THE ADAPTATION-MITIGATION DILEMMA: IS NUCLEAR POWER A PRACTICAL SOLUTION FOR CLIMATE CHANGE?

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A Thesis
Submitted in partial fulfillment
of the requirements for the degree
Master of Environmental Studies
The Evergreen State College
June 2009

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ABSTRACT

The Adaptation-Mitigation Dilemma:
Is Nuclear Power A Practical Solution For Climate Change?

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According to recent evidence, the impacts of global climate change are now being felt. Synergies and tradeoffs exist between adaptation and mitigation measures needed to address those impacts, yet insufficient research exists in this arena. Criteria developed in this study evaluated nuclear power as a mitigation practice. Coastal and inland reactors were studied separately to account for different climate impacts at each location. GIS analysis modeled inundation from sea level rise for all nine coastal reactors in the U.S. within 2 miles of the Pacific and Atlantic oceans. Reports from the U.S. Nuclear Regulatory Commission provided supplementary information on operational responses and problems encountered during coastal storms. Sea level rise models revealed that nuclear power plants in Florida are the most vulnerable to inundation, followed by nuclear power plants in the northeast. Safety stands out as the primary concern at all coastal locations. Heat waves, drought, flooding, and biological fouling affect reactors located on inland water bodies in France, the United States, and Canada. Thermal pollution and legal water battles already affect inland reactors, and the expense of changing cooling systems to use less water at inland sites will make many locations uneconomical for nuclear power. This study demonstrates that applying the criteria to inland and coastal nuclear power plants reveals several significant weaknesses of nuclear power as a mitigation measure for climate change. Cumulatively, these weaknesses make nuclear power an unsuitable mitigation strategy for climate change. Additionally, this analysis underscores the importance of considering the interaction of adaptation and mitigation strategies for climate impacts at the regional level.

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Acknowledgments

This thesis would have never happened if it were not for one informative and influential class: *Chernobyl and Ukraine: Recovery from Catastrophe and the Future of Nuclear Power.* Thank-you to John Perkins and Tanya Murza for sharing their passion on the subject, organizing a remarkable group of presenters, and being brave enough to take students overseas. I also want to thank my Chernobyl classmates whose intellectual curiosity and passion made the experience all the more rewarding.

I must also thank John Perkins for his work as my thesis reader and the valuable feedback he gave during the entire writing process. Thanks to Greg Stewart for his advice on the organization of my thesis and for his assistance in using ArcGIS. Thanks to Michael Mariotte for suggesting this as a thesis topic to our class, and for providing valuable details on the nuclear industry.

I'd like to acknowledge all the support I received from my fellow MES classmates, in particular Kathleen Saul who also caught the nuclear bug from the Chernobyl class. Several people were helpful not only in answering questions, but their enthusiasm for the topic provided wonderful encouragement including: Dominique Bachelet, Mary Lampert, and Dave Lochbaum. I'd also like to thank the following organizations for their assistance and for fantastic work in climate change and/or nuclear power: Nuclear Information Resource Services (NIRS), The Union of Concerned Scientists, Pilgrim Watch, and The Nature Conservancy. Thanks to Judy Cushing and my co-workers in the Scientific Database lab for their support, and for animating my sea level rise visualizations. Last but not least thanks to all my family and friends for their support especially my husband Lyle Higgs.

Executive Summary

Humanity must live with the consequences of climate change now. Mitigation alone will no longer be enough to address climate change; therefore countries must also adapt. Synergies and tradeoffs exist between adaptation and mitigation; yet insufficient research exists in this arena. The Adaptation-Mitigation Dilemma applies to two broad adaptation problems that afflict mitigation projects. First, mitigation projects must adapt to climate change to continue operating. Second, mitigation projects can impair the ability of systems to adapt to climate change or cause other environmental problems. In this study, five criteria were developed specifically to evaluate these two problems and used to assess nuclear power as a mitigation practice.

The criteria evaluate the consequences of climate change for the mitigation measure. First, can climate change block the continued operation of the mitigation measure? Next, are the financial costs needed to adapt the mitigation measure for climate change prohibitively high? In addition, the criteria evaluate the consequences of the mitigation measure to the environment. Does continued operation of the mitigation measure impair the ability of natural systems to adapt? Does continued operation impair the ability of human systems to adapt? Can climate change cause the mitigation practice to create other health or environmental problems? In the case of nuclear power, this last criterion identifies safety concerns and increased probability of accidents due to climate impacts on the operation of nuclear power plants.

Coastal and inland reactors were studied separately to account for different climate impacts at each location. The coastal portion of the study focused on reactors in the United States. GIS analysis modeled inundation from sea level rise for all nine coastal reactors within 2 miles of the Pacific and Atlantic oceans. In many coastal regions erosion processes pose a greater threat than inundation; therefore, relative coastal vulnerability data from the U.S. Geological Survey for the nine coastal reactors was included in the analysis. Hurricanes also pose problems for reactors located several miles from the coastline particularly in estuarine sites. Reports from the U.S. Nuclear Regulatory Commission provided information on operational responses and problems encountered during coastal storms.

Sea level rise models revealed that nuclear power plants in Florida are the most

vulnerable to inundation followed by nuclear power plants in the northeast. Calvert Cliffs in Maryland has some flooding under the most severe conditions, while reactors in California are not threatened by inundation. However, San Onofre in California and Calvert Cliffs in Maryland received a high and very high ranking respectively according to the coastal vulnerability index. Therefore, development at these sites impedes the ability of natural and human systems to adapt to changes in the coastal environment.

In terms of climate impacts, hurricanes currently pose the greatest threat to safe operation. Several issues pertaining to safety arise during storms including: loss of off-site power, loss of communications, blockage of evacuation routes, and equipment malfunction. Frequently reactors must be shutdown during hurricanes and restart of reactors can take weeks. Evacuations and damage to transmission lines, however, ensures low customer demand during these storm emergencies.

The inland portion of the analysis focused on the operation of nuclear power plants in the United States, France and Canada. The United States with 104 reactors has the largest nuclear fleet in the world. France generates the largest proportion of its energy supply, approximately 80%, from nuclear power. Canada receives a small proportion of energy from nuclear power. The province of Ontario, however, receives 50% of its energy from nuclear.

Heat waves, drought, flooding, and biological fouling affect reactors located on inland water bodies. Additionally, the experiences of nuclear operation in each of these countries provide unique insights into climate impacts. France has encountered problems exceeding design capacities with summer droughts, heat waves, and floods. Drought and heat waves posed problems for reactor operation in the U.S. particularly in the southeastern states. Reactors along the Great Lakes, in both Canada and the U.S., continue to have problems with biological fouling due to *Cladophora*. Regulatory agency reports, utility company reports, and legal documents allowed evaluations of climate impacts at inland locations.

When reactors must shutdown during heat waves it occurs at a time of peak energy demand. During heat waves in France issuing of thermal release waivers in excess of environmental regulations assured a reliable supply of energy. Thermal pollution, however, reduces the ability of aquatic ecosystems to adapt to warmer temperatures. In the United States legal water battles between states occurred in regions with nuclear power, such as the Catawba River Basin in the Carolinas and the Lake Lanier/Chattahoochee River system. These battles indicate water scarcity concerns and problems with adapting human systems to a reduced supply of water. Newly constructed reactors could use dry or hybrid cooling systems; the energy and financial costs to run these systems, however, are likely prohibitive. Adapting flood protection devices can also be costly: Raising the dyke by 1 m at the Belleville site in France cost over 13 million U.S. dollars. Safety supersedes cost concerns when dealing with flooding. Flooding in excess of historical levels impairs safety in multiple ways, similar to hurricanes, but without the benefit of anticipation and preparation. In a similar manner, biological fouling causes revenue losses and safety problems due to the inability to predict its occurrence.

Applying the criteria to inland and coastal nuclear power plants reveals several weaknesses of nuclear power as a mitigation measure for climate change. Safety stands out as the primary concern at coastal locations. Adaptation problems from sea level rise are almost certain. Thermal pollution and legal water battles already affect inland reactors. The expense of changing cooling systems to use less water at inland sites will make many locations uneconomical for nuclear power. The culmination of this analysis underscores the importance of considering climate impacts at the regional level. Decisions on adaptation and mitigation to climate change must, therefore, also be made at the regional level by taking account of projected interactions between nuclear power and climate change. A national or international push for particular mitigation strategies will unfortunately, likely overlook regional events and effects.

1. Nuclear Power and Climate Change

Climate change, due largely to emissions from burning fossil fuels, presents one of the greatest challenges the world faces today. Posited as a solution to climate change, nuclear power could replace some of the energy currently generated by burning fossil fuels. However, climate change permeates every facet of humanity; therefore, many factors must be considered in addressing this problem. Due to the complexity of the climate change, it was recognized that policymakers needed an objective source of information about the causes of climate change, its potential environmental and socio-economic consequences and the adaptation and mitigation options to respond to it. The Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization and by the United Nations Environment Program to fill this need (2007a).

Adaptation and mitigation are two distinct, but equally important measures that reduce the impacts of climate change. An impact describes a specific change in a system caused by its exposure to climate change. Vulnerability to climate change is the degree to which systems are susceptible to, and unable to cope with the adverse impacts (Schneider et al., 2007).

Mitigation reduces the sources or enhances the sinks of greenhouse gases, thereby, diminishing the severity of climate impacts (IPCC, 2001). Adaptation is an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (IPCC, 2001). Adaptation diminishes the vulnerability of the system. Nuclear power is viewed as one option for mitigation, because it emits little greenhouse gas during the generation of electricity.

Climate change, however, can no longer be avoided; the consequences are being felt now and will continue to be felt due to current emissions, and the latent impacts from greenhouse gases already in the atmosphere. According to the IPCC (2007b), warming of the climate system is unequivocal, as is now evident from observed increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level. Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases.

Human influences have:

- Very likely contributed to sea level rise during the latter half of the 20th century.
- Likely contributed to changes in wind patterns, affecting extra-tropical storm tracks and temperature patterns.
- Likely increased temperatures of extreme hot nights, cold nights and cold days.
- More likely than not increased risk of heat waves, area affected by drought since the 1970s and frequency of heavy precipitation events.

Evidence shows that with current climate change mitigation policies and related sustainable development practices, global greenhouse gas emissions will continue to grow over the next few decades. Moreover, for the next two decades a warming of about 0.2˚C per decade is projected regardless of emission levels. Beyond that timeframe future warming depends on the level of greenhouse gas emissions (IPCC, 2007b).

Therefore, adaptation is necessary to cope with changes that will occur despite mitigation efforts. While adaptation and mitigation are distinct responses to climate change, the two approaches must be considered in concert. The implications of some mitigation strategies for adaptation and other development and environment concerns have been recognized, but remain unexplored. Moreover, information on interrelationships between adaptation and mitigation at regional and sectoral levels is scarce (Klein et al., 2007).

The Adaptation-Mitigation Dilemma pertains to the two broad adaptation problems that arise in mitigating for climate change. First, adaptation poses a challenge to mitigation projects because climate change impacts their operation. The mitigation project must adapt to climate change or continued operation is threatened. Second, operation of the mitigation measure can impair the ability of natural and human systems to adapt, or cause other environmental concerns. In order to address these two problems, I propose using the following criteria to judge any mitigation measure:

Interrupted Operation: Could climate change thwart the future operation of the mitigation action?

Financial Costs: Does climate change increase the costs of the mitigating action?

Adaptation Impairment - Human Systems: Does operation of the mitigating action have the potential to reduce the ability of human systems to adapt?

Adaptation Impairment - Natural Systems: Does operation of the mitigating action have the potential to reduce the ability of natural systems to adapt?

Other Environmental Problems: Could climate impacts lead the mitigating action to have other health or environmental problems?

These criteria were established because the consequences for each are significant. (1) If the mitigation measure is no longer able to operate, then carbon-emitting sources of energy may be used as a replacement thereby voiding any benefit. (2) Financial resources are limited, so it is important to consider which projects provide the most benefits with the least amount of cost. If climate change itself increases the cost of operations of the mitigation strategy, the benefits might no longer outweigh the costs and/or other mitigation options may become more financially attractive. (3) If the mitigation measure compromises the ability of natural or human systems to adapt then it can no longer be considered a solution to climate change. (4) The mitigation measure adopted by one group could interfere with adaptation in another sector or a neighboring state or nation. (5) Alternatively, adaptation could be impaired in the region that adopts the mitigation measure. The benefit of mitigation is global; therefore, reducing the ability to adapt places an inequitable burden on regions that adopt the particular mitigation measure. (6) This holds true if the mitigation measure leads to other environmental problems.

The primary objective of this thesis is to examine these issues for a particular mitigation measure: nuclear power. The results of this thesis show that nuclear power has various vulnerabilities to climate change that diminish the ability of nuclear power to act as a mitigating agent and impair the ability of systems to adapt. Nuclear power plants are sited either along large inland bodies of water or close to the coast due to the need for large volumes of cooling water. Each of these environments has unique challenges and therefore impacts at coastal and inland locations are considered separately. Sea-level rise (as the climate warms and glacial and polar ice melts) threatens the stability and operations of nuclear power plants located on shorelines. Warmer temperatures may force shut-downs of nuclear power plants located on inland waters, (a) if the water temperature increases, (b) water quantity decreases, or (c) biological fouling occurs because of ecosystem changes. Hurricanes and intense precipitation events also pose a threat to the operation of nuclear plants.

Geographic Information System (GIS) models show that a number of reactors in the United States are vulnerable to the sea-level rises predicted for the 21st century. A literature review demonstrates that reactors on inland waters in the United States, France, and Canada have already been affected by a warming climate. These findings demonstrate that nuclear reactors located on both coastal and inland sites are vulnerable to climate change; therefore, in terms of adaptation currently existing nuclear power plants in many regions will not be a suitable mitigation of or solution for climate change.

The remainder of this introductory chapter reviews major features of nuclear reactors, their design, their location, and how climate change will affect existing reactors. The final section of this chapter addresses current obstacles to the expansion of nuclear power. Part I of the thesis deals with coastal climate impacts, while Part II evaluates the impacts at inland sites. Both Part I and Part II follow the same general format. First, a literature review of climate science provides details on the past, current and future climatic challenges at each of these locations. Next, the methods used to analyze climate impacts on nuclear power plant operation are described. Finally, the results are presented. The final chapter synthesizes the two pieces first by focusing on the climate impacts to nuclear power and then by addressing the adaptation-mitigation dilemma in general.

1.1. Reactor Operation, Design and the Environment

Electricity production from nuclear power involves the transformation of kinetic energy from fission into heat, the conversion of heat into steam, the utilization of steam to rotate a turbine, and the conversion of the energy of rotation into electrical energy. Alternatively, heated gas is used directly to rotate the turbine. The coolant transfers energy from the hot fuel to the electrical turbine, either directly or through intermediate steps. The coolant can be either a liquid or a gas: light water, heavy water, helium, and carbon dioxide are the most common coolants. For a more detailed description of nuclear power operation and components refer to Appendix 1. The type of coolant is one determinant of reactor type as described in Appendix 2.

Turbo-generator systems that convert thermal energy to electrical energy are termed heat engines. The maximum conversion efficiency of any heat engine, determined by the laws of thermodynamics, is the Carnot efficiency expressed as: $\eta = (T_{in} - T_{out})/T_{in}$. T_{in} is the absolute temperature (K) of the gas entering the turbine and T_{out} is the absolute temperature of the gases leaving the turbine. Therefore, more of the thermal energy is converted to electrical energy with higher entering temperatures and/or lower outlet temperatures. The inlet temperature is limited by the water/ steam pressure rating of the boiler or reactor vessel in a steam cycle, or by the temperature limitations of the turbine blades, while the outlet temperature is limited by the ambient temperature of the cooling water used in the condenser of a steam cycle (Shultis & Faw, 2008). The conversion efficiency is the ratio of electrical power to thermal power and provides an important measure of a power plant's performance. In modern nuclear power plants, conversion efficiencies of about 40% can be achieved; fossil-fired units can achieve only slightly greater efficiencies, while older plants efficiencies range from 30-35% (Shultis & Faw, 2008).

In a nuclear reactor the coolant has an additional importance. Since radioactive decay causes heat production to continue even after the reactor is shut down and electricity generation has stopped, it is essential to maintain cooling to avoid melting the reactor core. Furthermore, the power level at which a reactor can operate safely is limited by the rate at which the primary coolant can carry away the heat generated in the reactor core (Mounfield, 1991). If heat is generated at a rate faster than it is carried away by the coolant, the fuel would overheat and could melt or vaporize. Efficient and safe operation of a nuclear power plant is dependent on the coolant which in turn is dependent on the cooling system.

1.1.1. Cooling Systems

The cooling systems are vital to the safe operation and shutdown of nuclear reactors. In addition, service water systems that use water from nearby water sources and supplies are necessary to cool the equipment associated with the nuclear reactor such as the chillers in air-conditioning units, heat exchangers, and lubricating oil coolers for the main turbine (Lochbaum, 2007). The most significant cooling concerns are the ultimate heat sink and condenser cooling.

The International Atomic Energy Agency (IAEA, 2004) defines the ultimate heat sink as a medium to which the residual heat can always be transferred, even if all other means of removing the heat have been lost or are insufficient. The ultimate heat sink is normally a body of water, the groundwater or the atmosphere.

When water is the medium selected as the ultimate heat sink, the following should be considered: size of the water supply, type of cooling water supply, make-up sources to the ultimate heat sink, and capability of the heat sink to deliver the necessary flow of cooling water at appropriate temperatures for operational states, accident conditions or shutdown conditions of the reactor (IAEA, 2004).

Some member states of the IAEA require that both the ultimate heat sink and its directly associated transport systems be designed with sufficient capability and capacity to bring the plant to cold shutdown (90˚C at atmospheric pressure) within 36 hours (IAEA, 1981). Furthermore, regulations in the United States stipulate that 30 days is the required period for which the capacity of the sink should be sufficient to provide cooling. Procedures should be available for ensuring the continued capability of the sink beyond 30 days (U.S. Nuclear Regulatory Commission, 1976).

Water and/or air may be chosen as the transport medium. The relative dependability and capacity of available sources should be taken into account. In general, access to natural, inexhaustible supplies of water such as oceans, large lakes, or large rivers is preferable to limited-capacity man-made sources.

The sizing of the heat transport system directly associated with the ultimate heat sink are governed by: the maximum heat rejection rate, environmental parameters for design, and the supplies of coolant (IAEA, 1981, 2004). In determining the capacity of the ultimate heat sink and its directly associated heat transport systems, design basis environmental parameters must be established. These parameters include water temperature of the ultimate heat sink for once-through water cooling systems, dry-bulb temperature for dry cooling towers, and wet- and dry-bulb air temps for heat transport systems which use evaporative cooling such as wet cooling towers, cooling or spray ponds.

Consideration of critical time periods is particularly important in determining capacity. Ponds require establishment of design basis environmental parameters based on longer several days, while dry cooling tower are dependent only on dry bulb temperature and the critical period may be much shorter (IAEA, 1981). Appendix 3 provides a more thorough description of the requirements associated with the Ultimate Heat Sink.

Two basic types of cooling systems are used for condenser cooling: the once-through system and closed loop system. In the once-through cooling system, water is circulated through the steam condenser once and the heated water is discharged directly to the water body from which it was taken. Supplemental cooling by means of cooling towers or cooling ponds may be necessary in order to dissipate heat directly to the atmosphere before water is discharged to public waters (Eichholz, 1976). In closed cooling systems, water is continuously circulated through the condensers. The water is cooled through evaporation by means of towers, ponds, spray canals, or a combination of measures. The water consumed is replaced with water taken from a water body. In closed systems some water is discharged to the water body to prevent an excessive buildup in the concentration of salts and plant chemicals in the circulating cooling water and to maintain steady-state conditions in the quantity and quality of water used in cooling (Eichholz, 1976; Giusti & Meyer, 1977).

The benefit of the closed-loop system is that it has very little warm-water discharge to a receiving water body, since it is designed to dissipate the waste heat into the atmosphere. The once-through cooling system has much higher water requirements; however, less of the water is consumed compared to the closed-loop system. Once-through cooling systems with large cooling reservoirs can reject 40 percent of the excess heat through evaporation, while cooling towers lose approximately 80 percent through evaporation (J. Z. Reynolds, 1980). The choices in cooling systems have other tradeoffs in efficiency and land use. For instance, the area required for locating physical facilities on site may be as low as 15 acres per generating unit for sites with once-through cooling but is typically in the 50-acre range when switchyard and cooling tower areas are included (Burwell et al., 1979). Cooling ponds also consume land requiring 1-2 acres per megawatt of installed capacity with a recommended minimum depth of 2-4 m (Eichholz, 1976). A spray pond requires smaller volume and surface areas compared to surface cooled ponds, but at the same time increased evaporative water losses require additional makeup water (Codell, 1981; Eichholz, 1976).

Cooling towers may be used to provide full cooling requirements only during certain periods of the year and may be combined with cooling ponds as back-up systems. Cooling towers and cooling ponds have limitations in the extent to which the temperature of warm water can be reduced, due to the decrease in evaporative cooling as the wet bulb temperature is approached; moreover, pond performance is affected by surface air temperature, relative humidity, wind speed, wind fetch, solar radiation, aquatic growth and erosion (Eichholz, 1976). These factors lead to performance reductions during hot weather.

In addition to the environmental parameters that impede the efficiency of energy generation, cooling systems require energy that lowers the output of the reactor. Cooling towers reduce the overall efficiency of a power plant by 3-5% (Australian Uranium Association, 2007). The efficiency is dependent on the type of cooling tower. Cooling towers can be classified as dry or wet. In dry towers warm water is contained in pipes and air flow cooling occurs primarily by conduction across the pipe interface, while in wet towers the warm water is in direct contact with a flow of air and heat is dissipated principally by evaporation. While dry cooling towers uses less than 10% of the water required for wet cooling towers, they have a much greater cost for construction and require approximately 0.5% to 1.5% of the power station's output to run (Australian Uranium Association, 2007; World Nuclear Association, 2008b). Cooling towers are also classified by how the air flow is produced. Air flow can be induced by mechanical draft, using one or more powerful fans, or natural draft, using a tall, typically hyperbolically shaped "chimney," to provide a natural updraft (Eichholz, 1976). The power requirements to provide the extra pumping power for circulation in mechanical draft towers further reduce the effective efficiency value of the power plant; moreover, problems from fogging and drift of discharged air requires distance from the plant thereby increasing piping costs (Eichholz, 1976). In light of climate change, the costs of cooling towers, dry cooling and lower thermal efficiencies for inland sites will be significant and, in some cases, this may be sufficient to turn the economic balance against nuclear (Kidd, 2008).

Cooling systems depend greatly on the type of reactor and some newer reactor designs have very different needs. For example, the passive cooling design of the Advanced Pressurized 1000 (AP1000) does not require a separate safety Ultimate Heat Sink. Nonetheless, the high water requirements of nuclear power plants will continue at least in the near future. For instance, the Pebble Bed Modular Reactor (PBMR) is estimated to need 724,974 gallons per minute (gpm) for an 8-module plant if once-through cooling is used. If the plant uses mechanical draft cooling towers, the flow is estimated at 260,991 gpm and makeup flow is estimated at 15,659 gpm (Dominion Energy Inc. Betchel Power Corporation, 2002). The Advanced Pressurized 1000 (AP1000) is estimated to need between 450,000 to 750,000 gpm and makeup flow is anticipated to be approximately 4%. Moreover, the service water for reactors such as the AP1000 and International Reactor Innovative and Secure (IRIS) have separate cooling towers that require from 250 to 500 gpm (Dominion Energy Inc. Betchel Power Corporation, 2002).

Solutions to thermal waste from nuclear power plants will continue to be determined by economics and siting. The least costly means of discharging waste heat is to dissipate it in large rivers, lakes, or the ocean (Foster & Wright Jr., 1977). Refer to Appendix 4 for a description of other issues considered when siting nuclear power plants.

Nuclear power plants are located along the coast or near large inland bodies of water, and thus need to be designed to withstand environmental impacts related to these sites.

1.1.2. External Events and the Design of Nuclear Power Plants

The primary goal in design of nuclear power plants is to maintain defense in depth. The principle of defense in depth is implemented primarily by means of a series of barriers which would in principle never be jeopardized. When properly applied, it ensures that no single human or equipment failure would lead to harm to the public (International Nuclear Safety Advisory Group, 1999). In order to maintain defense in depth, the design should prevent as far as practicable: challenges to the integrity of physical barriers, failure of a barrier when challenged, and failure of a barrier as a consequence of failure of another barrier. All levels of defense should be available at all times, although some relaxations may be specified for the various operational modes other than power operation (IAEA, 2003a).

The anticipated operational occurrence and design basis accident are used to establish the structures and defenses necessary for proper design. The IAEA (2004) defines the anticipated operational occurrence as an operational process deviating from normal operation which is expected to occur at least once during the operating lifetime of a facility but which, in view of appropriate design provisions, does not cause any significant damage to items important to safety or lead to accident conditions. The design basis accident is the accident conditions against which a nuclear power plant is designed according to established design criteria, and for which the damage to the fuel and the release of radioactive material are kept within authorized limits (IAEA, 2004). The design basis accident includes the design basis flood and design basis external event. During the site assessment data is gathered for the purpose of establishing the design basis accident. The site hazard and the layout of the plant are used to determine the design basis external event, while the flood hazard is utilized to determine the design basis flood (IAEA, 2003a).

Data must also be collected to establish long-term removal of heat from the core in the event of an accident. In addition to flood protection, the design should accommodate the effects of temperature extremes, and the statistical analyses should provide the necessary data in forms usable for such purposes. The persistence of very high or very low temperatures is a factor that should be considered (IAEA, 2003d). For a more complete coverage of how external events factor into design refer to Appendix 5.

Climate has always been an important factor in nuclear power plant operation. First, suitable sites must provide a source of ample cooling water. Second, extreme events must be considered in the establishment of design parameters. A certain amount of climate variability can be accommodated in design and site selection. Climate change leads to an increase in climate variability thereby making planning in design and operation increasingly difficult. The next section explores the impacts of climate change to nuclear power operation.

1.2. The Influence of Climate Change on Nuclear Power Plants

The dependency of nuclear power on water dictates that reactors be located along the coast or near large inland bodies of water, and this fact more than any other is crucial to nuclear power's vulnerability to climate change. It is also the reason why nuclear power plant operation can impair the ability of human systems and ecosystems to adapt. The aforementioned criteria elucidate the consequences of each of these climate problems for coastal and inland reactors as shown in table 1 and 2 respectively.

Table 1. The consequences of climate impacts for coastal reactors.

Criteria	Climate Problem	Consequence
Interrupted Operation	Storms and sea level rise	Storms and flooding cause power reductions and reactor shutdowns.
Financial Costs	Storms and sea level rise	Revenue loss & costs incurred to implement shoreline and flood protection.
Adaptation Impairment Human Systems	Storms and sea level rise	Coastal development reduces the ability of human systems to adapt.
Adaptation Impairment Natural Systems	Storms and sea level rise	Developed/engineered shorelines reduce the ability of coastal ecosystems to adapt.
Other Environmental Problems	Storms and sea level rise	Safety is impaired thereby increasing the probability of an accident.

Table 2. The consequences of climate impacts for inland reactors.

Criteria	Climate Problem	Consequence
Interrupted Operation	Drought, heat waves, intake biofouling	A lack of cooling water causes power reductions and reactor shutdowns.
	Flooding	Flooding causes reactor shutdowns.
Financial Costs	Drought, heat waves, intake biofouling	Financial costs are incurred to implement dry cooling systems and to adjust intakes.
Adaptation Impairment Human Systems	Drought	Demand for cooling water limits the ability of regions to adapt to drought conditions.
	Heat waves	Power outages reduce the ability of populations to adapt to heat waves.
Adaptation Impairment Natural Systems	Drought and heat waves	Thermal releases reduce the ability of aquatic systems to adapt.
Other Environmental Problems	Flooding, intake biofouling	Safety is impaired thereby increasing the possibility of an accident.

Impacts of climate change to safe and continued operation of nuclear power plants has been recognized by the International Atomic Energy Agency (IAEA); as a result, they are currently creating guidance on adapting nuclear power plant design and operation to climate change. The IAEA is an independent organization related to the United Nations system that works to build and strengthen international safety and security for nuclear operations by advising on international standards, codes, and guides; binding international conventions; international peer reviews to evaluate national operations, capabilities, and infrastructures; and an international system of emergency preparedness and response (IAEA, 2008a). According to the IAEA (2003c), the major hazards to nuclear power plants are changes in the following:

a) Temperatures of the air and the sea
b) The patterns, frequency and storminess of winds
c) The characteristics of precipitation such as higher peak levels
d) Rises and anomalies in sea levels
e) The flow rates of rivers

The most important consequence of the recognized effects of global warming is the need for the continuous long term monitoring of environmental parameters. An accurate estimation of such effects should be carried out in the site assessment phase (IAEA, 2003c). The IAEA (2003c; 2006a) advises that some safety margin should be taken into account in the design of a nuclear power plant and changes in natural hazards may need to be considered at the time of Periodic Safety Reviews.

If the entire plant lifetime is considered, the following generally agreed estimated variations in parameters may be considered: rise in mean sea level of 35-85 cm, rise in air temperature 1.5-5˚C, rise in sea or river temperature 3˚C, increase in wind strength 5-10%, increase in precipitation 5-10% (IAEA, 2003c).

The IAEA proposes that immediate action to address climate change may not be necessary; however, careful monitoring and site hazard evaluation for the lifetime of the facility is of the utmost importance to ensure that action is taken when necessary (IAEA, 2003b, 2003c). Furthermore, land should be reserved in order to allow further development of water defenses when deemed necessary in particular during the construction of a new plant (IAEA, 2003c). An example of appropriate action was that of a regulatory body in one Member State who sent a generic letter to all nuclear site licensees in November 1997, stating that it expected safety submissions for new construction projects plants and periodic safety reviews of existing facilities to take account of the potential effects of climate change (IAEA, 2006a).

The potential for climate change to affect nuclear power plants can be inferred from prior experience of extreme weather impacts on reactors. The IAEA has a database containing 20 years of feedback from the operation of nuclear power plants. Only 3% of reported events where degradation of plant safety occurred were due to external events (IAEA, 2003b). However, external events have the highest percentage in serious consequences often involving challenges to the defense in depth of the plant. Moreover, the reporting categories of external events include the degradation of barriers, identification of generic problem of safety, identification of design and construction, potential safety significance, release of radioactive material or exposure (IAEA, 2003b). The most serious consequences were recorded for low temperatures, high winds, flooding, lightning, biological fouling, electromagnetic interference and earthquakes. These either directly affected the plant or caused the degradation of safety features through the unavailability of off-site power, the ultimate heat sink and evacuation and/or access routes (IAEA, 2003b).

In such a situation, some new innovative reactor designs take advantage of passive safety features provided within the protected reactor building or inner containment, disregarding the availability of external sources of supply of electricity or cooling water. Several designs provide for physical presence of large thermal capacity heat sinks available to cool the reactor core without depending on availability of externally powered pumps within the containment or elsewhere (IAEA, 2006a).

