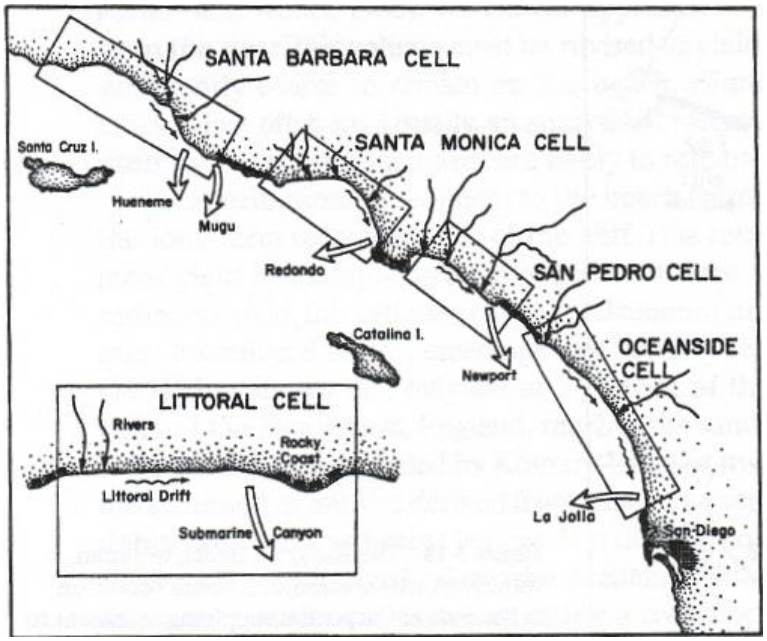

Figure 19. Series of littoral cells along the California coast (Adapted from Komar, 1998; from D.L. Inman and J. D. Frautschy, 1966)

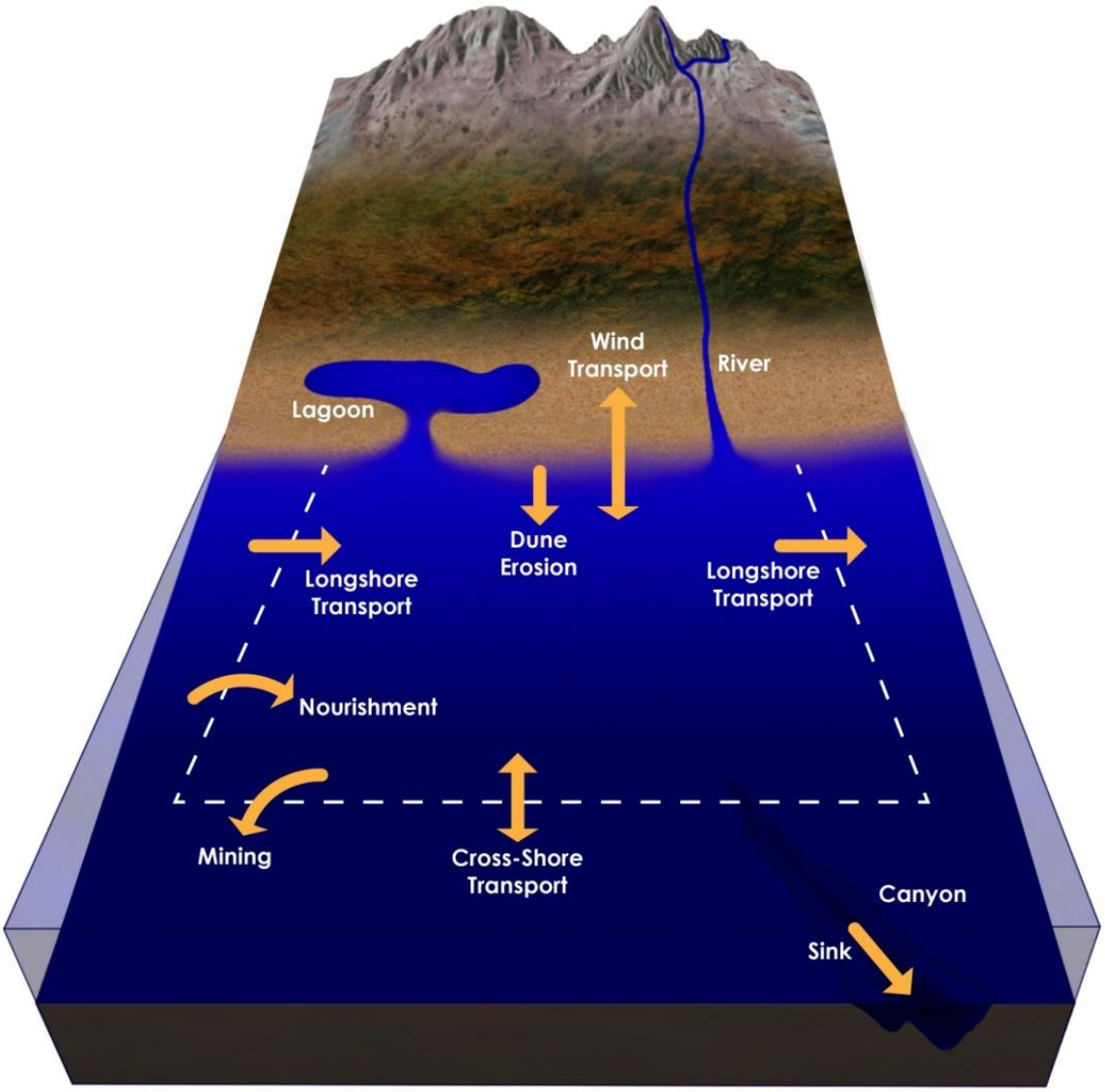

Figure 20. Elements to consider in the near-shore sediment budget.

5.1.1.2. Shoreline Configuration

The shoreline provides a basic onshore boundary for the system. Even if the site is far offshore, the location of the shoreline and any historical evolution of the shoreline can yield critical information on the long term geomorphology of the system and on rates of change. Typical data sources include aerial photography, satellite imagery (e.g. Google Earth), NOAA maps, NOAA National Geodetic Data Center (NGDC) digital elevation models (DEMs) and U.S. Geological Survey (USGS) data and maps. Local Geographic Information System (GIS) databases maintained by state and local government agencies are often available online and can be found with a thorough internet search. Historical and recent maps of the shoreline can provide important information not only on the site boundaries, but on historical changes in the system

geomorphology. For example, sources of incoming sediment can be identified or an accreting/eroding beach may be observable in historical aerial photography.

Figure 21 provides a nationwide example of shoreline stability assessment.

5.1.1.3. Bathymetric Data

Bathymetric data provides the basic underwater configuration of the system that is used to bound the conceptual site model and supply data for environmental and engineering analysis. It may also be used to construct computer numerical and/or physical models of the system during a higher tier investigation. Furthermore, higher resolution bathymetric data can provide critical information on the system geomorphology and improve accuracy of hydrodynamic and sediment transport models.

Hydrographic surveying techniques and procedures have advanced greatly in recent years with rapidly evolving sonar technology. Single-beam technology paired with global positioning system (GPS) positioning provides for high-accuracy, single-point soundings (Figure 22). Moreover, multi-beam sonar technology makes it possible to collect full bottom (swath) coverage of an area that otherwise may not be known (i.e. submarine features may go undetected if surveyed with single-beam as opposed to multi-beam technology). Side-scan sonar and multi-beam acoustic backscatter (ABS) technology are two methods of utilizing backscattered intensity to characterize the seafloor. Each yields bird's eye view imagery of the seafloor from different perspectives, can indicate morphologic features, and can assist with bottom classification.

Each technology, however, has its advantages and disadvantages that should be weighed against the project needs and priorities. Bathymetric maps and data may already be available for the site of interest from the NOAA or from local or state government records. Dredging and bathymetric records from the U.S. Army Corps of Engineers (USACE) may have information about historical bathymetric changes, sediment accumulation rates and whether the local environment is depositional or erosional.

5.1.1.4. Site History and Future Development Plans

Information regarding navigation, dredging, past and future construction activities, and other future use issues should be obtained from various sources including the Navy, USACE, U.S. Coast Guard, and state, regional, or local agencies. Locations, diameters and types of outfalls at or near the site also should be determined. Information on human activities at the site (e.g. dredging, shipping, fishing, recreation) will allow for evaluation of the potential impacts a wind farm may have on these operations. USACE and NOAA maintain records on the navigation and commercial fishing activities throughout the coastal United States. State agencies also maintain public information on site usage.

5.1.1.5. Seabed Properties

The characteristics of sediment and the sediment bed often provide insight into the sediment transport environment based on distributions of sediment grain sizes, densities, and other seabed properties. Biological information also is needed to assess the potential effects of benthic (i.e. bottom dwelling) communities on sediment transport and eventually to assist in determining the effects of a wind farm on benthic habitat. Sediment type (i.e., particle size distribution) is one of the most important parameters for characterizing sediment transport as it is inherently related to both the transport properties of the sediment and the geotechnical stability of the seabed. If possible, the horizontal and vertical distribution of sediment type (i.e., stratigraphy) should be established. Figure 23 shows an example of contoured grain size data in the Santa Cruz, CA region based solely on the median grain size of the distribution. Patches of fine and coarse sediment can be identified by the light- to dark-color changes.

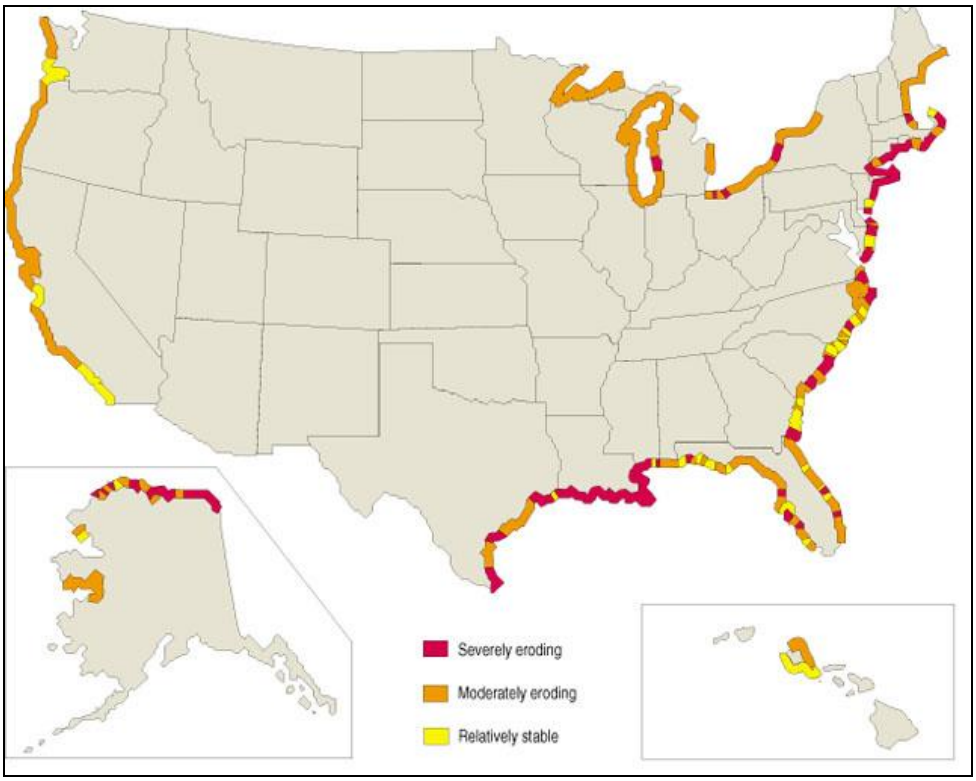

Figure 21. Map of shoreline stability assessment (NASA).

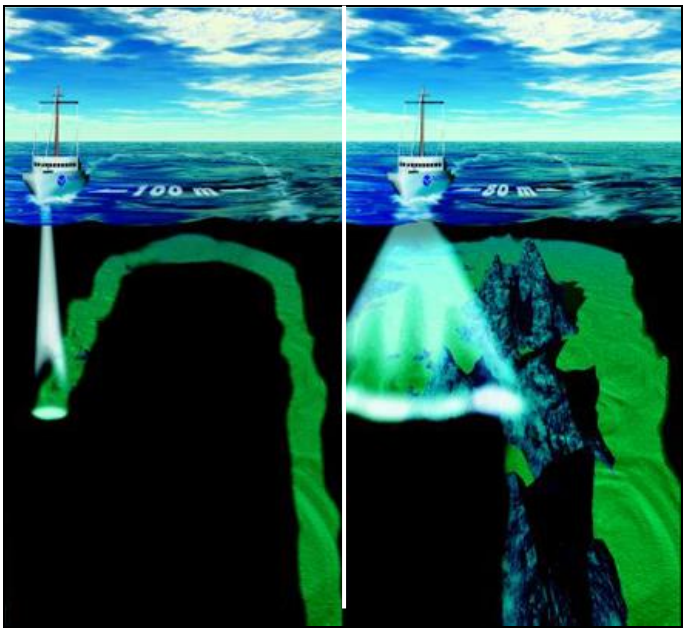

Figure 22. Illustration of single- (left) and multi-beam swath (right) survey technology bottom coverage (NOAA).

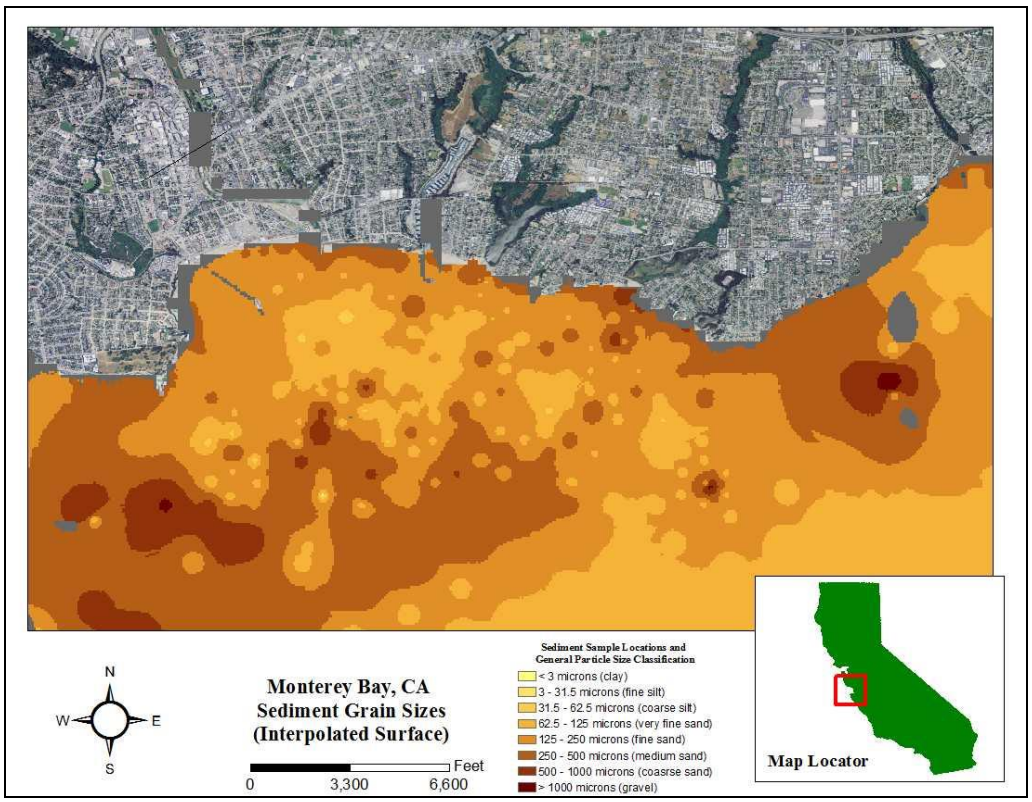

Figure 23. Contours of sediment grain size based on USGS sediment characterization activities.

5.1.2. Coastal Forcing Mechanisms

5.1.2.1. Hydrodynamic and Meteorological Data

Hydrodynamic processes (e.g. waves and currents) are, generally, the physical forcing mechanisms that have the highest potential to be altered by an offshore wind farm installation. Determining the natural (ambient) hydrodynamic characteristics will provide a fundamental understanding of the natural system. Then the potential impacts of a wind farm on the ambient hydrodynamics can be investigated. When combined with other common oceanographic data (e.g. sea surface temperature, winds, salinity), the overall system and sediment transport potential can begin to be specified. Site-specific or regional data on hydrodynamic forces may be available from various sources, including the U.S. Navy, USACE, NOAA, USGS, National Weather Service (NWS), universities, and state, regional, and local agencies. Figure 24 shows example real-time hydrodynamic at meteorological data collected from the mouth of Chesapeake Bay.

Data are typically available for locations along all United States coastlines. NOAA maintains the National Data Buoy Center (NDBC) which records and retains real-time and historic data readily accessible online. Scripps Institute of Oceanography (SIO) maintains a cooperative wave data network, the Coastal Data and Information Program (CDIP). Figure 25 shows an example of data from a CDIP buoy used to initiate a real-time wave propagation model of the central California coast. The data from similar programs like CDIP are available online and are funded by a combination of local, state, and federal entities.