Monitoring and improved designs may ensure safe operation of nuclear power plants. However, safe operator action during an extreme external event often requires reactor shutdown. Presently the costs to deal with external events are deemed to be on the low end at 12-22% of total plant costs (IAEA, 2003b). Climate change could increase these costs substantially. Climate change threatens the operation of nuclear power plants in two important ways: direct damage of the power plant and reduced availability of cooling water.

1.2.1. Flooding and Storm Damage

The safety of nuclear power plants can be seriously affected by flooding, both for sites on rivers and for sites on the sea coast, or large lakes (IAEA, 2003c). Seawater level is influenced by changes in average sea level induced by climate change, an increase in storm surges coming from the open sea, wind waves, human made structures such as tide breaks and jetties and for plants located in an estuary, and the river's discharge (IAEA, 2003d).

Flooding can have major bearing on the safety of the plant and may lead to a postulated initiating event that is to be included in the plant safety analysis. A postulated initiating event is an event identified during design as capable of leading to anticipated operational occurrences or accident conditions (IAEA, 2002). The presence of water in many areas of the plant may be a common cause of failure for safety related systems, such as the emergency power supply systems or the electric switchyard, with the associated possibility of losing the external connection to the electrical power grid, the decay heat removal system and other vital systems. Unavailability of power can have a significant adverse impact on a plant’s ability to achieve and maintain safe-shutdown conditions (Eide et al., 2004). Water pressure on walls and foundations may challenge their structural capacity. Deficiencies in the site drainage systems and in non-waterproof structures may cause flooding of the site. A flood may also affect the communication and transport networks around the plant site, which in itself could cause an emergency (IAEA, 2003c). Flooding can contribute to the dispersion of radioactive material to the environment in an accident. The dynamic effects of the water can cause damage to structures and erosion at the site boundary. Moreover, debris of all types may be transported by floods causing not only physical damage, but also damaging the water drainage system and obstructing water intakes (IAEA, 2003c).

1.2.2. Availability of Cooling Water

Sea level rise along with increase in storms could potentially affect the availability of cooling water due to biological fouling (IAEA, 2003c). Increased temperatures can affect the species composition of algae. There should be provisions for continuous biological monitoring of the ultimate heat sink to give early warning of changes which might significantly affect its performance such as the introduction of new strains of algae with different growth habits or greater tolerance to cooling water conditions (IAEA, 1981, 2003a). However, clogging of intakes is not the only factor limiting the availability of cooling water.

An important consideration related to plant siting along rivers concerns periods of low stream flow. This consideration is particularly relevant for those plants which do not use cooling ponds with a sufficiently large storage capacity to allow within-pond recirculation of water for several days (Giusti & Meyer, 1977). Low flows threaten the ability of the ultimate heat sink to perform adequately. During low-flow periods the flow consists of groundwater discharge and evaporation is at a maximum; as a result, the water has much higher mineral concentrations and may exceed standards for cooling water (Giusti & Meyer, 1977). Ecological impact may occur on aquatic organisms because of the reduced water flow, thermal pollution, or a combination of both. Moreover, low-flow and extreme high temperatures often occur at the same time.

Water demands increase with temperatures. In particular, closed systems with cooling ponds or canals need more water to cool the same amount of steam when ambient temperature increases (Yang & Dziegielewski, 2007). Cool water is needed to operate reactors safely, but efficiency will decrease before safety becomes a concern. The efficiency of nuclear power plants depends on site with the most important factor being water temperature (Australian Uranium Association, 2007). The lack of available cooling water can force the shutdown of the plant, with costs and loss of revenue to the plant operators and loss of service to consumers.

Climate change affects nuclear power in multiple ways. This thesis evaluates the impacts of climate change to nuclear power operation and the consequences of nuclear power to climate change adaptation. However, it is also necessary to explore other issues that arise when electing to use nuclear power. The problems climate change poses to nuclear power must be evaluated in the context of the nuclear choice and the costs associated with that choice.

1.3. The Nuclear Choice

The adaptation problems related to any mitigation measure should be considered, but nuclear power is of particular interest. Nuclear power has tremendous benefits. When compared to coal nuclear power is capable of generating considerable amounts of energy from a very small amount of fuel without harmful greenhouse gas emissions. Compared to the renewable alternative sources of energy (e.g. photovoltaic, solar thermal, wind, and geothermal), nuclear technology is a now-familiar way to make electricity. It is a technology that is proven to be able to generate large amounts of concentrated power, whereas alternative energy technologies have an extremely limited history as proven practices. However, nuclear power is associated with considerable costs and risks independent of climate impacts. The IPCC stated in the latest report that nuclear power has the potential for an expanded role as a cost-effective mitigation option, but the problems of potential reactor accidents, nuclear waste management and disposal and nuclear weapon proliferation will still be constraining factors (Sims et al., 2007).

Concern regarding proliferation and waste has led to debate on whether to pursue an open or closed fuel cycle. In an open fuel-cycle, once the fuel is used it is disposed of as waste, while a closed-fuel cycle involves the utilization of spent fuel in another reactor. Reprocessing of nuclear waste raises concerns over nuclear proliferation, since it is difficult for reprocessing facilities to keep track of small amounts of plutonium. For instance, a total of 70 kg of plutonium, enough for 10 nuclear weapons was unaccounted for over a five year period in a Japanese reprocessing facility (Union of Concerned Scientists, 2007). Moreover, an international research effort in advanced reprocessing would itself spread expertise in the chemistry of radioactive elements, including plutonium (Butler, 2004).

Nuclear proliferation is a concern regardless of whether open or closed fuel cycles are chosen. ^{235}U must be enriched to 90% to create a bomb and 2-5% to be used as fuel in a nuclear reactor. Seemingly a large difference, but more work is required per kilogram of ^{235}U to enrich it from 0.7% to 5% than to carry it the rest of the way to 95% enrichment; therefore, 3% enriched uranium fuel is more than "halfway" to 95% enrichment (Bodansky, 2004). Pressurized heavy water reactors use less expensive natural uranium; however, proliferation remains a concern because the continuous refueling process in these reactors makes it difficult for international inspectors to monitor (Energy Information Administration, 2007).

A MIT study looking at the future of nuclear power concluded that for the next few decades, government and industry in the U.S. and elsewhere should give priority to the deployment of the once-through fuel cycle, rather than the development of more expensive closed fuel cycle technology involving reprocessing and new advanced thermal or fast reactor technologies (MIT, 2003). The predominance of the once-through fuel cycle will cause continued demand of new fuel from mines and increasing waste to store. Commercial spent nuclear fuel is the major contributor to high level radioactive waste. Taking into account worldwide projections of nuclear power growth, it is determined that eventually a new repository of the capacity of the Yucca Mountain Repository will have to be built somewhere in the world every three to four years. In U.S. alone it is estimated that by 2100 the country will have accumulated more than 300 000 t of spent fuel; however, the proposed Yucca Mountain Repository can receive only 70 000 t of waste (IAEA, 2006b). The issue of waste-storage is more than an environmental issue, since uncertainty about the cost of waste-storage continues to worry potential investors (Giles, 2006).

Paffenbarger (1998) cautioned that attaining publicly acceptable safety in plant operation and spent fuel management could render nuclear power uneconomic in comparison to other options. In addition to these financial concerns, the nuclear industry has a history of delayed construction and cost overruns. In the United States between 1975 and 1989, the average period required to complete a plant increased from 5 years to 12 years. Consequently, many utilities collapsed due to construction debts (Aston et al., 2006). The expectation is that standardized reactor design and streamlined licensing processes will reduce the likelihood of cost overruns and delays. Nonetheless, two years ago, the price of a 1,500 megawatt reactor was $2 billion to $3 billion, while presently the cost is up to $7 billion due to the higher cost for concrete, steel, and labor (Carey et al., 2008). In addition, construction of an Evolutionary Pressurized Water Reactor in Finland is several years behind and approximately $2 billion over budget. Similarly, construction of two Advanced Boiling Water Reactors in Taiwan is now five years behind schedule. Their estimated cost has grown from $3.7 billion to between $7.4 and $9.1 billion (Schlissel & Biewald, 2008). The building of new reactors is unlikely to happen without significant support from the government. In the United States, federal subsidies for nuclear power include a 1.8 cent tax credit for each kilowatt hour of electricity produced, which could be worth more than $140 million per reactor per year. Additionally, the federal government is providing $18.5 billion in loan guarantees, and a payout of $500 million for each of the first two plants built if there are delays for reasons outside company control (Carey et al., 2008).

In addition, research money is needed for expansion of nuclear power, since no new reactors and fuel cycle technologies simultaneously overcome the problems of cost, safety, waste and proliferation (Hoffert et al., 2002; MIT, 2003). For a description of new reactor developments and research goals refer to Appendix 6. Research investment in energy has varied greatly from country to country, but in most cases has declined significantly in recent years since the levels achieved soon after the oil shocks during the 1970s (Sims et al., 2007). In the U.S. it is obvious that nuclear has historically won in the competition for research dollars. Wind, solar, and nuclear power received approximately $150 billion in cumulative federal subsidies over roughly fifty years with over 96% supporting nuclear power (Goldberg, 2000). The assessment of adaptation problems associated with nuclear power must be considered in the context of these problems. The safety of nuclear power remains a concern in the public eye independent of climate impacts. In addition, nuclear power requires considerable investment dollars independent of the financial resources needed to adapt operations to climate change.

Policy-makers arrive at different conclusions on whether the risks, including financial risks, of nuclear power are worth the benefit. Agreeing to disagree does not give nuclear power the push it needs on a global scale. In order to make a significant reduction in greenhouse gas emissions 1000 or more new reactors will need to be deployed worldwide (MIT, 2003; Socolow et al., 2004). In addition, the mitigation potential of nuclear power in both the short and long-term is under debate as discussed in Appendix 7**.** Discussions regarding the sustainability of nuclear power have taken place within the UN Commission on Sustainable Development (CSD), which in 2006 and 2007 focused on energy for sustainable development, industrial development, air pollution/atmosphere and climate change. The IAEA (2007b) deems a decision by the CSD that nuclear power is inconsistent with sustainable development as potentially a significant constraint on the development of nuclear power. This is particularly true since new international arrangements are needed for nuclear power to make a significant reduction of greenhouse gas emissions (Socolow et al., 2004). However, leaders of 16 Asian nations including China and India signed a pact on the environment pledging action on climate change in part through the cooperation in promoting and developing the use of nuclear energy (Agence France Presse, 2007). In contrast, environment ministers from Austria, Germany, Ireland, Italy, Latvia and Norway made a joint declaration that nuclear energy and sustainable development are not compatible; furthermore, nuclear energy is not an option to answer the challenge of climate change (BMU, 2007).

Nevertheless, nuclear power is currently an important source of electricity in many countries. In 2006, 15.2 % of the world's electricity needs were met by nuclear power (IAEA, 2007a). As many of the existing nuclear power plants approach the end of their operating life, new plant construction will be necessary to continue to meet this proportion of the world's electricity needs through nuclear. The demand for power plant construction will be even greater if nuclear power becomes the preferred choice for climate change mitigation. Clearly nuclear power has at once many risks and many benefits. The impact of climate change on nuclear power operation might add enough risk to shift the focus away from nuclear as a mitigation solution.

Part I Coastal Climate Impacts

This section evaluates the climate impacts at coastal nuclear power plants. The first step in the evaluation is to review the challenges associated with the coastal environment and how climate change will amplify these problems. In Chapter 2, a literature review provides details on sea level rise, coastal storms, erosion, coastal defenses, and the uncertainty in predicting climate change. The methods used to evaluate nuclear power plant operation at coastal locations are explained in Chapter 3, while Chapter 4 presents the results of the analysis.

2. Coastal Hazards Background

The abundance of cool water available at coastal locations makes them an attractive site for nuclear power plants. However, coastal environments are stressful and dynamic. Climate change impacts the coastal environment in a variety of ways that interact. For instance, the intensity of coastal storms are predicted to increase due to warmer ocean temperatures (K. Emanuel, 2005; K. A. Emanuel, 1987). Stronger storms combined with sea level rise increase the risk of flooding. Furthermore, a rise in mean sea level will increase flooding along the coast for four reasons: a higher sea level provides a higher base for storm surges to build upon, erosion will increase the vulnerability of oceanfront developments, higher water levels will reduce coastal drainage and thus would increase flooding attributable to rainstorms, and a rise in sea level will raise water tables (U.S. EPA, 1989).

2.1. Sea level Rise

On a global scale mean sea level has been rising. For the 20th century, the average rate was 1.7 ± 0.5 mm/yr, while the average rate from 1961 to 2003 was 1.8 ± 0.5 mm/yr. There is high confidence that the rate of sea level rise has increased between the mid-19th and the mid-20th centuries. Furthermore, there is evidence for an increase in the occurrence of extreme high water worldwide related to storm surges, and variations in regional climate (Bindoff et al., 2007). Satellite observations available since the early 1990s provide more accurate sea level data with nearly global coverage. This decade-long satellite altimetry data set shows that since 1993, sea level has been rising at a rate of around 3 mm/yr, significantly higher than the average during the previous half century. Coastal tide gauge measurements confirm this observation, but indicate that similar rates have occurred in some earlier decades (Bindoff et al., 2007).

There are uncertainties in the estimates of the contributions to sea level change, but understanding has significantly improved for recent periods. For the period 1961 to 2003, the average contribution of thermal expansion to sea level rise was 0.4 ± 0.1 mm/yr (Bindoff et al., 2007). During recent years (1993–2003), for which the observing system is much better, thermal expansion and melting of land ice each account for about half of the observed sea level rise, although there is some uncertainty in the estimates. Thermal expansion is projected to contribute more than half of the average rise, but land ice will lose mass increasingly rapidly as the century progresses (Bindoff et al., 2007). Inability to account for all the processes leads to one uncertainty in sea level rise projections. Although simulated and observed sea level rise agree reasonably well for 1993 to 2003, the observed rise for 1961 to 2003 is not satisfactorily explained, as the sum of observationally estimated components is 0.7 ± 0.7 mm/yr less than the observed rate of rise. This indicates a deficiency in current scientific understanding of sea level change and may imply an underestimate in projections (G.A. Meehl et al., 2007).

The observational constraint on sea level rise projections is also weaker, because records are shorter and subject to more uncertainty. As well, current scientific understanding leaves poorly known uncertainties in the methods used to make projections for land ice. The IPCC sea level rise projections are integrated with scenarios of CO_2 concentration; yet, uncertainties in carbon cycle feedbacks are not included in the results. The carbon cycle uncertainty in projections of temperature change cannot be translated into sea level rise because thermal expansion is a major contributor and its relation to temperature change is uncertain (G.A. Meehl et al., 2007).

Possible interactions between freshwater fluxes from ice sheets, ocean circulation, and climate may also lead to unexpected changes in the melting of glaciers (Alley et al., 2005). A local change in the density distribution through temperature and salinity anomalies will alter the horizontal pressure gradients, and therefore will be balanced by a change in circulation patterns. Large-scale circulation changes may redistribute characteristic water masses, leading to different sea level changes regionally. In the case of the Atlantic meriodonal overturning ciruculation (MOC), if the deep-water formation rate was decreased or if the deep water formed became less dense, sea level rise in the North Atlantic region would be expected to be stronger than the global average (Landerer et al., 2007). Anomalies on an ever smaller scale may cause significant concern. For instance, along the California coast high tide levels are rising faster than mean sea level for reasons that are not understood (D. Cayan et al., 2006).

Changing mass of the great ice sheets of Greenland and Antarctica represents the largest unknown in predictions of global sea level rise over the coming decades. The flow of several large glaciers draining the Greenland Ice Sheet is accelerating. This change, combined with increased melting, suggests that existing estimates of future sea level rise are too low (Dowdeswell, 2006; Hansen et al., 2007). While the IPCC acknowledges discharge of ice from the ice sheet has accelerated due to increased ice flow in recent years, limited understanding of the relevant processes prohibits projections of how much it would add to sea level rise (Bindoff et al., 2007). For instance, glacier discharge to the sea has increased in recent years in both Greenland and the Antarctic as warm water melts the floating ends of glaciers from below. This new evidence indicates that ocean temperature plays a more critical role in determining how much glacial melt contributes to changes in sea level than the warming atmosphere (Bindschadler, 2006). Positive feedbacks in ice sheet collapse are also of concern. The lower albedo of the exposed ice-free land causes a local climatic warming whereby melt water on the surface might accelerate ice flow. A climate forcing that switches the abledo of a sufficient portion of an ice sheet could be catastrophic. The unknown is how much human-made climate forcing is needed to cause the albedo-flip mechanism on West Antarctica and/or Greenland on a scale large enough to initiate multiple feedbacks and nonlinear ice sheet collapse (Hansen et al., 2007)?

The IPCC concurred that ice shelf collapse due to surface melting is unlikely during the 21st century, but expressed low confidence in the inference because of large systematic uncertainty in the regional climate projections, and the uncertainty of episodic surface melting (G.A. Meehl et al., 2007). Satellite and in situ observations of ice streams behind disintegrating ice shelves highlight some rapid reactions of ice sheet systems. This raises concern about the overall stability of the West Antarctic Ice Sheet, the collapse of which would trigger another five to six meters of sea level rise (G.A. Meehl et al., 2007).

Hansen et al. (2007) contend that existing ice sheet models are missing realistic representation of the physics of ice streams and icequakes, processes that are needed to obtain realistic nonlinear behavior. In the absence of realistic models, Hansen et al. (2007) argue that it is better to rely on information from the Earth's history which reveals that large changes of sea level occur within century and shorter timescales. Regardless of the potential for abrupt climate change, the IPCC scenarios might be overly conservative. The rate of rise for the past 20 years of the reconstructed sea level is 25% faster than the rate of rise in any 20-year period in the preceding 115 years (Rahmstorf et al., 2008). Therefore, a rise of over 1 m by 2100 for strong warming scenarios cannot be ruled out, because all that such a rise would require is that the linear relation of the rate of sea level rise and temperature, which was found to be valid in the 20th century, remains valid in the 21st century (Rahmstorf, 2007).

Uncertainty remains on the exact amount of future sea level rise. Nevertheless, sea level is currently rising and will continue despite mitigation efforts. Sea level rise alone is a problem that is perceived to have a long lead-time. The real problem is the combination of storms and sea level rise: when flood levels exceed a design basis that was determined decades ago. This holds true for any type of coastal defense structure. Protective structures built to withstand past conditions can not withstand elevated water levels in conjunction with storms (Leatherman & Kershaw, 2001).

2.2. Coastal Storms

The Pacific coast contends with storms primarily in the winter months. Higher sea levels occur during autumn and winter due to seasonal wind patterns, and upwelling along the California coast worsens the impact of storms (D. Cayan et al., 2006). In addition, the tide remains near the maximum level for approximately two hours, and during winter, higher-high water always occurs during very early morning hours, thereby hindering preparations that must be carried out the night before the storm arrives (Flick & Badan-Dangon, 1989).

The Atlantic has two storm seasons. Generally, most hurricanes occur from June to September, with hurricane season officially ending in November, and northeasters prevail from October to May (Farris, 2007; Zhang et al., 2000). Hurricanes and nor'easters differ in the type of impact. Although hurricanes produce higher surges, they have shorter duration and influence a relatively small length of coastline. While nor'easters are typically lower-energy, they pose more of a threat to shoreline erosion, since they occur more frequently, last longer, and cover larger areas (Frumhoff et al., 2007; Pilkey Jr. et al., 1984; U.S. National Research Council, 1990; Zhang et al., 2000).

The major damage from hurricanes occur within 100 to 150 km of the landfall position, except when torrential rains continue after a hurricane moves far inland, causing extensive river flooding (Simpson & Riehl, 1981). Typically, the storm surge is the most dangerous component of a coastal storm with historically disastrous coastal flooding occurring when strong storm surge coincides with high tide (Pugh, 1987). A storm surge is a sudden movement of water caused by a rise in sea level due to low barometric pressure and high wind (Pugh, 1987). Water weighs approximately 1,700 pounds per cubic yard, and currents created by the tide combine with the action of the waves to severely erode beaches and coastal highways. Many buildings withstand hurricane force winds until their foundations, undermined by erosion, are weakened and fail (National Hurricane Center, 2008). The importance of storm surge is not just the simple flooding it brings, but rather the elevation of still-water surfaces upon which waves may extend their cascade of energy, erosive action, and battering for hundreds of meters- sometimes kilometers - in-land from ocean and bay shores (Simpson & Riehl, 1981). Moreover, wave energy increases with the square of the wave height. Thus, a 0.6 meter (2 foot) wave would have 4 times the energy of a 0.3 meter (1 foot) wave. Small changes in water level can cause significant changes in wave energy and the potential for shoreline damage from wave forces (California Coastal Commission, 2001).

Bathymetry influences the height of the surge caused by a storm. A shallow slope off the coast will allow a greater surge to inundate coastal communities. While areas with a steeper continental shelf will not see as much surge inundation, large breaking waves can still present major problems (National Hurricane Center, 2008). In a closed basin, such as Chesapeake Bay, the effects of a surge can be increased because the water is trapped at one end. The shallow depths throughout most of the Bay make its shores susceptible to flooding during storm surges (Ward et al., 1999).

However, analysis of storm surges is not straightforward. During Hurricane Eloise in 1975 a tidal maximum of 4.9 m (16 feet) was observed. Post analyses were unable to account for more than a 2.8m (9.2 feet) rise caused by the storm surge, plus 0.7 m (2.3 feet) attributable to longer-term anomalies in sea level. The remaining 1.4 m (4.6 feet) is considered to have resulted from an unusual contribution from wave setup due to the peculiar bathymetry. Here water depths average less than 3 m (9.8 feet) nearshore and then drop rapidly to depths of more than 15 m (49.2 feet) in less than 1 km. The evidence is that significant waves of about 10.5 m (34.4 feet) approached within several kilometers of shore before breaking and cascading massive amounts of water shoreward (Simpson & Riehl, 1981).

Coastal storms have dramatic impacts, but the occurrence of storms is highly variable. The relationship between climate change and increased storm frequency and intensity is difficult to establish due to muti-decadal oscillations. The El Niño Southern Oscillation cycle (ENSO) is a natural coupled oscillator of the tropical Pacific Ocean and atmosphere. The warm and cool episodes are phases of a self-sustaining cycle (Graham & White, 1988). Sea level atmospheric pressures measured at Easter Island, representing the South Pacific subtropical high, and Darwin, Australia, representing the Indonesian equatorial low, oscillate in opposition and this phenomenon is termed the southern oscillation. El Niño is preceded by strong trade winds and coincides with a relaxation of the winds and is evident in the presence of excessively warm water off the coast of Peru (Wyrtki et al., 1976).

Most of the major damage in coastal California over the past century has taken place during El Niño years due to high tides, higher-than-normal sea level, and more frequent and larger storm waves (Andrews et al., 2004; Griggs et al., 2005). During certain intense ENSO periods, very large atmospheric lows develop north of the Hawaiian Islands resulting in extremely long west-to east fetches and high winds. These wind fields generate large amplitude, long-period waves out of the west that result in the impacting of exceptional swell on the southern and central coasts of California (Seymour, 1996). These same storms pick up considerable moisture from the warm tropical waters producing high rainfall causing coastal landslides and greatly accelerating cliff erosion (Griggs et al., 2005). Sea surface temperature is also shown to be well correlated with increases in large wave events, and while overall wave intensity has decreased in the last 20 years, the number of large wave events has increased (Seymour, 1996).

The pattern of steric sea level rise in the Pacific coincides with a tendency towards more prolonged and stronger El Niños over this same period. Strong west to east gradients in the Pacific have weakened, since it is now cooler in the western Pacific and warmer in the eastern Pacific (Bindoff et al., 2007). The observed trend for more ENSO events since 1976 has a probability of occurrence of once in every 1,100 years. Given the unlikelihood of this trend, sustained El Niños conditions could be a consequence of climate change (K. E. Trenberth & Hoar, 1996). Furthermore, the most recent period of time with a climate warmer than today was during the early Pliocene when sea surface temperature differences across the equatorial Pacific was similar to a modern El Niño event (Wara et al., 2005).

Similar to ENSO, the occurrence of hurricane landfalls on the United States might be related to alternating intervals of persistent above-average and below-average surface temperature of the North Atlantic Ocean. The cycle of temperature variations, known as the Atlantic Multidecadal Oscillation (AMO), has been identified by studying records based on thermometer readings that date back to the late 1800s. The historical record of major hurricane landfalls on the U.S. east coast from 1903 to 2000 shows that landfalls are generally more common during warm phases of the AMO than they are during cold phases (Poore et al., 2006).

The number of tropical cyclones and cyclone days as well as tropical cyclone intensity has increased over the past 35 years in particular a large increase was seen in the number and proportion of hurricanes reaching categories 4 and 5. The North Atlantic shows a statistically significant increase since 1995. The increase in category 4 and 5 hurricanes has not been accompanied by an increase in the actual intensity of the most intense hurricanes (Webster et al., 2005). However, models have linked increased temperature with an increase in storm intensity (K. Emanuel, 2005; K. A. Emanuel, 1987). The potential intensity of tropical cyclones does not respond directly to sea-surface temperature, but on the whole temperature profile of the troposphere. Potential intensity of the storm increases much more because observed atmospheric temperature does not keep pace with sea-surface temperature (K. Emanuel, 2005).

The 2005 North Atlantic hurricane season was the most active on record by several measures, surpassing the very active season of 2004. Even before the peak in the seasonal activity, the seven tropical storms in June and July were the most ever, and hurricane Dennis was the strongest on record for the month of July and the earliest ever fourth-named storm. The record 2005 North Atlantic hurricane season featured the largest number of named storms. It had the largest number of hurricanes recorded, and is the only time there have been four category 5 storms. Six of the eight most damaging storms on record for the USA occurred from August 2004 to September 2005 (K. E. Trenberth et al., 2007).

Nonetheless, until very recently the coastal environment has been relatively calm; this is not the norm on a longer time scale. From 1965 to 1990, when the populations of Florida and other southern states grew enormously, and nuclear power plants were constructed to meet energy needs, only two major hurricanes (Gloria and Hugo) struck the East Coast and none struck Florida (Neumann et al., 2000). Similarly, in California, considerable coastal development took place between the mid-1940s and the mid-1970s, a period characterized by below-average rainfall and storm frequency (Griggs et al., 2005).

Proxy records provide evidence of climate further back in time. Corals and marine sediment cores record vertical wind shear and sea surface temperature and these records indicate that the average frequency of major hurricanes decreased gradually from the 1760s until the early 1990s, reaching anomalously low values in the 1970s and 1980s. The phase of enhanced hurricane activity since 1995 is not unusual compared to other periods of high hurricane activity in the record (Nyberg et al., 2007).

While it is anticipated that the southern states must live with hurricanes, history shows that the northeast can be devastated by hurricanes as well. The most intense hurricane to strike the Northeast in recorded history was in 1938. The Great New England Hurricane of 1938 made landfall in central Long Island, then moved north into Connecticut, Massachusetts, and Vermont (Frumhoff et al., 2007). Sustained hurricane winds occurred throughout most of southern New England and the eye of the storm was observed in New Haven, Connecticut. Rainfall from the hurricane resulted in severe river flooding across sections of Massachusetts and Connecticut. Storm tides were 4.3 m to 5.5 m (14 to 18 feet) across most of Connecticut and 5.5 m to 7.6 m (18 to 25 feet) from New London east to Cape Cod (Vallee & Dion, 1998).

Along the California coast, the long-term variability of storminess can be estimated from nearly continuous hourly tide gauge data from San Francisco (SFO) that span from 1858 to 2000. Although heightened storminess has occurred during the last two decades, the activity levels observed are not exceptional compared to earlier periods such as the early 1900s and the late 1930s to early 1940s (Bromirski et al., 2003). Moreover, tree ring data, ship logs, and insurance records for the past two centuries clearly show that from the 1940s until the 1970s rainfall and high storm winds have been far less critical than in most preceding periods. Ship logs describe storms with 15 m to 18 m (50 to 60 foot) waves and land subdivision plots on record show that entire city blocks and streets along the coast have disappeared (Kuhn & Shepard, 1981, 1983). In particular, the winters of 1884, 1886, 1889, 1890 and 1891 brought unusually severe cyclonic sea storms to Southern California. The intense rainfall caused sediment saturation of the bluffs, and a large storm swell coupled with high tides coincided with river basin flooding (Kuhn & Shepard, 1981). Flooding in 1862 was so severe that all coastal valleys and deltaic areas in southern California were inundated. High tides prevented the runoff of flood waters for a considerable period (Kuhn & Shepard, 1981).

These historical storm events indicate that until recently nuclear power plants have operated in a relatively calm coastal environment. An increase in storm frequency or intensity has consequences to safe operation of nuclear power plants. In addition, measures must be taken to protect coastal sites from storm damage and erosion. Protecting shorelines come with additional financial costs and costs to the environment that will be explored in the next section.

2.3. Shoreline Erosion and Coastal Defenses

Erosion of shorelines is most apparent during storm events. Sea level rise allows energetic storm waves to attack higher elevations of the shoreline thus enabling erosion; furthermore, high sea level has been found to exert a more significant impact on erosion rates than changes in offshore wave conditions (Dickson et al., 2007; Leatherman, 2000; Zhang et al., 2004). Sea level rise will cause the waters of the continental shelf to deepen reducing bottom stresses, thereby enhancing wave generation (U.S. National Research Council, 1987). Along open-ocean beaches, over 90% of the retreat due to sea level rise is caused by erosion; the opposite is generally true for coastal marshes in sheltered bays, lagoons, and estuaries with limited wave action (Leatherman, 2000). The primary reason that sea level rise would induce beach erosion is that natural beach profiles are concave upward; this geometry results in wave energy being dissipated in a smaller water volume than without sea level rise, and thus the turbulence generated within surf zone is greater. The profile responds by conforming to a more gentle nearshore slope, which requires a redistribution of sand from the beach face to offshore (U.S. National Research Council, 1987; Zhang et al., 2004). The rate of erosion at any particular location is dependent on a number of factors that include land use, sediment composition, and orientation of the shoreline, bathymetry of the offshore region, and the local wind fetch for generation of waves (Cronin et al., 2003).

High-energy and high impact events, from wave, tide and wind forces are characterized by large spatial and temporal variability. As a result coastal landforms can give the impression of robustness rather than sensitivity to environmental stresses over the short-term (Pethick, 2001). Long-term changes to the energy environment can, therefore, result in adjustments to coastal landforms that are not anticipated by coastal users that tend to adopt a short-term variations as the norm (Pethick, 2001). For instance, the cliffs of southern California and Chesapeake Bay experience sudden or episodic erosion events. In southern California erosion was traditionally measured by placing nails in cliffs. When the nails did not change over years or even decades it was concluded that erosion was not a problem in the region. However, cliff retreat in this region occurs suddenly during storms that bring heavy rains causing landslides of the cliff and undercutting from wave action (Kuhn & Shepard, 1981, 1983). Failure or slumping occurs when the material composing a bluff collapses due to gravity; as a result, the cliff has a more gradual slope, which increases the bluff's stability. However, wave action continues to remove material from the base of the bluff, which steepens the slope again, decreasing stability. Consequently, coastal bluffs rarely attain stable slopes (Ward et al., 1999). Steep cliff faces surrounding Chesapeake Bay have been known to collapse catastrophically when they become saturated with water. Sandy soils above the clay layer become saturated and the water seeps out causing soil particles to be removed just above the clay layer. The overlying soil can collapse as this support is removed (Mayrland DNR, 1999; Ward et al., 1999).

While some events might be catastrophic events, not all shoreline erosion is detrimental. Dunes, beaches, and wetlands are critical habitats for a diverse array of estuarine flora and fauna. Erosion delivers sediment that is critical to maintaining the elevations of these habitats, particularly in response to sea level rise (Cronin et al., 2003). Moreover, wave action also serves to transport sediments to beaches along the shore thereby building beaches and buffering the cliffs against further erosion (Cronin et al., 2003; Dickson et al., 2007; Maryland DNR, 2007).

Engineered measures to protect shorelines alter the sediment supply to local beaches. Shoreline changes induced by variability of sediment supply can be much larger than those resulting from sea level rise on some coasts (Zhang et al., 2004). In addition, shore armoring reduces bluff erosion in the short term, but increases erosion of the beach in front of the armored bluff due to wave reflection (Gutierrez et al., 2007).

Furthermore, coastal armoring hinders the ability of habitats and species to migrate inland in response to rising sea levels leading to coastal squeeze and the loss of valuable habitat (Glick & Clough, 2006; Neumann et al., 2000; Pethick, 2001). Adopting a more dynamic viewpoint of coastal management ensures that coastal landforms remain intact with a change in only their relative location (Pethick, 2001). One strategy for planned retreat restricts coastal development thereby reducing the need for shore armoring (Neumann et al., 2000). Long-term investments such as nuclear power plants require shore armoring to operate in the coastal environment; therefore, these types of developments prevent the implementation of the coastal retreat strategy.

Regardless of the environmental costs the demand for protection along developed shorelines is likely and a necessary feature to protect nuclear power plants. The choice of coastal structure for erosion mitigation depends on site-specific factors. Structures that work satisfactorily in one location can be totally inadequate or detrimental in another location (U.S. National Research Council, 1987). Sandy coastal shores are made of natural units and must be treated as such. The effect of a structure on the remainder of the shoreline must be analyzed before construction, and the plan must mitigate for adverse effects. The direction and magnitude of sediment transport is the most uncertain feature for coastal project plans, and site-specific data are difficult and expensive to obtain (U.S. National Research Council, 1987). Moreover, sea level rise makes predictions of sediment transport increasingly difficult. A change in depth alters the propagation of tides and can alter the near-shore net transport thus changing the direction of net sediment transport (Liu, 1997).

Several options are available to protect coastal developments including seawall, revetments, jetties, and beach nourishment. Failure of defenses is always a possibility particularly if the defenses are not heightened to accommodate sea level rise. While extensive flooding results when the still-water level exceeds the top of the defense structure, before this level is reached considerable flooding is likely to occur from overtopping by waves (Pugh, 1987). Breakwaters, jetties, and seawalls will need to be reinforced to withstand greater forces due to sea level rise. For seawalls, the foundation will also be exposed to greater scour (California Coastal Commission, 2001). The cost of a defense wall grows more rapidly than a simple linear increase with increases of design height: the width of the footings must also be increased in proportion to the height, so that in terms of material alone the increase is more closely proportional to the square of the height (Pugh, 1987).

Estimates of the fixed construction costs for dikes or levees built to protect against a one meter rise in sea level range from $150 to $800 per linear foot (1990 dollars). Corresponding cost estimates for sea wall and bulkhead construction range from $150 to $4,000 per linear foot (1990 dollars) (Neumann et al., 2000). Beach nourishment is generally favored over the construction of hard structures and may be necessary to mitigate for the adverse impacts from shore armoring. However, beach nourishment is costly at $2.6 million per mile in 1990 dollars (U.S. National Research Council, 1990). Loss rates associated with beach nourishment are still only 30 percent due to the lack of ability to forecast storms, and quantify wave and sediment conditions (U.S. National Research Council, 1990). Erosion of a replenished beach will occur at a rate that it is at least 10 times that of the natural beach; therefore, the beach must be repeatedly nourished requiring long-term financial commitment (Pilkey Jr. et al., 1984; Pilkey et al., 1998). Other drawbacks of replenishment projects include the unknown environmental impact of replenished beaches to coastal flora and fauna and the lack of availability of sand (Pilkey et al., 1998).

Adapting to the hazards of the coastal environment comes with financial and ecological costs. For this reason, limiting coastal development and abandoning existing developments remains an option for adapting to climate change. Adaptation of coastal developments is particularly challenging because of the uncertainty regarding the exact amount of sea level rise. Nevertheless, coastal sites have an aesthetic that attracts development and in the case of nuclear power coastal sites provide much needed cooling water. The next section discusses the methods used to model sea level rise and analyze climate change impacts at coastal sites.

3. Coastal Methods

The analysis of climate impacts at coastal nuclear power plants focuses on plants in the United States due to: the large fleet of nuclear power plants at coastal locations in this country (both Atlantic and Pacific), the availability of elevation data, and relatively easy access to reports on operational problems during storms. Adaptation to climate risks can be viewed at three time-scales including responses to: current variability (which also reflect learning from past adaptations to historical climates); observed medium and long-term trends in climate; and anticipatory planning in response to model-based scenarios of long-term climate change (Adger et al., 2007). In this section these three different approaches are used to evaluate nuclear power adaptation to the coastal environment. First, future sea level rise and storms conditions are modeled using ArcGIS. Next, in order to understand how nuclear power operations deal with current climate variability the impacts of recent storm events are reviewed. Finally to determine if the necessary anticipatory measures are being made current practices used to determine design parameters for external events are evaluated.

These three approaches are necessary to evaluate the criteria outlined in Chapter 1. For instance, impairment to adaptation might not be immediately apparent, rather it is a future problem revealed by sea level rise modeling and coastal vulnerability analysis. However, direct impacts to operation can only be assessed by looking at operational experience. Indicators are used to determine whether the criteria are met at the coastal locations as shown in Table 3.

Table 3. Criteria and indicators used to evaluate nuclear power plants at coastal locations.

Criteria	Indicator
Interrupted Operation	Unplanned shutdowns, power reductions
Financial Costs	Flood protection, revenue loss
Adaptation Impairment - Human Systems	Loss of adjacent lands
Adaptation Impairment - Natural Systems	Loss of coastal habitat (coastal squeeze)
Other Environmental Problems	Safety problems that include: Loss of off-site power Communication failure Restriction of evacuation routes Equipment malfunction Unplanned shutdowns

3.1. Sea Level Rise Methods

Inundation modeling and analysis of shoreline vulnerability was performed on nuclear power plants currently operating within 2 miles of the Pacific and Atlantic coastlines of the United States. Figure 1 shows locations of reactors examined in this study.

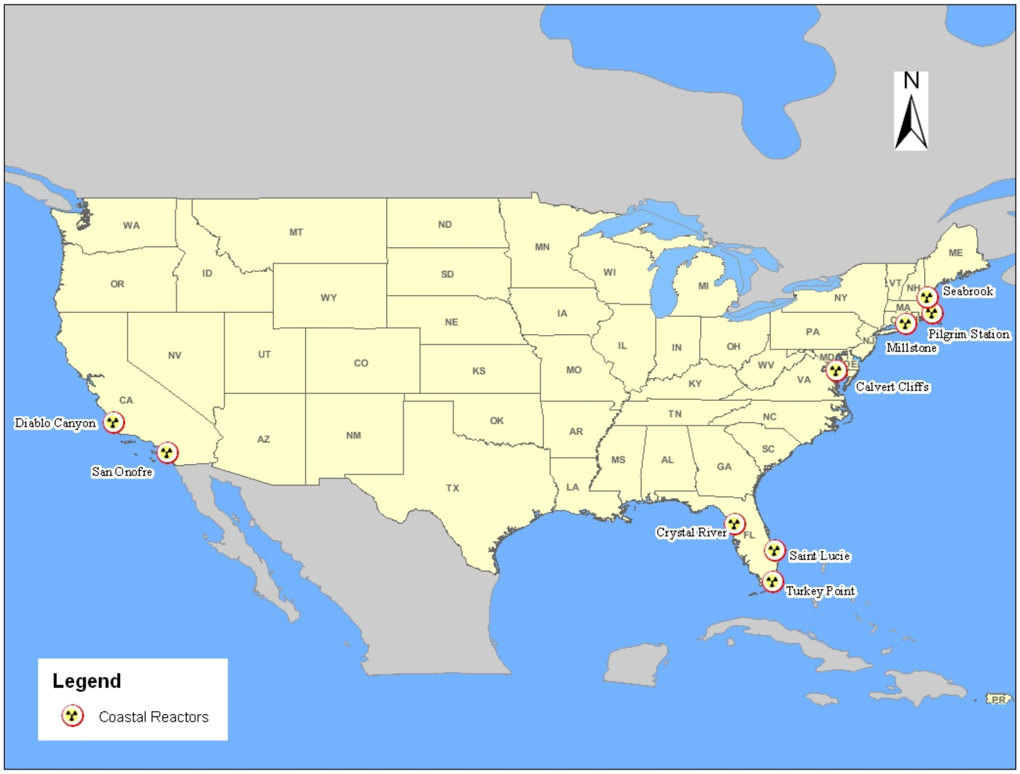

Figure 1. Location of coastal reactors analyzed for vulnerability to sea level rise.

In reality sea level rise and coastal storms can impact reactors located farther inland; however, difficulties in interpretation arise for sites located farther inland. For instance, the model would show all elevations below sea level as flooded, even if a berm is present that would block the flow of water. Sites that are located farther inland are more likely to have topographical variation that would make interpretation of results difficult. In this study only two reactors are a considerable distance from the shoreline: Seabrook Station and Crystal River are 2 miles from the shore, but each site has a gentle slope that permits the use of this type of model. Including these reactors in the study provides valuable information because one potential adaptation strategy is to locate reactors farther inland. This involves extra costs in constructing longer intakes, so it is worthwhile to see whether this will ensure the sites are not flooded during storms.

The exact amount of sea level rise that is going to impact each of the sites is not certain; therefore, it is necessary to develop scenarios. Time scenarios and the corresponding rise in sea level were based on the work of the International Atomic Energy Agency (IAEA) and the Intergovernmental Panel on Climate Change (IPCC) respectively. The IAEA's report, *Flood Hazard for Nuclear Power Plants on Coastal and River Sites* recommends utilizing the results of investigations by the IPCC to assess the effect of climate change on nuclear power plants; in addition, to account for uncertainty, the upper bound of the 95% confidence interval should be used. The lifetime of a nuclear power plant, including decommissioning time, can be taken to be 100 years, but it should be possible to take measures to prolong this as far as necessary (IAEA, 2003c). Considering the entire plant lifetime an agreed upon estimate for increase in mean sea level ranges from 35-85 cm; in addition, the IAEA advises that land subsidence should be considered along with climatic changes.

Four different time ranges (base year 2008) were considered in evaluating sea level rise including: 1) the end of reactor operation, 2) the end of reactor lifetime, 3) 100 years, and 4) 150 years as shown in Table 4.

Table 4. Description of time-frames used in sea level rise modeling.

Time-frames	Description
End of Reactor Operation	Determined by years remaining in operating license.
End of Reactor Lifetime	100 years from when reactor began operating.
100 years in the future (2108)	Assuming new reactor construction begins today.
150 years in the future (2158)	New reactor construction within the next 50 years.

The years remaining in operation for each reactor were determined by the license expiration date. Pilgrim Station is currently in the application process for a license extension and therefore two reactor operation scenarios were determined: one based on the current license and a second based on the license extension. Reactor lifetime was determined by subtracting the years in operation from 100 as recommended by the IAEA. Construction time was not included in calculating the reactors lifetime because of extended construction periods at several of the reactors included in the study. In order to determine the appropriateness of these sites for new reactor construction sea level rise was modeled for 100 years in the future (assuming new reactor construction begins today) and a time-frame of 150 years to take into account future construction.

The four time-frames were used to generate sea level rise scenarios as described in Table 5.

Table 5. Scenario description and corresponding quantity of sea level rise for California and Florida, and the Northeast region.

Scenario	Description/Rationale	CA/FL	Northeast
End of Operation/ Life of Reactor	Global average of sea-level rise since 1993	3 mm/yr	4.3 mm/yr
100 year low	Upper limit of low IPCC emission scenario	0.39 m	0.51 m
100 year mid	Upper limit of high IPCC emission scenario	0.59 m	0.72 m
100 year high	Estimate suggested in IAEA report	0.85 m	0.85 m
1 m	Possible by end of century if linear trend continues	1 m	1 m
150 year low	Low 100 + 50 x (3.9 mm/yr) or (4.3 mm/yr)	0.59 m	0.72 m
150 year high	Mid 100 + 50 x (9.7 mm/yr)	1.21 m	1.21 m

Aside from land subsidence in the mid to north Atlantic region all locations have sea level rise rates approximately equal to the global average. The current rate of sea level rise of 3 mm/yr was assumed to remain constant for reactor operation and the total life of the reactor. The average rate of subsidence is 1.3 mm/yr for Atlantic sites outside of Florida (Frumhoff et al., 2007; Maryland DNR, 2007; Neumann et al., 2000). Therefore, the lowest sea level rise scenario for Seabrook, Pilgrim, Millstone, and Calvert Cliffs included the rate of subsidence at 4.3 mm/yr (3 mm/yr + 1.3 mm/yr). The various 100 to 150 year scenarios are based on scenarios developed by the IPCC. The 100 year low scenario is 0.39 m, equivalent to the upper limit of the lowest IPCC emission scenario, while the mid-scenario is 0.59 m, the upper bound of the high emission scenario (G.A. Meehl et al., 2007). These are global averages, so for sites in the northeast an additional 1.3 mm/yr is added to account for land subsidence. These 100-year scenarios arrive at figures that are less than 0.85 m, the upper limit recommended in the IAEA report; therefore, this amount was included as the 100 year high scenario. In addition, 1 m sea level rise was modeled for all sites because this amount of sea level rise by the end of the century can not be ruled out (Rahmstorf, 2007). The low 150 year corresponds to the upper limit for the lowest emission scenario developed by the IPCC. This scenario uses the low 100 scenario for the first 100 years, and projects the next 50 years to have a rate of sea level rise of 3.9 mm/yr. This is lower than the current trend for sea level rise for sites experiencing land subsidence; therefore, 4.3 mm/yr was held constant for the next 50 years under the low emission scenario. The high 150 year scenario used the mid-100 year scenario for the first 100 years, and for the next 50 years a rate of 9.7 mm/yr corresponding to the highest IPCC emission scenario. The 100 year mid scenario and

150 year low scenario have equivalent amounts of sea level rise.

Just looking at change in mean sea level is not sufficient in analyzing the impact of sea level rise. Societal impacts of sea level change occur via the extreme levels, mainly in the form of storm surges generated by tropical or extra tropical cyclones, rather than as a direct consequence of mean sea level changes (Bindoff et al., 2007). In the case of nuclear reactor operation, the rate of sea level rise is slow enough that defenses can be maintained to protect the day to day operations. The real problem is during storms when suddenly flood levels are higher than they were in decades past; therefore, storm scenarios were included in the analysis. As a baseline the extent of flooding currently experienced during storms was modeled. Next surge heights for specific storms and hurricane categories were added to the projected rise in sea level. The effect of El Niño, storm surges, and wave induced surges were modeled for sites in California. In California, low pressure fronts change air pressure and can cause a short, one or two day long increase in water elevation, while El Niños can lower atmospheric pressure for many months increasing sea level by as much as 0.3 m (California Coastal Commission, 2001). Storm surge along the California coast, excluding the effect of waves, rarely exceeds 0.7 m in amplitude. However, a wave induced surge on a beach, depending on breaker height, can reach 1.5 m or more (D. R. Cayan et al., 2008). Along the east coast surges created from nor'easters and hurricanes were modeled. Nor'easters or winter storms are common at all sites on the east coast and often have a storm surge greater than 0.6 m (Coastal Zone Management, 2007). The storm surges associated with the Saffir-Simpson Hurricane Scale was utilized for the east coast as shown in Table 6. The height of surge associated with a particular hurricane category is given as a range. For the model, the low and high values of the Category I and Category IV were modeled, while the highest value in the range was used for the Category II and Category III storms.

Table 6. The Saffir-Simpson Hurricane Scale (National Weather Service, 2007).

Category	Wind speed	Storm surge
I	119-153 km/hr (74-95 mph)	1.2-1.5 m (4-5 ft)
II	154-177 km/hr (96-110 mph)	1.8-2.4 m (6-8 ft)
III	178-209 km/hr (111-130 mph)	2.7-3.7 m (9-12 ft)
IV	210-249 km/hr (131-155 mph)	4.0-5.5 m (13-18 ft)
V	> 249 km/hr (>155 mph)	>5.5 m (>18 ft)

In addition, climate models have shown the potential for more intense storms due to climate change (K. Emanuel, 2005; K. A. Emanuel, 1987; Poore et al., 2006); therefore, areas currently experiencing hurricanes lower on the scale were modeled with a one step increase. For instance, during Hurricane Isabel the storm surge that impacted Maryland was equivalent to a Category II hurricane, so a Category III storm was modeled for the site (Hennessee & Halka, 2003). The sites of Millstone, Pilgrim Station, and Seabrook were impacted by a Category III storm in 1938; therefore, a Category IV hurricane was modeled (Frumhoff et al., 2007). While historical evidence shows that California has experienced greater storms than those of recent history, a reliable way of predicting increased storms in California was not available.

Once the sea level rise scenarios were established, the conditions were modeled using ArcGIS version 9.2. Coordinates for the reactors, presented in Table 7, were available through various sources including the Virtual Nuclear Tourist (Gonyeau, 2007) and were easily verified from the satellite imagery.

Table 7. Coordinates for reactors included in sea level rise analysis.

Nuclear Power Plant	State	N	W
Seabrook	NH	42.898	-70.851
Pilgrim	MA	41.944	-70.577
Milstone	CT	41.312	-72.169
Calvert Cliffs	MD	38.435	-76.432
Saint Lucie	FL	27.348	-80.246
Turkey Point	FL	25.434	-80.329
Crystal River	FL	28.962	-82.697
San Onofre	CA	33.369	-117.557
Diablo Canyon	CA	35.211	-120.855

The USGS Digital Elevation Models (DEM) corresponding to the reactor locations were downloaded from GeoCommunity in Spatial Data Transfer Standard (SDTS) format (GeoCommunity, 2008). The SDTS conversion tool in Arc Toolbox was used to convert the Digital Elevation Model (DEM) from SDTS format to raster. The DEM was then projected onto satellite imagery for each reactor site. The satellite imagery is available through Environmental Systems Research Institute (ESRI) and is created from a variety of data sources including the U.S. Geological Survey (USGS) imagery for metropolitan areas, and the best available U.S. Department of Agriculture data through the National Agriculture Imagery Program, enhanced versions of USGS Digital Orthophoto Quarter Quadrangle, and imagery assembled by ESRI through the ArcGIS Online Content Sharing Program (ESRI, 2007).

The DEM was also used as the input layer for the raster calculator in spatial analyst. The raster calculator created a shapefile that covered elevations equivalent to a given rise in sea level. Analysis of elevation data to quantify land inundated due to sea-level rise is a commonly used method (Bales et al., 2007; Johnson et al., 2006; Michael, 2006; Neumann et al., 2000; Titus & Richman, 2001). ArcGIS allows one to develop clear visualizations of inundation from available elevation data.

The digital elevation model data consist of a sampled array of regularly spaced elevation values. These values are referenced horizontally to the North American Datum of 1927 and vertically to the National Geodetic Vertical Datum of 1929 (NGVD 1929). The NGVD 1929 was determined by holding mean sea level constant at the sites of 26 tide gauges, 21 in the U.S.A. and 5 in Canada. The reference plane in all other locations was based on a leveling technique, thus the datum was not mean sea level, the geoid, or any other equipotential surface (National Geodetic Survey, 1986).

The digital elevation models pose several problems during analysis. Because a leveling technique was used, NGVD 1929 was not sea level in areas where water levels diverge from the ideal plane even in 1929. Furthermore, Titus and Richman (2001) have determined that rising sea level and subsidence have caused sea level and NGVD to diverge 10 to 20 cm in most areas. Thus the elevation models are not an accurate reflection of how far the land is above sea level. Although the raster calculator was used to create a shapefile that covered the area at an elevation of 0 m at each site, and the resulting shapefiles followed the coastline at each site, these models should not be used for planning purposes. This model limits the ability to delineate between tides and storm generated waves because mean sea level is unknown. Moreover, several of the digital elevation models used in the study have low resolutions as shown in Table 8. Seabrook, Pilgrim, Millstone, and Crystal River have vertical resolutions of only 1 m limiting the sea level rise scenarios that could be examined. In addition, a 30 m horizontal resolution does not accurately capture the change in elevation at sites where elevation can change quickly over a short distance such as Calvert Cliffs.

Table 8. Resolution of Digital Elevation Models.

Site Name	State	X Resolution	Y Resolution	Z Resolution
Seabrook	New Hampshire	30 m	30 m	1.0 m
Pilgrim Station	Massachusetts	30 m	30 m	1.0 m
Millstone	Connecticut	30 m	30 m	1.0 m
Calvert Cliffs	Maryland	30 m	30 m	0.1 m
St. Lucie	Florida	10 m	10 m	0.1 m
Turkey Point	Florida	10 m	10 m	0.1 m
Crystal River	Florida	30 m	30 m	1.0 m
Diablo Canyon	California	10 m	10 m	0.1 m
San Onofre	California	10 m	10 m	0.1 m

Results are summarized in tables for each reactor site. Table 9 provides an example (portion) of a results table. The numbers in each cell represent the amount of sea level rise in meters. The top row is sea level rise alone and each subsequent row contains increasingly intense storm conditions, while the columns are successive time-scenarios. This particular reactor has 35 years until end of operation and 75 years until the end of reactor life. The rate of sea level rise is 3 mm/yr. The amount of sea level rise until the end of operation is determined by:
(3 mm/yr × 35 yrs) ÷ 1000 mm = 0.1 m. The amount of sea level rise at the end of reactor life is determined by: (3mm/yr × 75 yrs) ÷ 1000 mm = 0.2 m. The amount of sea level rise during the life of the reactor surrounded in a bold border is 0.2 m this is added to the 1.2 m during a Category I hurricane to reach a total of 1.4 m for sea level rise at the end of the reactor lifetime combined with a Category I hurricane.

Colors indicate the level of flooding. In those elevation models with only 1 m resolution the cells are colored grey to indicate that the level of flooding can not be determined by the model. "Potential for Flooding" is when the site first appears to start flooding according to model results, but the flood waters have not reached structures on the site, or covered the roads. "Considerable Flooding" describes conditions that cause flood waters to reach structures on the site or block roads to the site. The red color code, "Site Inundated" indicates that the entire site is covered in flood waters. The scenarios generated here are also compared to the Design Basis Flood levels for each of the sites that are available from U.S. NRC reports.

Table 9. Example of sea level rise results table. Values for sea level rise are in meters.

No Flooding	Potential For Flooding	Considerable Flooding	Site Inundated

Conditions	Scenarios: Current Storms	End of Operation	Life of Reactor	Low 100
Sea Level Rise		0.1	0.2	0.4
Northeastern	0.6	0.7	0.8	1.0
Category I Low	1.2	1.3	1.4	1.6
Category I High	1.5	1.6	1.7	1.9
Category II	2.4	2.5	2.6	2.8
Category III	3.7	3.8	3.9	4.1
Category IV Low	4	4.1	4.2	4.4
Category IV High	5.5	5.6	5.7	5.9
Category V	6.1	6.2	6.3	6.5

One limitation of this method is that elevation alone can not determine the location of a future shoreline after sea level rises. Erosion, in addition to inundation, is a concern and therefore a measure of the vulnerability of the coastline supplements this model.

Coastal vulnerability is difficult to quantify; however, data on vulnerability of shorelines throughout the U.S. coastline is available through a national assessment conducted by the U.S. Geological Survey (Thieler & Hammar-Klose, 1999a, 1999b, 2000). This is the most thorough study of coastal vulnerability in the U.S. The methods used in the data collection provide an index of the relative vulnerability of different shoreline segments to sea level rise based on coastal geomorphology, rate of sea level rise, past shoreline evolution, and coastal slope. The coastal vulnerability model used the rate of sea level rise for the past 50-100 years, and therefore has different results compared to the inundation model that considered the rate of sea level rise in the past decade only. Looking at these variables identifies those portions of the U.S. coastal regions the most at risk and the nature of that risk. Each coastal segment receives an overall ranking of risk: low, moderate, high, or very high. In order to develop the database Thieler and Hammar-Klose (1999, 2000) gathered relevant data from local, state and federal agencies, as well as academic institutions. Refer to Appendix 8 for a description of methods used by Thieler and Hammar-Klose.

The Coastal Vulnerability Index is a relative measurement of risk. The strength of this method is in the details, as they shed light on risks other than inundation. For instance, erosion rates are included in the analysis and the geomorphology variable expresses the relative erosion rates of different landform types. Inundation modeling reveals whether on-site flooding will occur, and if evacuation routes or site access will be affected indicating safety concerns and the need to invest in flood protection. The Coastal Vulnerability Index reveals the potential land lost due to erosion and sea level rise indicating impairment in the ability of natural and human systems to adapt.

3.2. Literature Review of Nuclear Operations at Coastal Sites

The next two sections of the coastal impacts analysis entail a literature review. The primary source of literature comes from documents generated by the U.S. NRC available through Agency wide Documents Access and Management System (ADAMS). This information system provides access to all image and text documents that the U.S. NRC has made public since November 1, 1999 and bibliographic records that the NRC made public before November 1999. These reports are reviewed for indicators of safety problems. Utility reports and industry journals provide additional information such as length of reactor shut-down and revenue losses.

The first section evaluates the vulnerability of nuclear power plants to climate change by reviewing problems encountered during past storms. Hurricanes can impact reactors much further inland; therefore, the impact hurricanes have had on reactors located in New Jersey, Pennsylvania, North Carolina, Virginia, Mississippi, Louisiana, and Texas are included in this part of the analysis. The purpose is to not only review impacts, but to look for evidence of adaptation and determine areas that continue to be vulnerable. The second section provides a review of how external events are currently incorporated in design of reactors located close to the coast. This is important to understand whether anticipatory measures are being taken, such as consideration of increases in precipitation, wind intensity, and sea level rise in design basis flood estimates.

4. Coastal Results

The coastal environment provides an ideal location for nuclear power plants, in terms of availability of cooling water; however, it is a challenging environment worsened by storms and sea level rise due to climate change. Section 4.1 contains results of inundation modeling and relative coastal vulnerability of each U.S. coastal reactor within 2 miles of the Atlantic and Pacific. The design basis flood levels for each reactor, available through the U.S. NRC, are compared to the scenarios generated in this study. The order of reactors analyzed in this section progresses from the most severe site flooding to those sites with the least amount of flooding.

The results described in Section 4.2 reveal that past hurricanes have provided vital learning opportunities, in that procedural changes have allowed for some adaptation to hurricane conditions. Still, specific areas remain a challenge to safety. Finally, in Section 4.3 the models used to generate probable storm conditions were found to give disparate results; moreover, the models that gave appreciably lower surge levels were adopted for use by the U.S. NRC.

4.1. Sea Level Rise Model Results

4.1.1. St. Lucie

The second reactor on the St. Lucie site began operation in 1983 and the operating license expires in 2043. St. Lucie has 35 years remaining in operation and the total life of the reactor was determined to be 75 years. St. Lucie is located on Hutchinson Island south of Fort Pierce Inlet in St. Lucie County, Florida. Hutchinson Island is the northern most barrier island on the east coast of Florida. Figure 2 provides a view of the site with the digital elevation model used in the study.

For the St. Lucie site, the probable maximum hurricane (PMH) causes a probable maximum surge elevation of 5.2 m (17.2 feet) above mean low water (MLW), and is the basis for the probable maximum flood. The plant grade level is 5.8 m (19 feet) above MLW. Additional measures to protect the plant are used such as reinforced concrete flood walls and building entrances elevated to 5.94 m (19.5 feet). Some important safety-related systems and components have additional protection such as an elevation of 6.71 m (22 feet) above MLW (Haney, 2006).

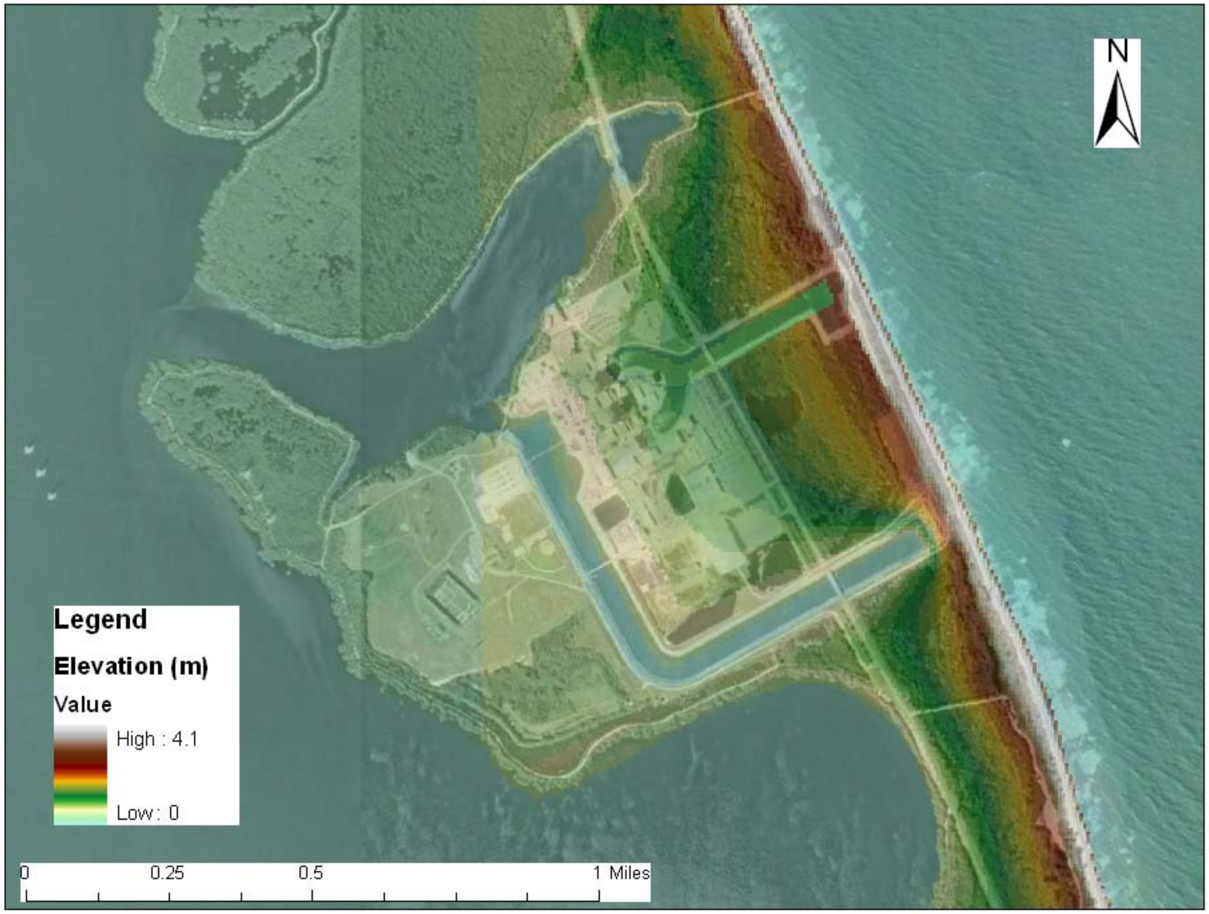

Figure 2. Satellite imagery of St. Lucie with Digital Elevation Model overlay.