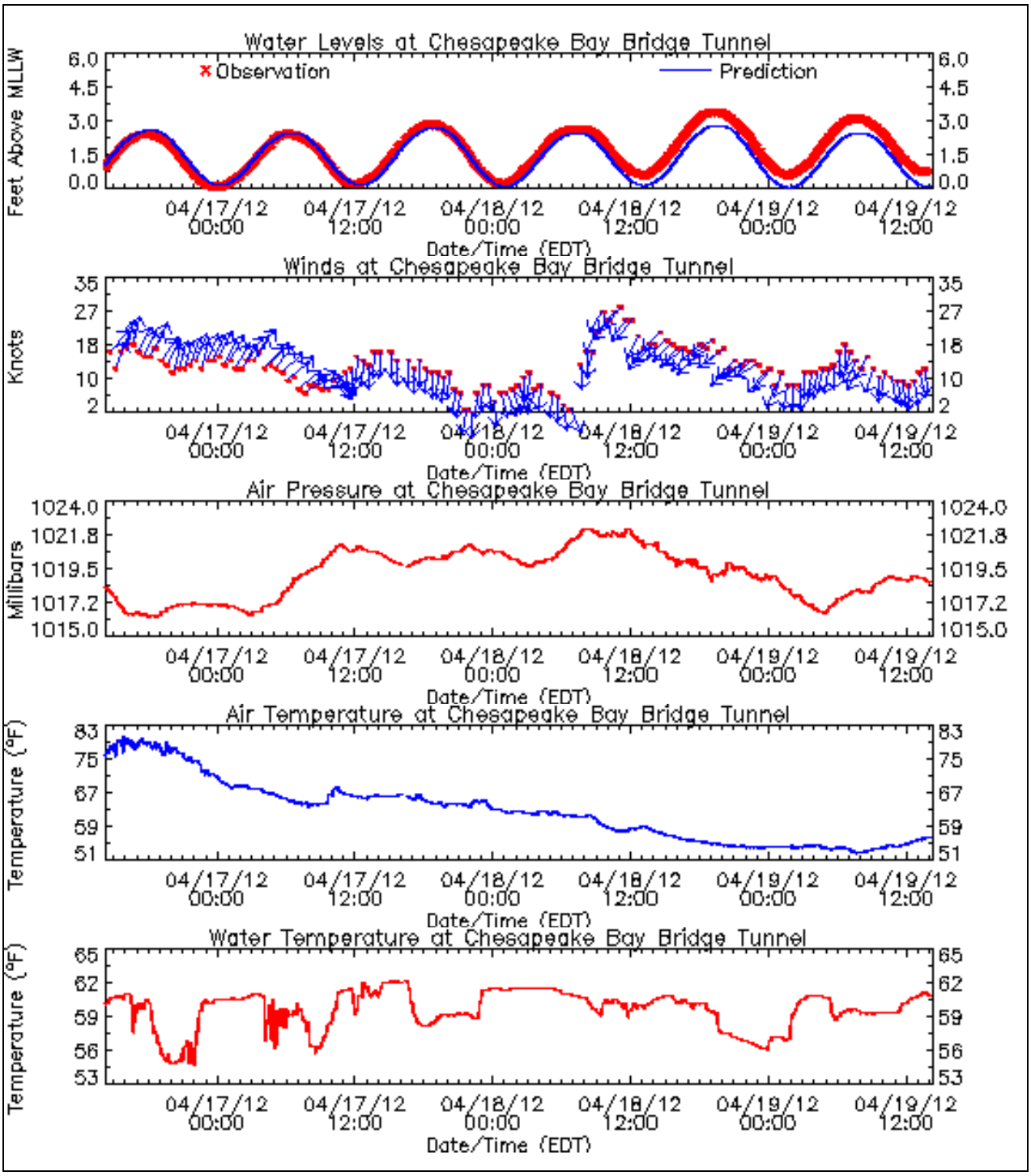

Figure 24. Example meteorological and oceanographic data from the mouth of Chesapeake Bay (NOAA).

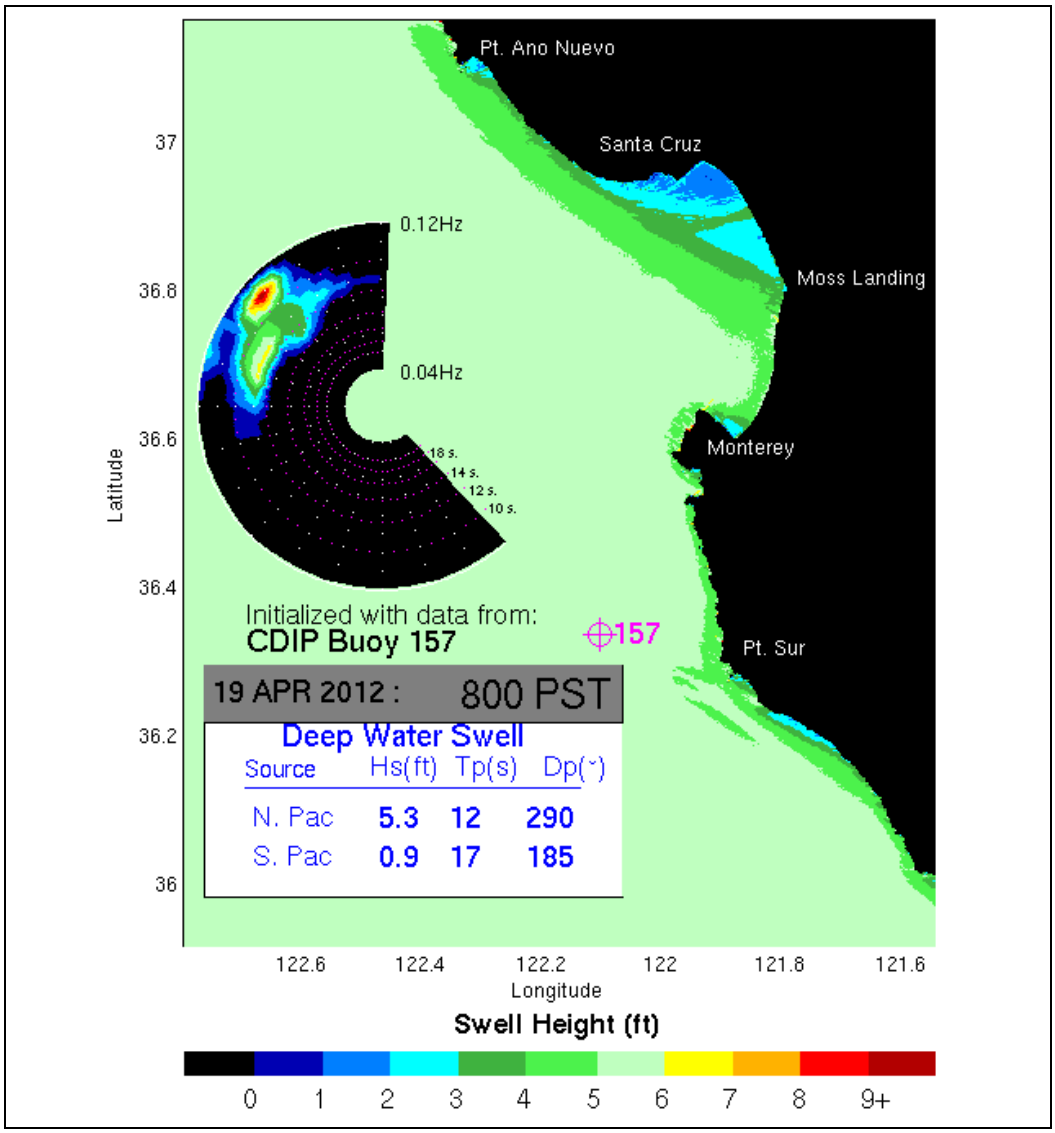

Figure 25. Example spectral wave data from a buoy coupled with a real time coastal wave model (CDIP)

5.1.2.2. Water Column Properties

Information on the temperature, salinity, suspended solids and other properties might be required to understand the horizontal and vertical structure of the water column, and to draw conclusions about potential effects from offshore wave installation. The three-dimensional distribution of these characteristics offers insight into how the system presently behaves, any gradients that are resultantly generated, and how a wind farm may affect this behavior. NOAA and USGS often maintain large databases of site specific measurements, but also conduct real-time measurements throughout the coastal United States. Site specific measurements may be required in complex regions to augment basic knowledge. Additionally, available satellite imagery may be used to look at regional trends in relative suspended sediment concentrations.

5.1.3. Coastal Response to Forcing Mechanisms

Once the site-specific physical forcing parameters are defined and categorized for an area, their natural effect on the local coastal response should be characterized and included in the CSM, to the extent possible. This will allow baseline characterization of the short- and long-term evolution of the area of interest. On the simple end of the spectrum, coastal response to the natural hydrodynamics can be assessed qualitatively and quantitatively through observation of historical aerial imagery. Historical photos yield valuable information of the evolution of a coastal region, indicating shoreline erosion and deposition trends, historical land and coastal development and may even illustrate offshore morphology changes (e.g. movement of sand bars and sand spits over time).

Alternative methods that increase in complexity include a thorough evaluation of the sediment budget (i.e. determining if the sediment budget is out of balance) and an analytical evaluation of coastal response to the forcing (utilizing well known coastal engineering and oceanographic equations – CEM, 2002), and numerical and physical modeling. Each of these methods will yield valuable information regarding the response to the ambient physical processes. Evaluation of the anticipated coastal response to the actual installation of an offshore wind farm will be completed in the Design Impact Assessment phase, following completion of the CSM and refined design of the array.

5.1.3.1. Evaluating Responses to Coastal Hydrodynamics

Circulation and mixing in coastal regions are controlled by a combination of winds, tides, waves, river discharges, storm surges and other hydrodynamic processes. During low wave energy events, near-shore circulation may dominate the near-shore mixing processes. During large wave events, however, the wave effects may dominate the near-shore currents and mixing.

As discussed, a first step at estimating the wave and current magnitudes near the coastline is through data analysis and utilizing established coastal engineering equations (CEM, 2002). However, to capture complex wave-induced currents and mixing as well as tide and wind-driven currents over a large spatial region, it is often useful to employ a numerical model for computational efficiency. Numerical models describing wind, waves, currents and sediment transport are widely available, and are efficient tools to utilize whether or not site-specific data exists. This method may require the use and integration of both a wave propagation model and a transport/circulation model. Model results can be used to support knowledge of, or assist in determination of, the natural transport characteristics of the area and calculate bottom shear stresses throughout the region to evaluate sediment stability. They also can assist in determining the uncertainty in predictions, which is an indication of the confidence a manager/engineer should have in the coastal response predictions. Further, the level of uncertainty will indicate the relative need (if any) for additional data collection or model refinement.

To accurately calculate the transport of water quality parameters and sediments in the coastal environment, it is critical to describe both the fluid transport and the near-bottom shear stress. Currents (whether, for example, generated by waves, tides or river discharges) are responsible for overall transport, which comprises advective and diffusive transport.

Advective transport is that due to the bulk movement of the surrounding fluid. The advective transport flux (q) can be quantitatively calculated by the mass concentration, C, of the substance of interest multiplied by the velocity, u, yielding $q = uC$. The advective flux generally accounts for the majority of transport in coastal systems. The currents move masses around much more rapidly than diffusive processes. The advective velocities, as previously shown, are a result of tidal forces, river discharges, wave forces, and wind.

Diffusive transport is a secondary transport process due to molecular and turbulent transport processes. The molecular component is dispersion of a dissolved mass caused by the random motion of molecules in the water. The turbulent component of diffusion is the dispersion of mass due to the random motions in the fluid associated with turbulent flow generated by the waves and currents. In coastal systems, turbulent diffusion generally exceeds molecular diffusion rates by many orders of magnitude.

When described mathematically in one dimension, the summation of the advective and turbulent diffusive components of mass transport into a mass flux (i.e. transport, q) term is

Eqn. 20

$$q = uC - K\frac{\partial C}{\partial x}$$

The second term defines the diffusive transport where K is the coefficient of turbulent diffusivity. The determination of K is a key component of mass transport and must be considered carefully. The diffusivity must be described in both the vertical and horizontal directions.

Turbulent eddies are responsible for mixing fluid in the horizontal, and the larger eddies mix more fluid. In general, the horizontal diffusivity (K_H) responsible for the dispersion of freshwater and/or sediments, is proportional to the velocity in the fluid and the physical size of eddies.

Many quantifications use the Smagorinsky (1963) method to calculate the horizontal diffusivity. The magnitude of the diffusivity in the model is proportional to the horizontal current shear. The Smagorinsky model has been well validated in coastal circulation modeling studies over the past three decades. In addition to the diffusivity due to the current shear, wave dissipation plays a role in K_H in the near-shore. As waves move into shallow water regions, they disperse energy in the form of turbulence. This is considered the wave energy dissipation. The dissipation of wave energy through the generation of turbulence increases as the wave shoals and is at a maximum as the wave breaks. Wave dissipation is responsible for significant vertical mixing in near-shore regions where water depth is small; however, in deeper water, waves may not contribute as much

to mixing because wave energy tends to dissipate in the upper water column. This dissipation is often calculated in a wave model and used as an input to a circulation model.

Vertical mixing is the product of not only current gradients in the vertical, but also buoyancy gradients. Many coastal circulation models, for example, implement the Mellor and Yamada (1982) second moment turbulence closure model in the vertical that has been well validated for coastal ocean applications. The model has been improved and further validated by Galperin et al. (1988). The Mellor and Yamada model relates vertical turbulent diffusivity to turbulent intensity, turbulent length scale, and the Richardson number (a measure of the buoyancy effects in the flow). Once the vertical diffusivity has been calculated through the Mellor and Yamada model, the wave dissipation from a wave model is added to the circulation/transport model as an additional source of turbulence.

Bottom shear stress, τ_b, is produced at the sediment bed as a result of friction between moving water and a solid bottom boundary. It has been studied in detail for currents and waves, and can be defined and quantified mathematically given sufficient information about the hydrodynamics of the system. Shear stress is responsible for the initiation of sediment transport (i.e., erosion) and the ability of the flow to keep sediments in suspension. The calculations of shear stress in areas where waves play a large role are outlined in more detail in Christoffersen and Jonsson (1985), and Grant and Madsen (1979).

The overall quantification of coastal processes is generally limited by the availability of site-specific data used to describe the processes outlined above. Many times, a site-specific study can be designed to address a specific impact question; on the other hand a model driven using available data can help address where negative impacts may be expected and may be an acceptable substitute for additional data collection. The use of modeling alone can produce order-of-magnitude estimates of transport due to the dominant processes in the region (i.e. waves and tides). These results are used to develop qualitative conclusions about impacts and then more detailed site-specific studies (field and modeling) can be used to address specific impacts if needed.

5.1.3.2. Modeling Wave Propagation

As deepwater waves approach the coast, they are transformed by certain processes including refraction (as they pass over changing bottom contours), diffraction (as they propagate around objects such as headlands), shoaling (as the depth decreases), and energy dissipation (due to bottom friction, white-capping, and, ultimately, by breaking). Since waves are the primary source of energy at the seabed in near-shore coastal settings, the accurate description of their propagation is a fundamental component in assessing sediment transport potential.

The propagation of deepwater waves into a region can be modeled using a wave propagation algorithm that has the capability of modeling all of these processes in shallow coastal waters. Examples of publicly available and for-purchase wave propagation models include Simulating WAves Nearshore (SWAN, a part of the DELFT-3D modeling suite, developed by Delft Hydraulics

Laboratory), STWAVE and CMS-WAVE (developed by the U.S. Army Corps of Engineers), REF-DIF (developed by the University of Delaware), and the MIKE21 suite (developed by the Danish Hydraulic Institute). These models can often be run in unstructured and structured grid modes for additional detailed modeling capability. As each of the above-mentioned wave models incorporates slightly different physical processes, care should be employed to select the proper model for the region under investigation.

5.1.3.3. Modeling Near-shore Circulation

Oceanic currents are driven by several factors: tide cycles, wind stress, and thermohaline circulation (caused by density differences due to temperature and salinity gradients). In deeper water depths, the effects of these processes are not as significant as they are in shallower depths. As water depths decrease, these, as well as other effects such as storm surge and sea level rise become more important and pronounced. In the near-shore coastal regions, currents due to tide fluctuations, wind setup, storm surge and river/estuary discharge will likely be the dominant forcing mechanisms, though thermohaline circulation may still be present.

Circulation of coastal waters in a region can be modeled using algorithms that have the capability to resolve many of these processes. Examples of circulation models that are publicly available and available for purchase are the Environmental Fluid Dynamics Code (EFDC, John Hamrick, 1992), ADCIRC (maintained by the USACE), FVCOM (joint development by the University of Massachusetts – Dartmouth and the Woods Hole Oceanographic Institute), and modules within the MIKE21 and DELFT3D suites. As with the wave models mentioned above, these models can often be run in unstructured and structured grid modes for additional detailed modeling capability. And, as each of the circulation models incorporates slightly different physical processes, care should be employed to select the proper model for the region under investigation.

5.1.3.4. Refine Conceptual Site Model

As new data and analysis is generated that describes the offshore wind site and the processes that control site characteristics it is important to reconsider the CSM, assess the relative uncertainty in predictions and revisit the questions the study is trying to answer. The information generated in the data gathering and analysis phase can now be used to develop a refined and quantitative CSM, as appropriate. Site conditions should be thoroughly described; and extreme-, seasonal- and event-driven (e.g. storm) effects on the local processes should be investigated. Information that should be noted in the CSM includes the following, but may not be comprehensive:

- Site layout, topography, water body configuration, regional boundaries
- Nature of the shoreline (e.g., presence of riprap, beaches, and intertidal areas; slope, density, and type of vegetation; location of high and low tide lines)
- Nature of offshore seabed (e.g., particle size distributions, sediment distribution, sand waves, ripples or other transport features, shelf breaks, marine canyons)
- Anthropogenic activities (navigation, fishing, recreational use, dredging)

- Potential sources of sediment to the coastal zone (rivers, inlets)
- Current magnitudes and directions (tide ranges, frequency)
- Wave environment (typical and extreme wave heights, periods and directions)
- Other local information (storm surge, sea level rise, tsunami potential)
- Environmental concerns (contaminated sediment/water, listed and endangered species)

When developed, the CSM will indicate any data gaps and the relative importance of those data can be assessed. The full CSM is typically a concise written document with basic maps denoting information gained during the initial data collection and analysis phase. This document can provide information not only for determining impacts, but assisting the offshore wind design, construction, and operation teams.