Table 10. Sea level rise scenarios and results for St. Lucie.

No Flooding	Considerable Flooding	Site Inundated

Conditions	Current Storm	End of Operation	Life of Reactor	100 Years Low	100 Years Mid/150 Years Low	100 Years High	Sea Level Rise 1 m	150 Years High
	Scenarios							
Sea Level Rise		0.1	0.2	0.4	0.6	0.9	1.0	1.1
Northeastern	0.6	0.7	0.8	1.0	1.2	1.5	1.6	1.7
Category I Low	1.2	1.3	1.4	1.6	1.8	2.1	2.2	2.3
Category I High	1.5	1.6	1.7	1.9	2.1	2.4	2.5	2.6
Category II	2.4	2.5	2.6	2.8	3.0	3.3	3.4	3.5
Category III	3.7	3.8	3.9	4.1	4.3	4.6	4.7	4.8
Category IV Low	4	4.1	4.2	4.4	4.6	4.9	5.0	5.1
Category IV High	5.5	5.6	5.7	5.9	6.1	6.4	6.5	6.6
Category V	6.1	6.2	6.3	6.5	6.7	7.0	7.1	7.2

The site potentially begins flooding at 0.3 m with some flooding of roads at this stage, while considerable flooding of roads begins at 0.4 m as shown in Figure 3. A substantial amount of the site is flooded at 0.6 m, and the site is completely flooded at 0.7 m as shown in Table 10 and Figure 4. The site experiences considerable flooding under current storm conditions and high intensity hurricanes would cause flooding that approaches design limits within the life of the reactor. As shown in Table 11 the site receives a very high and high coastal vulnerability index (CVI) ranking for the coast and river side respectively.

Table 11. Relative vulnerability of each of the coastal variables and overall vulnerability of the coastline at St. Lucie.

Reactor	Tide	Waves	Erosion	Sea Level Rise	Geomorphology	Slope	CVI
Saint Lucie (coast)	Very High	High	Moderate	Low	Very High	Very High	Very High
Saint Lucie (river)	Very High	High	Moderate	Low	Moderate	Very High	High

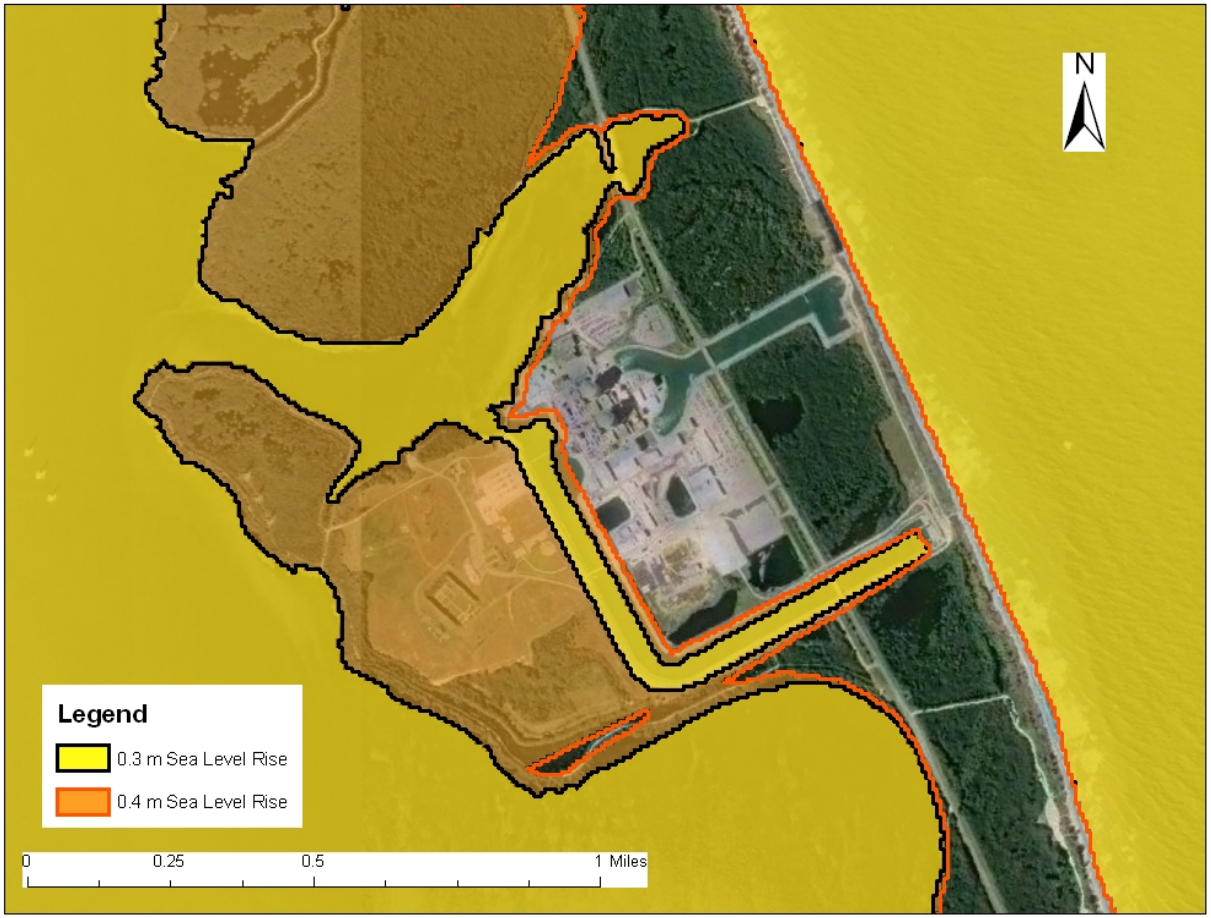

Figure 3. St. Lucie with a sea level rise of 0.3 m and 0.4 m.

Figure 4. St. Lucie with a sea level rise of 0.6 m and 0.7 m.

4.1.2. Crystal River

Crystal River unit 3 began operation in 1977 and the license expires in 2016. The reactor has 8 years remaining in the operating license and the total life of the reactor remaining was determined to be 69 years. Construction of a new reactor adjacent to this site has been proposed. The Crystal River plant is located on Florida's west coast approximately 1 mile from the Gulf of Mexico in Citrus County, Florida. Figure 5 provides a view of the site superimposed with the digital elevation model used in the study.

For Crystal River 3, the PMH results in a probable maximum surge elevation of 10.2 m (33.4 feet) above mean low water (MLW). The plant grade level is 9.3 m (30.5 feet) above MLW. Buildings housing class 1 components have been designed to withstand a surge of water of 12.5 m (41 feet) above MLW which also accounts for wave action and run-up. Therefore, the systems and components inside these buildings are protected from the effects of external flooding by the use of retaining walls, steel and concrete barriers, watertight equipment hatches, and watertight walls and doors. Additional specific provisions for flood protection include administrative procedures; such as, installation of dewatering pumps to control leakage through doors and walls. MLW is the zero reference height for the site as measured at the Crystal River plant intake canal at the Gulf of Mexico (Haney, 2006).

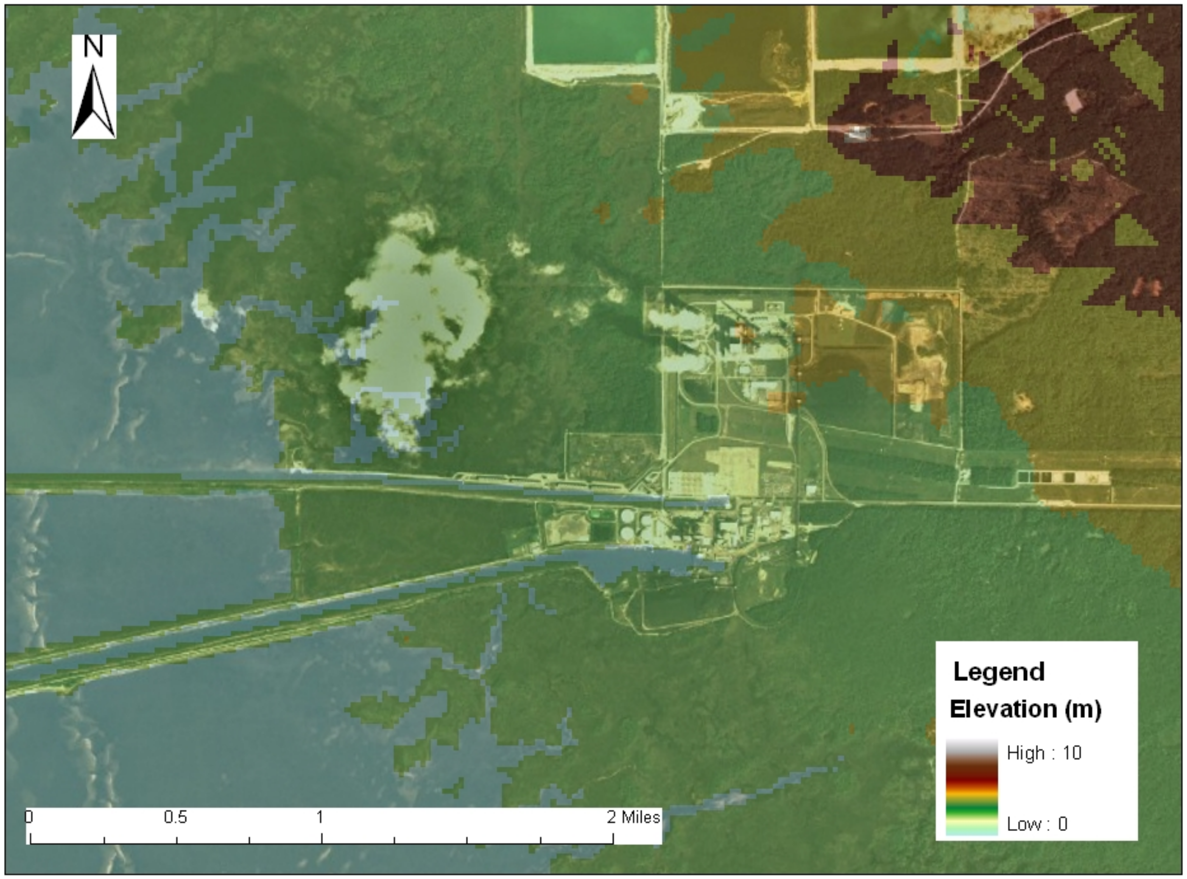

Figure 5. Satellite imagery of Crystal River with Digital Elevation Model overlay.

Table 12. Sea level rise scenarios and results for Crystal River.

Model Cannot Determine	Considerable Flooding	Site Inundated

Conditions	Scenarios: Current Storms	End of Operation	Life of Reactor	100 Years Low	100 Years Mid/150 Years Low	100 Years High	Sea Level Rise 1 m	150 Years High
Sea Level Rise		0.02	0.21	0.38	0.59	0.85	1.00	1.09
Category I Low	1.2	1.22	1.41	1.58	1.79	2.05	2.20	2.29
Category I High	1.5	1.52	1.71	1.88	2.09	2.35	2.50	2.59
Category II	2.4	2.42	2.61	2.78	2.99	3.25	3.40	3.49
Category III	3.7	3.72	3.91	4.08	4.29	4.55	4.70	4.79
Category IV Low	4	4.02	4.21	4.38	4.59	4.85	5.00	5.09
Category IV High	5.5	5.52	5.71	5.88	6.09	6.35	6.50	6.59
Category V	6.1	6.12	6.31	6.48	6.69	6.95	7.10	7.19

The digital elevation model for Crystal River has a 1 m vertical resolution; therefore, flooding can not be determined for sea level rise scenarios below 1 m as shown in Table 12. The site has considerable flooding with 1 m sea level rise and the entire site is covered with a 2 m increase in sea level as evident in Figure 6. However, the design basis flood level (12.5 m) for this site is higher than all scenarios generated here. The Crystal River site ranked moderate in the coastal vulnerability index (CVI) as shown in Table 13.

Table 13. Relative vulnerability of each of the coastal variables and overall vulnerability of the coastline at Crystal River.

Reactor	Tide	Waves	Erosion	Sea Level Rise	Geomorphology	Slope	CVI
Crystal River	Very High	Very Low	Low	Very High	Low	Very High	Moderate

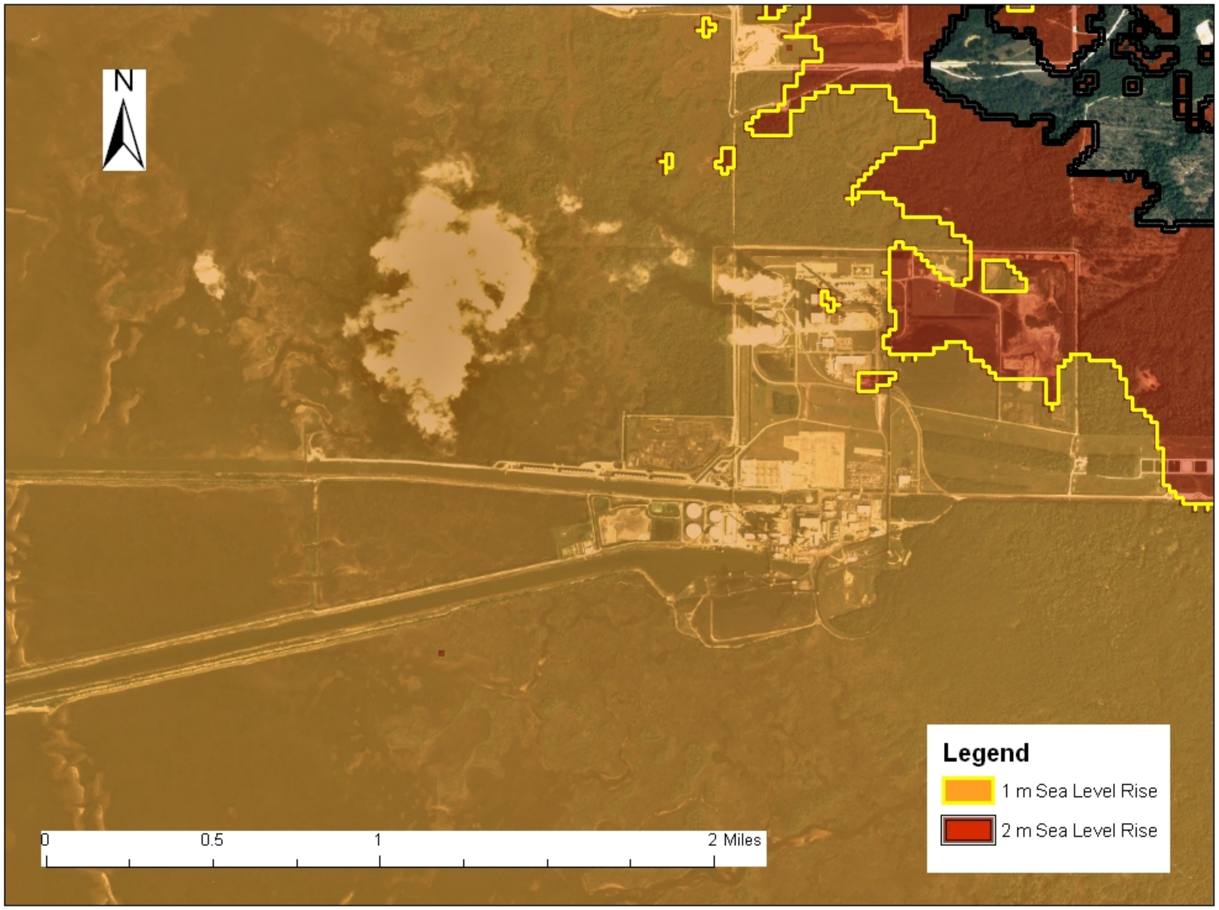

Figure 6. Crystal River with a sea level rise of 1 m and 2 m.

4.1.3. Turkey Point

Turkey Point Reactor-4 began operation in 1973 and the license expires in 2033. Turkey Point has 25 years remaining in operation and the total life of the reactor was determined to be 65 years. The Turkey Point units are located on the west shore of Biscayne Bay in Miami-Dade County, Florida. A new reactor has been proposed for this site. Figure 7 provides a view of the site superimposed with the digital elevation model used in the study.

For Turkey Point, the probable maximum hurricane results in a probable maximum surge elevation of 5.6 m (18.3 feet) above mean low water (MLW). The plant grade level is 5.49 m (18 feet) above MLW, and has been flood protected to an elevation of 6.1 m (20 feet) above MLW. Components vital to safety, with the exception of the intake cooling water (ICW) pumps, are protected against flood tides, and wave runup, to 6.7 m (22 feet) above MLW on the east side of the units by a continuous barrier consisting of building exterior walls and stop logs for the door openings. Additional protection against flooding is provided by placing safety equipment on pedestals or providing curbs, use of closed doors with water-tight sills, floor drainage systems with sumps and sump pumps, and water level alarms (Haney, 2006).

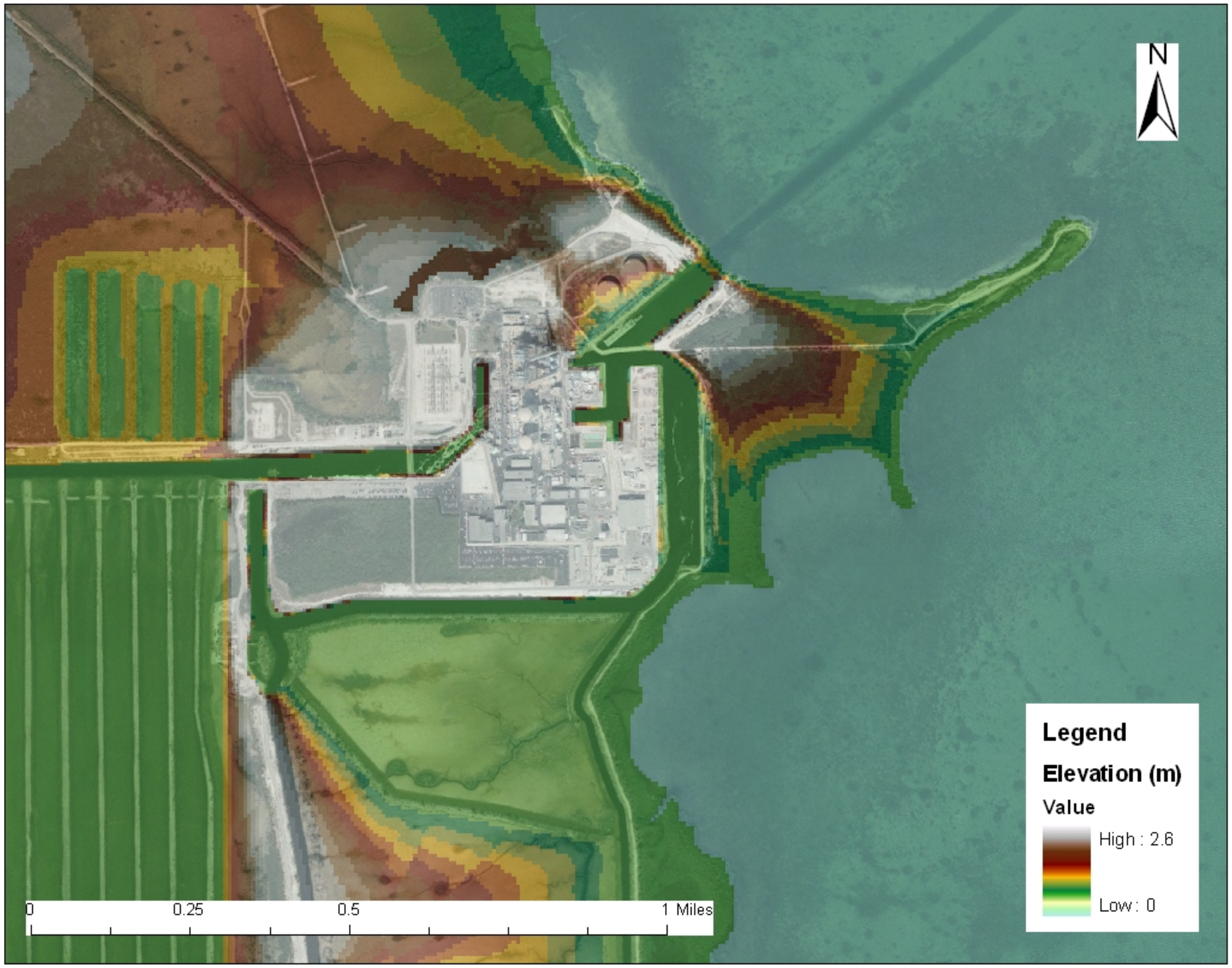

Figure 7. Satellite imagery of Turkey Point with Digital Elevation Model overlay.

Table 14. Sea level rise scenarios and results for Turkey Point.

No Flooding	Potential For Flooding	Considerable Flooding	Site Inundated

Conditions	Current Storms	End of Operation	Life of Reactor	100 Years Low	100 Years Mid /150 Years Low	100 Years High	Sea Level Rise 1 m	150 Years High
Sea Level Rise		0.1	0.2	0.4	0.6	0.9	1.0	1.1
Northeastern	0.6	0.7	0.8	1.0	1.2	1.5	1.6	1.7
Category I Low	1.2	1.3	1.4	1.6	1.8	2.1	2.2	2.3
Category I High	1.5	1.6	1.7	1.9	2.1	2.4	2.5	2.6
Category II	2.4	2.5	2.6	2.8	3.0	3.3	3.4	3.5
Category III	3.7	3.8	3.9	4.1	4.3	4.6	4.7	4.8
Category IV Low	4	4.1	4.2	4.4	4.6	4.9	5.0	5.1
Category IV High	5.5	5.6	5.7	5.9	6.1	6.4	6.5	6.6
Category V	6.1	6.2	6.3	6.5	6.7	7.0	7.1	7.2

Considerable flooding occurs at the site under current storm conditions as shown in Table 14. The potential for flooding occurs at 0.4 m and flooding becomes evident with a 0.5 m rise in sea level as shown in Figure 8. This level of sea level rise is somewhere between the low 100 and mid 100 year scenarios. Roads could potentially flood at 0.7 m, and are completely covered at 0.9 m as seen in Figure 9. As revealed in Figure 10 the site is almost completely flooded at 2.5 m. According to these scenarios, a Category V storm would cause flooding conditions that exceed the probable maximum surge (5.6 m) for the site and approach the design basis flood level (6.1-6.7 m) within the lifetime of the reactor. The Turkey Point site receives an overall coastal vulnerability index (CVI) ranking of high due to very high rankings received in geomorphology, slope, and tides as shown in Table 15.

Table 15. Relative vulnerability of each of the coastal variables and overall vulnerability of the coastline at Turkey Point.

Reactor	Tide	Waves	Erosion	Sea Level Rise	Geomorphology	Slope	CVI
Turkey Point	Very High	Moderate	Moderate	Low	Very High	Very High	High

Figure 8. Turkey Point with a sea level rise of 0.4 m and 0.5 m.

Figure 9. Turkey Point with a sea level rise of 0.9 m.

Figure 10. Turkey Point with a sea level rise of 2.5 m.

4.1.4. Seabrook Station

Seabrook Station began commercial operation in 1990 and the license expires in 2026. The reactor has 18 years remaining in operation and the total life of the reactor remaining was determined to be 82 years. Seabrook Station is located on the western shore of Hampton Harbor in Rockingham County, in the township of Seabrook, New Hampshire. It is approximately 11 miles south of Portsmouth, New Hampshire and 2 miles west of the Atlantic Ocean. The site area is characterized by broad open areas of tidal marsh, dissected by numerous tidal creeks and man-made linear drainage ditches (U.S. Nuclear Regulatory Commission, 2008c). Figure 11 provides a view of the site superimposed with the digital elevation model used in the study.

The design basis flood was determined to be 6.19 m (20.6 feet) from a combination of the probable maximum hurricane combined and precipitation from the standard project storm (U.S. Nuclear Regulatory Commission, 2008c). Safety related equipment is designed to withstand a depth of still water of 0.18 m (0.6 feet) on the plant grade of 6.1 m (20 feet) above mean sea level. The walls of safety related structures can withstand a wave runup of 6.64 m (21.8 feet) above mean sea level (U.S. Nuclear Regulatory Commission, 2008c).

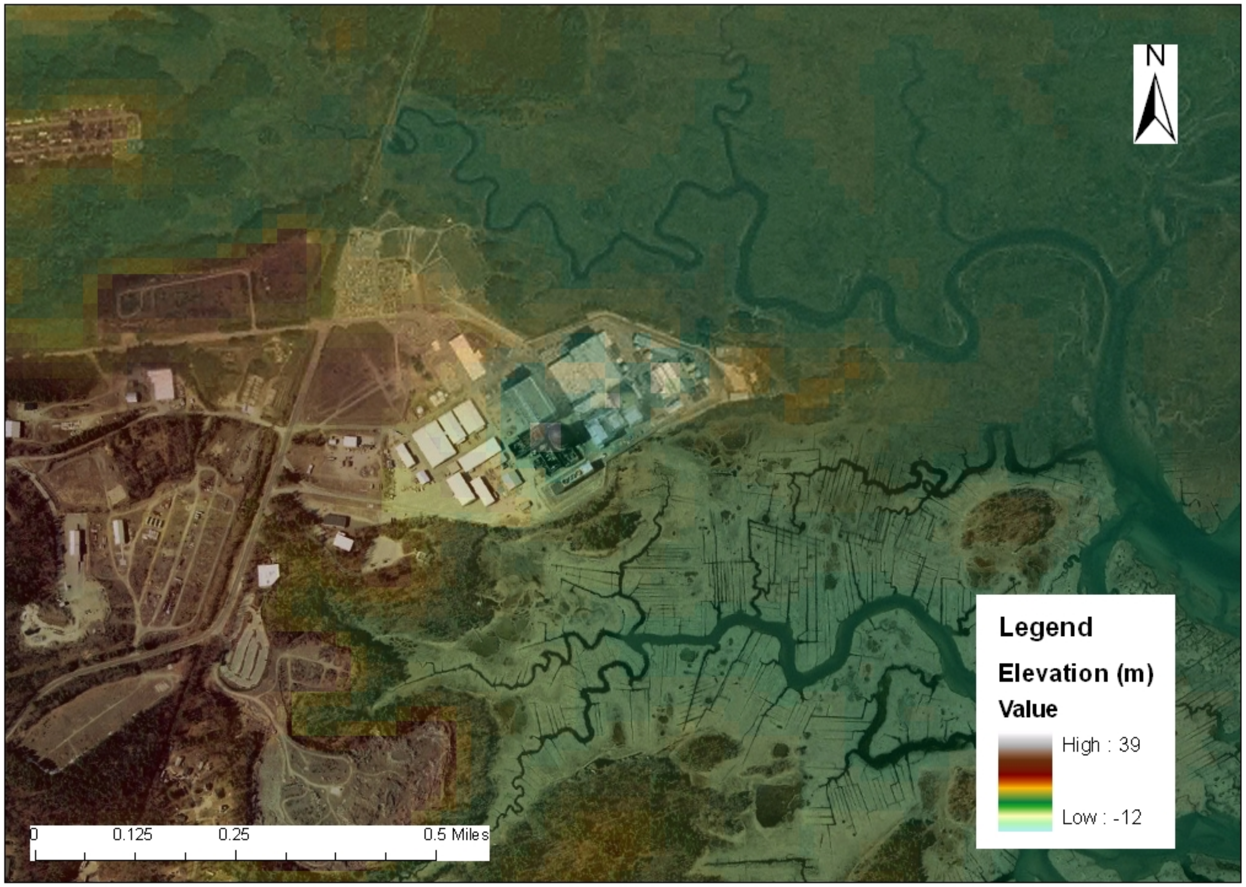

Figure 11. Satellite imagery of Seabrook Station with Digital Elevation Model overlay.

Table 16. Sea level rise scenarios and results for Seabrook Station.

Model Cannot Determine	Considerable Flooding

Conditions	Scenarios: Current Storms	End of Operation	Life of Reactor	100 Years Low	100 Years Mid/150 Years Low	100 Years High	Sea Level Rise 1 m	150 Years High
Sea Level Rise		0.08	0.35	0.51	0.72	0.85	1.00	1.21
Northeastern	0.6	0.68	0.95	1.11	1.32	1.45	1.60	1.81
Category I Low	1.2	1.28	1.55	1.71	1.92	2.05	2.20	2.41
Category I High	1.5	1.58	1.85	2.01	2.22	2.35	2.50	2.71
Category II	2.4	2.48	2.75	2.91	3.12	3.25	3.40	3.61
Category III	3.7	3.78	4.05	4.21	4.42	4.55	4.70	4.91
Category IV Low	4	4.08	4.35	4.51	4.72	4.85	5.00	5.21
Category IV High	5.5	5.58	5.85	6.01	6.22	6.35	6.50	6.71

The digital elevation model for Seabrook Station has a 1 m vertical resolution; therefore, flooding can not be determined for sea level rise scenarios below 1 m as shown in Table 16. A rise in sea level of 1 m appears to cause significant flooding of the site as shown in Figure 12. In Figure 13, roads to the north of the site flood with a rise in sea level of 3 m. A rise of 6 m leads to a substantial increase in flooding, and in particular access becomes increasingly limited due to flooding of roads as shown in Figure 14. All scenarios for the life of the reactor are less than the design basis flood event. Overall the coastal vulnerability index (CVI) is ranked low, but geomorphology and waves rank very high and high respectively as shown in Table 17. Changes in wave height and strength due to sea level rise and storms could be a future concern.

Table 17. Relative vulnerability of each of the coastal variables and overall variability of the coastline at Seabrook Station.

Reactor	Tide	Waves	Erosion	Sea Level Rise	Geomorphology	Slope	CVI
Seabrook	Moderate	High	Moderate	Very Low	Very High	Very Low	Low

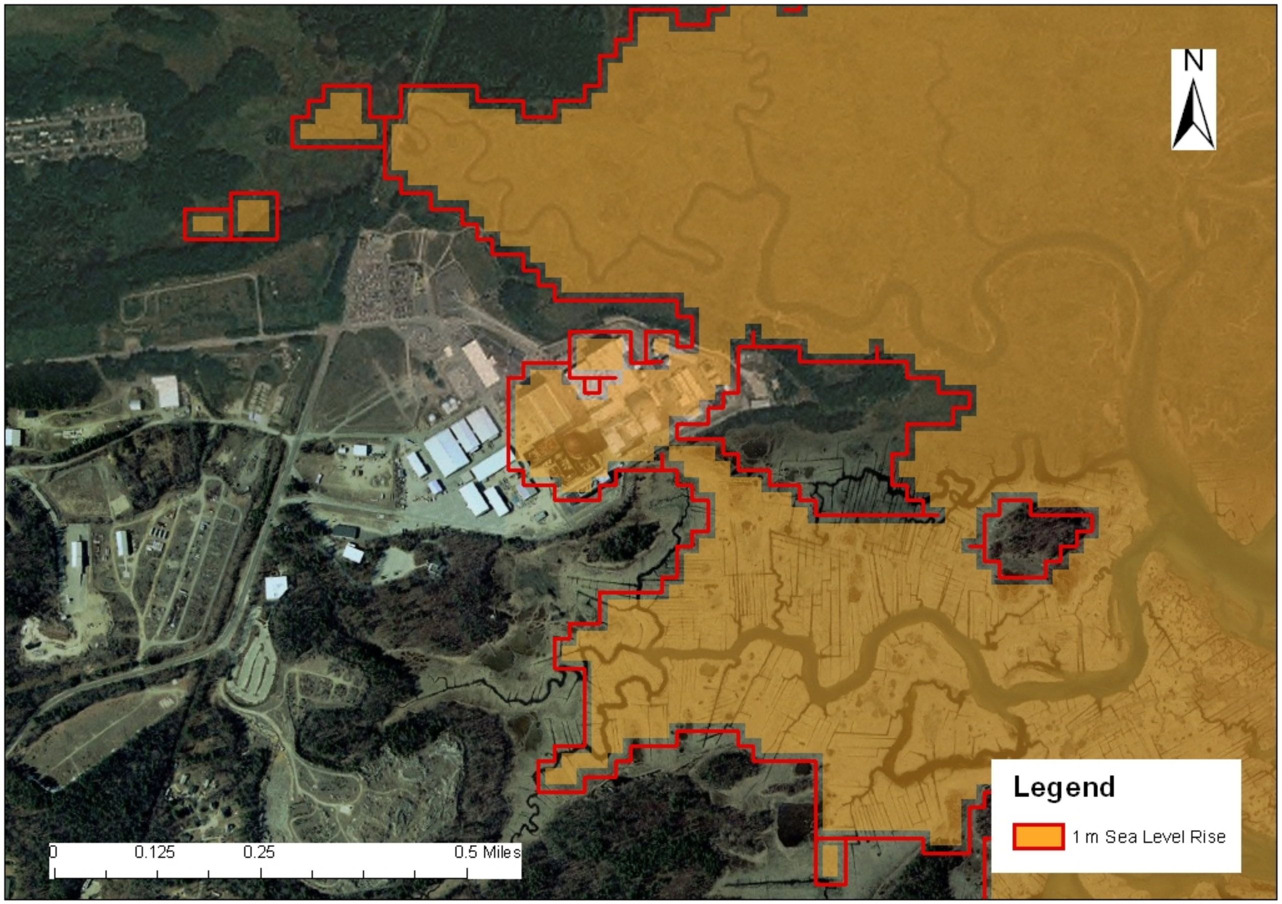

Figure 12. Seabrook Station with a sea level rise of 1 m.

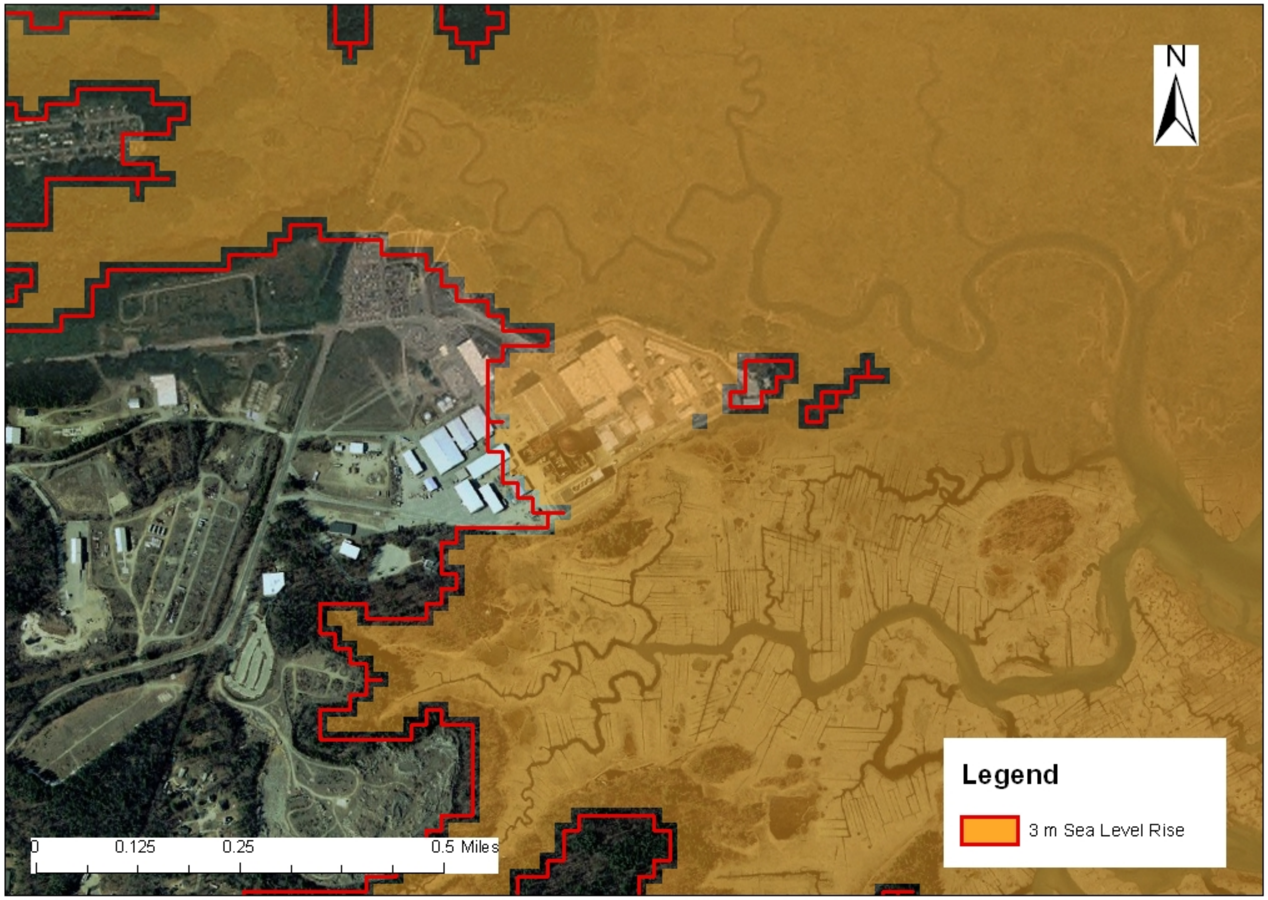

Figure 13. Seabrook Station with a sea level rise of 3 m.

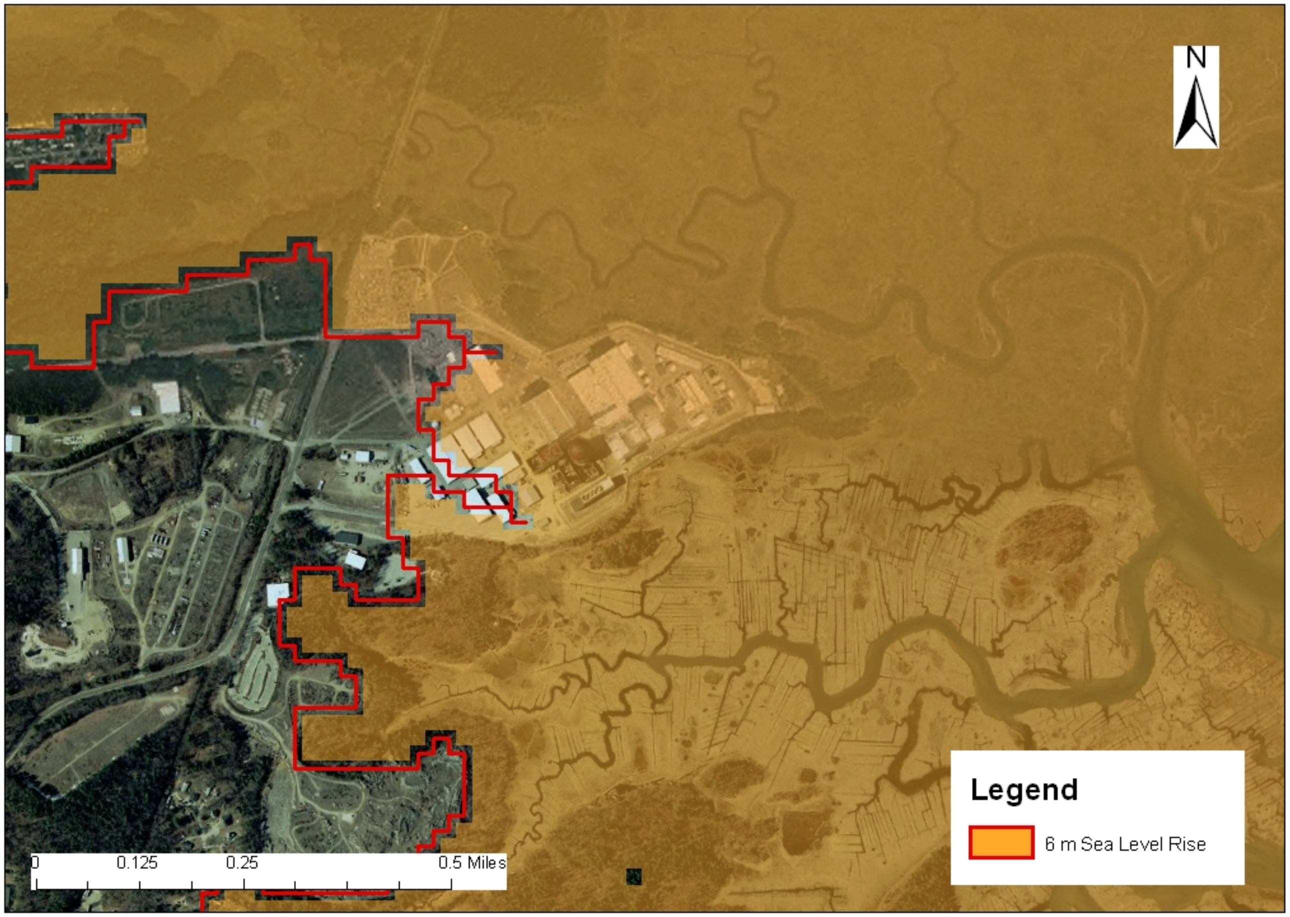

Figure 14. Seabrook Station with a sea level rise of 6 m.

4.1.5. Pilgrim Station

Pilgrim Station began operation in 1972 and the license expires in 2012. Pilgrim Station has 64 years remaining in the reactor lifetime. The reactor has 4 more operating years and 24 years if the license is renewed. Pilgrim Station is located on the western shore of Cape Cod Bay in the Town of Plymouth, Plymouth County, Massachusetts. Approximately 60% of the area within a 50-mile radius of Pilgrim Stations is open water (Entergy, 2005). Figure 15 provides a view of the site superimposed with the digital elevation model.

The maximum flood level for Pilgrim Station is 4.4m (14.7 feet), but this calculation does not include wave runup. The site is flood protected to an elevation of 6.9 m (23 feet) (U.S. Nuclear Regulatory Commission, 2002).

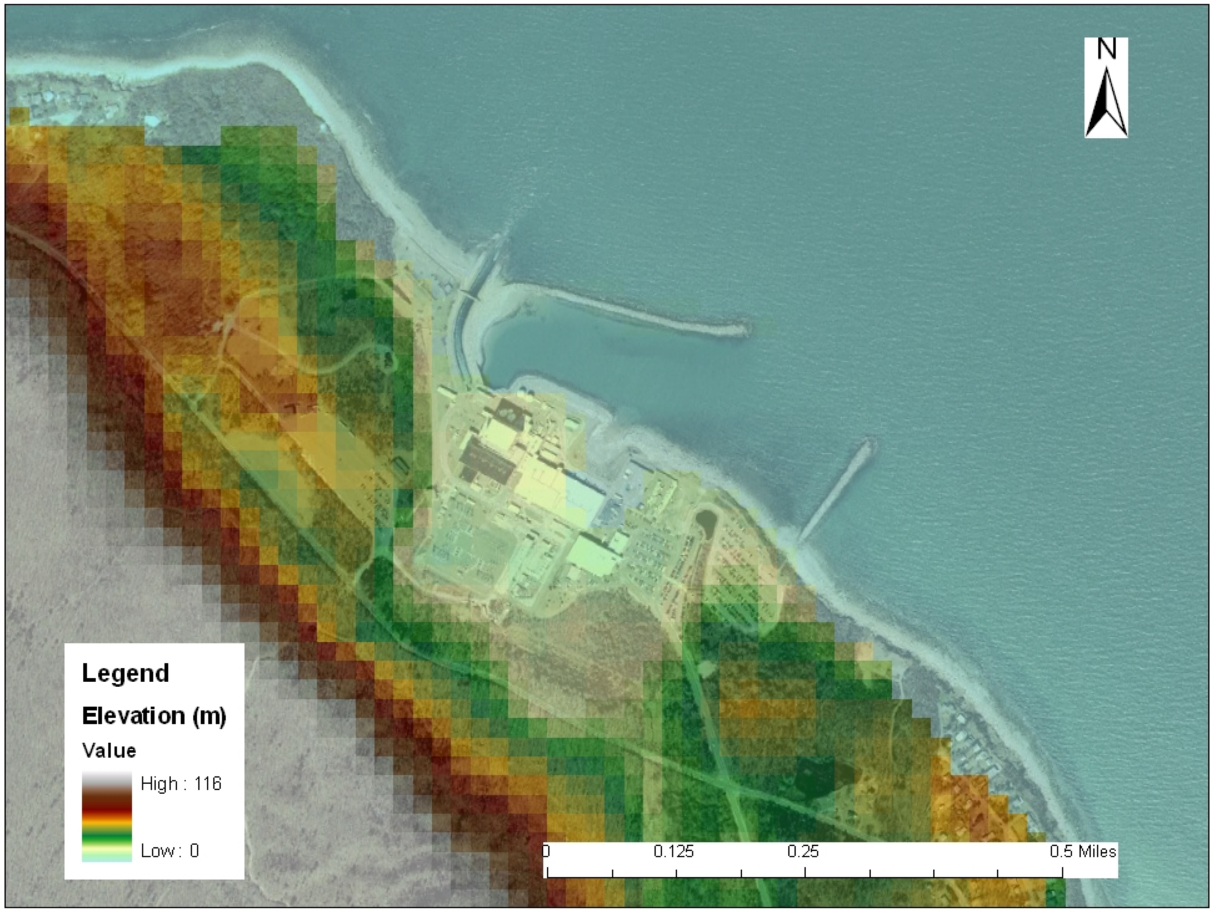

Figure 15. Satellite imagery of Pilgrim Station with Digital Elevation Model overlay.

Table 18. Sea level rise scenarios and results for Pilgrim Station.

Model Cannot Determine	Considerable Flooding

Scenarios

Conditions	Current Storms	End of Operation	License Extension	Life of Reactor	100 Years Low	100 Years Mid/ 150 Years Low	100 Years High	Sea Level Rise 1m	150 Years High
Sea Level Rise		0.02	0.10	0.28	0.51	0.72	0.85	1.00	1.21
Northeastern	0.6	0.62	0.70	0.88	1.11	1.32	1.45	1.60	1.81
Category I Low	1.2	1.22	1.30	1.48	1.20	1.92	2.05	2.20	2.41
Category I High	1.5	1.52	1.60	1.78	1.50	2.22	2.35	2.50	2.71
Category II	2.4	2.42	2.50	2.68	2.91	3.12	3.25	3.40	3.61
Category III	3.7	3.72	3.80	3.98	4.21	4.42	4.55	4.70	4.91
Category IV Low	4	4.02	4.10	4.28	4.00	4.72	4.85	5.00	5.21
Category IV High	5.5	5.52	5.60	5.78	5.50	6.22	6.35	6.50	6.71

The digital elevation model for Pilgrim Station has a 1 m vertical resolution; therefore, flooding can not be determined for sea level rise scenarios below 1 m as shown in Table 18. The site floods with 1 m sea level rise as shown in Figure 16. Roads begin to flood at 3 m, and at 4 m the roads are flooded considerably as shown in Figure 17. Figure 18 reveals that exits may be blocked with a rise in sea level of 6 m, and at 7 m the entire site is close to inundation. The site is designed to withstand all flood scenarios generated here. The coastal vulnerability index (CVI) of the site is low, while geomorphology receives a high ranking as shown in Table 19.

Table 19. Relative vulnerability of each of the coastal variables and overall vulnerability of the coastline at Pilgrim Station.

Reactor	Tide	Waves	Erosion	Sea Level Rise	Geomorphology	Slope	CVI
Pilgrim	Moderate	Moderate	Very Low	Low	High	Very Low	Low

Figure 16. Pilgrim Station with a sea level rise of 1 m.

Figure 17. Pilgrim Station with a sea level rise of 4 m.

Figure 18. Pilgrim station with a sea level rise of 6 m and 7 m.

4.1.6. Millstone

Millstone-3 began operation in 1986 and the license has been extended to 2045. Millstone has 37 years remaining in operation and the total life of the reactor remaining was determined to be 78 years. Millstone Power Station is located in Waterford, Connecticut, on Millstone Point, between the Niantic and Thames Rivers on Long Island Sound. Millstone is sited on a peninsula that includes rocky beaches, coastal tidal marshes, and second-growth hardwood forests (U.S. Nuclear Regulatory Commission, 2005). Figure 19 provides a view of the site superimposed with the digital elevation model used in the study.

The probable maximum flood at the Millstone site is 7.5 m (25.1 feet). Flood gates and other measures provide protection to a height of 8.4 m (28 feet) above mean sea level (U.S. Nuclear Regulatory Commission, 2002)

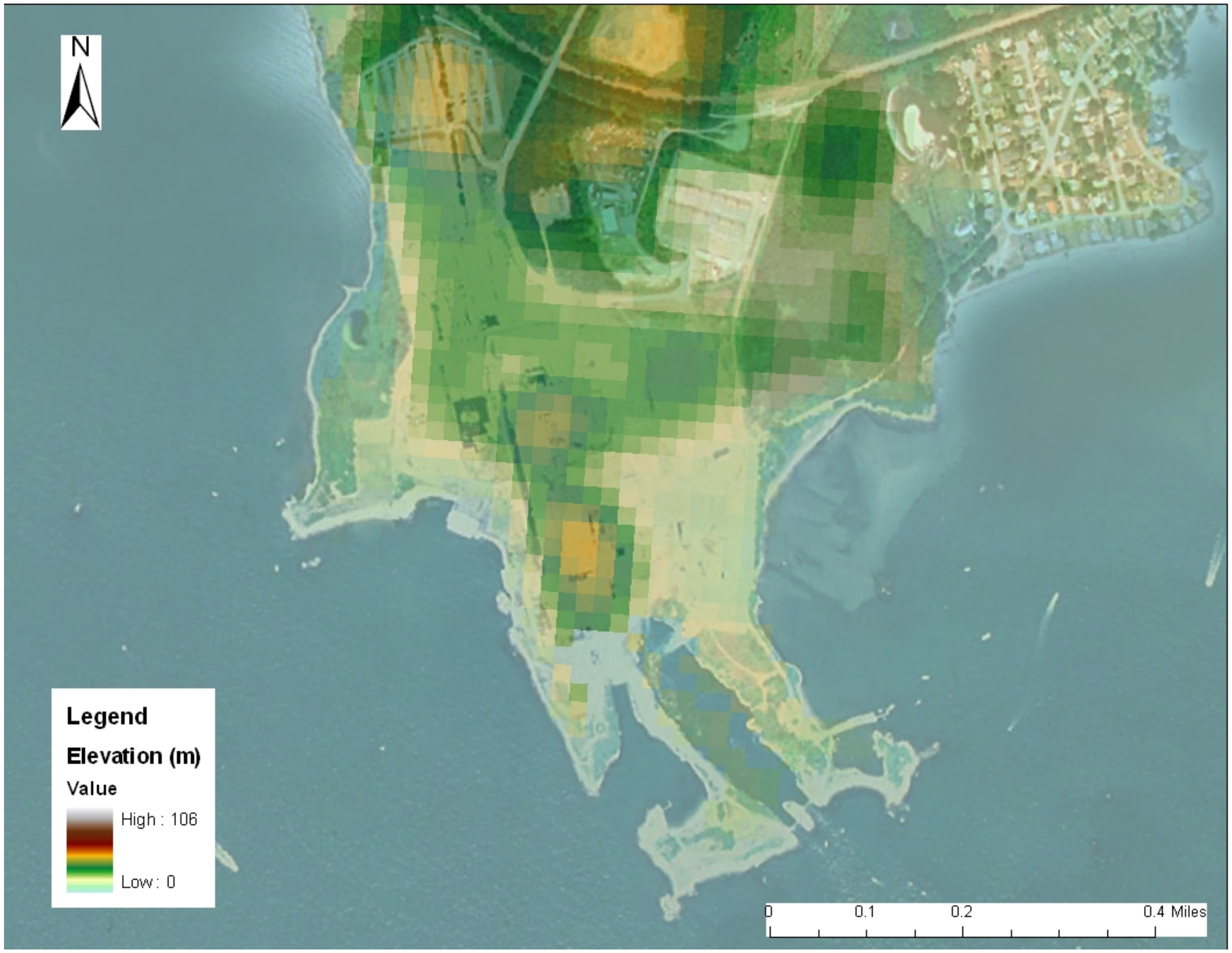

Figure 19. Satellite imagery of Millstone with Digital Elevation Model overlay.

Table 20. Sea level rise scenarios and results for Millstone.

Model Cannot Determine	No Flooding	Potential For Flooding	Considerable Flooding

Conditions	Scenarios: Current Storms	End of Operation	Life of Reactor	100 Years Low	100 Years Mid/ 150 Years Low	100 Years High	Sea Level Rise 1 m	150 Years High
Sea Level Rise		0.20	0.30	0.50	0.70	0.90	1.00	1.20
Northeastern	0.6	0.80	0.90	1.10	1.30	1.50	1.60	1.80
Category I Low	1.2	1.40	1.50	1.70	1.90	2.10	2.20	2.40
Category I High	1.5	1.70	1.80	2.00	2.20	2.40	2.50	2.70
Category II	2.4	2.60	2.70	2.90	3.10	3.30	3.40	3.60
Category III	3.7	3.90	4.00	4.20	4.40	4.60	4.70	4.90
Category IV Low	4	4.20	4.30	4.50	4.70	4.90	5.00	5.20
Category IV High	5.5	5.70	5.80	6.00	6.20	6.40	6.50	6.70

The site potentially begins to flood at 2 m as shown in Table 20 and Figure 20. At 3 m the buildings on the southern and eastern side of the site, and the intake structures on the west side experience flooding. Further flooding occurs from 4 to 6 m as shown in Figure 21 and 22 respectively. Flooding does not reach the reactors or the main buildings located at the center of the site, or cover the roads that enter the site in the north. Furthermore, the site is flood protected for conditions greater than the flood levels in any of the scenarios. Overall the Millstone site received a low ranking for the coastal vulnerability index (CVI) as shown in Table 21.

Table 21. Relative vulnerability of each of the coastal variables and overall vulnerability of the coastline at Millstone.

Reactor	Tide	Waves	Erosion	Sea Level Rise	Geomorphology	Slope	CVI
Millstone	Very High	Moderate	Moderate	Very Low	Very Low	Very Low	Low

Figure 20. Millstone with a sea level rise of 2 m.

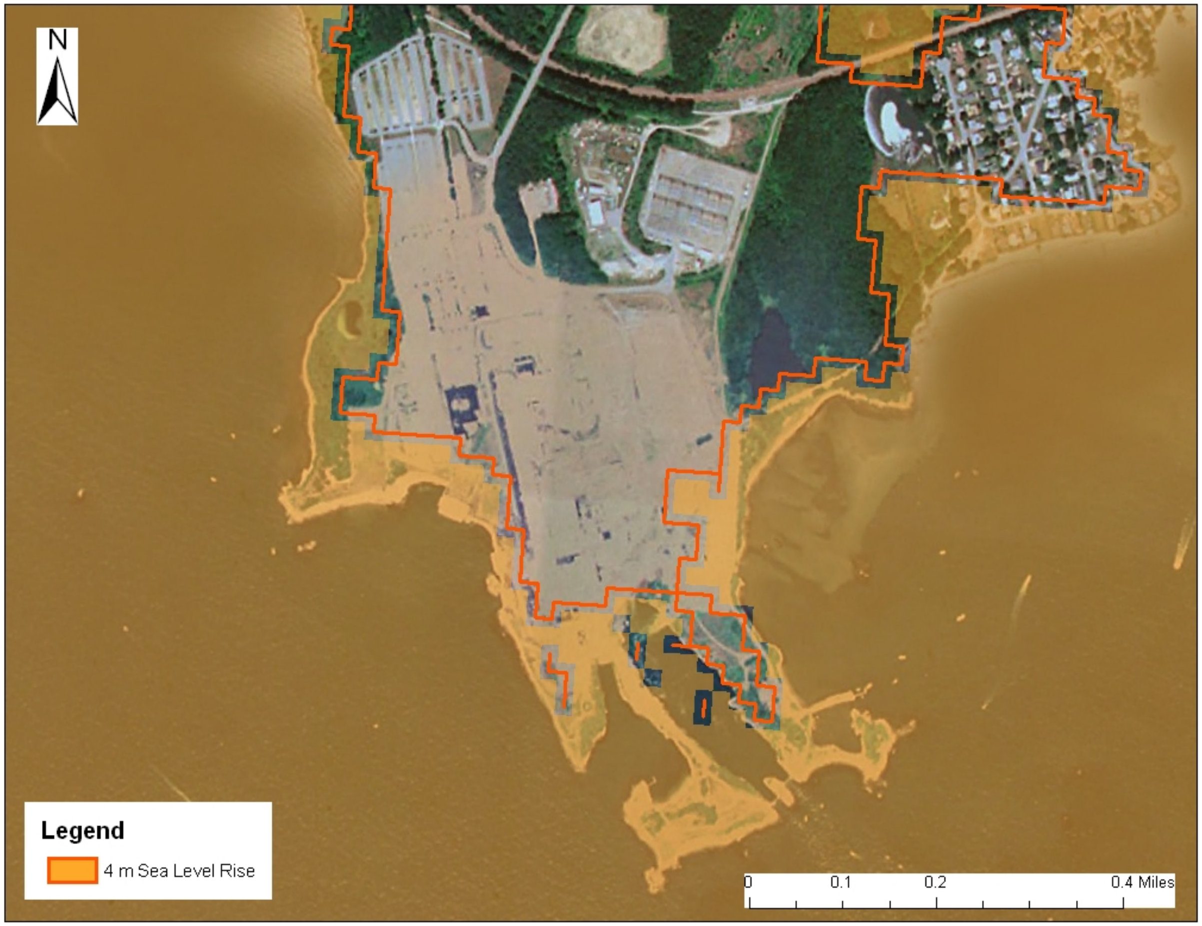

Figure 21. Millstone with a sea level rise of 4 m.

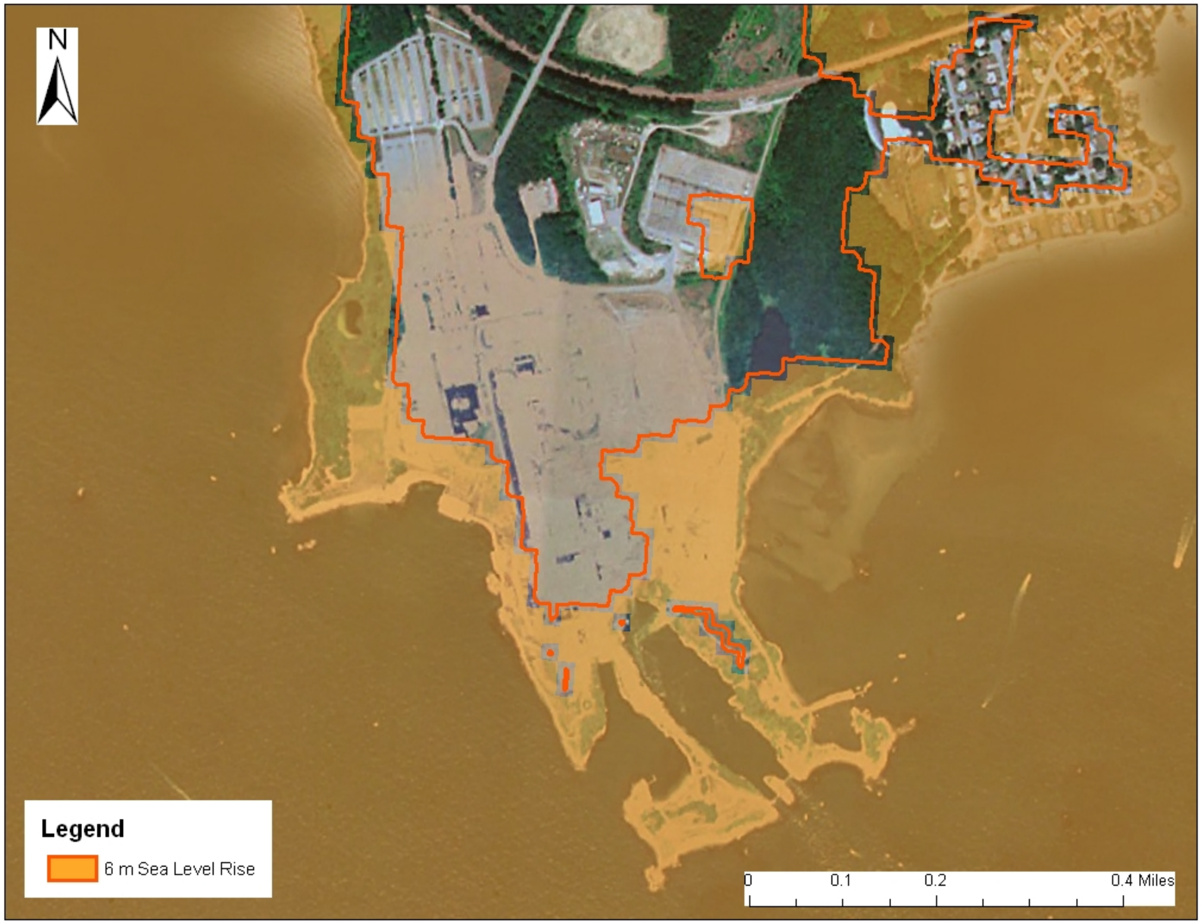

Figure 22. Millstone with a sea level rise of 6 m.