5.1.4. Wind Farm Characteristics

To supplement the development of the CSM, preliminary offshore wind farm design parameters should be defined and included to assist with the CSM evaluation. This is in preparation for assessment of likely environmental effects of the offshore wind farm. Most wind turbine installation schemes are similar to those used in the oil and gas industry: solid supports (monopoles, tripods and/or jacket structures) driven into, or resting on, the seafloor; gravity based foundations, which rely on their own weight to remain fixed to the seafloor); moored, floating systems; or, some combination of systems. The type of placement and fixing technique is dependent on the physical characteristics of the deployment locations (i.e. water depth, namely), balanced by the cost of design and installation.

Solid support systems are deployed in water depths ranging between 10 and 30 m that can typically be found within a few miles of the US coastline. Gravity based foundations are typically deployed in shallow coastal regions where the equipment to drive piles for solid point connections have difficulty accessing the site. Both of these technologies are deployed in relatively shallow waters where sediment mobility and scour can be significant concerns. Also, the relatively shallow water depths where these foundation technologies are generally deployed regularly correspond to locations close to the US coastline (within a few miles), often within visual range of the shoreline, and potentially in high vessel traffic areas. As such, important impediments to their use in US waters are visual pollution and navigation safety (DTI, 2005a; DTI, 2005b).

Moving further from the coast and into transitional and deeper waters requires investigation of alternative deployment schemes, but can also cause installation costs to become prohibitive. Although less explored, moored systems seem to alleviate some of these concerns. Large floating structures of this type were first developed by the offshore oil and gas industry and the technology can be directly applied to wind turbines. Placement of offshore wind turbines further offshore has a twofold benefit: the wind is typically stronger and more consistent during daylight

peak energy times, and the negative aesthetic effect of turbine visibility to coastal residents is mitigated. The offshore wind industry is currently investigating moored systems in water depths larger than 100 m.

5.1.4.1. Solid Support Systems

Solid support systems are based on hard connections, often a hollow pile (or multiple piles in the case of tripods or jacket structures) or a concrete-filled pile(s) extending from the turbine to the seabed. Solid support systems may also include gravity-based turbines, which are anchored to the seafloor with a large weight. Solid support systems require a sufficient connection with the ground (or anchor to the ground), otherwise the turbine and its support system will move irreversibly. The foundation must transfer the forces from the structure to the surrounding soil. It is critical that the foundation sustain all loads that may be applied, particularly during extreme environmental conditions (e.g. wind and waves during storms) to reduce maintenance and/or replacement costs associated with structural failures. As structures are subjected to repeated loading (whether by ambient hydrodynamic forces or augmented forces due to scour and loss of support) structural stiffness degradation becomes an important consideration. The structural design must consider the cumulative lifetime stresses to which the support members may be subjected.

The types and approaches for hard connections widely vary and are chosen based on sediment bed characteristics including soil conditions such as sand density and depth to the clay stratum, as well as the strength of the underlying clay. Solid support systems can be as simple as concreting a monopile into holes drilled into the bedrock (Figure 26). This approach was successfully deployed in Blyth, Northumberland, UK.

Monopiles work well in shallow waters with hard bottoms, but are not suitable for loose, mobile sand banks, glacial till and soft clay. These types of sites require different types of foundation such as suction caisson multi-foundation structures (jacket structures) and suction caisson monopod structures (Figure 26). Jacket structures prove more economical for use when it is favorable to displace structural load only on surface sediments. These foundations contain perimeter ‘skirts’ embedded into the sea floor so that the effect of scour is mitigated. Overturning loads applied by the wind and waves in Jacket structures are resisted predominantly by equal and opposite vertical loads at foundation level. In this design, the foundations are likely embedded in sand where the response of the foundation to vertical loads is critical. For monopiles, the overturning load is applied directly to the single large foundation in the form of shear and moment; as opposed to traditional axial compression and tension loading methods. Additional variations of wind turbine foundations are likely under development; only the basic solid support foundation types are discussed here to provide representative examples.

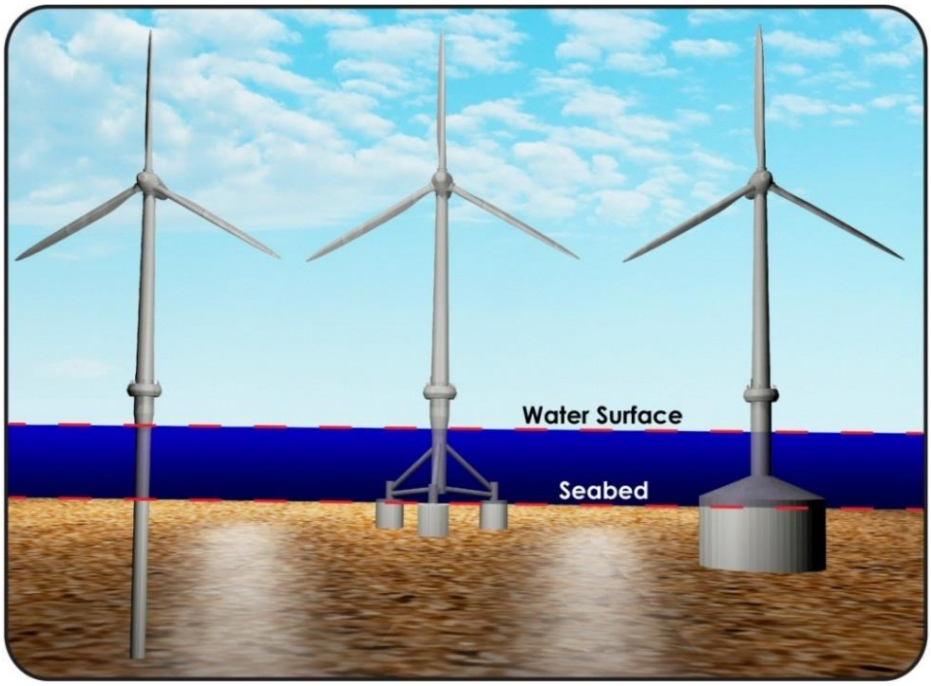

Figure 26. Solid support systems used for offshore wind applications: (a) monopile structure; (b) suction caisson multi-foundation structure; (c) a suction caisson monopod structure.

Gravity based foundations (GBFs) offer an alternative to pile and jacket structures. They are often most advantageous in shallow waters where pile-driving is not a feasible option. GBFs can be floated or towed to location and anchored in place, without the need to anchor into the seabed substructure. At the simplest level, they often consist of a larger, heavily weighted base resting on, or partially beneath the surface sediments. Figure 27 shows a sample GBF design.

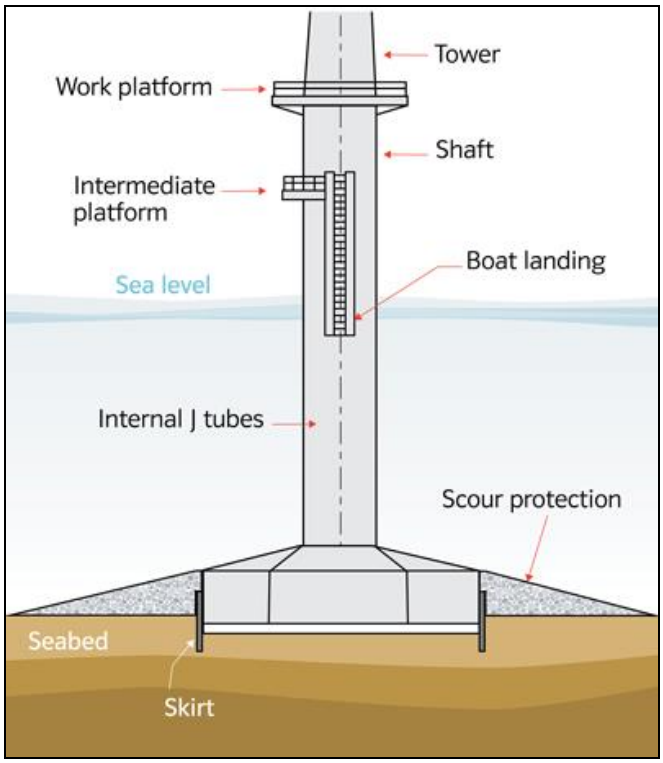

Figure 27. Example gravity based foundation (http://www.eon-uk.com).

5.1.4.2. Floating Systems

Floating wind turbines fall into two main categories: 1) tension leg mooring, and 2) Catenary mooring. Tension leg mooring systems have vertical tethers under tension providing large restoring moments in pitch and roll. The vertical tethers are taut and run relatively straight to the sea bed (Figure 28).The stabilizing tension in the tethers results from a heavy sea bed anchor on the seabed side, and a large buoyant force on the topside (floating platform). Catenary moorings, on the other hand, get their restoring force through the weight of the chain and steel shackles, and not necessarily line tension. The tether lines are not as taut as those seen in tension mooring systems, and often arc to the seabed. Catenary systems provide station-keeping yet provide little stiffness at low tensions. Higher tensions and ballasted catenaries can be used to increase the stiffness and stability of these types of systems.

Floating moored structures, primarily as a result of development in the oil and gas industry, have matured to allow installation in depths well over 1000 meters, permitting the development of offshore wind turbines in vast stretches of ocean. Installation and maintenance costs for these systems must strongly be considered for a viable project. The key design parameters of a floating wind turbine platform, whether tension or catenary moored, is the selection of the optimal combination of floater shape and size, ballast weight, and mooring attributes (angle and tension of mooring lines or chains). The goal is to keep the floater responses within acceptable bounds of pitch, roll, and heave, yet minimize construction and installation costs.

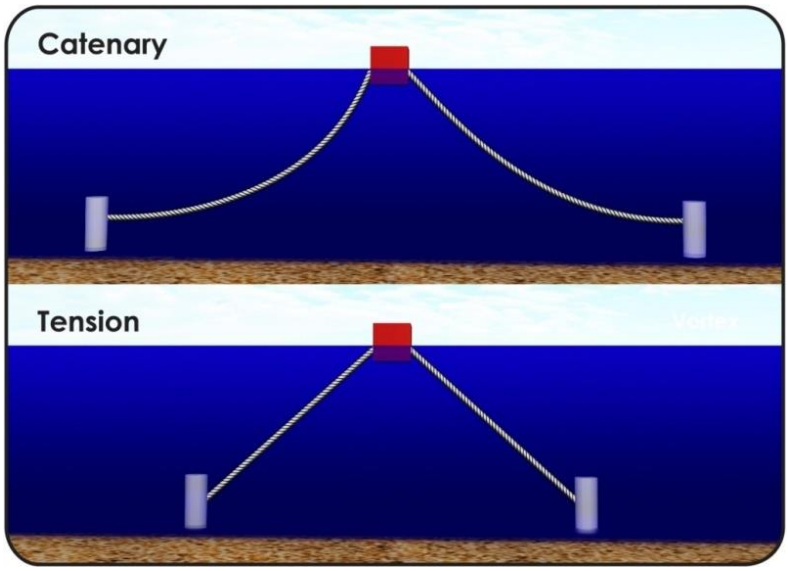

Figure 28. Top panel shows a general catenary moored platform where the tethers are arced. Bottom panel shows an exaggerated general tension leg moored platform where the tethers are drawn taut.

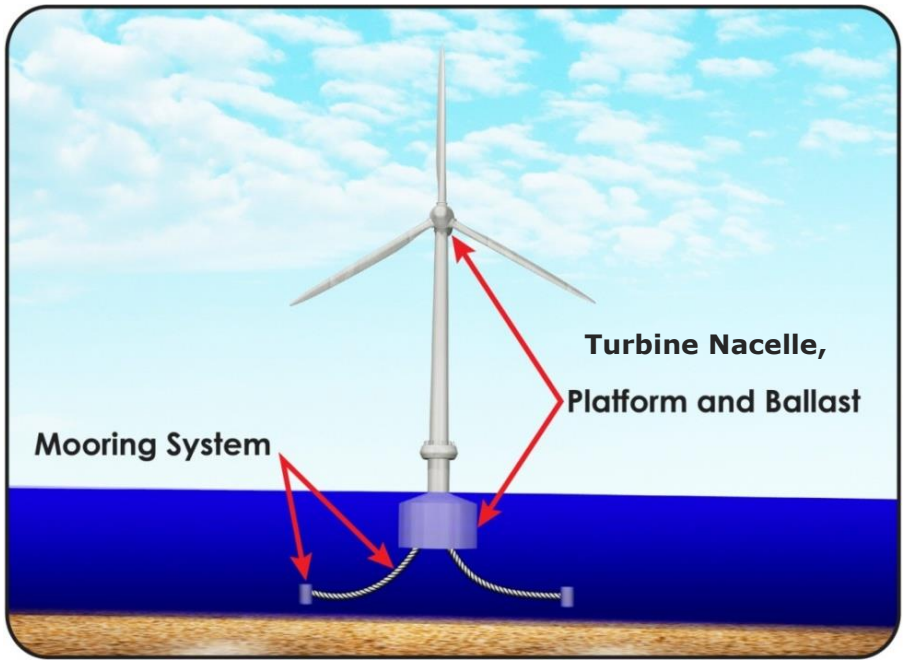

Figure 29. Pictorial representation of a moored floating wind turbine. The main components of the support system are the nacelle, platform, ballast and mooring system.

The support system of a floating wind turbine can be described by its main components: the nacelle, platform, ballast, and the mooring system (Figure 29). The platform geometry is defined by the barge radius and draft. It gives rise to the buoyancy force required for tension mooring systems, and provides the necessary connection and foundation for the turbine itself. The bottom

side of the platform is often weighted with a concrete ballasted steel cylinder to achieve static floatation stability in pitch and roll. The mooring system is defined by an anchor and the tether lines or chains that connect the platform to the anchor. Water depth, line tension and the angle between the free surface and the anchor line segment are key parameters in mooring design. Mooring systems often consist of grouped tethers that are evenly spaced around the platform to enhance stability.

5.2. Impact Assessment

Once developed, the CSM provides the launch pad for a thorough site analysis and environmental impact assessment of installing an offshore wind farm (or other obstructing structures) at a particular location. The following sections focus on specific considerations and methods for evaluating the seabed stability, and other environmental impacts, as a result of offshore wind installations, but can easily be applied to other alternative energy installations. They are organized to provide the reader with a representative sample of impact considerations such that a preliminary assessment of changes to the hydrodynamics and sediment transport patterns caused by the offshore wind farm can be completed. However, as previously mentioned, these may not be all-inclusive; and a thorough site-specific determination of important considerations should be made. Once general hydrodynamic and sediment dynamics changes are understood, the impact analyses can be iteratively focused on specific areas of concern for both the design (e.g. near-field, fine-scale scour development) and the environment (e.g. far-field sediment transport pattern changes and/or ecological changes). These final impacts can then be described and mitigated for in the wind farm planning and development phases.

5.2.1. Site Impacts

Once the CSM has been constructed to the satisfaction of site planners and managers, a site analysis can be completed which evaluates the baseline condition (existing scenario) with project development alternatives. The result should be a comparison of before and after hypothetical scenarios that project the potential positive and negative impacts to a site based on the alteration of site characteristics and physical processes. From the perspective of this guidance document, the two objectives of the site analysis should be:

- *Quantitatively evaluate the local coastal forcing mechanisms and response to installation of an offshore wind farm*
- *Quantitatively evaluate the local morphological reaction to installation of an offshore wind farm.*

These objectives and comparison can be addressed through analytical methods, physical modeling and/or numerical modeling. In the example in Appendix A, a numerical model example has been created to show utility of this option in completing an initial site analysis of before and after construction scenarios. It is a simple model created as a basic example of a potential site analysis. Reality may require more detailed investigations.

5.2.2. Environmental Impacts

Some common environmental concerns for offshore wind farms include noise production, avian/bat blade strike, visual pollution, altering aquatic habitat or spawning/migratory behavior, and interruption of anthropogenic activities. However, the focus of the present document is to identify and evaluate potential impacts to the water and the seabed (physical environment) as a result of wind farm installation. This information may then be used to support aquatic habitat studies, but that is beyond the scope of this document.

The previous discussion of scour highlights one of the primary impacts to be evaluated: the disturbance of marine benthic habitat. Where significant scour occurs or scour protection measures are implemented, the seabed will be disturbed or altered. The extent of the scour locally and globally, relative to ambient seabed movement, must be established so that benthic ecologists can be engaged to determine the potential risk to the local habitat. Structures installed on hard bottoms, while unlikely to generate scour, may alter the flows in the region enough to damage plant and animal life on the local bottom. Structures located on soft muddy bottoms may substantially alter the local bottom by scouring away valuable habitat; may negatively increase ambient water clarity/turbidity; or the local sediment may be sufficiently cohesive to prevent creation of any benthic impact. On the other hand, structures on mobile, sandy bottoms may cause cyclic transport at a rate and magnitude that renders additional local scour insignificant (i.e. nearby bedforms may move into and through local scour holes frequently, resulting in no net scour over time). The identification of the native seabed transport environment is essential to evaluating any of these potential scenarios in the context of the CSM.

Other considerations, such as interruption of local fish migratory or spawning behavior due to altered wave and current patterns must be evaluated by appropriate biological and marine mammal experts. The potential for altered hydrodynamics due to the presence of offshore wind structures should be incorporated into the biological assessment. Determining the magnitude of the biologic changes, again, beyond listing potential to cause physical disturbances, is beyond the scope of this document.

Offshore wind farms also have the potential to generate a number of far-field environmental effects such as large-scale circulation disruption and downstream wave energy propagation disturbance. Tidal circulation often dominates the currents on the continental shelf and plays an important role in the exchange of sediment and nutrients between the near-shore and offshore. Potential adverse environmental responses to alteration of these large-scale currents as a result of wind farm construction require consideration.

In addition, the incident wave field will likely be affected by the presence of large offshore wind arrays. While a single device may have a negligible effect on incoming waves, hundreds of devices may alter large-scale wave patterns. Wave energy will be reflected, dissipated or absorbed by surface obstructions, causing a decrease in wave energy in the immediate lee of the

obstructions. The extent and magnitude of the wave diffraction and shadowing is directly dependent upon incident wave conditions (e.g. wave directions, directional spreading of the wave spectra) and wind farm design parameters (e.g. size of individual obstructions, proximity of individual obstructions).

If a wave energy decrease in lee of offshore obstructions extends to the shoreline, the potential for shoreline erosion and general morphological change should be evaluated. In this scenario a wave height gradient will exist between the waves unaffected by the obstructions and those directly in lee of the obstruction. Larger wave heights will break further offshore while smaller wave heights will break nearer to shore. The resulting wave-driven currents in the near-shore have the potential to create "hot spots" of erosion and/or deposition, potentially causing coastal reaches to change from erosional to depositional (or vice a versa).

Generally shoreline erosion is viewed as a negative impact, due to the loss of real estate and tidal habitat, whereas shoreline accretion may be a positive impact of the wind farm array. These determinations, though, will need to be evaluated in terms of the site-specific impacts and interests. It is feasible that an offshore wind farm array may limit wave activity thereby reducing near-shore energy and causing shoreline accretion; however this effect may have a negative impact in terms of the sediment budget and natural littoral transport. One consequence, for example, may be starvation of downstream shoreline sediment.

Alterations to sediment transport processes may also affect the available nutrients, nutrient mixing, or the spatial extent of nutrient availability. In some coastal regions, minor alterations to water quality could have larger impacts to the local ecosystem. For example, a large array near an important coastal canyon may limit water up-welling or down-welling in the canyon, thereby affecting the normal nutrient cycling processes.

As with scour, the size of the hydrodynamic disturbance caused by an offshore wind farm array is proportional to the size of the area obstructing wave and current propagation. Additionally, fixed structures extending from the seabed to the water surface (e.g. monopiles) will have a greater disturbance than more porous structures (e.g. jacket foundations) or floating structures since they are obstructing more water column flow. Therefore, the potential for flow alteration (from waves and currents) must be included in the CSM.

As discussed, potential environmental impacts may arise from offshore wind farm installations that are caused by alterations to the natural hydrodynamic and sediment dynamic regime, and must be evaluated to the extent possible. Once the site physics have been characterized and quantified in the CSM, the objective is to relate the processes to environmental risks such as alteration of habitat, near-shore circulation, beach processes, water quality and general coastal zone management. The primary questions arising are:

1) What are the effects on the near-field sediment transport patterns, seabed dynamics, water quality, biology and ecology?
2) What are the effects on far-field sediment transport patterns, dynamics, water quality, biology and ecology?

5.2.3. Design Impacts

When the local environment has been characterized in the CSM and the ambient forcing mechanisms have been adequately described, a quantitative evaluation of seabed stability can be conducted in a manner similar to that described in Appendix A which provides an example for the setup and use of coastal hydrodynamic and sediment transport model. A primary objective is determination of the potential for local and global seabed instability and magnitude (breadth and depth) of each. Scour research has been ongoing for many years to support the safety and reliability of structures (e.g. bridges) placed in various types of water bodies (rivers, lakes, oceans, estuaries). Recent interest in offshore wind has spawned new research and guidance in scour related specifically to offshore wind structures (den Boon et al., 2004; CEFAS, 2008a, CEFAS, 2008b; Stahlmann and Schlurmann, 2010; Yang et al., 2010). The preceding sections described some basic methods and considerations for estimating scour depths and extents in various scenarios specific to offshore wind. The following sections detail specific considerations that should be evaluated when assessing design impacts of offshore wind structures.

The primary offshore wind farm design impact discussed in this guidance document is that due to nearby sediment transport. The individual wind turbine design is assumed to already consider oceanographic forcing considerations (e.g. wind, wave, and current effects) on structural stability, but also should consider additional loading effects if foundation scour occurs, for example. The objective herein, therefore, is to develop a general outline to evaluate the potential impacts of the coastal processes on the sub-aqueous offshore wind infrastructure design; these impacts primarily include foundation scour and pipeline / transmission line stability.

The overall wind farm design process may include:

1. Preliminary design
    a. A site assessment and selection based on approximate power needs and wind magnitudes.
    b. A general offshore wind farm array designed to meet power requirements and structural needs.
    c. A survivability design and assessment to withstand the local meteorological, oceanographic, and seabed conditions for the life of the project.
    d. A preliminary estimate of local scour that may influence initial designs.
2. Site specific analysis
    a. Gathering of existing site-specific data on meteorological, oceanographic, and geophysical conditions necessary to support the design.

   b. Collection of additional site-specific data, numerical and physical modeling to support design needs.
   c. An evaluation of the design with respect to seabed stability, anthropogenic activities, other environmental considerations, and impact mitigation.
3. Design Iterations
   a. Interim and/or full design for site specific conditions.
4. Construction
   a. Implementation of the offshore wind farm design on-site.
5. Operation and Maintenance
   a. Operation, maintenance and monitoring for wind farm stability and performance.
6. De-commissioning wind farm planning and implementation.

The assessment of seabed interactions with all facets of the offshore wind farm should be conducted during the preliminary design and site specific analysis phase. Consideration of seabed interactions, once identified and evaluated, can be utilized in design in one of two ways. The first is prevention, whereby the array location and layout will be modified to avoid undesirable seabed features at installation. The second is protection that involves specific design features (e.g. scour protection measures) to minimize or eliminate risk to the structure from seabed alteration processes.

The primary seabed risk to offshore wind infrastructure is seabed scour, which may occur in proximity to foundation/substation/anchorage structures, pipes and cable transmission lines, and any other ancillary infrastructure. Therefore, it is important to attempt to quantify fine-scale scouring that may occur around any of the subaqueous offshore wind infrastructure that obstructs flow. This should include an assessment of both local and global (live-bed) scour likelihood and extent, as applicable, in proximity to all susceptible offshore structural components.

Leading guidance agencies (CEFAS, 2004; DNV, 2011) as well as professional prudence dictate that the risk of scour around the foundation of an offshore wind structure shall be taken into account unless it can be demonstrated that the foundation soils will not be subject to scour for the expected range of water flow velocities.

Furthermore, the effect of scour shall be accounted for according to at least one of the following methods (DNV, 2011):

1) Scour protection placement immediately following foundation installation
2) Adequate design assuming all non scour-resistant materials are removed
3) Institute a monitoring and surveillance program and carry out remedial activities soon after the discovery of scour formation.

The rate of scouring is directly related to the magnitude of disturbances in the incident flow field as well as scour progression towards equilibrium. In other words, in a flow rate large enough to

cause scour, the scour rate will be initially high, and will decrease as the bed morphology approaches equilibrium with the flow disturbance.

5.2.4. Define and Assess Near-Field Effects

The following table gives a partial list of physical coastal processes that are induced or altered by offshore wind installations and the corresponding potential near-field environmental impacts that need to be addressed and/or mitigated. The list is not comprehensive and a site-specific list of effects will need to be generated for each project location.

Table 3. Near-field processes and effects.

Physical Coastal Process	Potential Near-Field Impact
Induced scour around offshore wind infrastructure	• Structural instability or failure • Unacceptable stiffness degradation • Benthic habitat disruption
Altered local seabed sediment mobility	• Benthic habitat disruption • Alteration of natural sediment transport patterns
Altered Wave propagation (i.e. wave height, direction, period, etc…)	• Disruption in fish/marine mammal behavior • Benthic habitat Disruption • Water quality degradation • Alteration of shoreline response {caused by alteration of wave driven flow and sediment circulation patterns}
Altered local circulation patterns	• Disruption in fish/marine mammal behavior • Benthic habitat Disruption • Water quality degradation • Alteration of shoreline response {caused by alteration of wave driven flow and sediment circulation patterns}

5.2.5. Define and Assess Far-Field Effects

The following Table gives a partial list of physical coastal processes that are induced or altered by offshore wind installations and the corresponding potential far-field environmental impacts. The list is not comprehensive and a site-specific list of effects will need to be generated for each project.

Table 4. Far-field processes and effects.

Process	Potential Impact
Altered regional seabed sediment mobility/morphology	Structural instability or failure Habitat Disruption
Altered shoreline erosional or depositional regions	Shoreline "hot spot" developments of erosion and/or deposition
Altered Wave propagation (i.e. wave height, direction, period, etc…)	• Disruption in fish/marine mammal behavior • Benthic habitat Disruption • Water quality degradation • Alteration of shoreline response {caused by alteration of wave driven flow and sediment circulation patterns}
Altered regional circulation patterns	• Disruption in fish/marine mammal behavior • Benthic habitat Disruption • Water quality degradation • Alteration of shoreline response {caused by alteration of wave driven flow and sediment circulation patterns}

5.3. Impact Assessment and Prioritization

With the key impacts defined, they must be assessed in more detail to assess the relevant concern level and likelihood of occurrence. The following procedure and questions can be iteratively approached so that a design may be developed that characterizes and addresses the impact.

- Is the potential impact important?

- Why is it important (large uncertainty/confidence bounds, data gaps, design concern, environmental harm)?
- What is the best way to address the impact (address data gaps, mitigation, and design alteration)?
- Address issue(s) of concern and iterate the CSM process.
- Continue feedback and iteration process until issues of concern are fully addressed or characterized to the satisfaction of site managers

Table 5 presents a sample matrix for impact evaluation. Every potential impact can be ranked with the information developed in the impact analysis. The probability of a given impact can be weighted with its potential effect to determine the priority it should take in further analysis and mitigation. For example, insignificant impacts only warrant further study if they will occur all of the time. It may be found in further analysis that these impacts will never present an environmental or design risk. The corollary is a major environmental (e.g. large scale destruction of habitat) or design impact (e. g. monopile failure) that would only occur during a rare storm. Though the expected frequency of occurrence may be very low, the consequential effect of this impact is considered high, meaning that it warrants further study and potential mitigation. In this way, all of the impacts can be cataloged and ranked for review by the entire offshore wind farm design and assessment team.

5.4. Monitoring Program

Once an offshore wind farm EIA has been approved and the project is progressing, a monitoring program must be established to validate (or disprove) the predicted impacts to a project site. The monitoring program must be hypothesis-driven with measureable outputs (CEFAS, 2004); thereby allowing for direct quantitative evaluation of project performance and environmental impact.

The monitoring program should begin by collecting a sufficient amount of baseline data (of ambient conditions) if none exists. Monitoring shall continue through the construction phase to assess environmental impacts during the wind farm installation. Subsequently, a program should be established post-construction to evaluate short- and long-term environmental impacts as a result of the existence of the wind farm. Finally, a monitoring program shall be implemented during and following the decommissioning stage to evaluate changes as a result of removal of the wind farm.

Table 5. Matrix to evaluate the relative importance of an impact.

Probability	Impact				
	Insiginificant (well within the normal phyisical dynamics)	Minor (small disruption in localphysicalprocesses, but little damage)	Moderate (sustained alteration requring continuous mitigation or	Major (impacts that severely damage environment or cause	Catastrophic (Full loss of wind farm, local environment is irrepairably
Certain (> 90%)	**High**	**High**	**Extreme**	**Extreme**	**Extreme**
Likely (50% to 90%)	**Moderate**	**High**	**High**	**Extreme**	**Extreme**
Moderate (10% to 50%)	**Low**	**Moderate**	**High**	**Extreme**	**Extreme**
Rare (<10%)	**Low**	**Low**	**Moderate**	**High**	**High**

The frequencies of measurements/sampling and the technologies utilized shall be determined based upon site-specific requirements and site location. In high energy environments, or areas subjected to environmental protection, for example, monitoring may be required more frequently, at least in the initial efforts. In another example, shoreline change measurements will not be necessary (or as frequently necessary) if the project is located far from shore and no shoreline impact is anticipated.

The key objectives of a monitoring program shall be to (a) compare the altered state of the hydrodynamics and sediment dynamics to the baseline state and (b) compare the measured changes to those predicted in the EIAs. As subsequent monitoring data are analyzed, they can be directly incorporated into the decision-making framework. Further, the knowledge gained from the data collection will streamline future offshore wind development efforts.

6. SUMMARY

In general, the preceding sections have served to describe the various forms of data that need to be researched, assembled, collected, analyzed and evaluated when developing a comprehensive oceanographic and sediment dynamics CSM for offshore wind development. To summarize the previous sections, the following outline describes the basic procedure that should be adopted when developing an offshore wind CSM; but, again, it should not be considered all-inclusive, as each site will have different considerations, stakeholders and issues of importance. In addition, Figure 30 illustrates the outlined procedure in a general flowchart form that can be used as a starting point in developing an offshore wind CSM and design impact assessment. Figure 31 is the example CSM flowchart from Section 1 that might be used specifically for offshore wind development.

1) **Site Description and Classification [Tier 1 Analysis]**
    a. Define the CSM boundaries
        i. *Littoral cells, other structures and boundaries*
        ii. *Sediment sinks, sources*
    b. Define the relevant physical processes
        i. *Winds (typical, extreme)*
        ii. *Waves (typical, extreme)*
        iii. *Currents (river flows, tidal flows, Coriolis effect)*
    c. Define the planned wind farm design parameters
        i. *Water depth*
        ii. *Size of individual units*
        iii. *Size of array of units*
        iv. *Proximity to shore*
    d. Define the scour and sediment mobility potential
        i. *Sediment size, cohesiveness*
        ii. *Near-bed shear stresses that may be present based on known currents*
    e. Define the environmental parameters to evaluate
        i. *Water quality*
        ii. *Biology/Ecology*
        iii. *Sediment transport potential*
        iv. *Erosion/Deposition at shoreline*
    f. Assemble all existing site-specific data
        i. *Bathymetry/Topography*
        ii. *Hydrodynamic data*
        iii. *Sediment Characteristics*
        iv. *Water Quality*
        v. *Aerial photographs*

vi. *Agency/stakeholder communications*
vii. *Personal communications*

g. Define the project objectives
h. Evaluate the project objectives in terms of the available data
i. Can the project objectives and questions be answered to an acceptable level of uncertainty with the existing information?
    i. *If yes, there is no need for additional data collection and analysis. The Impact Assessment can commence.*
    ii. *If no, define additional needs and proceed to Site Analysis [Tier 2].*

Site Description and Classification [Tier 2 Analysis]

j. Collect additional data if needed
    i. *Bathymetry/topography*
    ii. *Wave, current wind measurements*
    iii. *Sediment transport measurements*
    iv. *Water quality measurements*
    v. *Obtain marine/terrestrial development permits and/or plans*
k. Construct, validate and operate computer numerical model(s) if needed
    i. *Wave propagation models*
    ii. *Current models*
    iii. *Sediment transport models*
l. Construct, validate and operate physical model(s)
m. Evaluate newly collected data and model results in terms of the project objectives
n. Can the project objectives and questions be answered to an acceptable level of uncertainty with the existing information?
    i. *If yes, there is no need for additional data collection and analysis. The Impact Assessment can commence.*
    ii. *If no, define additional needs and proceed to Site Analysis [Tier 2] again.*

2) Impact Assessment [Full Evaluation]

a. Site Analysis
    i. *Quantitatively evaluate the local coastal forcing mechanisms and response to installation of an offshore wind farm*
    ii. *Quantitatively evaluate the local morphological reaction to installation of an offshore wind farm.*
        1. Does the analysis suggest that the planned offshore wind farm array could significantly alter wave propagation or coastal circulation?