4.1.7. Calvert Cliffs

The younger of the two power plants on the Calvert Cliffs site began operation in 1977 and the license expires in 2036. Calvert Cliffs has 28 years remaining in operation and the total life of the reactor was determined to be 69 years. UniStar is currently applying for construction of a new reactor at this site. The Calvert Cliffs nuclear power plant is in Calvert County, Maryland, on the west bank of Chesapeake Bay, approximately halfway between the mouth of the bay and its headwaters at the Susquehanna River. The current reactor is approximately 152.4 m (500 feet) from the shore, while the new proposed reactor will be a 304.8 m (1000 feet) from the shoreline (MACTEC Engineering and Consulting Inc., 2008). Figure 23 provides a view of the site superimposed with the digital elevation model used in the study.

The flooding conditions considered in design include: the probable maximum flood (PMF) on streams and rivers, potential dam failures, probable maximum surge and seiche flooding, probable maximum tsunami and ice effect flooding. The Nuclear Island of the new site is at an elevation of 24.8 m (81.5 ft) with respect to the reference level. Safety-related structures of Nuclear Island have a minimum grade slab or entrance at elevation 25.8 m (84.6 feet). The maximum flood level at the intake location is an elevation of 12 m (39.4 ft) as a result of the surge, wave heights, and wave run-up associated with probable maximum hurricane (UniStar Nuclear Development, 2008).

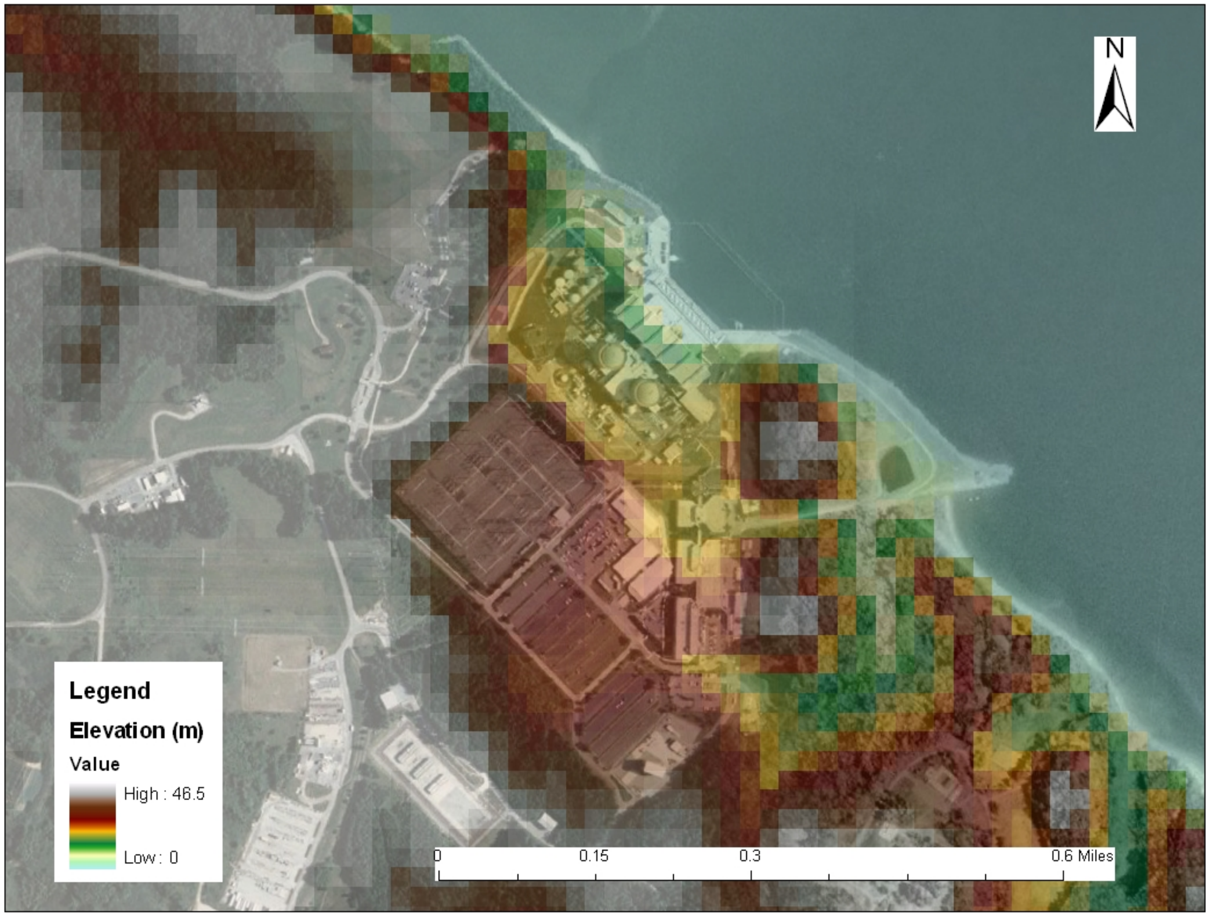

Figure 23. Satellite imagery of Calvert Cliffs with Digital Elevation Model overlay.

Table 22. Sea level rise scenarios and results for Calvert Cliffs.

No Flooding | Potential For Flooding

	Scenarios							
Conditions	Current Storms	End of Operation	Life of Reactor	100 Years Low	100 Years Mid/ 150 Years Low	100 Years High	Sea Level Rise 1 m	150 Years High
Sea Level Rise		0.12	0.30	0.51	0.72	0.85	1.00	1.21
Northeastern	0.6	0.72	0.90	1.11	1.32	1.45	1.60	1.81
Category I Low	1.2	1.32	1.50	1.71	1.92	1.92	2.20	2.41
Category I High	1.5	1.62	1.80	2.01	2.22	2.22	2.50	2.71
Category II	2.4	2.52	2.70	2.91	3.12	3.12	3.40	3.61
Category III	3.7	3.82	4.00	4.21	4.42	4.42	4.70	4.91

The site is at a high enough elevation that flooding from storm surges does not pose a considerable problem. Flooding could potentially happen at 3.9 m and above, corresponding to an increase in storm intensity as shown in Table 22. Figures 24 and 25 illustrate the flooding of the intake structure at 3.9 m and at 4.6 m respectively. Calvert Cliffs ranked very high in erosion and geomorphology and received a very high ranking for the coastal vulnerability index (CVI) as shown in Table 23.

Table 23. Relative vulnerability of each of the coastal variables and overall variability of the coastline at Calvert Cliffs.

Reactor	Tide	Waves	Erosion	Sea Level Rise	Geomorphology	Slope	CVI
Calvert Cliffs	Very High	Moderate	Very High	High	Very High - High	Low	Very High

Figure 24. Calvert Cliffs with a sea level rise of 3.9 m.

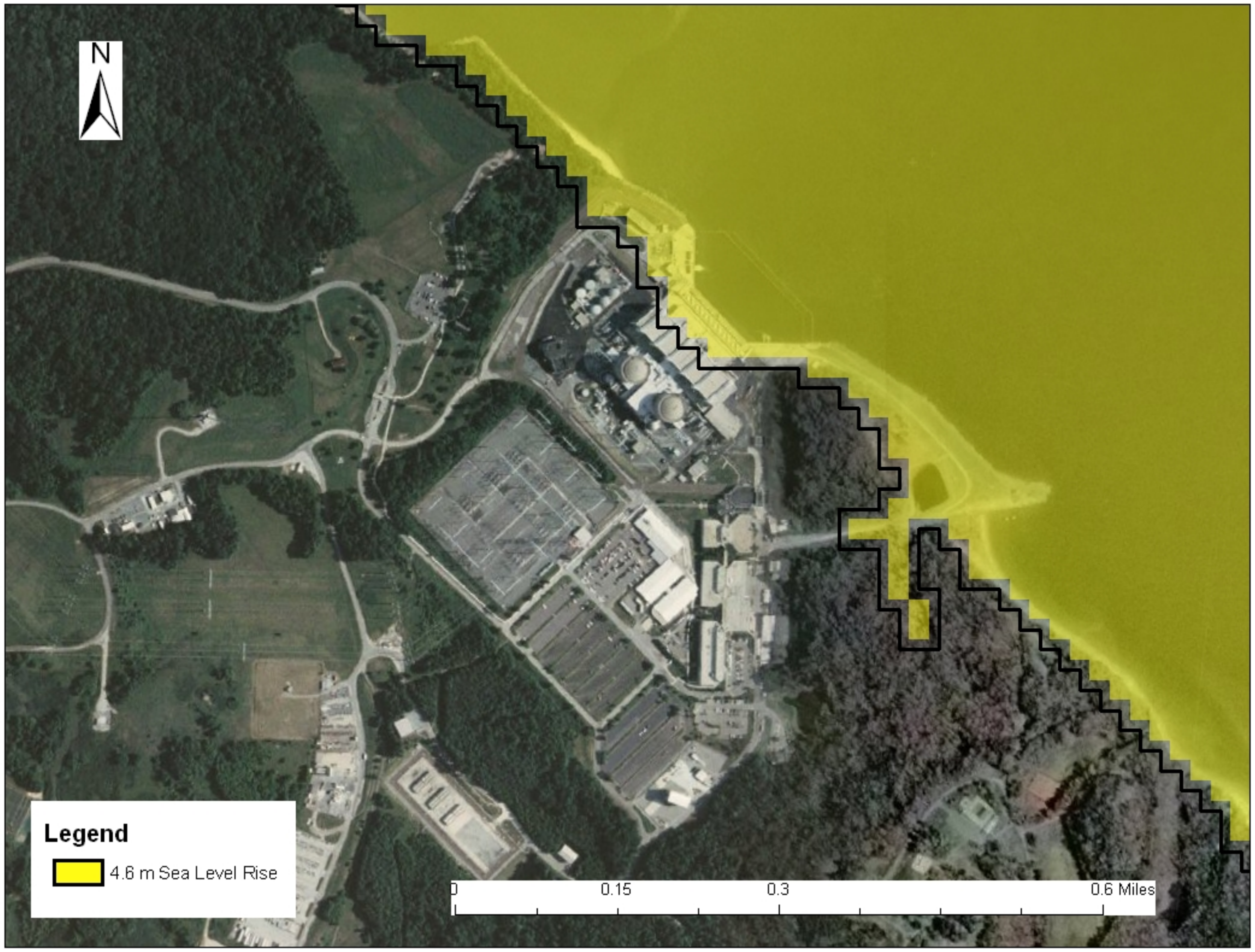

Figure 25. Calvert Cliffs with a sea level rise of 4.6 m.

4.1.8. San Onofre

San Onofre Nuclear Generating Station (SONGS) Unit-3 began operation in 1983 and the license will expire in 2022. The reactor has 14 years remaining in the operating license and the life of the reactor was determined to be 75 years. San Onofre is located in north San Diego County, California and is fronted by a narrow beach along the Pacific Ocean. Figure 26 provides a view of the site superimposed with the digital elevation model used in the study.

For purposes of determining and analyzing potential flood sources, consideration was given to the San Onofre Creek Basin and the foothill drainage area east of the site. The probable maximum flood level (PMFL) for the SONGS 2 and 3 site is 7.3 m (24.1 feet). Topographical feature of the basin would contain this flow and thereby preclude flooding of the site by this source. Any openings and penetrations below the PMFL are either sealed, protected by watertight doors/hatches, protected by waterstops, or analysis has shown that PMF cannot impact safety-related equipment. Tsunamis caused by active trench system are considered along with those generated by large scale tectonic movement. Structures designed to protect the site include the seawall. The plant grade is at an elevation of approximately 6.1 m (20 feet) MLLW (Southern California Edison Company et al., 2002). This elevation is well above the maximum seawater elevation of 4.8 m (15.8 feet) mean lower low water that is predicted to occur in the event of a maximum tsunami coincident with storm surge and high tide (Haney, 2006)

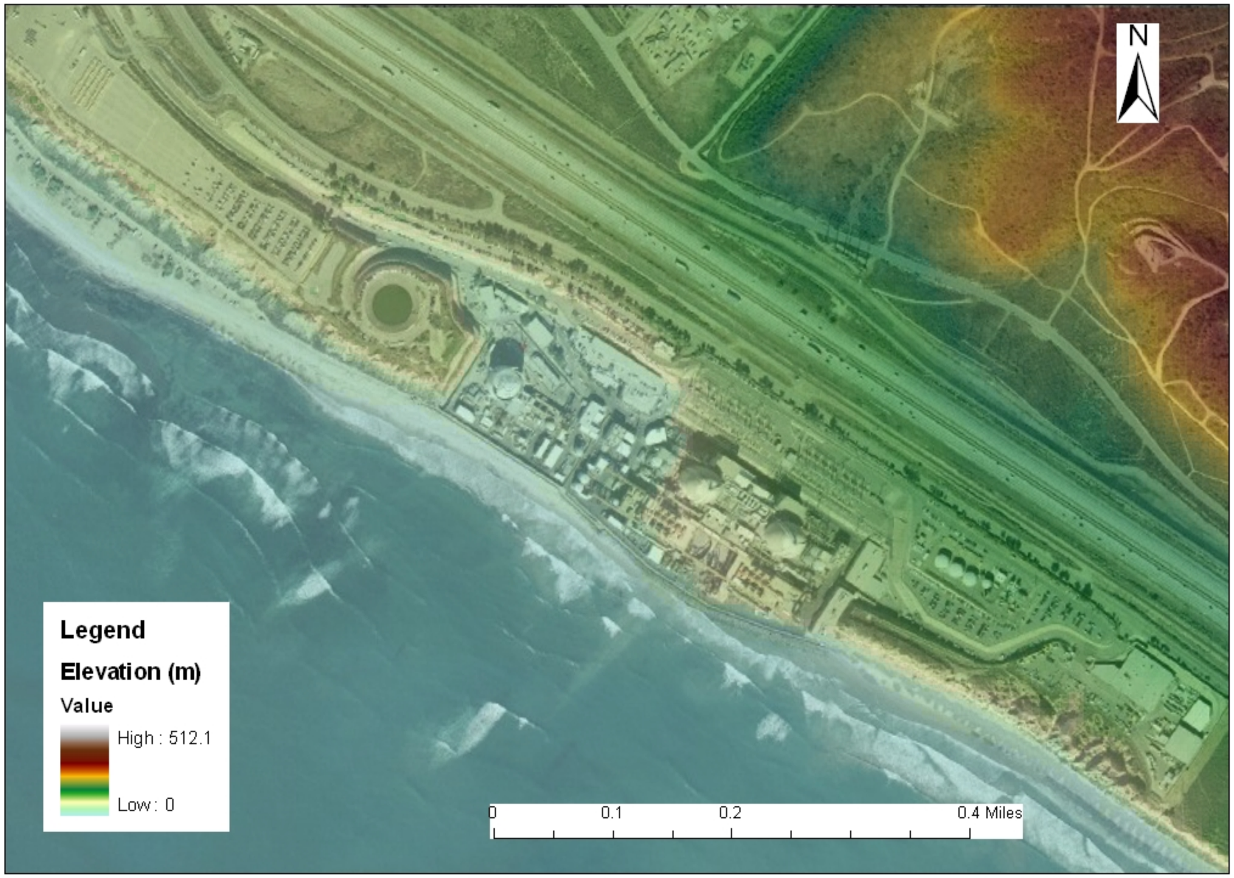

Figure 26. Satellite imagery of San Onofre with Digital Elevation Model overlay.

Table 24. Sea level rise scenarios and results for San Onofre.

No Flooding

Conditions	Scenarios: End of Operation	Life of Reactor	100 Years Low	100 Year Mid/150 Years Low	100 Years High	Sea Level Rise 1 m	150 Years High
Sea Level Rise	0.04	0.23	0.38	0.59	0.85	1	1.1
SLR and El Niño	0.3	0.53	0.68	0.89	1.15	1.3	1.4
Storm Surge	0.7	0.93	1.08	1.29	1.55	1.7	1.8
Wave Induced Storm	1.5	1.73	1.88	2.09	2.35	2.5	2.6

Flooding does not occur under any of the scenarios as shown in Table 24. The sea wall and the plant grade is at a high enough elevation to prevent flooding from coastal storms. The coastal vulnerability index (CVI) for the San Onofre site ranks high as shown in Table 25.

Table 25. Relative vulnerability of each of the coastal variables and overall vulnerability of the coastline at San Onofre.

Reactor	Tides	Waves	Erosion	Sea Level Rise	Geomorphology	Slope	CVI
San Onofre	High	Low	Moderate	High	Moderate	Low	High

4.1.9. Diablo Canyon

The second reactor unit at Diablo Canyon began operation in 1986, and the license will expire in 2025. The reactor has 17 operating years remaining, and the total life left in the reactor was determined to be 78 years. The Diablo Canyon nuclear power plant is located on the Pacific Ocean coastline in San Luis Obispo County, California, approximately 12 miles west-southwest of the city of San Luis Obispo. Figure 26 provides a view of the site superimposed with the digital elevation model used in the study.

Site flooding includes the combined effects of flooding from steams and rivers (Diablo Creek), a tsunami, wind-generated storm waves, storm-surge, and tides. For flooding from steams and rivers, there is the probable maximum flood (PMF) from the probable maximum precipitation (PMP) with duration of 24 hours and all culverts plugged. The combination of tsunami, wind-generated storm waves, storm-surge, and tidal effects results in a rise and fall of the ocean surface level relative to a defined datum level, the mean lower low water level (MLLWL). For the plant site, the MLLWL is 0.7 m (2.6 feet) below the mean sea level (MSL) (Haney, 2006). The PMF was found to have a peak discharge of 6878 cubic feet per second for the 24-hour storm. For the tsunami runup and drawdown, the wave heights for distantly-generated and locally-generated (near shore) tsunamis were considered. For distantly-generated tsunamis, the design combined drawdown and wave runup is 2.74 m (9 ft) and 9.14 m (30 ft), respectively. For near-shore tsunamis, the design combined drawdown and wave runup is 1.3 m (4.4 ft) and 10.5 m (34.6 ft). This is the probable maximum surge (PMS) for the site (Haney, 2006).

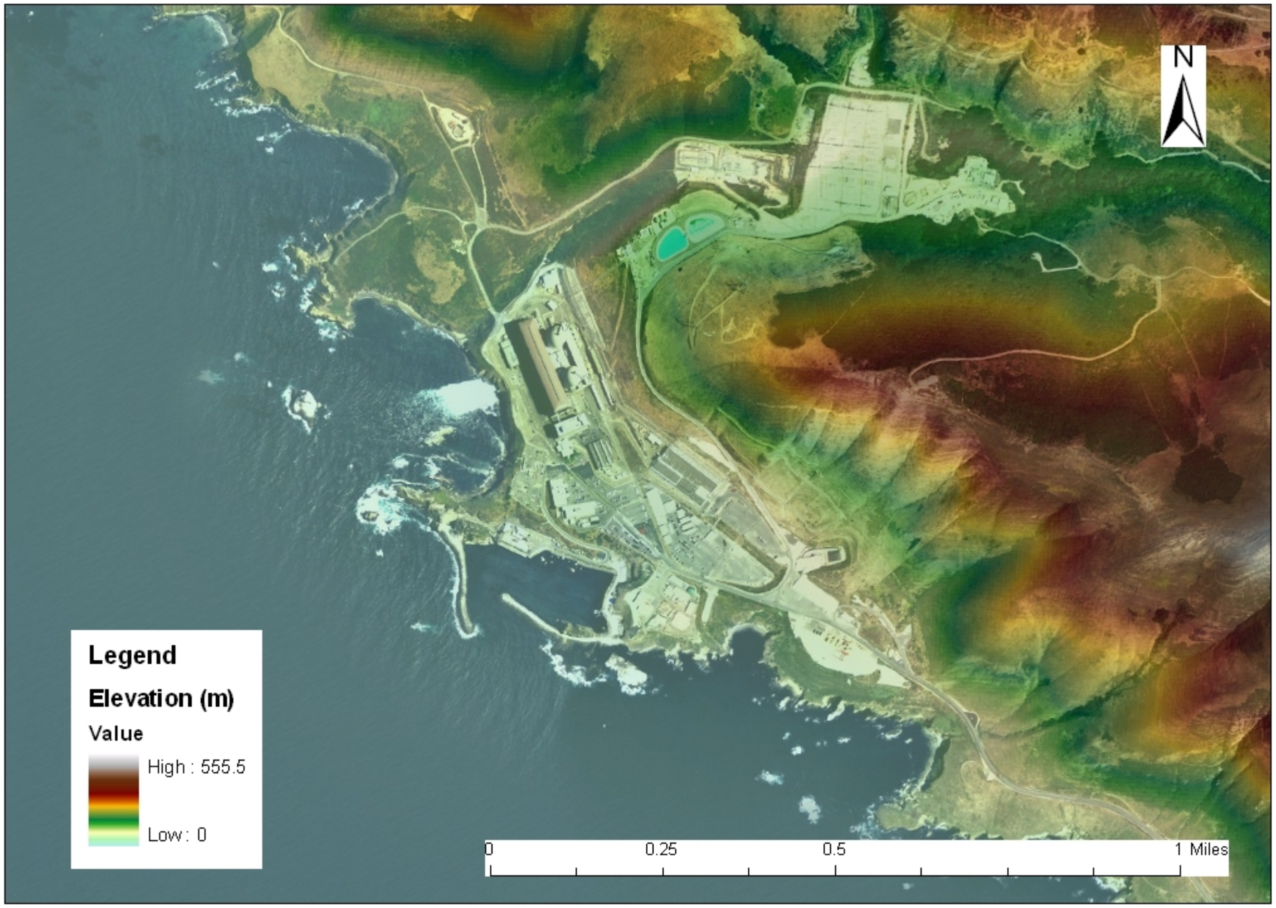

Figure 27. Satellite imagery of Diablo Canyon with Digital Elevation Model overlay.

Table 26. Sea level rise scenarios and results for Diablo Canyon.

No Flooding

Conditions	Scenarios: End of Operation	Life of Reactor	100 Years Low	100 Years Mid/150 Years Low	100 Years High	Sea Level Rise 1 m	150 Years High
Sea Level Rise	0.05	0.23	0.38	0.59	0.85	1	1.09
SLR and El Niño	0.4	0.534	0.68	0.89	1.15	1.3	1.4
Storm Surge	0.8	0.93	1.08	1.29	1.55	1.70	1.79
Wave Induced Storm	1.6	1.73	1.88	2.09	2.35	2.50	2.59

The site did not flood under any of the scenarios as shown in Table 26. The elevation of the site is high enough to prevent flooding from storm surges and the design basis flood is also greater than any of the sea level rise scenarios. The coastal vulnerability index (CVI) for the Diablo Canyon site ranks low as shown in Table 27.

Table 27. Relative vulnerability of each of the coastal variables and overall vulnerability of the coastline at Diablo Canyon.

Reactor	Tides	Waves	Erosion	Sea Level Rise	Geomorphology	Slope	CVI
Diablo Canyon	High	Low	Moderate	Low	Very Low	Moderate	Low

4.1.10. Sea Level Rise and Coastal Vulnerability Discussion

The models used here have limitations that must be considered when interpreting the results. For the most part the limitations in the model will lead to results that underestimate the level of flooding that will occur rather than overestimate. First, there is a great deal of uncertainty in the amount of sea level rise that can be expected by the end of the century. Generating scenarios that cover a range of possibilities provide a means to deal with some of that uncertainty; however, abrupt changes in sea level still remain a possibility.

Depending on site conditions, storm surges could be less than the surge heights used in this model or they could be greater. Storm surge always coexists with astronomical tides and the model's limitation prevents the prediction of the effects of a storm hitting at high tide. The Saffir-Simpson surge table is a crude estimate of the amount of surge generated by hurricanes. In reality, bathymetry determines the amount of storm surge created by a particular strength of hurricane. Moreover, as sea level rises allowances must be made for changing depths and boundary positions which will affect bottom stresses (Pugh, 1987). Higher sea levels create a larger expanse of shallow water resulting in increased storm surge elevations compared to areas of steep offshore slopes. However, if the shoreline is fixed and the offshore water depths increase, then the storm surges will be reduced (U.S. National Research Council, 1987). This method was limited in that it is unable to account for tides which on the California coast extreme tide ranges approach 3 m (10 feet) (Flick & Badan-Dangon, 1989). The California sites also did not include an estimate for an increase in storm intensity.

In addition, the model is not able to allow for the possibility of large waves that could overtop defensive flood structures and the precipitation that accompanies storms. While the coastal vulnerability index considers current wave height, changes in wave height and energy are not included in the model. Wave height will change because the offshore water depth will be greater with rising sea level, and storm waves that propagate inland will be larger than before (U.S. National Research Council, 1987). Moreover, complex changes in sediment transport processes in the near shore environment can occur with a change in sea level and makes predicting erosion increasingly difficult.

Nonetheless, the inundation model and coastal vulnerability index reveal those sites that are the most vulnerable to sea level rise. In particular, it is worthwhile to understand potential problems that each of these sites might have from flooding, erosion, and landslides. Refer to Appendix 9 for the actual numerical values for the variables considered in the coastal vulnerability assessment at each site.

Seabrook and Pilgrim Station in New Hampshire and Massachusetts respectively, and all three sites in Florida were found to be the most vulnerable to flooding from rising sea level as shown in Table 28. The reactors are designed to withstand the flood scenarios generated here, but Turkey Point and St. Lucie approach design limits within the life of the reactor. In addition, future reactor construction at these locations will need more flood protection. While the Florida sites have the most dramatic impact from inundation, Turkey Point and St. Lucie also have a high to very high coastal vulnerability index.

Table 28. Summary of results for flooding due to sea level rise and coastal vulnerability.

Site Name	State	Flooding Level	Coastal Vulnerability
St. Lucie	Florida	Inundated	Very High – High
Crystal River	Florida	Inundated	Moderate
Turkey Point	Florida	Inundated	High
Seabrook	New Hampshire	Considerable	Low
Pilgrim	Massachusetts	Considerable	Low
Millstone	Connecticut	Considerable	Low
Calvert Cliffs	Maryland	Potential	Very High
San Onofre	California	None	High
Diablo Canyon	California	None	Low

St. Lucie is particularly vulnerable due to its location on a barrier island. Erosion has been occurring along Hutchinson Island at a rapid rate and is apparent from tree stumps and clay beds on the beach. Furthermore, several beach nourishment projects have been conducted over the years (Pilkey Jr. et al., 1984). Evacuation is a major problem from the islands of St. Lucie County, since all bridges are drawbridges, and the escape road along the island's length is frequently at elevations of less than 1.5 m (5 feet) and within a few feet of the Indian River shoreline. During a severe storm there is a strong likelihood that new inlets will break through some of the narrow portions of the islands, thereby, challenging evacuations even further (Pilkey Jr. et al., 1984).

The Calvert Cliffs site has only a potential of flooding. The surge model used in this study might be too conservative. The largest tidal flood that is likely to occur under the most severe meteorological and hydrological conditions in Cheaspeake Bay is 4 m (13 feet) above the national geodetic vertical datum, while waves can reach an additional 1.5 m (5 feet) (Ward et al., 1999). Nonetheless, this level of surge is accounted for in the design of the new reactor and the existing reactors are at an elevation of at least 11 m (36 feet). While Calvert Cliffs appears resistant to flooding it received a very high ranking for coastal vulnerability. The Chesapeake Bay region is ranked the third most vulnerable to sea level rise behind Louisiana and Southern Florida. Maryland is currently losing approximately 580 acres of land per year to shore erosion; therefore, coastal erosion is and will continue to be one of the most severe impacts of sea level rise in Maryland (Maryland DNR, 2007; Mayrland DNR, 1999).

Similar to Calvert Cliffs, San Onofre is resistant to flooding, but receives a high rank for coastal vulnerability. The San Onofre power plant is located on the coastal terrace, which is underlain by Miocene marine rock capped by Pleistocene marine and nonmarine sediments (Kuhn, 1980). These Pleistocene sediments are essentially horizontal and are easily eroded from the bluff face and along the canyons. Approximately 80 percent of the cliffs between the power plant and Target Canyon six miles to the south, on Camp Pendleton, consist of landslides (Kuhn, 1980). Furthermore, where protective measures project or extend seaward beyond adjacent unprotected lots, there is immediate erosion and notching of the unprotected sites. As beach sand levels fall, storm waves tend to converge on projecting structures and the waves refract toward unprotected lots (Kuhn & Shepard, 1983). The San Onofre facility itself is not at risk from erosion or flooding owing to massive double-seawall protection; however, adjacent beaches have narrowed since 1985 (Griggs et al., 2005).

Diablo canyon received a low ranking for coastal vulnerability, erosion in the area is moderate, and sea level rise is not a concern due to the elevation of the site. Increases in precipitation from coastal storms likely pose more of a hazard at this site than ocean conditions. During two El Niño years, mud slides and flooding from an intense precipitation event restricted access to the plant (Becker, 1995; Skaggs, 1997). In the 1995 event, site personnel could not come on site to relieve the watch, emergency sirens were inoperable due to power outages, and one of the switching centers experienced flooding. Furthermore, power for one of the units was reduced to about 50% as a precautionary measure due to ocean conditions (Becker, 1995). The impact of a coastal storm is not limited to flooding: low tides can also be hazardous. In 1985, rough seas combined with low tide caused a build up of kelp at the intake at Diablo Canyon. The kelp broke down and plugged the unit-2 circulators. During controlled shutdown of unit-2 a digital rod position indication failure alarm was received, resulting in the need to manually shut-down the reactors (Sicard, 1985).

The frequency of hazardous events, in particular flooding, will increase due to climate change. What measures were taken in the past to adapt operations to the harsh coastal environment? What problems remain despite the lessons learned from past experience? The next section will evaluate the operational experience at coastal locations and explore these vulnerabilities further.

4.2. Operational Experience

When one considers the variability of climate on longer time-scales, the operation of nuclear power plants has benefited from a relatively calm coastal environment. Nonetheless, storms have reached coastal nuclear power plants, and from that we can infer the problems that will arise from storms of increasing intensity or frequency. Several safety issues repeatedly arise during storm events including: the loss of offsite power, failure of communication systems and alarm systems, and obstruction of evacuation routes.

The availability of AC power to commercial nuclear power plants is essential for safe operations and accident recovery; therefore, a loss of offsite power event is an important contributor to total risk at nuclear power plants. An assessment conducted in 1998 of loss of offsite power events at U.S. nuclear power reactors found that sixteen of the 22 events resulting from severe weather occurred at only 5 sites. The five sites were Pilgrim Station in Massachusetts, Crystal River in Florida, Brunswick in North Carolina, Millstone in Connecticut**,** and Turkey Point in Florida. The units at these sites have diverse designs with little similarity in electrical power supply design or redundancy; therefore, it was concluded that the proximity of the sites to the east coast was a major factor in loss of power frequency (Atwood et al., 1998).