2. Does the analysis suggest that the offshore wind farm array could significantly alter seabed shear stress and sediment transport?

b. Design and Environmental Impacts

i. *Estimate expected scour around foundations, pipes and cables*

ii. *Estimate all anticipated environmental effects such as alteration of sediment transport patterns and harmful changes to important aquatic habitat*

1. What is the potential for local and global seabed instability?
2. What are the large scale ongoing seabed changes?
3. What are the effects on the near-field seabed, hydrodynamics, water quality and ecology?
4. What are the effects on far-field transport patterns, hydrodynamics, shoreline change, water quality and ecology?
5. Define the small-scale sediment stability and risk of sediment motion
    a. *Foundation scour*
    b. *Pipe/cable scour*
6. Define the far-scale sediment stability and risk of sediment motion
    a. *Alteration of sediment transport patterns*
    b. *Alteration of natural littoral sediment transport*
    c. *Creation of erosional "hot spots" or new depositional areas*
7. *Investigate the effects on water quality of alterations to currents and sediment transport patterns*
8. *Investigate the effects on local ecology and benthic habitat of alterations to currents, water quality and sediment transport patterns.*

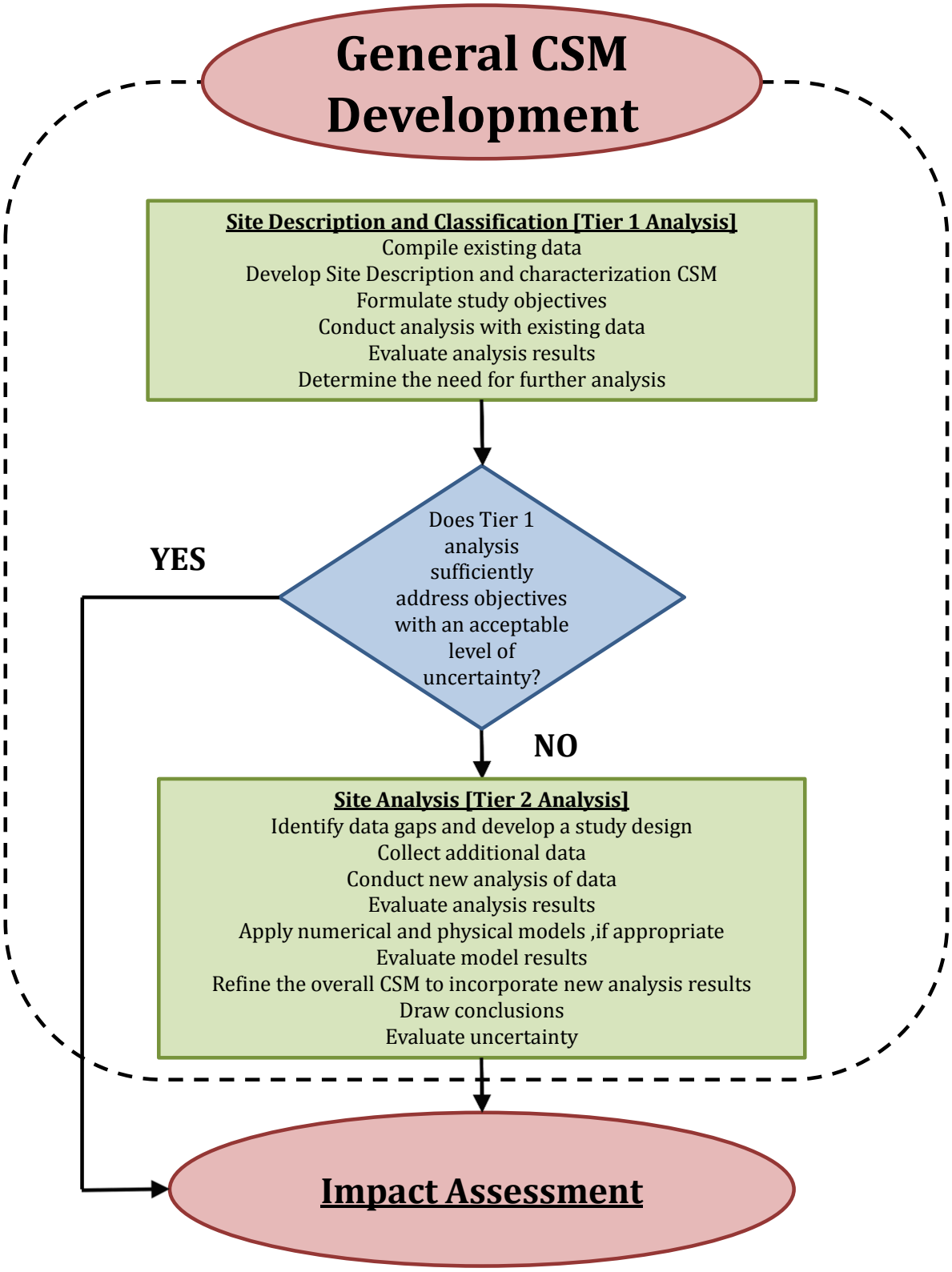

Figure 30. General CSM flowchart.

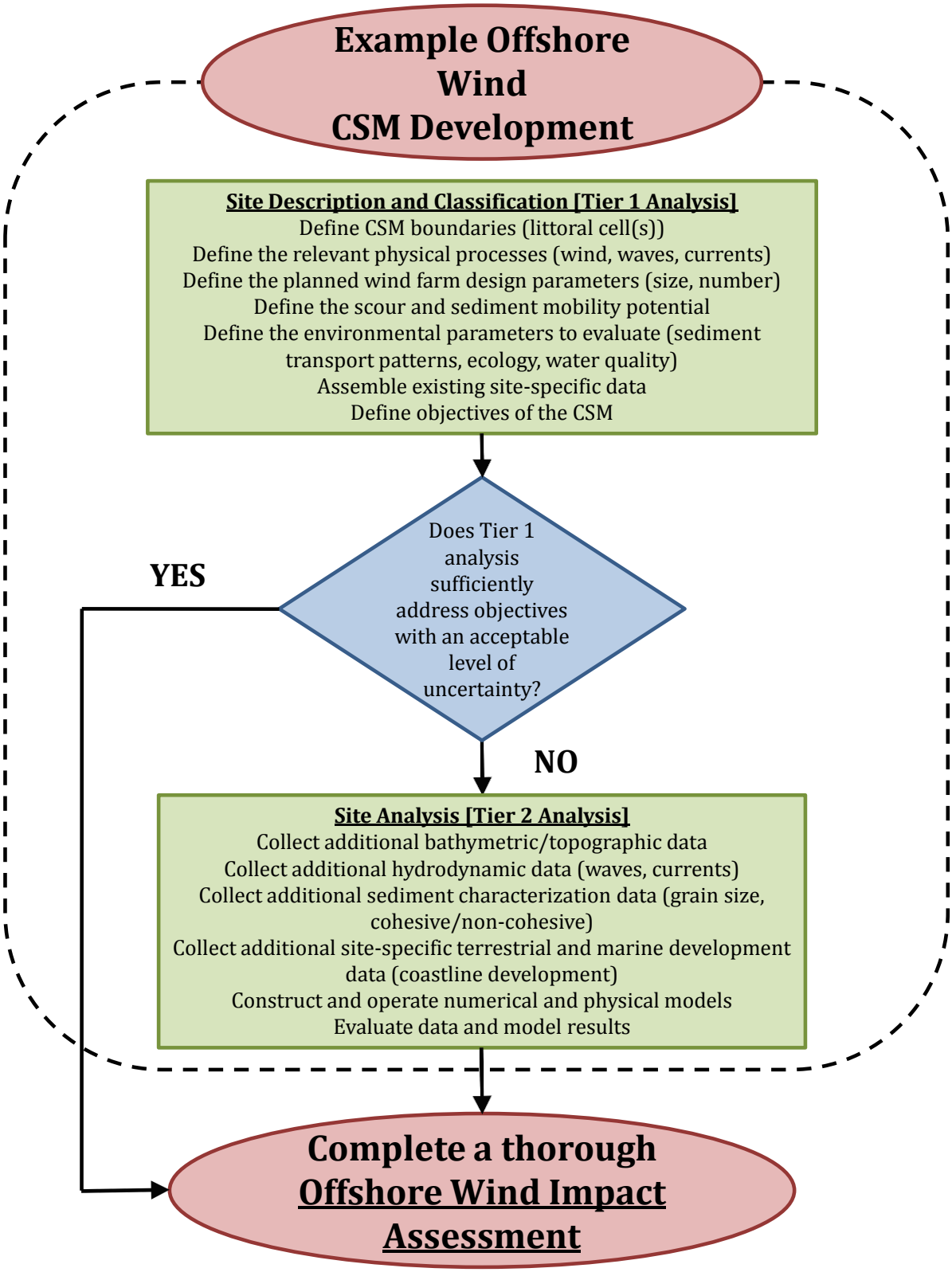

Figure 31. Offshore wind specific CSM flowchart example.

7. REFERENCES

1. Angus, N.M. and R. L. Moore. (1982). Scour repair methods in the Southern North Sea. Paper OTC 4410 in Proceedings 14th OTC Conference, 1982, pp. 385-389 plus 10 pages tables and figures.

2. ASCE Manual 54. 1975. "Sedimentation Engineering," Vito A. Vanoni, ed., ASCE Task Committee, American Society of Civil Engineers, New York.

3. Bijker, E. W. and W. Leeuwenstein. (1984). Interaction Between Pipelines and the Sea Bed under the Influence of Waves and Currents. Sea Bed Mechanics, Proc. IUTAM-IUGG Symposium, September. Ed: B. Denness, Graham and Trotman. London. pp 235-242.

4. Bijker, E. W. (1986). Scour Around Structures. Proc. 21st International Conference on Coastal Engineering. ASCE. pp. 1754-1768.

5. Biron, C.L. (2013). For First Time, U.S. to Lease Offshore Wind Blocks. www.ipsnews.net.

6. Black, K. (2010). Sediment Benthic Flume Device. http://www.partrac.com.

7. Black, S. (2013). Fair Winds for Offshore Wind Farms: Innovations in blades, turbines and foundations are helping spur growth in a very big way. www.compositesworld.com.

8. Blake, A.C., D.B. Chadwick, P.J. White and C.A. Jones. (2007). User's Guide for Assessing Sediment Transport at Navy Facilities. Technical Report 1960. September 2007.

9. Booij, N., Holthuijsen, L.H. and R.C. Ris, 1996, The SWAN wave model for shallow water, Proc. 25th Int. Conf. Coastal Engng., Orlando, USA, Vol. 1, pp. 668-676.

10. Briaud, J.L., Ting, F.C.K, Chen, H.C., Cao, Y, Han, S.W., 2001, Erosion function apparatus for scour rate predictions. Journal of Geotechnical and Geoenvironmental Engineering, ASCE Vol. 109(GT5): pp.105-113.

11. Bruessers, H.N.C. (1972). Local scour near offshore structures. Delft Hydraulics Publication 105, Delft.

12. Breusers H. N. C., G. Nicollet and H. W. Shen. (1977). Local Scour around Cylindrical Piles. J. Hydraulic Research. Vol. 15 (3). pp 211-252.

13. CEFAS. (2004). Guidance note for Environmental Impact: Assessment In Respect of FEPA and CPA Requirements. Version 2 – June 2004.

14. CEFAS (2008a). Review of Round 1 Sediment Monitoring Data – Lessons Learnt. Synthesis report and recommendations.

15. CEFAS (2008b). SED02 Seabed and Coastal Process Research, Dynamics of scour pits and scour protection. Synthesis report and recommendations (Milestones 2 and 3). EX 5588. R. 2.0.

16. Chabert, J. and P. Engeldinger. (1956). Etude des affouillements autour des piles des ponts. Laboratoire National d'Hydraulique, Chatou, France (in French).

17. Chang, G and C. Jones, D. Hansen, M. Twardowski and A.. Barnard. 2010. Prediction of Optical Variability in Dynamic Near-shore Environments: Task Completion Report #3 – Numerical Modeling and Verification. 28 pp (unpublished).

18. Cheng, N. S. 1997. "Simplified Settling Velocity Formula for Sediment Particles," *Journal of Hydraulic Engineering 123*(2): 149–152.

19. Chiew, Y. M. (1991). Flow Around Horizontal Circular Cylinder in Shallow Flows. Proc. American Society of Civil Engineers, J. Waterway, Port, Coastal and Ocean Engineering. Vol. 117 (2). pp. 120-135.

20. Christoffersen,J.B. and I. G. Jonsson. 1985. Bed friction and dissipation in a combined current and wave motion. Ocean Engineering. Volume 12, Issue 5, 1985, Pages 387-423.

21. Clukey, E., K. Israel, C. Jones and C.K. Ziegler. (2007). Pipeline Risk Assessment in Deep-Sea Furrow Regions. Offshore Technology Conference. Houston Texas, 2007.

22. Coastal Engineering Manual, CEM (2002). U.S. Army Corps of Engineers, Coastal and Hydraulics Laboratory.

23. Dahlberg, R. (1981). Observation of scour around offshore structures. Symposium of Geotechnical Aspects of Coastal and Offshore Structures. Bangkok, 159-172, December.

24. De Bruyn, C. A. 1988. Scour near platform pier due to current and breaking waves,(in Dutch), *Dept. of Coastal Eng.*, Delft Univ. Technology, Deft, The Netherlands.

25. den Boon, H., Sutherland, J., Whitehouse, R., Soulsby, R., Stam, C-J., Verhoeven, K., Høgedal, M. and Hald, T. (2004). Scour Behaviour and scour protection for monopile foundations of offshore wind turbines. Proceedings of the European Wind Energy Conference.

26. Det Norske Veritas AS, DNV (2010). On-Bottom Stability Design of Submarine Pipelines. Recommended Practice. DNV-RP-F109.

27. Det Norske Veritas AS, DNV (2011). Design of Offshore Wind Turbine Structures. Offshore standard. DNV-OS-J101.

28. DOE. (2012). Strengthening America's Energy Security with Offshore Wind (Brochure). DOE Wind and Water Power Program.

29. DTI. (2005a). Guidance on the Assessment of the Impact of Offshore Wind Farms. Seascape and Visual Impact Report: Guidance for Offshore Wind Farm Developers.

30. DTI. (2005b). Guidance on the Assessment of the Impact of Offshore Wind Farms. Methodology for Assessing the Marine Navigational Safety Risks of Offshore Wind Farms.

31. EC. (2009). Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009.

32. Ehler, Charles, and Fanny Douvere. Marine Spatial Planning: a step-by-step approach toward ecosystem-based management. Intergovernmental Oceanographic Commission and Man and the Biosphere Programme. IOC Manual and Guides No. 53, ICAM Dossier No. 6. Paris: UNESCO. 2009 (English).

33. Ettema, R. (1990). Design Method for Local Scour at Bridge Piers. Proc. American Society of Civil Engineers, J. Hydraulic Engineering. Vol 116 (10). pp 1290-1292.

34. EWEA. (2013). The European offshore wind industry – key trends and statistics 2012. A report by the European Wind Energy Association. January 2013.

35. Fredsoe, J., B. M. Sumer and M. M. Arnskov. (1992). Time scale for wave/current scour below pipelines. Int. Journal of Offshore Polar Engineering. Vol. 2 (1). pp. 13-17.

36. Goreham, S. (2013). Offshore Wind: The enormously expensive energy alternative. http://communities.washingtonpost.com.

37. Grant, W. D. and O.S. Madsen. 1979. "Combined Wave and Current Interaction with a Rough Bottom," *Journal of Geophysical Research 84*(C4): 1797–1808.

38. Grass, A. J. and A. Hosseinzadeh-Dalir. (1995). A simple theoretical model for estimating maximum scour depth under sea bed pipelines. Proc. HYDRA 2000. Vol. 3 XXVIth IAHR Congress. London, Thomas Telford. pp . 281-287.

39. Hamrick, J. M. (1992). A Three-Dimensional Environmental Fluid Dynamics Computer Code: Theoretical and Computational Aspects *Virginia Institute of Marine Science* (pp. 63): The College of William and Mary.

40. Hamrick, J. M. (2007a). The Environmental Fluid Dynamics Code: Theory and Computation. In I. Tetra Tech (Ed.), (Vol. 1-3). Fairfax, VA: US EPA.

41. Hamrick, J. M. (2007b). The Environmental Fluid Dynamics Code: User Manual. In I. Tetra Tech (Ed.). Fairfax, VA: US EPA.

42. Hebsgaard, M., F. Ennemark, S. Spangenberg, J. Fredsoe and H. Gravesen (1994). Scour Model tests with bridge piers. PIANC bulletin, 82, 84-92.

43. Hirai, S. and K. Kurata. (1982). Scour around multiple- and submerged circular cylinders. Memoirs Faculty of Engineering. Osaka City Univ., 23, 183-190.

44. Hoffmans, G. J.M.C. and H.J. Verheij (1997). Scour Manual. Balkema, Rotterdam.

45. HR Wallingford. (1972). Field Tests on the Behaviour of Pipes when Laid on the Sea Bed and Subjected to Tidal Currents. HR Wallingford Report INT 113 (internal).

46. Inman, D.L. and J.D. Frautschy (1966). Littoral Processes and the Development of Shorelines. Proceedings of the Coastal Engineering Specialty Conference, Santa Barbara, CA: American Soc. Civil Engineers, pp 511-536.

47. Jepsen, R., J. Roberts, and W. Lick. (1997) Effects of bulk density on sediment erosion rates, Water, Air and Soil Pollution, 99:21-31.

48. Jepsen, R., J.D. Roberts, J.Z. Gailani and S. J. Smith. (2002). The SEAWOLF Flume: Sediment Erosion Actuated by Wave Oscillations and Linear Flow. Prepared by Sandia National Laboratories. January 2002.

49. Katsui, H. and T. Toue. (1992). Bottom Shear stress in coexistent field of superimposed waves and current and scouring around a large-scale circular cylinder. Coastal Engineering in Japan, 35, (1), 93-110.

50. Kjeldsen, S.P., O. Gjorsvik and K.G. Bringaker (1974). Experiments with local scour around submarine pipelines in a uniform current. Rover and Harbour Laboratory, Technical University of Norway, Trondheim, VHL/SINTEF Report STF60 A730085.

51. Komar, P.D. (1998). Beach Processes and Sedimentation. Prentice Hall, Upper Saddle River, NJ. 544 pgs.

52. Komen, G.J., L. Cavaleri, M. Donelan, K. Hasselman, S. Hasselman, and P.A.E.M. Janssen (1994) Dynamics and Modeling of Ocean Waves, Cambridge University Press, New York, 532 pp.

53. Kroezen, M., P. Vellinga, J. Lindenburg and A. M. Burger. (1982). Geotechnical and Hydraulic Aspects with Regard to Sea Bed and Slope Stability. Delft Hydraulics Laboratory. Publication 272. Delft.

54. Krone, R. B. 1962. "Flume Studies of the Transport of Sediment in Estuarial Shoaling Processes."

55. Final Report to San Francisco District, U.S. Army Corps of Engineers, Washington, DC.

56. Lambkin, D.O, J.M. Harris, W.S. Cooper and T. Coates. (2009). Coastal Process Modeling for Offshore Wind Farm Environmental Impact Assessment: Best Practice Guide. COWRIE, Ltd.

57. Langhorne, D. N. (1980). A Preliminary Study of the Haisborough Sand Sandwave Field and its Relevance to Submarine Pipelines. Institute of Oceanographic Sciences Report 100.

58. Laursen, E.M. and A. Toch. (1956). Scour around bridge piers and abutments. Bulletin No. 4, Iowa Highway Research Board, Ames, Iowa.

59. Lucassen, R. J. (1984). Scour underneath submarine pipelines. MSc thesis, Department Civil Engineering, Delft University of Technology.

60. Mann, K. (1991). Sedimentation at Jetties. HR Wallingford Special Report SR 285.

61. Mao, Y. (1986). The Interaction Between a Pipeline and Erodible Bed. Inst. Hydrodynamics and Hydraulic Engineering. Technical University of Denmark. Series Paper 39, March.

62. May, R.P. and I. R. Willoughby (1990). Local Scour around large obstructions. HR Wallingford Report SR 240.

63. McNeil, J., C. Taylor, and W. Lick, 1996, Measurements of erosion of undisturbed bottom sediments with depth, J. Hydr. Engr., 122(6):316-324.

64. Mehta, A. J., E. Hayter, W. Parker, R. Krone, and A. Teeter. 1989. “Cohesive Sediment Transport, I: Process Description,” *Journal of Hydraulic Engineering 115*(80): 1076–1092.

65. Mehta, A. J. and W. H. McAnally. 1998. “Fine-Grained Cohesive Sediment Transport.” In *Sedimentation Engineering American Society of Civil Engineers Manual 54, Volume 2*, American Society of Civil Engineers, New York, NY.

66. Mellor, G. L. and T. Yamada. 1982. “Development of a Turbulence Closure Model for Geophysical Fluid Problems,” *Reviews of Geophysics and Space Physics 20*: 851–875.

67. Melville, B.W. and A.J. Sutherland. (1988). Design methods for local scour at bridge piers. J. Hydraulic Engineering, ASCE, Vol. 114, No. 10. p: 1210-1226.

68. O’Riordan, N.J. and D.G. Clare (1990). Geotechnical considerations for the installation of gravity base structures. Paper OTC 6381, 22nd Offshore Technology Conference, Houston, 309-216, May.

69. Rance, P.J. (1980). The potential for scour around large objects. Scour Ptevention Techniques around Offshore Structures. Proceedings of a one-day seminar, 16 December 1980, Society for Underwater Technology, London. pp 41-53.

70. Reid, J. A., J. M. Reid, M. Zimmermann, C. J. Jenkins, S. J. Williams and M. E. Field. 2006. usSEABED: Pacific Coast Offshore Surficial-Sediment Data Release, version 1. U.S. Geological Survey Data Series 182. 62 pp.

71. Roberts, J. and Jepsen, R., 2001, Separation of bedload and suspended load with modified high shear stress flume. SAND2001–2162. Sandia National Laboratories, Albuquerque, NM, 87185.

72. Roberts, J., R. Jepsen, D. Gotthard, and W. Lick, 1998, Effects of particle size and bulk density on erosion of quartz particles, J. Hydr. Engr., 124(12):1261 - 1267.

73. Roberts, J., Jepsen, R., and James, S. (2003). ”Measurements of Sediment Erosion and Transport with the Adjustable Shear Stress Erosion and Transport Flume.” *J. Hydraul. Eng.*, 129(11), 862–871.

74. Rouse, H. 1938. “Experiments on the Mechanics of Sediment Suspension.” Reprint from *Proceedings of the Fifth International Congress for Applied Mechanics* (pp. 550–554). 12–16 September, Harvard University and the Massachusetts Institute of Technology, Cambridge, Massachusetts.

75. Rutgers. (2011) Ex-situ Erosion Testing Machine. University of Rutgers Center for Advanced Infrastructure and Testing.

76. Shields, A. (1936). Anwendung der Ahnlichkeits-Mechanik und der Turbulenz-forschung auf die Geschiebebewegung. Preussische Versuchanstalt fur Wasserbau und Schiffbau, vol. 26, Berlin.

77. Soulsby, R. (1997). Dynamics of Marine Sands: A manual for practical applications. HR Wallingford.

78. Stahlmann, A. and T. Schlurmann. (2010) Physical Modeling of Scour around Tripod Foundation Structures for Offshore Wind Energy Converters. Coastal Engineering Proceedings No. 32.

79. Staub, C. and R. Bijker. (1990). Dynamic numerical models for sandwaves and pipeline selfburial. Proc. 22nd International Conference on Coastal Engineering. Delft. pp. 2508-2521.

80. Sumer, B. M., N. Christiansen, and J. Fredsoe (1992). Time scale of scour around a vertical pile. Proceedings of the 2nd International Offshore and Polar Engineering Conference, ISOPE, San Francisco, Vol. 3, 308-315.

81. Sumer, B. M., N. Christiansen and J. Fredsoe. (1993) Influence of Cross Section on Wave Scour Around Piles. Proc. American Society of Civil Engineers, J. Waterway, Port, Coastal and Ocean Engineering. Vol. 119 (5). pp. 477-495.

82. Sumer, B. M. and J. Fredsoe. (1990). Scour Below a Pipeline in Waves. Proc. American Society of Civil Engineers, J. Waterway, Ports, Coastal and Ocean Engineering. Vol. 116 (3). pp. 307-322.

83. Sumer, B. M. and J. Fredsoe. (1991). Onset of Scour below a Pipeline Exposed to Waves. Proc. 1st International Offshore and Polar Engineering Conference. pp 290-295.

84. Sumer, B. M., J. Fredsoe and N. Christiansen. (1992). Scour Around Vertical Pile in Waves. Proc. American Society of Civil Engineers, J. Waterway, Port, Coastal and Ocean Engineering. Vol. 118 (1). pp 15-31.

85. Sumer, B. M. and J. Fredsoe. (2002). The Mechanics of Scour in the Marine Environment. World Scientific, Advances Series on Ocean Engineering – Vol 17.

86. Tison, L.J. (1940). Erosion autour des piles de ponts en riviere. Annales des Travaux Publics de Belgique, vol. 41, No. 6. P: 813-817 (in French).

87. Torsethaugen, K. (1975). Lokalerosjonved store konstruksjoner. Modellforsok. SINTEF Report STF60 A75055. Norwegian Hydrotechnical Laboratory, Trondheim (in Norwegian).

88. Trabish, H. (2013). US Offshore Wind Fact Sheet. www.greentechmedia.com.

89. Venkatadri, C., G.M. Rao, S.T. Hussain and K.C. Asthana. (1965). Scour around bridge piers and abutments. Irrig. Power, Jan 35-42.

90. Vittal, N., U.C. Kothyari and M. Haghighat. (1994). Clear-water Scour Around Bridge Pier Group. Proc. American Society of Civil Engineers, J. Hydraulic Engineering. Vol. 120 (11). pp 1309-1318.

91. Wald, M. (2013). A Floating Wind Tower is Launched in Maine. www.NYTimes.com.

92. Watson, C.B. (1979). Scour in the North Sea. Journal Petroleum Technology, 26, (3).

93. Whitehouse, R. (1998). Scour at Marine Structures; a Manual for Practical Applications. HR Wallingford Ltd and Thomas Telford Publications. London. 198 pp.

94. Yang, R-Y, H-H Chen, H-H Hwung, W-P Jiang and N-T Wu. (2010). Experimental Study on the Loading and Scour of the Jacket Type Offshore Wind Turbine Structure. Coastal Engineering Proceedings, No 32.

APPENDIX A: EXAMPLE COASTAL HYDRODYNAMICS AND SEDIMENT DYNAMICS MODEL

An example model from the Monterey Bay and Santa Cruz, CA, coastline is used here to illustrate the utility of combining the SWAN wave propagation and EFDC circulation/transport models to predict near-shore sediment stability in the presence of an offshore wind array. A coarse-grid regional wave model of Monterey Bay was established (domain shown in Figure 32) within which a finer resolution grid model was nested to assess near-shore impacts in proximity to Santa Cruz. The overall modeling approach described herein has the following limitations:

- It is a simplification of a turbulent, chaotic, near-shore process.
- Coriolis forces, salinity and temperature gradients are not included at the offshore boundaries. In other words, large scale (e.g. CSM scale, regional scale, scales larger than the littoral cell) ocean circulation is not incorporated into the near-shore region.
- Measurements of currents were only available at near-shore locations for model validation.

Even though the above limitations are considered when assessing the results, this methodology produces reasonable estimates of transport when forced with the dominant near-shore processes in the region (i.e. wind, waves and tides).

A.1. Models

The SWAN wave propagation model is a non-stationary (non-steady state) third generation wave model, based on the discrete spectral action balance equation and is fully spectral (over the total range of wave frequencies). Wave propagation is based on linear wave theory, including the effect of wave generated currents. The processes of wind generation, dissipation, and nonlinear wave-wave interactions are represented explicitly with state-of-the-science, third-generation formulations. Model boundary conditions can be explicitly specified by the user or may be obtained from nested, larger-domain modeling efforts (either a larger SWAN domain, or other, global models such as WaveWatch III). SWAN allows for numerous output quantities including two dimensional (frequency and direction) spectra, significant wave height, mean wave period, mean wave direction and bottom orbital velocities (due to wave oscillations). The SWAN model has been successfully validated and verified in laboratory and complex field cases worldwide.

The hydrodynamic model, EFDC (Environmental Fluid Dynamics Code), is an US EPA approved, state-of-the-art, three dimensional hydrodynamic model developed at the Virginia Institute of Marine Science by John Hamrick (1992) to simulate hydrodynamics and water quality in rivers, lakes, estuaries, and coastal regions. The EPA describes the model as “one of

the most widely used and technically defensible hydrodynamic models in the world." This model has the following capabilities and features:

- The model is 3-dimensional, which allows for the simulation of variations in current structure in the vertical as well as horizontal.
- It allows input of near-shore wave radiation stresses and wave energy dissipation for simulation of surf zone circulation and transport.
- The model allows incorporation of complex bathymetry.
- The model allows input of time varying flows, winds, water levels, and discharges.

To accurately model the transport of particles in the coastal environment, it is critical to describe both the transport and the bottom shear stress. EFDC handles advective transport using the modeled water column velocities. These velocities are computed from tidal forces, wave forces, and wind.

EFDC uses the Smagorinsky (1963) method to calculate the horizontal diffusivity. The magnitude of the diffusivity in the model is proportional to the horizontal current shear. The dissipation of wave energy can be calculated in the SWAN wave model and used as an input to EFDC. The wave dissipation then acts as another source of turbulence and can be added to the K_H determined from the currents in the Smagorinsky model.

EFDC implements the Mellor and Yamada (1982) second moment turbulence closure model in the vertical orientation. The model, as implemented in EFDC, has been improved and further validated by Galperin et al. (1988). Once the vertical diffusivity has been calculated through the Mellor and Yamada and Galperin model, the wave dissipation from the SWAN model is added in as a source of turbulence. The wave and current generated bottom shear stresses can then be calculated using the Christoffersen and Jonsson (1985) formulation.

A.2. Setup and Validation

The first phase of any modeling analysis is to verify that the model is functioning correctly and also reasonably simulating the natural processes occurring at the site. To ensure that the model closely simulated currents in the project area, measured wave and current data were compared with modeled values. The SWAN results were validated with nearby NOAA NDBC buoy wave data (Figure 33). Output wave conditions from the SWAN model were incorporated into the EFDC model and measured tide and winds were applied to the EFDC domain. The EFDC results were validated with near-shore measured current velocities (Figure 34).

Figure 35 illustrates the peak wave heights simulated within the near-shore Santa Cruz EFDC model.

Figure 36 shows an expanded view of the modeled wave heights with superposed velocity vectors from the study area. These results indicate along shore velocities propagating to the east and are consistent with previously conducted drifter observations and ADCP measurements collected during a field measurement period (Chang et al., 2010). The combined wave and current shear stresses and velocities derived from the coupled SWAN/EFDC model provide the fundamental physical parameters for assessing both environmental and design impacts of an offshore wind farm deployed in this region.

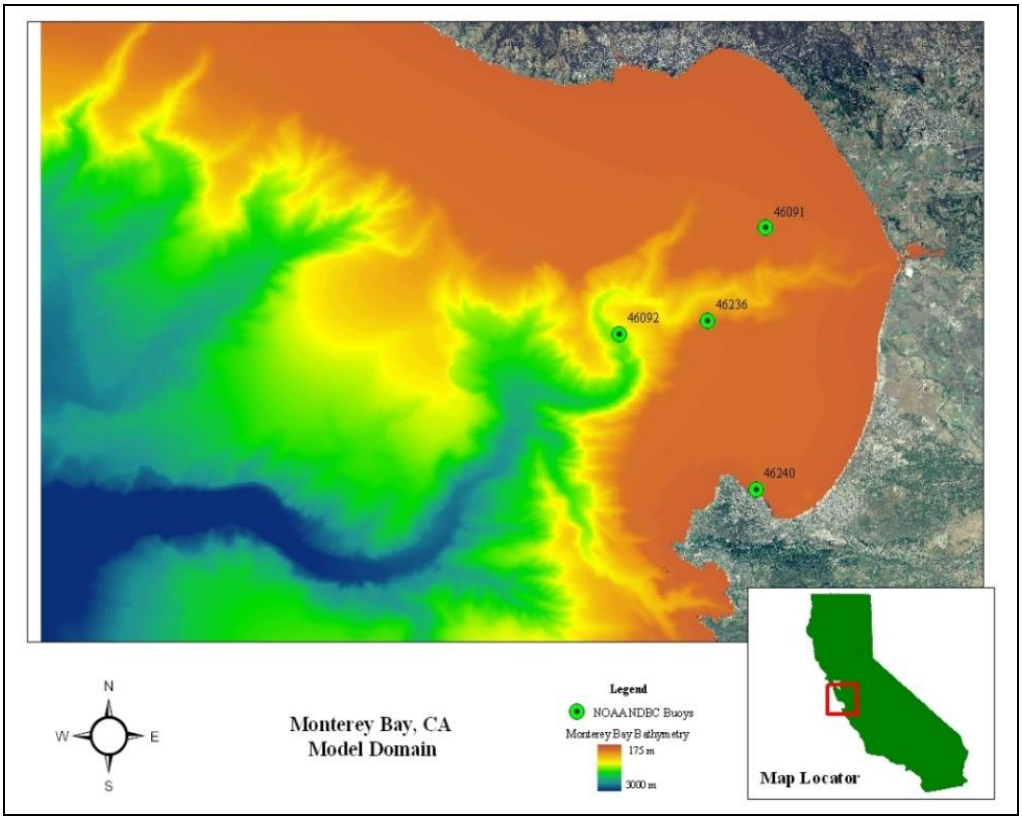

Figure 32.Monterey Bay model domain and bathymetry. NOAA NDBC buoys used for model validation are shown in green.

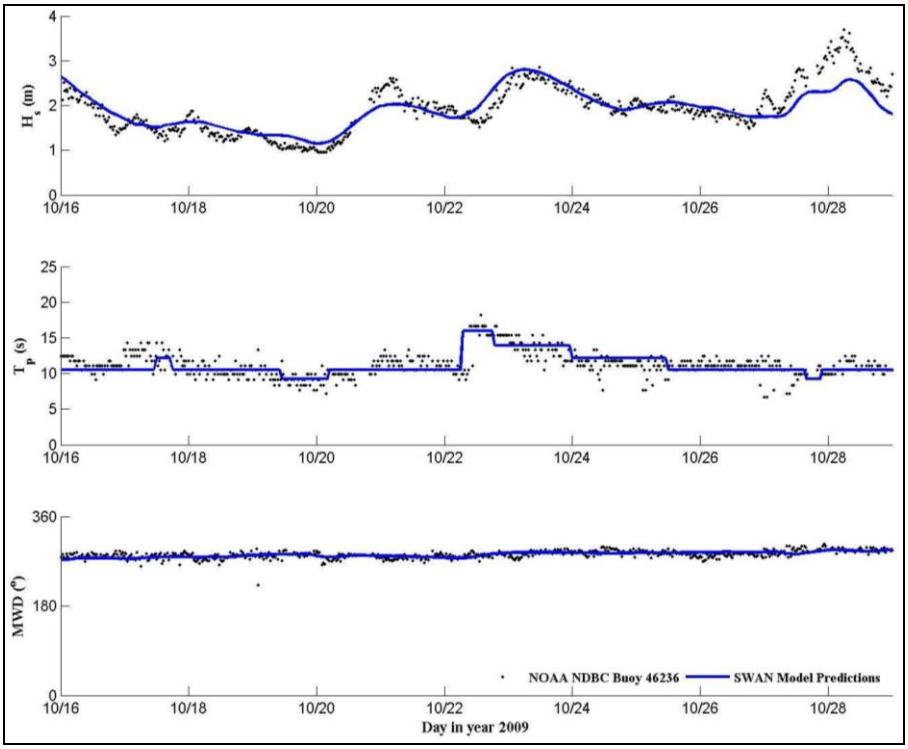

Figure 33.Model (line) representing the wave height (Hs), peak wave period (Tp) and mean wave direction (MWD) obtained from the Monterey Bay SWAN model. Measured data (dots) were obtained from the NOAA NDBC buoy 46236 in Monterey Bay.