However, the predictability of hurricanes does allow time for preparation. The U.S. Nuclear Regulatory Commission (NRC) has an established hurricane response program that is implemented each year during hurricane season. The NRC monitors potentially hazardous weather conditions in the Atlantic and Pacific Oceans, the Caribbean Sea, and the Gulf of Mexico. For the Atlantic basin, the NRC monitors tropical storm formations developing as far away as the African coast. The NRC relies on hurricane tracking computer programs and data provided by the National Oceanic and Atmospheric Administration that provides current and projected information about developing storms (Leach et al., 2006). Nuclear power plant licensees prepare well in advance by updating procedures and assessing their sites for readiness at the beginning of each hurricane season (Leach et al., 2006). Detailed site-specific emergency plans and implementing procedures provide instructions and guidelines for dealing with or responding to a variety of emergency situations, including natural phenomena such as hurricanes. These integrated emergency plans are developed in a coordinated manner between the facility licensee and State and local authorities, with oversight by the NRC and Department of Homeland Security/Federal Emergency Management Agency (DHS/FEMA)(Leach et al., 2006). Moreover, formal procedures require that each nuclear power plant take specific actions under weather conditions specific to each site including shutdown of the reactor in anticipation of hurricane force winds (Leach et al., 2006). While shutdown of the reactor is vital to safe operation, the restart of the reactor requires approval from both the NRC and FEMA that may take days to weeks thereby disrupting the power supply.

Hurricane Andrew in 1992 was the first time a hurricane significantly affected a commercial nuclear plant (U.S. Nuclear Regulatory Commission, 1994). The analysis for wind indicated a need to modify the flood wall and improve the emergency procedure for Category 5 hurricanes. Hurricane Andrew caused damage to a number of non-safety structures and equipment at Turkey Point including: collapse of all steel-framed turbine canopies, damage to one of the chimneys belonging to the fossil fuel units, movement of the base anchors for the vent stack on the Unit 4 containment, failure of the ductwork from the radioactive waste building, and the collapse of the non-safety high-water tank onto the fire protection pumps and pipes thereby rendering one of the fire protection systems inoperable. This event demonstrated the need to either design non-safety structures and equipment to withstand the postulated events, or assure that the consequences of their failure would not disable the safety functions of safety-related structures, systems and components (U.S. Nuclear Regulatory Commission, 1994).

Prior to the storm, on August 23, 1992, the licensee shut down both reactors and placed them in the “hot standby” condition as required by the plant emergency procedures. The plant lost all offsite power during the storm and for over five days after the storm (Leach et al., 2006). Furthermore, wind damage caused the loss of all communication at Turkey Point Nuclear Generating Station. As a result of this experience, the NRC arranged for portable satellite communication equipment to be available at sites as required (Leach et al., 2006). Many false alarms in the spent fuel containment created concerns because it was not accessible during the storm (IAEA, 2003b). In addition, the security system sustained extensive damage specifically to equipment including: lighting, cameras, intrusion detection equipment, protective area fencing, and the entrance building (Leach et al., 2006).

The impact of hurricanes on nuclear power plants is not limited to sites immediately along the coast, but can cause problems a considerable distance inland as demonstrated by Hurricane Isabel in 2003. Several nuclear plants had inoperable emergency sirens due to power outages resulting from the storm including: Hope Creek and Salem in New Jersey, Harris-1 in North Carolina, and Peach Bottom, Three Mile Island-1 and Limerick in Pennsylvania, and Calvert Cliffs in Maryland (Washington staff, 2003). The Surry units in southeastern Virginia were taken off line manually after a transformer that powers the water circulation pumps at an intake canal lost power. High winds also knocked down trees and temporarily blocked access to the site. Surry-1 returned to service within a few days after approval of the NRC and FEMA and reached full power after five days (Washington staff, 2003). The impact of a storm is not always immediate. Hope Creek and Salem shutdown for several days after Hurricane Isabel had passed. The storm had created heavy waves and fog in the Delaware River, producing saline water vapor that left salt deposits in the plants' switchyards causing electrical faults and arcing (Washington staff, 2003).

The 2004 and 2005 hurricane seasons had the most significant impacts on the operation of nuclear power plants. Multiple hurricanes affected the operation of nuclear power plants during the 2004 hurricane season: Hurricane Charley impacted the Brunswick site in North Carolina, Hurricane Frances impacted the operation of St. Lucie and Crystal River in Florida, and St. Lucie was impacted again by Hurricane Jeanne (Kauffman, 2005). The reportable impacts on the nuclear power plants were mainly confined to the loss of offsite power, loss of sirens, and loss of communications equipment. One insight gained was that site access during hurricanes is as important as the communications and siren issues. Security concerns were mentioned in a report on the impact of the 2004 hurricane season; however, due to the sensitivity of the subject matter details were not provided (Kauffman, 2005). The loss of off-site power at Brunswick and Crystal River was due to undetected degraded transmission line insulators failing during the storm conditions. Brunswick and St. Lucie had problems related to switchyard designs that were not robust during extreme weather conditions. All three sites had breaker faults or failures related to salt contamination or moisture intrusion. Moreover, the licensee at one site stated that preventive and corrective maintenance activities had not identified moisture buildup as a condition requiring corrective action (Kauffman, 2005).

In addition to these equipment problems, all three plants experienced unexpected equipment malfunctions or failures during their events. Brunswick had failures of the B-train standby gas treatment. St. Lucie experienced problems with a feed-water regulating valve and a breaker for an intake cooling water pump. Crystal River had an overloaded alarm system and failure of an emergency lube oil pump for a main feed-water pump turbine. The most significant finding was after the hurricane passed the St. Lucie site. The reactor auxiliary building's missile shield doors were found open; thereby, risking exposure of safety-related equipment to tornado-induced missiles. The licensee stated that the doors could have been open for several years (Kauffman, 2005).

The 2005 hurricane season took its toll on a different suite of nuclear power plants. The Grand Gulf plant in Mississippi, the River Bend plant in Louisiana, and the Waterford 3 plant in Louisiana, were more affected by Hurricane Katrina than the plants located in Florida (Leach et al., 2006). The three power plants did not sustain significant damage. Waterford -3 was the nuclear power plant closest to the hurricane's path and shut down on August 28th as Hurricane Katrina made its approach toward Louisiana (Weil, 2005a, 2005b). Waterford-3 received clearance to restart September 9th, but it took more than two weeks for the plant to return to service after shutting down (Weil, 2005c). River Bend and Grand Gulf did not shut down during the storm, but voluntarily reduced power to assist in restoring stability to the electrical grid when a drop in energy consumption caused grid voltage to fluctuate (Weil, 2005b). Winds knocked out 17 of the 43 emergency sirens in the area near the Grand Gulf station placing the number of required sirens less than the operability rate of 75% (Weil, 2005b). Land-line and cellular communications at the Waterford 3 site were lost because of flooding, electrical outages, and wind damage in the New Orleans area. To address the loss of land-line communication, extra land lines were installed and satellite communications equipment was employed for communication following the hurricane's passage at this site. However, satellite phones were not as robust as was anticipated, since cloud cover interrupted the reception, operators had to go outside to use them (Leach et al., 2006). In addition, offsite power was lost because of instability in the regional electrical grid. In response to the loss of offsite power, electrical power for key safety systems for the Waterford 3 plant was supplied automatically by the plant's standby diesel generators. Prior to the hurricane, the licensee for the Waterford 3 facility obtained two additional diesel generators to supplement the installed units and placed them on site (Leach et al., 2006).

The 2004 and 2005 hurricane season interrupted the operation of nuclear power plants and the transmission of power enough to cause financial concerns for the companies involved. However, the costs were more related to infrastructure damage rather than damage to the nuclear power plants. Uncertainty surrounding when hurricane costs will be fully recovered prompted Standard & Poor's Ratings Services (S&P) to revise its outlook to negative from stable on 'BBB' issuer credit ratings for Progress Energy Inc. Progress Energy which owns Brunswick and Shearon-Harris nuclear plants in North Carolina, Robinson-2 in South Carolina, and Crystal River-3 in Florida has estimated its costs from three of the four hurricanes that battered Florida and other parts of the south in 2004 at $310- to $330-million. Though the total includes all Progress Energy plants, the bulk of the costs were incurred at the Florida sites (Hiruo, 2004). After Katrina, Entergy Corporation warned investors in a September 6th filing with the Securities & Exchange Commission that the hurricane would have a financial impact on the company's earnings. It said revenues would be lower than expected because of extended outages and the inability to bill and collect revenues from customers whose property was destroyed. Moreover, it expected capital expenditures to rise as it begins restoration and repairs in the affected service areas (Weil, 2005c).

4.3. Design Concerns

Storms have caused safety problems regardless of the measures taken to address external events in design. An additional concern is whether the margins used in design are enough to accommodate climate change. The historical climate record can not be relied upon to predict future climate. Further, anticipatory measures must be taken to adapt to climate change and to ensure that structures withstand extreme climate events. In reviewing U.S. NRC documents I was unable to find any indication that models currently used to determine maximum flood and storm conditions incorporate climate change. Moreover, models generated by the National Oceanic and Atmospheric Administration (NOAA) and the Army Corps of Engineers lead to different results with the NOAA model indicating current design margins were not adequate at one nuclear power plant site. The U.S. NRC chose to use models that gave more conservative results when it would be prudent to use greater safety margins to accommodate climate change.

Hurricane design is based on studies conducted by the Environmental Science Services Administration and the Coastal Engineering Research Center for those sites that are exposed to the full force of hurricane winds. The design is considered to provide full protection against hurricane winds, tides, and wave action for the worst hurricane reasonably possible at the site: the probable maximum hurricane (PMH) (Haney, 2006). The PMH is defined by the National Weather Service as a hypothetical hurricane having that combination of characteristics which will make it the most severe that can probably occur in the region involved. The PMH is assumed to approach the plant site along the critical path, and at the optimum rate of movement (Haney, 2006). The values for the PMH are developed from storm history over a wide stretch of coast extrapolated out about 2000 years, while probable maximum precipitation values are developed from the 100 year record maximum for the area (U.S. Nuclear Regulatory Commission, 2008b). Precipitation events are predicted to increase in frequency and intensity due to climate change, and the 100 year record does not capture climate variability of longer time-scales.

Similarly, wind design should incorporate the possibility of changes in wind speed and direction, but these considerations are not apparent in the U.S. NRC model descriptions. The wind speeds used in the design of safety-related structures of east-coast plants vary from 177 to 210 km/h (110 to 130 mph). As the load factor used with the design wind loading is 1.7 these structures can withstand Category 4 and low intensity Category 5 hurricanes. The design against tornado generated loadings provides margin against failure of safety-related structures during hurricanes (U.S. Nuclear Regulatory Commission, 1994). Still, as shown in Table 29, St. Lucie and Crystal River are the only reactors designed specifically to withstand a category 5 hurricane.

Table 29. Wind designs for nuclear power plants that are in the direct path of hurricanes (Haney, 2006).

Reactor	State	Sustained Wind	Tornado
Brunswick	North Carolina	217 km/h (135 mph)	483 km/h (300 mph)
Crystal River	Florida	288 km/h (179 mph)	483 km/h (300 mph)
St. Lucie	Florida	312 km/h (194 mph)	483 km/h (300 mph)
South Texas Project	Texas	201 km/h (125 mph)	579 km/h (360 mph)
Turkey Point	Florida	233 km/h (145 mph)	542 km/h (337 mph)

The storm surge typically causes the most damage to structures, and determining surge levels is exceptionally difficult. A disagreement between two different models, one developed by the National Oceanic and Atmospheric Administration (NOAA) and the other by the U.S. Army Corps of Engineers for the Brunswick site in North Carolina was revealed in a 2000 U.S. NRC memo (Thadani, 2000). The Brunswick plant is located approximately two miles west of the Cape Fear River, and approximately five miles west of the Atlantic Ocean and due to the curvature of the coastline in this area, the ocean also lies about four miles south. The plant is subjected to the full force of hurricane winds (Haney, 2006). A NOAA study published in 1992 used a different methodology and found surge elevations which, in the case of the Brunswick nuclear plant, exceeded the design basis flood level by 2 m (6.4 feet). The surge elevation of 8.66 m (28.4 feet) calculated by NOAA for the Brunswick site was based on a combination of parameters consistent with an extreme hurricane. NOAA refused to release its model, so evaluating the model proved difficult. Nonetheless, the U.S. NRC communication had several critiques of the results. For instance, the storm may not be realistic, because the parameters were assumed to be independent, and because the combination of parameters used may be unrealistic. In addition, certain roads in the vicinity of the site may not have been included in the calculations. In particular, highways 211, 87, and 133 could act as levees along the storm path chosen, thus impeding storm surge propagation. The model showed considerable surge beyond the highways, suggesting that they may not have been properly represented in the model (Thadani, 2000). However, an alternative explanation is that the model determined that the roads would not hold up to the undercutting caused by the dynamic action of the surge. NOAA's findings cast doubt on the adequacy of the design basis for the Atlantic coast nuclear power plants and of the NRC regulations used to determine the design basis. Consequently, the Brunswick plant had an independent assessment made of the NOAA report, including a new set of calculations, to verify that the design basis flood level provides adequate safety for the plant.

The Army Corps of Engineers was contracted to derive realistic water level frequency relationships for the Brunswick plant using state-of-the-art techniques of modeling and statistical analysis (Thadani, 2000). The 2000 memo provided detailed description on how the new surge levels were determined. The Coastal and Hydraulics Laboratory (CHL) at the Engineer Research and Development Center of the U.S. Army Corps of Engineers performed hurricane stage-frequency analyses for the five plants using a statistical technique named the empirical simulation technique (EST). This approach takes historical data consisting of storms and their storm parameters plus the response vector (the storm surge) and builds up a larger database by introducing small perturbations to the parameters. The EST also uses statistical re-sampling and nearest neighbor, random walk interpolation. In this procedure, hurricanes from a data set are selected randomly. One of the hurricane parameters is selected and the three hurricanes with the closest values are determined for use in interpolation. The same procedure is then applied to other hurricane parameters. Historical data are used to develop joint probability relationships among the various measured storm parameters. No simplifying assumptions are used so that the interdependence of parameters is preserved. The only assumption used is that future events will be statistically similar to past events in magnitude and frequency. From a historical data set, the CHL selected a subset of storm events, called a "training" set that is representative of the entire set of historical storms (Thadani, 2000). Assuming the same magnitude and frequency of hurricanes is a flawed assumption; furthermore, the memo does not indicate the time period of the historical data set that was used. However, the memo does state that random perturbations may result in more intense storms than the historical events, so a future hurricane may be the storm of record (Thadani, 2000).

The new analyses were then compared with the hurricane induced surge elevations resulting from the NOAA and Brunswick studies. Later, the study was extended to include four more coastal nuclear plants, namely Crystal River, Turkey Point and St. Lucie, in Florida; and Oyster Creek in New Jersey. The EST analysis predicted a total surge elevation of 4.9 to 5.2 m (16 to 17 feet) MSL for a 2000 year return period. This elevation is 1.5 to 1.8 m (5 to 6 feet) lower than the 6.7 m (22 feet) design basis for the plant, which was computed using the probable maximum hurricane. The probable maximum hurricane is also estimated for a return period of 2000 years. In the case of the other four plants (Turkey Point, St. Lucie, Crystal River, and Oyster Creek), the EST derived levels were lower than the design levels by 0.3 m (1 foot), 2.4 m (7.8 feet), 8.1 m (26.5 feet), and 3.7 m (12.1 feet), respectively (Thadani, 2000). Considering predictions of sea level rise a 0.3 m (1 foot) margin is probably not adequate.

The U.S. NRC concluded that the NOAA study results are inconsistent with the other sets of data and provide storm surge levels that are overly conservative. This discrepancy was thought to be due to the fact that the hypothetical storms used in the study are based on the joint probability method, and do not realistically replicate the historic storms in the study region. Although the synthesized storms may be similar to historic ones, their probability of occurrence seems to be greater (Thadani, 2000). Thus, the methodology used by NOAA was criticized for predicting more intense storms that may occur more frequently.

The U.S. Army Corp of Engineers' analysis of hurricane storm surge levels for five plants on the Atlantic and Gulf coasts showed that the design basis flood levels of these plants are adequate and the U.S. NRC closed related safety issues. The two units of the Brunswick nuclear plant were licensed in 1974 and 1976 with a design basis flood level of 6.7 m (22 feet) derived from Reg. Guide 1.59 procedures. These procedures employ a bathystrophic storm surge theory to derive surge elevations induced by the probable maximum hurricane. The theory permits calculating surge levels along an ocean bottom transect. It is a 1-d method that cannot be applied to irregular shorelines involving inlets, or barrier islands. The method is considered obsolete today, but it was an accepted procedure at the time. The new storm surge methodology developed by the U.S. Army Corps of Engineers leads to different and often appreciably lower surge levels. Therefore, the U.S. NRC memo recommended that the existing regulatory guidance should be revised for use by new applicants. Revised guidance would incorporate new hurricane data and methodologies for determining design basis flood levels at locations on the Gulf or Atlantic coasts, and these new surge levels would be lower than what was previously used.

In addition, a recent task force report on hurricanes indicates that the data used in these models does not account for climate variability over longer time-scales. Oyster Creek in New Jersey is over 2 miles from the Atlantic Ocean and the site does not experience the full force of hurricane winds. The hurricane flood design for Oyster Creek is based on the historical data on nine severe hurricanes which threatened the plant site between 1935 and 1967 (Haney, 2006). This period of time coincides with hurricane intensity and frequency that is below the norm when considering a much longer timescale, and therefore may not provide adequate margins in design. The highest observed water elevation was 1.37 m (4.5 ft) above mean sea level. Water level would need to reach the plant grade level 1.83 m (6 ft) mean sea level before it would seep into any of the Oyster Creek buildings (Haney, 2006). Similarly, the hurricane flood design for the St. Lucie site is based on the historical data of 20 hurricanes which have threatened the plant since 1900 (Haney, 2006).

While always a dynamic environment, when hurricanes make landfall the coastal environment becomes hostile. Safety issues are currently the chief concern for nuclear power plant operation at coastal locations. The sea level rise models used in this study demonstrate that investment in shoreline and flood protection structures will be necessary to prevent flooding of coastal nuclear power plant sites. However, shore armoring can worsen erosion of adjacent lands and cause habitat losses, thereby impairing the ability of human and natural systems to adapt to climate change. The next section will explore the impacts of climate change at inland locations.

Part II Inland Climate Impacts

Similar to the coastal environment, at inland locations it is not a change in average conditions, but rather a change in variability and extremes that is of primary concern for vulnerability and adaptation (Burton et al., 2001). While nuclear power plants located along the coast benefit from an ample supply of cooling water, heat waves and drought threaten to reduce the supply of cooling water at inland locations. At the same time, nuclear power plants at inland locations must also contend with flooding during storms and intense precipitation events. The first step in evaluating climate impacts to nuclear power is to understand the changes in extremes forms of climate that will occur at inland sites. In Chapter 5 a literature review provides details on heat waves, heavy precipitation events, drought, and changes to aquatic ecosystems that could increase the frequency of biological fouling of intake structures. This chapter explores the latest in climate science by looking at historical climate records, recent changes, and modeled predictions. Chapter 6 reviews the methods used to evaluate nuclear power at inland sites. Chapter 7 presents the results of 1) Flooding in France, 2) Heat Waves and Drought in France, 3) Drought and Heat Waves in the United States, and 4) Biological Fouling in Canada and the United States.

5. Inland Climate Concerns Background

Storms are only one form of extreme weather. While the El Nino-Southern Oscillation (ENSO) causes storms events on the California coast, it is also responsible for both droughts and floods in regions throughout the world. The warm ocean temperatures trigger changes in atmospheric circulation creating dry conditions in some regions and wet conditions in others. La Niña, which follows El Niño tends to reverse the trend causing dry periods in areas that were wet during El Niño and vice versa (K. Trenberth et al., 2004). How climate change will impact this cycle remains uncertain. However, results of observational studies suggest that in many areas, changes in total precipitation are amplified at the tails, and changes in some temperature extremes have been observed. Furthermore, models show changes in extreme events for future climates, such as increases in extreme high temperatures, decreases in extreme low temperatures, and increases in intense precipitation events (Easterling, 2000).

Basic theory, climate model simulations and empirical evidence all confirm that warmer climates, owing to increased water vapor, lead to more intense precipitation events even when the total annual precipitation is reduced slightly, and with prospects for even stronger events when the overall precipitation amounts increase (K. E. Trenberth et al., 2007). The warmer climate increases risks of both drought and floods but at different times and/or places. For instance, the summer of 2002 in Europe brought widespread floods but was followed a year later in 2003 by record-breaking heat waves and drought

(K. E. Trenberth et al., 2007). Higher water temperatures and changes in extremes are projected to affect water quality and exacerbate many forms of water pollution including: sediments, nutrients, dissolved organic carbon, pathogens, pesticides, salt, and thermal pollution (Bates et al., 2008). These impacts cause changes to the structure of aquatic ecosystems which can in turn lead to intake fouling. Ultimately, nuclear power operation is threatened by too much water from flooding, too hot of water from heat waves, and too little water due to drought or intake biological fouling.

5.1. Heat Waves

Compared to other extreme weather events, heat waves typically receive little attention. This lack of recognition increases the vulnerability of populations to heat waves. For instance, in the United States loss of human life by hot spells in summer exceeds that caused by all other weather events (G.A. Meehl & Tebaldi, 2004). During the 2003 European heat wave, data provided by the Director-General of the French Institut de Veille Sanitaire estimated an excess mortality in France of 11, 435 people from August 1st to 15th (World Health Organization Europe, 2003), while other estimates have been as high as 15, 000 (Lagadec, 2004; Poumadere et al., 2005). Multi-day events make it more difficult to attribute the loss of life due to temperature extremes because affected individuals often suffer from other health problems heat is sometimes recorded as a secondary cause of death (Changnon et al., 1996). Therefore, it is recognized that deaths due to heat waves are underestimated. This has been confirmed by research that finds much higher death rates, by comparing death counts in summer during heat-wave and non-heat-wave periods (Palecki et al., 2001).

Currently heat waves are more severe in the southeast United States and less severe in the northwest United States. For Europe, there is more of a north-south gradient in both observations and models, with more severe heat waves in the Mediterranean region and less severe heat in the north (G.A. Meehl & Tebaldi, 2004). Many of the areas most susceptible to heat waves in the present climate experience the greatest increase in heat wave severity in the future; however, other areas not currently as susceptible also experience increased heat wave severity in the 21st century models (Diffenbaugh et al., 2005; G.A. Meehl & Tebaldi, 2004). This poses a challenge to adaptation because these regions are not accustomed to dealing with heat waves.

Furthermore, according to the IPCC 2007 report, it is very likely that heat waves will be more intense, more frequent and longer lasting in a future warmer climate (G.A. Meehl et al., 2007). Climate model simulations show increases in the intensity of heat waves of all durations. For example, in the Great Lakes region a 1-in-20-yr event lasting 5 days has an intensity range of between 28° and 34°C under present-day conditions. This range becomes 38° to 44°C in response to CO_2 doubling (Clark et al., 2006).

One method of quantifying changes in extremes is to calculate the frequency at which a fixed threshold is exceeded under different CO_2 levels simulations. Under doubled CO_2 conditions, the occurrence of days on which maximum temperatures exceed the simulated present-day 99th percentile threshold were found to be 20 and 28 times more frequent in January and July respectively (D. N. Barnett et al., 2006). The magnitude of the increases in daily temperature extremes varies substantially with region. In July, for example, the largest increases are found over western parts of North America, the northern half of South America, and much of southern Europe, northern Africa and the Middle East (D. N. Barnett et al., 2006).

Analyzing temperature distributions is a more illustrative approach to understanding climate change. For instance, there is a tendency for increasing temperature variability in summer and decreasing variability in winter and spring (Scherrer et al., 2005). While significant shifts to warmer conditions occur in June, July, and August, changes in extremely hot days are shown to be significantly larger than changes in mean values in some regions (Clark et al., 2006). Furthermore, not all regions show the same change in temperature distributions. Under CO_2 doubling conditions, the Czech Republic temperature distribution shifts to warmer conditions and the warm tail extends slightly, whereas in the Great Lakes region, a shift to warmer conditions is accompanied by a subtle change in shape with a wider distribution for temperatures and a broader maximum peak. Eastern China and southwestern France have particularly complex changes in distribution shape. The two regions have a bimodal distribution under doubled CO_2 with peaks at 32° and 40°C in eastern China and 25° and 40°C in southwestern France (Clark et al., 2006).

Regional differences may be due in part to fine-scale processes that act as feedbacks either mediating or intensifying heat waves. Soil moisture, number of wet days, and nocturnal cooling are significant factors responsible for changes in heat wave intensity, duration, and frequency (Clark et al., 2006). For instance, analysis of daily temperatures during simulated heat waves, demonstrates that increases in intensity and frequency are explained mainly by reductions in nocturnal cooling during hot spells, rather than by increases in daytime heating (Clark et al., 2006). Moreover, peak increases in hot events are amplified by surface moisture feedback that appear to result from complex, two-way interactions between large-scale atmospheric circulation and fine-scale spatial variability in topography, natural land cover, and human land use (Diffenbaugh et al., 2005). Global Climate Model (GCM) simulations demonstrate that the greatest change in return values of daily maximum temperature are found in central and southeast North America, central and southeast Asia, and tropical Africa where there is a substantial decrease in summertime soil moisture. Reduced soil moisture means that maximum surface temperatures are less likely to be moderated by evaporative cooling. In contrast, the west of North America is affected by increased precipitation resulting in more soil moisture and a more moderate increase in extreme maximum surface temperature (Kharin & Zwiers, 2000).

During the 2003 European heat wave, the heat leaving the dry soil contributed to the rather rapid rise in temperature in the morning hours. Observations taken at the University of Reading indicate that the ground played an important role in the accumulation of heat during the day and its gradual release at night (Black et al., 2003). This acted to offset night-time cooling driven by upward long wave radiation under clear skies, slowing the decrease in air temperature before sunrise. For the duration of the heat wave, the night-time temperatures exceeded the daily average temperatures (Black et al., 2003).

A global coupled climate model shows that there is a distinct geographic pattern to future changes in heat waves. Observations and the model show that present-day heat waves over Europe and North America coincide with a specific atmospheric circulation pattern that is intensified by ongoing increases in greenhouse gases, indicating that it will produce more severe heat waves in those regions in the future (G.A. Meehl & Tebaldi, 2004). Model results suggest that under enhanced atmospheric greenhouse-gas concentrations, summer temperatures in Europe are likely to increase by over 4˚C on average, with a corresponding increase in the frequency of severe heat waves (Beniston, 2004). Using a threshold for mean summer temperature that was exceeded in Europe in

2003, but in no other year since the start of the instrumental record in 1851, estimates show that it is very likely that human influence has at least doubled the risk of a heat wave exceeding this threshold magnitude (Stott et al., 2004). Moreover, Regional Climate Models (RCM) simulations suggest that towards the end of the century about every second summer could be as warm or warmer and as dry or dryer than 2003 (Schar et al., 2004). The models demonstrate that the European summer climate might experience a pronounced increase in year-to-year variability in response to greenhouse-gas forcing. Such an increase in variability might be able to explain the unusual European summer 2003, and would strongly affect the incidence of heat waves and droughts in the future (Schar et al., 2004).

5.2. Precipitation

Globally, the area of land classified as very dry has more than doubled since the 1970s, while at the same time the frequency of heavy precipitation events has increased over most areas (Bates et al., 2008). It is very likely that the frequency of heavy precipitation events will increase over most areas during the 21st century, while at the same time the proportion of land surface in extreme drought is projected to increase (Bates et al., 2008; Frich et al., 2002).

A warmer atmosphere has a greater moisture-holding capacity; therefore, global climate model simulations demonstrate that extreme precipitation increases almost everywhere. Relative changes in extreme precipitation are larger than changes in total precipitation (Kharin & Zwiers, 2000). Over the Pacific Northwest and Gulf Coast regions, increases in extreme-event contribution were accompanied by increases in the frequency of dry days (Diffenbaugh et al., 2005). Similarly in Europe, increases in the amount of precipitation that exceeds the 95th percentile is very likely despite a possible reduction in average summer precipitation over a substantial part of the continent (Christensen & Christensen, 2002).

The impact of climate change on precipitation is often described as a wetter world; however, this oversimplifies the situation given that precipitation is highly variable regionally and temporally (Bell et al., 2004). Seasonal shifts in precipitation provide further challenges to adaptation as precipitation may increase in one season and decrease in another (Kundzewicz et al., 2007). In a warmer world, less winter precipitation falls as snow and the melting of winter snow occurs earlier in spring. Even without any changes in precipitation intensity, both of these effects lead to a shift in peak river runoff to winter and early spring, away from summer and autumn when demand is highest (T. P. Barnett et al., 2005). For instance, hydrological simulations suggest that this warming will shift the Rhine River basin from a combined rainfall and snowmelt regime to a more rainfall-dominated regime, resulting in an increase in winter discharge, a decrease in summer discharge, increases in the frequency and amount of peak flows, and longer and more frequent periods of low flow during the summer (T. P. Barnett et al., 2005).

In the mid-latitudes, the pattern of precipitation intensity increase is related in part to the increased water vapor being carried to areas of mean moisture convergence to produce greater precipitation, as well as to changes in atmospheric circulation. Advective effects contribute to greatest precipitation intensity increases over northwestern and northeastern North America, northern Europe, northern Asia, the east coast of Asia, southeastern Australia, and south-central South America (G. A. Meehl et al., 2005). Heavy precipitation events are increasing in both frequency and intensity. Since 1910, across the contiguous United States, precipitation has increased about 10% primarily from heavy and extreme daily events (Karl & Knight, 1998). Furthermore, the fraction of annual total precipitation from events wetter than the 95th percentile of wet days (≥1 mm) for 1961–1990 shows that major increases have been observed in many parts of the USA, central Europe and southern Australia (Frich et al., 2002). Observed changes in intense precipitation have been analyzed for over half of the land area of the globe utilizing three climate model simulations, all with greenhouse gas concentrations increasing during the twentieth and twenty-first centuries and doubling in the later part of the twenty-first century. Utilizing these models changes in heavy precipitation frequencies were found to be higher than changes in precipitation totals and, in some regions, an increase in heavy and/or very heavy precipitation occurred while no change or even a decrease in precipitation totals was observed (Groisman et al., 2005).

While heavy precipitation may increase in the winter, there is a tendency for drying of the mid-continental areas during summer, indicating a greater risk of droughts in those regions (G.A. Meehl et al., 2007). The term drought may refer to meteorological drought (precipitation well below average), hydrological drought (low river flows and water levels in rivers, lakes and groundwater), agricultural drought (low soil moisture), and environmental drought (a combination of the above) (Kundzewicz et al., 2007). The socio-economic impacts of droughts may arise from the interaction between natural conditions and human factors, such as changes in land use and land cover, water demand and use (Kundzewicz et al., 2007).

Hydrological drought integrates climate factors and additional influences such as plant transpiration, soil, and water withdrawals. Hydrological models have been used for watersheds throughout Europe. 100-year droughts show strong increases for large areas of southern and southeastern Europe, while typical 100-year floods are projected to occur more frequently in large areas of northern and northeastern Europe. Some smaller regions show indications for a rise in both flood and drought frequencies, which may be due to a change in the seasonal variability of precipitation and temperature that leads to both more extreme high and low-flow months (Lehner et al., 2006).