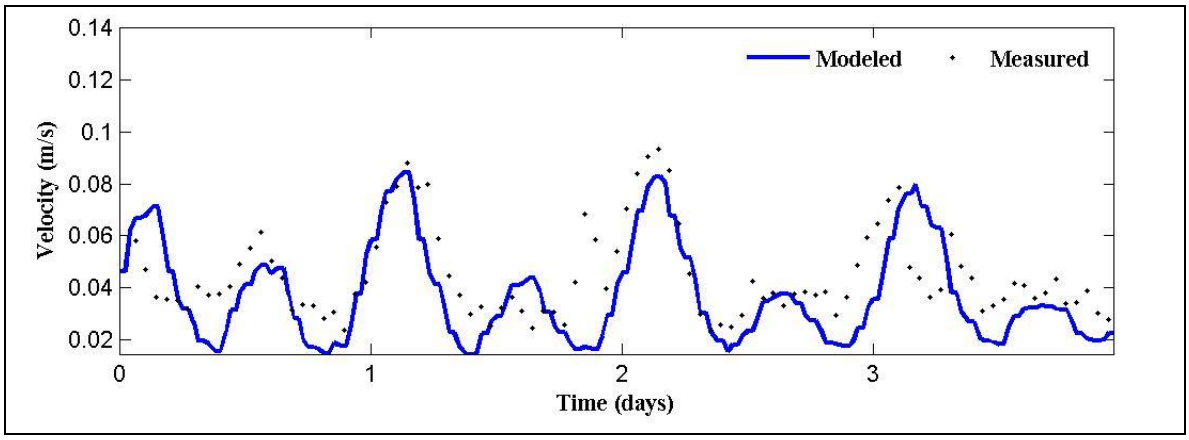

Figure 34. Model (line) representing the current magnitude obtained from the nearshore Santa Cruz EFDC model. Measured data (dots) were obtained from a Teledyne RDI ADCP deployed during the field study.

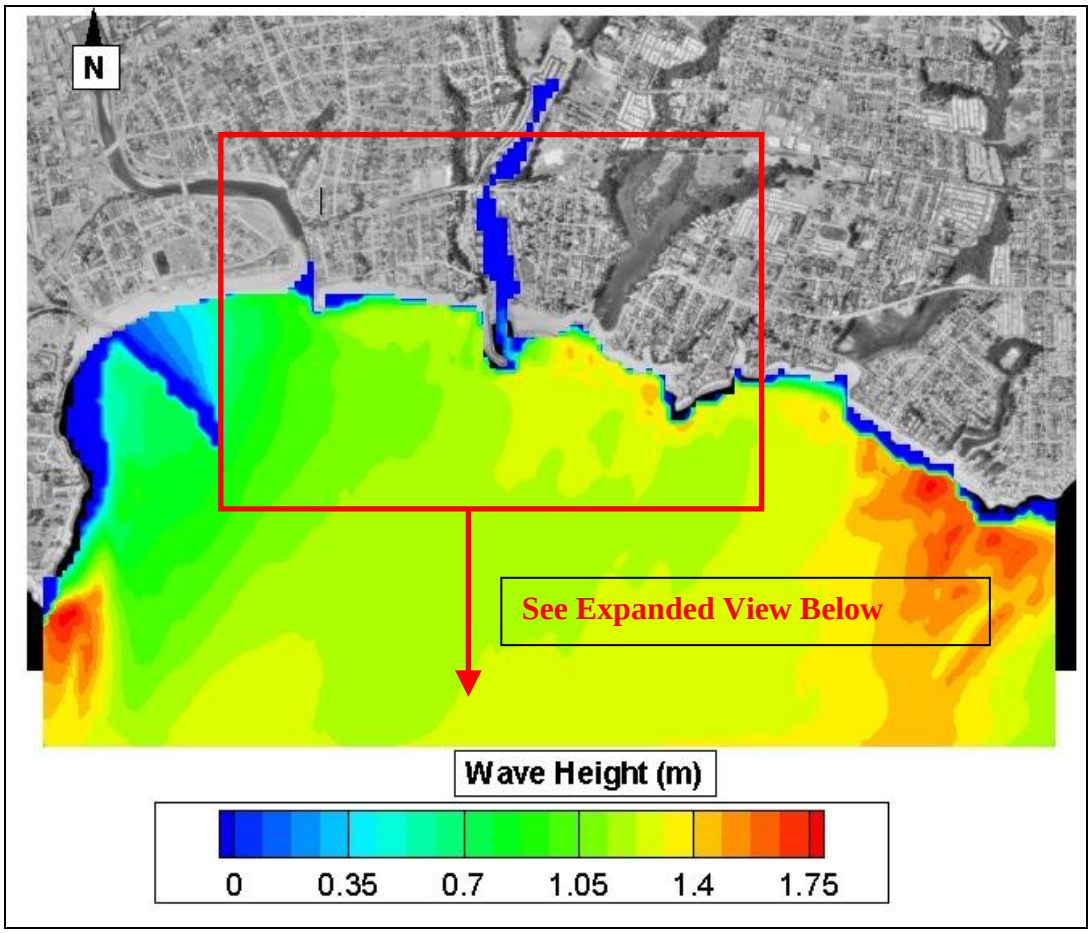

Figure 35. Peak wave heights modeled using SWAN in the Santa Cruz, CA region. Area of interest highlighted by red outline.

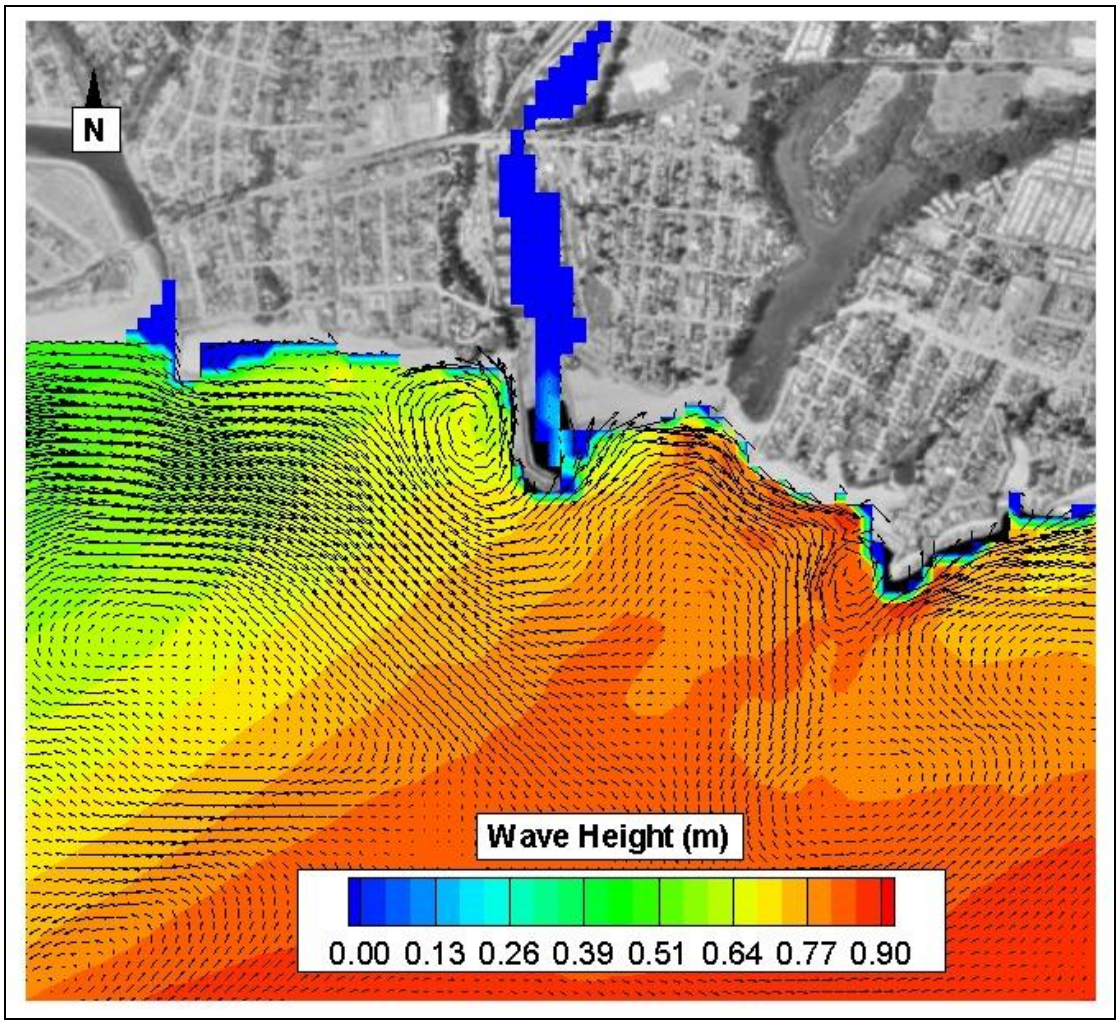

Figure 36.Peak wave heights and velocity vectors in the model domain. Expanded view of the above region.

A.3. Simulating Offshore Wind Devices

For the example modeling effort, individual support structures for a 200-turbine wind farm were simulated in the SWAN model, centered on 40 meter water depths. For this model each device was simply considered a monopole structure with a 10 meter diameter. Devices were spaced at 50 meters, center to center (i.e. 30 meter separation from device to device). *It is acknowledged that these water depths and dimensions may be in disagreement with some design standards. This geometry and location was selected for example purposes, to show functionality of the model. This methodology, device size, spacing, layout and location can be customized for any planned installation configuration.*

The SWAN model allows for multiple methods of obstructing wave energy; for this effort, offshore wind turbines were simulated as discrete obstructions to the propagating wave energy. A coefficient of reflection and transmission were specified, which dictated the percentage of

wave energy that was allowed to be reflected and propagated past the obstructions. To simulate an extreme scenario, wave energy was not reflected and was completely blocked from transmission at each obstacle. In essence, all wave energy was absorbed by the obstructions creating an obvious gradient in wave energy in lee. Specifying wave energy blockage in this manner is a relatively simple specification using existing SWAN functionality and capability.

The locations of the wind turbines defined in the model are illustrated in Figure 37. The wave heights predicted by the model both before and after offshore wind installation are shown in Figure 38. The most notable effect of the inclusion of a large 200-turbine array is that wave heights are substantially reduced in lee of the structures. This is due to the simulated absorption and of wave energy by the simulated foundations. The change in wave patterns as a result of the obstructions can be incorporated into the sediment transport assessment to examine both near- and far-field effects due to the presence of an offshore wind farm.

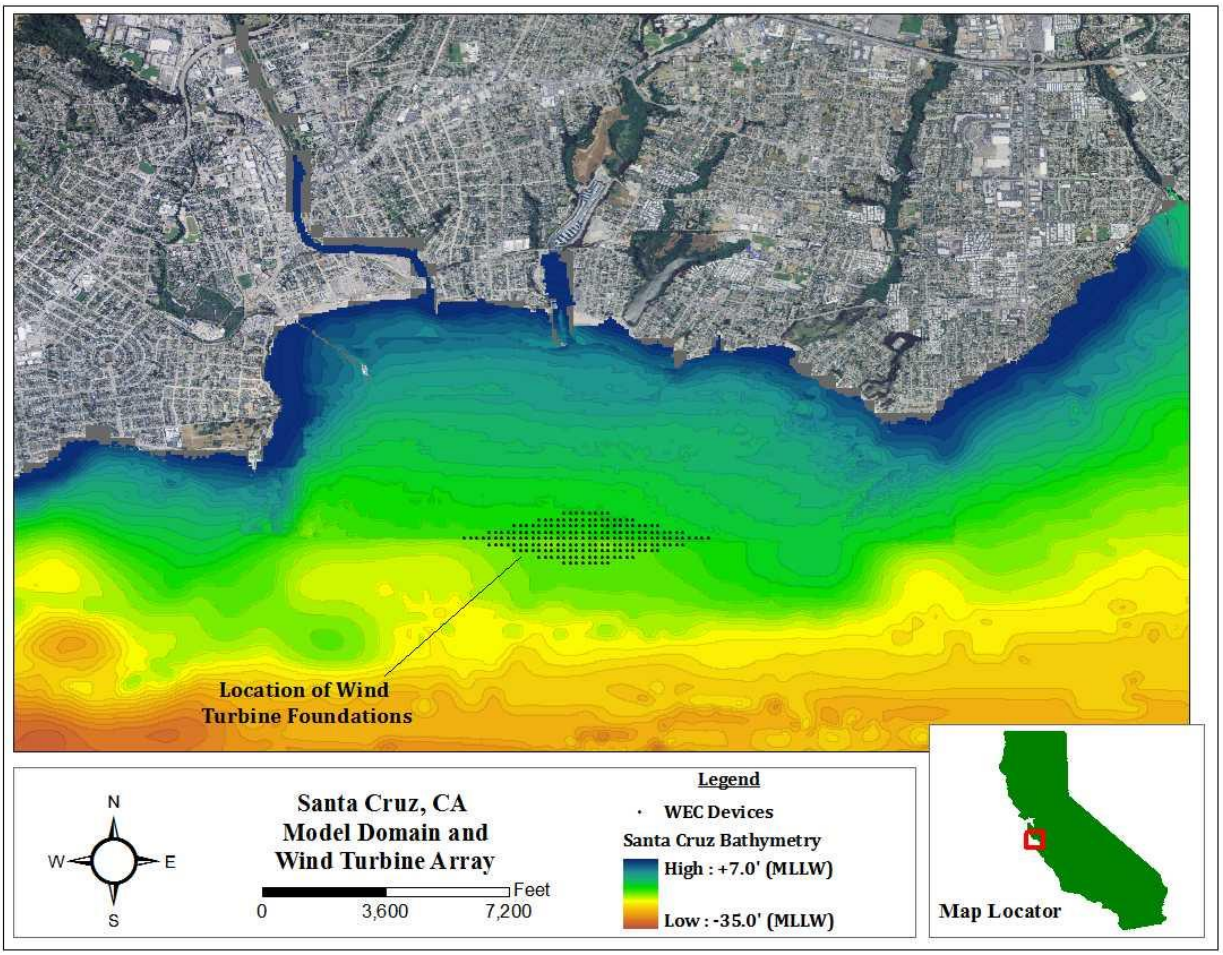

Figure 37. Monterey Bay model domain. 200 offshore wind turbine array.

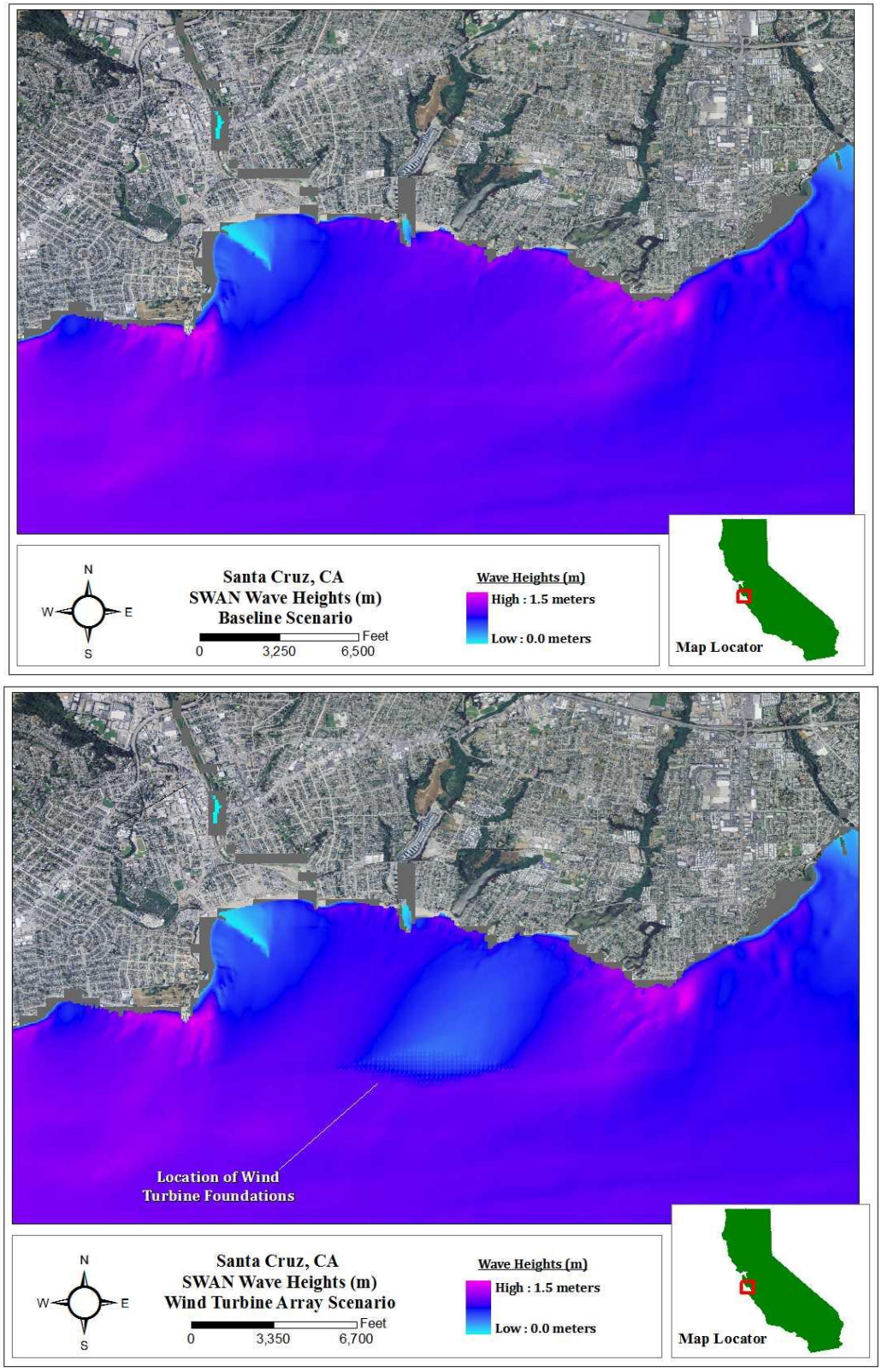

Figure 38. Modeled wave heights before (top) and after (bottom) the inclusion of a wind turbine array.

SWAN modeling runs were initiated using a combination of typically occurring, and extreme event, wave conditions as the boundary conditions. Modeling was completed in stationary mode during the technique development because of the smaller sized modeling domain (non-stationary processes were considered negligible at the present time, but can be easily incorporated at a later date). Model outputs included wave heights, wave periods and wave directions for the entire modeling domain. In addition, the near-bottom orbital velocities (due to shallow water, non-linear wave oscillations) were exported and included in near-bottom shear stress computations. Wave-driven currents were combined with current flow in EFDC and near-bed shear stresses were computed as a result of the combined action of waves and currents. The computed shear stresses were then used with site-specific sediment size information to estimate sediment mobility and susceptibility to erosion.

A.4. Evaluating Sediment Risk

As discussed, the movement of sediment in the coastal zone is dynamic and varies spatially and temporally. The scenario presented here describes a basic evaluation of the changes in sediment movement that may occur due to the offshore wind farm. When planning an offshore wind farm, more detailed evaluation of the site-specific impacts of the offshore structures might be necessary. These may include a fine-scale, detailed analysis of the near- and far-field scour and sediment transport potential as well as the prediction of any disruption to the natural sediment transport patterns.

To characterize seabed sediment mobility it is important to characterize the sediment and its spatial distribution in the system, as well as the near-bed shear stresses generated by the local waves and currents. Here, knowledge of the spatial distribution of sediment grain size and combined wave/current generated shear stresses at the site was used to establish an initial understanding of sediment mobility.

Sediment particle size distribution data were interpolated to the same model computational grid domain used in the hydrodynamic analysis in a GIS. Sediment phi sizes, where available, were converted directly to grain diameters and were assumed to be the median grain sizes:

Eqn. 21

$$\phi = -\log_2 d$$

where d is the sediment diameter, in millimeters.

Near-bottom shear stresses due to the wave activity were computed following the method of Christoffersen and Jonsson (1985), which accounts for the ambient current velocities, wave-induced orbital velocities and seabed roughness. Figure 39 shows sample results of shear stress calculations both before (baseline scenario) and after installation of wind turbine arrays. The sediment roughness used in the model is the individual median grain size of the gridded particle size distributions, and is based on the measurements reported by the USGS (Reid et al., 2006).

The bed shear stresses were computed and transferred to GIS for rapid evaluation and visualization of regional bed shear stresses. If the critical shear stress of the sediment is known with some degree of certainty, then the spatial location of the sediments can be classified according to the sediment erodibility likelihood. This is a function of the critical shear stress of the sediments and the expected (modeled) bed shear stress under the given wave boundary conditions.

The shear stress ranges were ordered into a 10-point magnitude risk scale. The estimated critical shear stress of the sediments at the site was established as the mid-point of the 10-point scale. Spatial areas with predicted shear stresses lower than this value had a low risk of mobilization. Areas with shear stresses higher than this value ere more susceptible to erosion (i.e. are at a higher risk of mobilization). A classification of 10 implied the sediments were highly susceptible to mobilization; a classification of 1 indicated the sediments were not very susceptible to mobilization, and, may, in fact, be more susceptible to deposition. The final results are illustrated on a sediment stability risk map for easy visualization of the risk or potential for sediment transport (Figure 40).

The baseline sediment stability risk map (absence of turbines) is extremely valuable, in that offshore wind developers can identify areas of natural high and low probability of sediment movement prior to installation, and therefore avoid high risk areas for both foundation deployment and cable routes. In the presence of offshore obstructions, the structures generally reduce the likelihood of sediment transport in the area in lee of the array by reducing wave activity behind the structures. As a result of the wave energy pattern changes modeled here, there may be an alteration of circulation in the region. The results suggest an array installed at this location may induce sediment deposition behind the structures.

Deposition could result in the potential for habitat alteration (e.g. sea grass burial), both in proximity to the array or further downstream near the shoreline. The far-field change in risk along the coast, however, does not show any widespread alteration. It is important to note that this report illustrates the expected bed shear stresses and associated sediment risk of sediment mobilization resulting from one applied wave and current scenario and may not be representative of all situations.

A more detailed quantitative analysis is required to fully evaluate the range of expected shear stresses due to typical and extreme wave and current conditions. At the scale of this model, sediment mobility caused by scour around foundations is not assessed. Foundation scour is a critical design impact to consider and will be discussed more in the next section. Conceptually, foundation scour pits will mobilize more sediment in the vicinity of the devices, making more sediment available for deposition in the lee of the array.

Figure 41 illustrates the components of the general sediment transport assessment methodology described in the preceding sections.

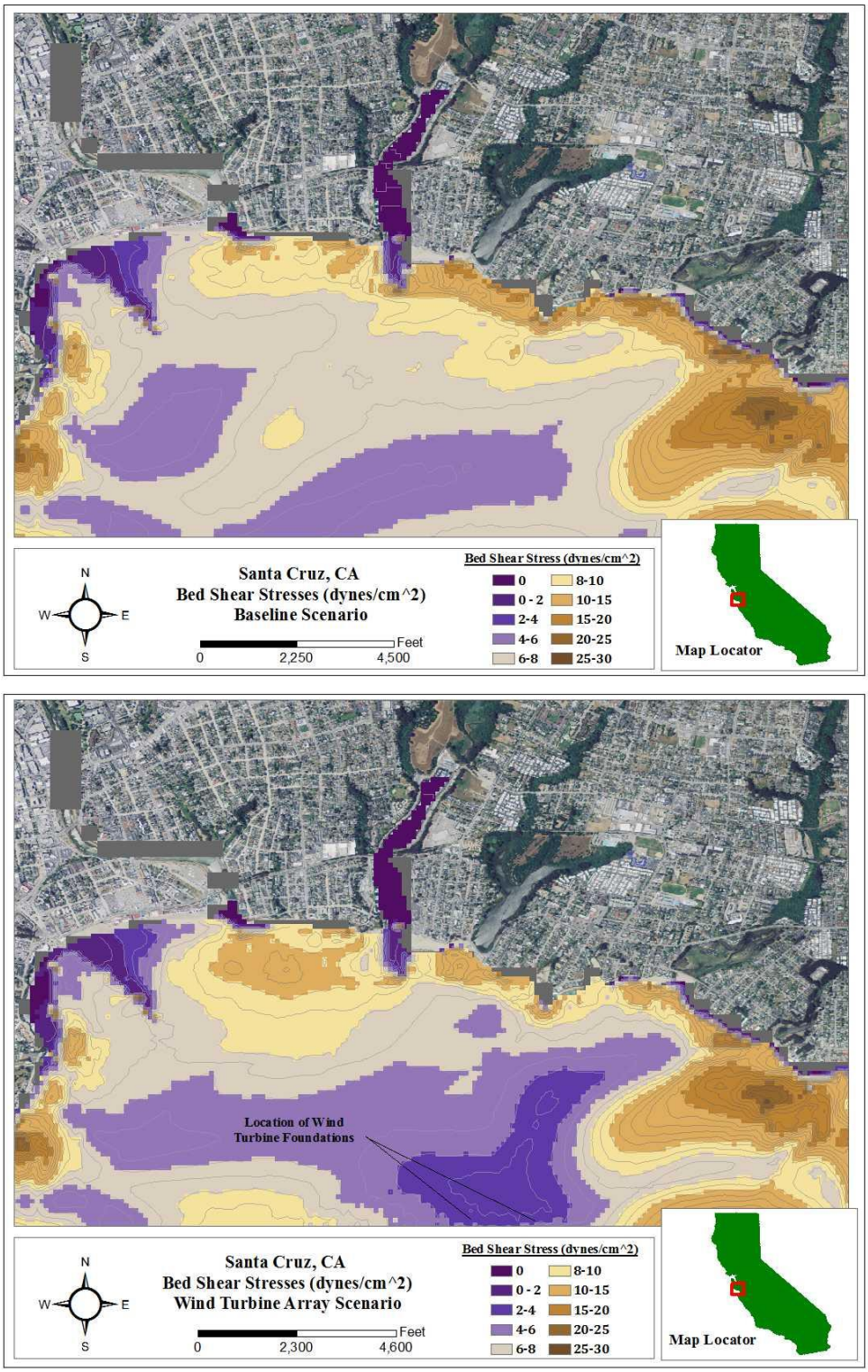

Figure 39. Modeled seabed shear stresses before (top) and after (bottom) the inclusion of a wind turbine array.

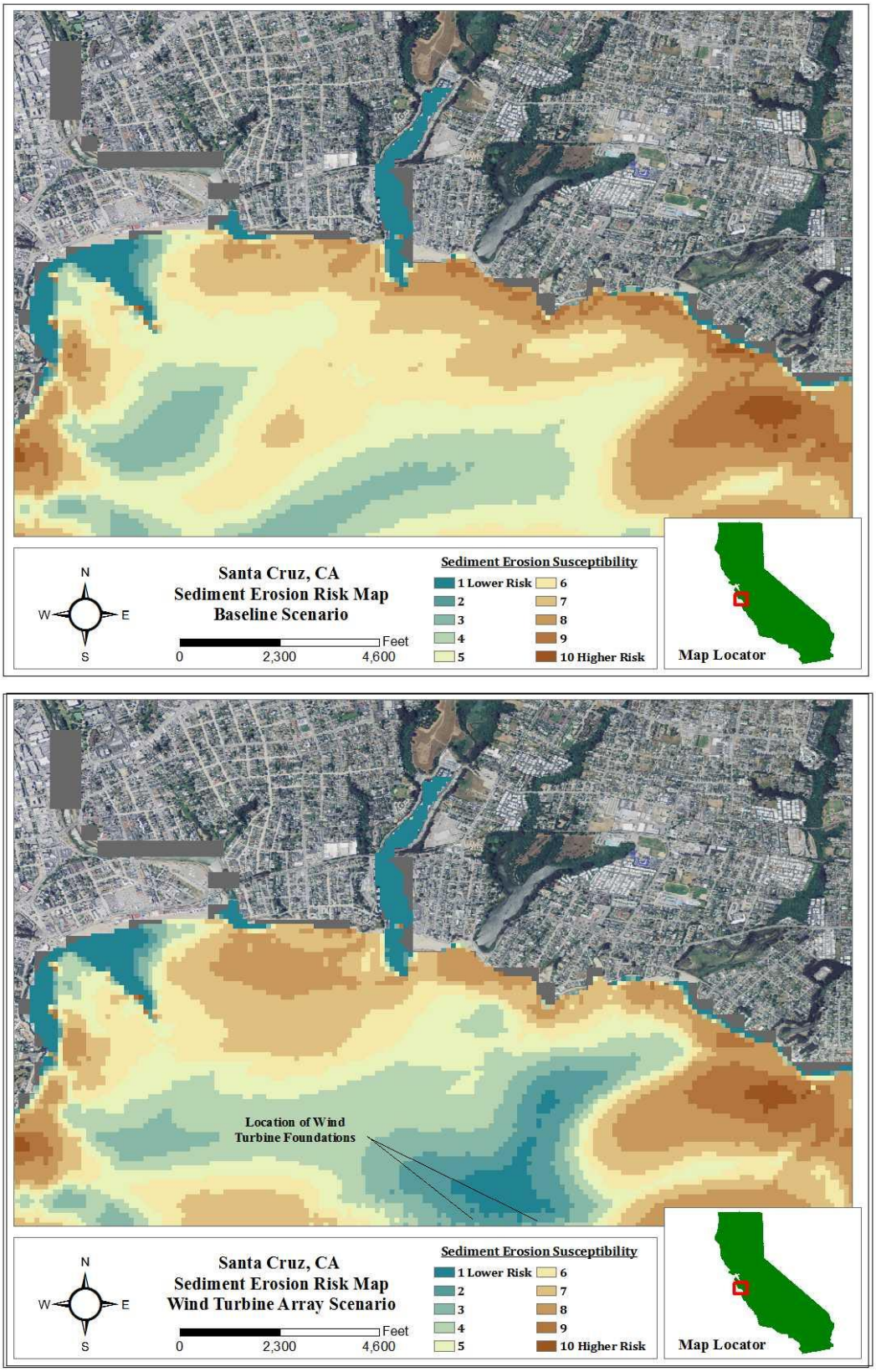

Figure 40. Risk of sediment transport before (top) and after (bottom) the installation of a wind turbine array.

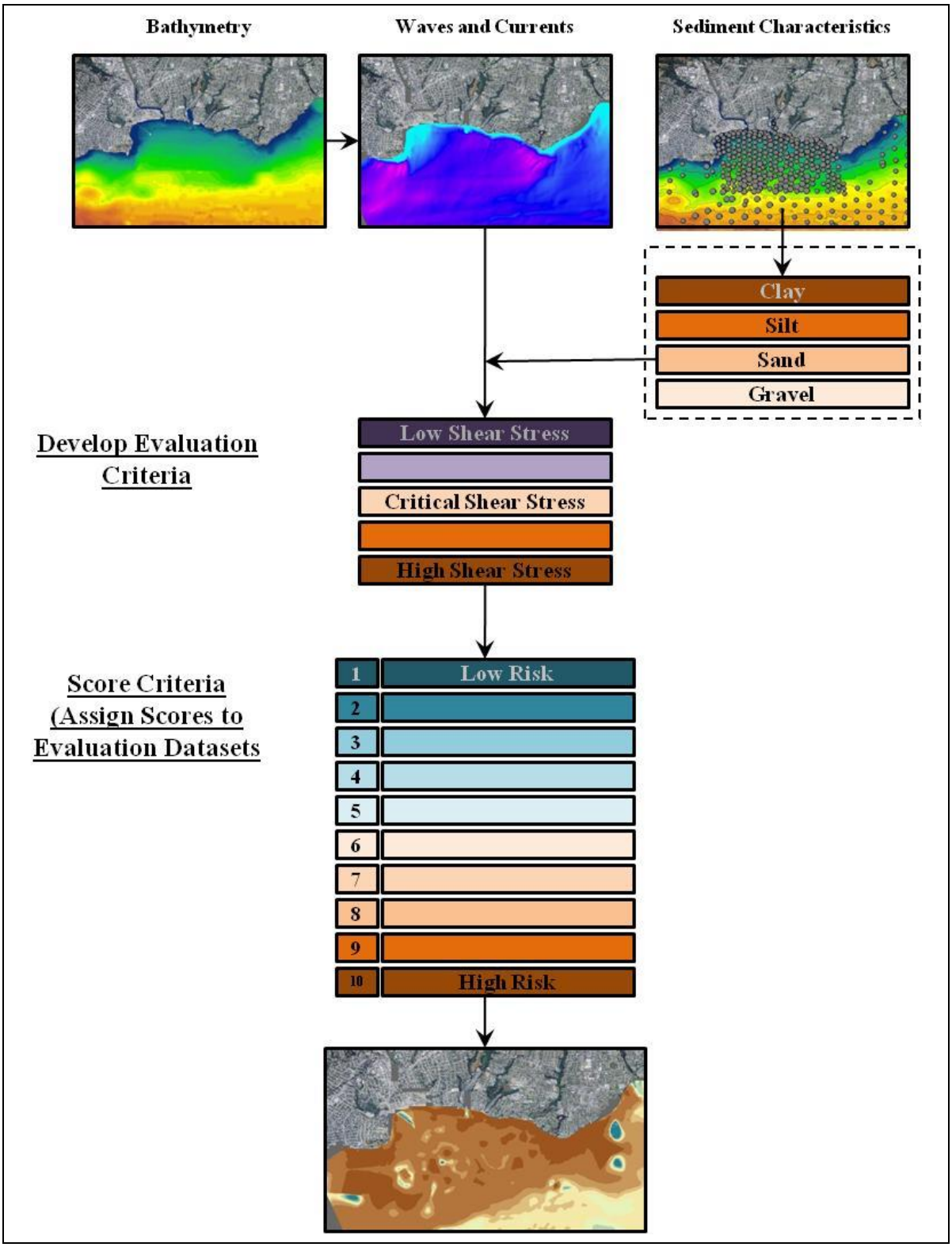

Figure 41.Flowchart of risk assessment methodology.

DISTRIBUTION

4 Lawrence Livermore National Laboratory
Attn: N. Dunipace (1)
P.O. Box 808, MS L-795
Livermore, CA 94551-0808

1	MS0899	Technical Library	9536 (electronic copy)

Sandia National Laboratories