Meteorological drought in the Hadley Centre Global Climate Model is assessed using the Palmer Drought Severity Index (PDSI). PDSI is an index of moisture supply and demand at the land surface determined by precipitation and evapotranspiration. At interannual time scales, for the majority of the land surface, the model captures the observed relationship between the El Niño–Southern Oscillation and regions of relative wetness and dryness. At decadal time scales, on a global basis, the model reproduces the observed drying trend since 1952. This model predicts that the proportion of the land surface in extreme drought will increase from 1% for the present day to 30% by the end of the twenty-first century. The number of extreme and severe drought events is projected to double. While the number of moderate drought events remains stable, there is a significant increase in the mean event duration for all forms of drought (Burke et al., 2006).

Causal factors of natural droughts are not well understood and are complicated by multiple feedback loops. In general, the underlying cause of a drought is a change in average atmospheric circulation patterns, which can result from both internal and external forcings. Internal forcings include sea-surface temperature (SST) and land-surface characteristics, whereas external forcings include the sun, the Earth's orbit , and volcanoes (K. Trenberth et al., 2004). Historical documents, tree rings, archaeological remains, lake sediment, and geomorphic data provide evidence that several droughts in

North American in the last 2000 years were worse than those of the twentieth century, including the droughts of the 1930s and 1950s. Furthermore, paleoclimatic data suggest a 1930s-magnitude Dust Bowl drought occurred once or twice a century over the past 300-400 years, and a decadal-length drought once every 500 years (Woodhouse & Overpeck, 1998). In the United States, three distinct periods of widespread and persistent drought stand out in these records for the latter half of the nineteenth century: 1856-1865, 1870-1877 and 1890-1896. Each of these events is shown to coincide with the existence of a cool, La Nina-like tropical Pacific (Herweijer et al., 2006). It is found that the correlation between modeled and observed soil moisture variability in the Plains region decreases from the nineteenth century to the twentieth century, indicating drought conditions that are forced more by sea-surface temperature in the earlier period. In the twentieth century, internal atmospheric variability and external forcing from anthropogenic changes in land use, atmospheric composition or solar variability had a larger influence on the drought variability in the Plains (Herweijer et al., 2006). Drought reconstructions reveal the existence of successive mega-droughts persisting for twenty to forty years, but similar in year-to-year severity and spatial distribution to the major droughts experienced in today's North America. These mega-droughts occurred during a 400-yr-long period in the early to middle second millennium A.D., with a climate varying as today's, but around a drier mean. The implication is that the mechanism forcing persistent drought in the West and the Plains in the instrumental era is comparable to that underlying the mega-droughts of the medieval period (Herweijer et al., 2007). However, the cause of historic drought is not fully understood. Models agree that tropical Pacific SSTs are important for North American drought, but the models disagree on the relative roles of Pacific, Indian, and Atlantic SST forcing (Herweijer et al., 2007).

The causes and global context of the North American drought between 1998 and 2004 were examined using atmosphere model simulations variously forced by global SSTs or tropical Pacific SSTs alone. The drought divides into two distinct time intervals. Between 1998 and 2002 it coincided with a persistent La Niña–like state in the tropical Pacific. During the later period of the drought, from 2002 to 2004, weak El Niño conditions prevailed and, while the global climate adjusted accordingly, western North America remained in drought. The climate models did not simulate the continuation of the drought in these years, suggesting that the termination of the drought was largely unpredictable in terms of global ocean conditions (Seager, 2007). Sea-surface temperature is not the main driver for all droughts particularly in certain regions. For instance, summer season precipitation variability in the Southeast United States appears governed by purely internal atmospheric variability; therefore, model simulations forced by historical SSTs are very limited in their ability to reproduce the instrumental record of precipitation variability in the southern United States (Seager et al., Submitted).

In the Southeast region, tree ring records show a two decade long drought in the mid Sixteenth Century, a long period of dry conditions in the early to mid Nineteenth Century, and that the Southeast was also impacted by some of the Medieval mega-droughts centered in western North America (Seager et al., Submitted). Climate model projections predict that in the near term future precipitation in the Southeast will increase, but evaporation will increase more. According to these projections climate change will not end the Southeast's water problems and is likely to make the problem worse (Seager et al., Submitted).

Current demands for water in many parts of the world will not be met under plausible future climate conditions, much less the demands of a larger population and a larger economy (T. P. Barnett et al., 2005). The recent two year drought that struck the Southeast, by summer and fall 2007, had caused serious water shortages in the region leading to the imposition of restrictions on water use and the opening up of legal conflicts within and between states on the regulation and use of the region's water resources. This is despite the most recent two year drought not being more severe than earlier droughts, including one as recently as 1998 to 2002, and indicates that the water shortage crisis was largely driven by rising demand (Seager et al., Submitted). Currently, human beings and natural ecosystems in many river basins suffer from a lack of water. In global-scale assessments, basins with water stress are defined either as having a per capita water availability below 1,000m^3/yr (based on long-term average runoff) or as having a ratio of withdrawals to long-term average annual runoff above 0.4. These basins are located in Africa, the Mediterranean region, the Near East, South Asia, Northern China, Australia, the USA, Mexico, north-eastern Brazil, and the western coast of South America (Kundzewicz et al., 2007).

Responses to climate change must be resolved at regional and local levels in order for effective action to be taken; therefore, it is important to assess the potential for climate change on a regional level (Bell et al., 2004). The gap between global climate modeling and local to regional applications is filled by statistical and dynamical downscaling, which utilize statistical relationships between large-scale circulation and regional climate models to derive regional climate information (Leung et al., 2003). Regional models are also valuable when dealing with impacts to aquatic ecosystems and local resources.

5.3. Water Quality and Aquatic Ecosystems

The interaction between climate change, land use, and other environmental problems must be considered when evaluating climate impacts. Changes in runoff patterns and water temperature pose water quality problems and can alter aquatic ecosystems. For instance, increases in summer water temperature can increase oxygen depletion in thermally stratified lakes, increase the rate of nutrient and contaminant releases from lake-bottom sediments, and cause algal blooms that restructure the aquatic food web (Bates et al., 2008; Kling et al., 2003).

Changes to aquatic ecosystems and water quality issues are a problem in many regions. The green filamentous alga, *Cladophora,* in the Great Lakes is an example of this problem. Control of *Cladophora* was achieved in the 1980s through programs that reduced runoff pollution and improved sewage treatment. In the latter part of the 1990's, excessive *Cladophora* growth reemerged as a problem in the Great Lakes (Ontario Power Generation, 2007). Climate change and the introduction of zebra mussels to the Great Lakes caused the problem to return.

Zebra mussels promote *Cladophora* growth through several mechanisms. *Cladophora* grow on rocky substrates, and the zebra mussel beds provide additional substrate for the algae to grow (Hecky et al., 2004). The feces from the zebra mussels provide new sources of available phosphorous for the algae, without requiring any increase in external phosphorous to the lakes. The filter-feeding zebra mussels improve the clarity of the water column; thereby, increasing the amount of light that reaches the growing *Cladophora* (Hecky et al., 2004; Ontario Power Generation, 2007; S. A. Reynolds, 2004). In addition, positive feedback occurs when the decomposition of the increased biomass of *Cladophora* causes oxygen depletion that leads to further release of phosphorous from sediments (Hecky et al., 2004).

Climate change affects *Cladophora* in several important ways. First, higher water temperatures and corresponding oxygen depletion cause the release of nutrients from sediment. Regression analysis demonstrates that significant changes have already occurred in the Great Lakes including a lengthening of the duration of summer stratification and an earlier transition to spring-like conditions (McCormick & Fahnenstiel, 1999). In addition, model projections indicate further increases in water temperatures, longer duration of warm water stratification, a shallower depth of warming and more extensive depletion of oxygen from deep waters (Lehman, 2002). Second, excessive *Cladophora* production has coincided with periods of low lake levels, both now and in the 1960s (Harris, 2008). Many assessments project lower net basin supplies and water levels for the Great Lakes–St. Lawrence Basin (Bates et al., 2008; Mortsch et al., 2000). Lower lake levels are due to decreased precipitation in this region (Mortsch et al., 2000), and greater evaporation from open water due to reduced ice cover (Kling et al., 2003).

Finally, climate plays a role in the detachment of *Cladophora* and seasonal biomass accrual. In terms of nuclear power plant operation, *Cladophora* growth in itself is not a concern, the real problem occurs after the algae detach from rocky substrate. Typically, growth is renewed in the spring when water temperature reaches 5˚C and attains its greatest development at 18˚C. The mass of filaments detaches and follows currents until it reaches the shore or is carried into deep water. New growth from the remaining stubs results in smaller summer population, while lower autumn temperatures result in another algal bloom which detaches as water temperatures decline toward 5˚C (Taft, 1975). Experimental evidence indicates that filaments are generally weaker when temperatures are close to the upper tolerance levels 25˚C(77˚F) (Storr & Sweeney, 1971). The weakened filaments cause the algae to detach from the substrate. Lester et al. (1988) found in lab studies the optimum temperature for *Cladophora* was between 28 and 31˚C. They found no evidence for a decline in photosynthetic rate with increasing temperature for this range of temperatures and high temperatures are not a likely physiological explanation of mid-season dieback (Lester et al., 1988). Higgins et al. (2006) attribute the dieback to self-shading exacerbated by moderately high water temperatures (~23°C). Dense mats of *Cladophora* at the water surface block light, thereby inducing negative growth rates and deterioration at the base of the mat (Higgins et al., 2006). A growth model for *Cladophora* predicts an earlier spring growth with increasing surface water temperatures, but only a marginal increase in peak *Cladophora* biomass (Malkin et al., 2008). However, self-shading and temperature are not the only mechanisms responsible for detachment. Large storm events can cause a large synchronous detachment of *Cladophora*. One consequence of a massive detachment event is an increase in irradiance and nutrient concentrations relative to the remaining *Cladophora* filaments, potentially serving to enhance growth. Furthermore, climate driven detachment events could affect total seasonal biomass accrual (Malkin et al., 2008). The detachment events combined with new algae growth could result in an increase in the frequency of biological fouling events at nuclear power plants.

The reemergence of the *Cladophora* problem demonstrates that the impacts of climate change are being felt now. In addition, evidence confirms that heat waves, drought and heavy precipitation events are increasing. The next section explores methods that evaluate how nuclear power has been adapting to these changes in climate.

6. Inland Methods

The inland portion focuses on how nuclear power plant operations deal with current climate variability. The countries studied in this section, France, the United States, and Canada, are currently constructing or planning to construct new nuclear reactors. It is necessary to look at nuclear reactor operation in these countries in order to get an understanding of the scope of the problem climate change poses.

France is the country with the highest dependence on nuclear power, generating over 75% of its electricity from nuclear in addition to being the world's largest net exporter of electricity (World Nuclear Association, 2008c). France was selected to understand the consequences of having a high dependence on nuclear power and because recently the country's nuclear fleet has encountered problems with both flooding and widespread heat waves at inland locations. France has 15 inland nuclear power plant sites with 44 operating reactors. The consequences of flooding to safe operations are evaluated, and the steps taken and costs to upgrade flood protection at inland locations in France are reviewed. In addition, all reactors at inland sites are included in the analysis for impacts felt during recent heat waves.

Almost 20% of the electricity generated in the United States comes from nuclear power and with 104 operating reactors the U.S. has the largest fleet of nuclear reactors in the world (World Nuclear Association, 2008d). The geographical extent provides an opportunity to look at the regional issues that arise from electing to use nuclear power. For instance, nuclear power plants located along rivers that depend on cool water from mountain reservoirs encounter different problems compared to reactors that are located along large lakes. Figure 28 shows the distribution of nuclear power plants in the United States.

The heat waves and drought section reviews sites throughout the United States that were affected by the 1988 heat wave, the impact of a reduced mountain snow pack on nuclear power plants in the Midwest (Region IV), and the drought and water scarcity problems in the Southeast (Region II). Nuclear power plants located along the Great Lakes in the U.S. (Region I and III) and Canada (Province of Ontario) have to deal with a specific problem: biological fouling from the green algae *Cladophora*. Analysis of the situation provides an opportunity to see how two different countries with different reactor types address the same problem. Canada receives 18% of its energy from nuclear power; however, the province of Ontario generates 50% of its electricity from nuclear power (World Nuclear Association, 2008a).

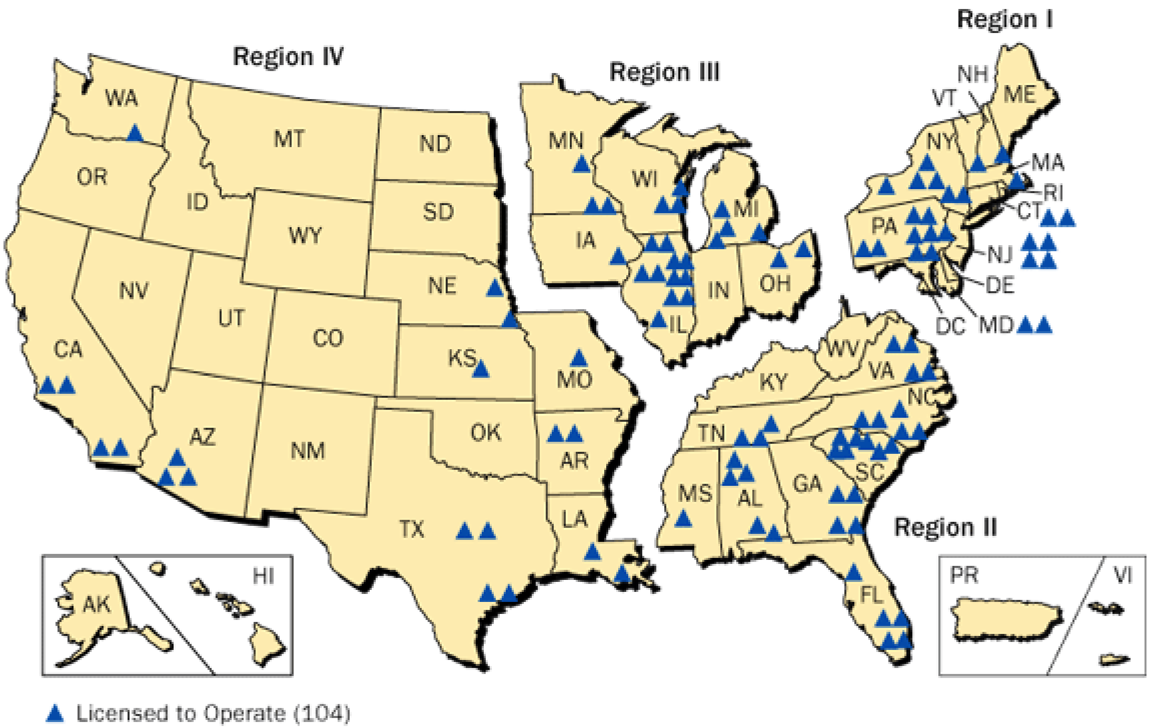

Figure 28. Nuclear power plants currently operating in the United States (U.S. Nuclear Regulatory Commission, 2008d).

The criteria described in Chapter 1 are used to judge the actions taken to adapt nuclear power plant operations to flooding, drought, heat waves, and biological fouling. Several indicators are used to gauge these criteria as outlined in Table 30.

Table 30. Criteria and indicators used to evaluate nuclear power plants located at inland sites.

Criteria	Indicator
Interrupted Operation	Unplanned shutdowns, power reductions
Financial Costs	Intake adjustments Alteration of cooling systems Flood protection
Adaptation Impairment - Human Systems	Legal Battles (pertaining to water)
	Brownouts/Blackouts (heat waves)
Adaptation Impairment - Natural Systems	Thermal pollution
Other Environmental Problems	Safety problems that include: Loss of off-site power Communication failure Restriction of evacuation routes Equipment malfunction Unplanned shutdowns

Reports generated by nuclear regulatory agencies, the Autorité de Sûreté Nucléaire (ASN) in France, the Nuclear Regulatory Commission in the U.S. (U.S. NRC), and the Canadian Nuclear Safety Commission (CNSC) in Canada, provides the information on length of reactor shutdown and safety issues arising from climate impacts. Utility reports and industry journals provide information concerning: the financial costs of adapting to climate, revenue losses from shut-downs, and changes to operating procedures such as temporary suspension of environmental regulations. Court documents that detail the legal battles pertaining to water, in regions with nuclear power plants, provide evidence of the reduced ability of human systems to adapt to climate change.

7. Inland Results

7.1. Flooding of Nuclear Power Plants in France

Inland reactors are threatened by flooding due to storms that reach inland and intense precipitation events. Reactors in France were impacted by floods during the winter of 2003; however, this was not the first time flooding has affected reactors in the country. It became apparent after the 1999 flood of the Le Blayais site that flood protection had to be investigated and improved at many sites.

Le Blayais nuclear power plant site consists of four 900 MW(e) pressurized water reactors (PWR) located 30 km southeast of the Atlantic ocean, on the banks of the Gironde estuary, in a swampy area. The Design Basis Flood (DBF) used to design dykes is 5.02 m French national datum level (NGF). The DBF was calculated as the level of water resulting from the maximum astronomical tide and the 1000 year storm surge. The site is surrounded by a dyke made of earth and protected on the River Gironde side by a pile of stone blocks (IAEA, 2003b). Alongside the River Gironde, its height is 5.2 m above the national datum, and its height is 4.75 m at the sides. The flooding event that occurred on December 27th,1999 resulted from a high tide, wind speeds of 100 km/h that generated waves estimated to reach a height of 2 m, combined with a 2.01 m storm surge. The maximum storm surge measured prior to December 27th, 1999 was 1.20 m for a 40 year historical series of data. Investigations carried out on the site after the storm showed that the water had overtaken obstacles from 5 to 5.30 m (Gorbatchev et al., 2000; IAEA, 2003b). According to the information provided by the nuclear operator, flooding began approximately two hours before high tide at around 7:30 pm on December 27th 1999 (Gorbatchev et al., 2000).

Loss of auxiliary power supplies and loss of the 400 kV grid for Units 2 and 4 occurred during the storm. Attempts to switch the units to house load operation to enable them to continue powering their auxiliaries following disconnection of the grid failed causing Units 2 and 4 to shutdown. The diesel generators of both units started up and operated correctly. The 400 kV line powering Units 1 and 3 continued to be unavailable. This led to the shut down of all 3 operating units. Meanwhile, strong waves submerged the plant platform, with water entering mainly on the northwest side of the dyke. The waves moved the rocks, protecting the dyke, and part of it was washed away alongside the River Gironde. The water reached a depth of around 30 cm in the northwest corner of the site (Gorbatchev et al., 2000; IAEA, 2003b). The volume of water which came into the facilities has been estimated to be about 90,000 m^3 (IAEA, 2003b). Units 1 and 2 were severely affected by incoming water: one of the essential service water pumps was lost as a result of immersion of the motors, some utility galleries were flooded, some rooms containing outgoing electrical feeders were flooded and electrical switchboards made unavailable, the bottom of the fuel building of Units 1 and 2 was also flooded (Gorbatchev et al., 2000).

After continuously monitoring the repair work for the three days following the incident, the Safety Authority asked EDF to repair all the flooded equipment and to upgrade the plant's protection against flooding. The dyke around the nuclear site was raised by 1 meter and the site was equipped with an alert system based on meteorological forecasts from Météo-France. An operational procedure was designed to bring the site reactors to a safe state and protect the premises felt to be most important. Under these conditions, the Nuclear Safety Authority authorized the two reactors most severely affected by the flood to restart in May 2000 (Autorité de sûreté nucléaire, 2000). The Safety Authority (ASN) also asked Électricité de France (EDF) to take steps against the risk of flooding due to surging of the Gironde River, before the first quarter of 2001. EDF in September 2000 proposed an anti-surge device consisting of riprap and a wall placed on top of the existing dyke that had already been raised in March 2000. The stability of this arrangement was examined by the Institute of Radiological Protection and Nuclear Safety (IPSN) and the Nuclear Installation Safety Directorate (DSIN), which approved its implementation. The height of the wall, determined following hydrodynamic modeling of the Gironde estuary and testing in a surge channel, was raised to 8.50 meters at the request of the Nuclear Safety Authority (Autorité de sûreté nucléaire, 2000).

The flooding which occurred at Le Blayais Nuclear Power Plant revealed a potential mode by which the safety of all the units of a single plant could be jeopardized (Gorbatchev et al., 2000). Inspection of the site revealed: that the operating teams were unprepared to deal with an incident that affected all the reactors on a site; that it was hard to perceive storm-related phenomena from the data available in the control room; and that the site had no suitable control procedures for managing a situation involving loss of outside electrical power sources combined with flooding (Autorité de sûreté nucléaire, 2000). The ASN wanted to take full advantage of the lessons learned from the flooding of Le Blayais and improve protection of all the reactors in France against flooding. In March 2000, the ASN asked EDF to produce an inventory of the existing constructive, material and organizational measures for dealing with the arrival of water on all of EDF's nuclear sites. On the basis of historical river flood data and of tides and storm surges for coastal areas, this exercise consists in determining the height of water opposite the nuclear site, with a return period of 1000 years. The DSIN asked EDF to propose protection measures such as dykes, curbs, alert systems, for DSIN to examine and validate prior to implementation (Autorité de sûreté nucléaire, 2000).

However, DSIN told EDF it must not wait to act until revised calculations of maximum flood risk are completed, and that it must take measures to protect reactor sites from external floods as soon as possible (MacLachlan, 2001). Action was particularly urgent at the Belleville PWR site, where EDF studies showed the "safe" flood level equivalent to the level of the maximum historical flood with a 15% safety margin was up to 1.4 meters higher than the level assumed in the plant's design (MacLachlan, 2001). In addition, protection of installations on the Tricastin site are particularly complicated to manage due to the large number of facilities and the proximity of the Rhone and the Rhone canal (MacLachlan, 2003d). DSIN asked EDF to advise it by June 9, 2001 what measures have been or will be taken to adapt the site's protections to the new data. A subsequent study by safety experts at IPSN showed that many EDF sites, as well as other French nuclear sites were under protected. The studies also focused on other external risks that might not have been sufficiently taken into consideration in original design

(MacLachlan, 2001). EDF announced May 16^{th} that it had proposed a 100-million-franc (approximately 13.5 million USD) program to build a levee around the Belleville site, to raise flood protection by roughly one meter. In the meantime, EDF planned to reinforce the site's system of mobile flood protection walls (MacLachlan, 2001).

The 1999 flooding was the first time the emergency center was activated by ASN. The same actions were necessary on the morning of December 2^{nd} 2003. The Cruas nuclear power plant takes its cooling water from the Rhone River. During the night of December 1^{st} and 2^{nd} 2003, intake of water containing large amounts of mud and vegetable matter impaired the efficiency of the cooling systems. Degradation of the heat sink according to normal operating procedures requires reactor shutdown. This state is referred to as the safe shutdown state. Loss of the heat sink requires initiation of the on-site emergency plan. The rapid deterioration of the exchange capacity of the cooling systems led the Cruas plant operator to trigger the on-site emergency plan as a preventive measure. The Tricastin plant, located further downstream than Cruas, takes its cooling water from the Rhone bypass canal at Donzère. Pumping of water containing large of amounts of vegetable matter and mud triggered safety shutdown of the cooling water pumping system and consequently automatic shutdown of the 3^{rd} and 4^{th} reactors on the 2^{nd} and 3^{rd} of December 2003 respectively (Autorité de sûreté nucléaire, 2003a). Fearing a deterioration of the situation, the Tricastin plant triggered its own emergency plan on the night of December 2^{nd} 2003. Late afternoon on December 3^{rd} 2003, the status of the nuclear installations, the weather forecast and the flow rate of the Rhone river were considered to be satisfactory enabling a number of alerts to be lifted and the gradual restart of reactors (Autorité de sûreté nucléaire, 2003a).

Lessons learned from 1999 flood were applied during the 2003 event. EDF head office services maintained a supervisory team in action in order to monitor the changing situation in the Rhone valley and in the Loire (Belleville, Dampierre, Saint-Laurent and Chinon) and Garonne (Golfech) valleys days before the maximum flood levels were to be reached on the rivers (Autorité de sûreté nucléaire, 2003a). In accordance with their procedures, the operators of the nuclear power plants on the Loire took preventive protection measures, in particular with regard to site access problems due to submersion of access roads and flooding of car parks. Furthermore, the build-up of detritus in the hydroelectric dam upstream of the Golfech plant was released in collaboration with the

Golfech plant operator (Autorité de sûreté nucléaire, 2003a). The 2003 floods demonstrated that some of the measures implemented after the storm of 1999 worked, but the increasing frequency of extreme weather conditions posed the question of whether further measures should be taken to protect nuclear installations (MacLachlan, 2003a).

The 2003 floods revealed another problem: the safety of certain installations during flooding events depends to a large extent on the behavior of the off-site structures not belonging to EDF. This is particularly important for the Cruas and Tricastin nuclear power plants. Evaluating the robustness and the surveillance and upkeep of these structures entails a decision-making process between the stakeholders, the authorities and EDF that is in principle highly complex. Therefore, ASN asked EDF to continue the exchanges initiated between the licensees of these structures and to keep it informed of any difficulties (Autorité de sûreté nucléaire, 2007).

ASN is taking part in updating the IAEA guide concerning the off-site flooding risk for nuclear sites. The objectives of this work are to create a single guide that can be used at all nuclear installations and includes feedback from operating experience and climate change studies. Current plans are for this guide to be published in February 2010 (Autorité de sûreté nucléaire, 2007).

7.2. Heat Waves and Drought in France

Many of the reactors that were affected by flooding in December 2003 were impacted by heat waves the previous summer. During the 2003 summer, a combination of low water levels and rising river temperatures, unmatched during previous heat waves, left the country's electricity supply situation very tight (Parey & Aelbrecht, 2005). The heat wave was also exceptional in its spatial extent. During July and August 2003, significantly above-average temperatures were observed throughout Europe, Scandinavia, and western Russia, with monthly mean temperatures exceeding the 90th percentile in each region (World Health Organization Europe, 2003). The meteorological conditions observed during the summer of 2003 raised the temperature of certain watercourses 5°C above the mean historical values observed during the past 25 years (Autorité de sûreté nucléaire, 2003b). Material and facilities at some nuclear power plants were potentially threatened by the increase in air temperature. Significant loss of power was already a problem prior to the heat wave due to constraints on thermal releases. River temperature forecasting depicted a critical situation from the 10th to the 20th of August with downstream water release temperature limits forecasted or observed upstream (Parey & Aelbrecht, 2005).

In order to comply with regulation, operators reduced power or halted production from several of their reactors, on the Le Blayais, Golfech, Tricastin and Bugey sites (Autorité de sûreté nucléaire, 2003a). The weekly voluntary nuclear power reduction was between 3500 to 6000 MW during the month of August. The total power reduction during the summer of 2003 was 5.3 TWh: equivalent to a loss of more than 200 reactor days (Parey & Aelbrecht, 2005). EDF attempted to balance production throughout its system by stopping certain units at certain plants rather than shutting entire multiple unit stations (Hibbs, 2003). Black-outs and brown-outs were avoided by exercising several options including: the purchase of energy on the wholesale power market (2800 MW), citizenship conservation (300 MW), negotiating lower loads from industry consumers (1700 MW) and reducing exportation to Italy (Parey & Aelbrecht, 2005). EDF was tied to firm export contracts and the contract with Italy was the only contract with a clause allowing interruption in the event of an emergency; nonetheless, EDF was able to cut its power exports by more than half (Hibbs, 2003; Poumadere et al., 2005). Electricity production and distribution hampered by the heat wave throughout Europe made energy supply much below demand; as a result, purchasing energy on the wholesale power market was a great expense to EDF. From August 10th to the 13th power prices were as high as a 1000 euros/MWh, a factor of 100 higher than normal prices (Hibbs, 2003; Parey & Aelbrecht, 2005).

Technical measures and operational changes also helped keep facilities operating. In order to optimize management of the cooling capacity of the cold source, the operators increased monitoring of the efficiency of those devices exchanging heat with this cold source. The building's ventilation system at Fessenheim-1 is connected to the cooling system and is less efficient than those at later French nuclear plants, which are connected to the raw water system. Technical specifications require the atmosphere inside containment to remain below 50˚C. The temperature reached 48.2˚C on July 31st, so EDF tested a system in which the outside of containment building was sprayed using groundwater. This system was proved to be ineffective when after four days the temp was still at 48.7˚C (Autorité de sûreté nucléaire, 2003a; Hibbs, 2003). Due to the temperature rise inside the reactor buildings on the Dampierre, Chooz, and Fessenheim sites, a waiver to the general operating rules was granted, so that a special air mixing system could be used inside the reactor buildings (Autorité de sûreté nucléaire, 2003b).

The use of groundwater to cool the containment structure at Fessenheim was contentious, but it was not the only unpopular decision made during the heat wave. In July 2003, the director of nuclear safety considered that the requests submitted by the operators of the Golfech, Tricastin and Bugey nuclear power plants, for thermal releases in excess of those authorized by the plants' release licenses, were non-significant modifications and therefore approved them (Autorité de sûreté nucléaire, 2003a). For those operator requests considered as significant, the Ministers for the Environment, Health and Industry issued an order on August 12th 2003, authorizing electricity production facilities located on the Rhone, Moselle, Garonne and Seine rivers to continue operating with thermal releases higher than the limits, while limiting the temperature rise in these watercourses to between 1 and 3 °C depending on the type of facility and the river. However, instead of an absolute maximum temperature the new order considered relative temperature or the difference between temperatures upstream and downstream of the plants. Initially, EDF had asked to increase the maximum temperature of the rivers downstream of the plants by around 1˚C (MacLachlan, 2003b).

The introduction of the order stated the rationale for its issuance. It was deemed that the climatic conditions faced by France and Europe during the summer of 2003 were exceptional circumstances threatening the safety of property and persons, the continuity of public services and the economic activity of the country. The order consisted of five articles with the first article pertained to the new thermal limits. Thermal electricity production (fossil fuel and nuclear) facilities discharging water into the Garonne, Rhone, Seine and Moselle river basins may continue to do so until such time as the difference between the water temperature measured upstream and downstream after mixing each of these installations is equivalent to 1 °C for installations fully equipped with cooling towers, 1.5 °C for those located on the Seine and Moselle rivers, and 3 °C for the other plants. In addition, the second article states that the use of these measures will be reduced whenever possible and limited only to the electricity production necessary for meeting national consumption and for complying with international agreements. The third and fourth articles pertain to monitoring of environmental impacts to river fauna and human health. The electricity producers shall closely monitor the environmental impact on river fauna and human health throughout the period in which the order is in force; in addition, they must keep the Director General for Nuclear Safety and Radiation Protection, the Director for the Prevention of Pollution and Risks and the Director for Water, and the Prefects with responsibility for river basin coordination, informed on a daily basis of the effective temperatures recorded after mixing downstream of each of the plants concerned, along with any repercussions observed on fish life. The order ended on September 30th 2003 (Autorité de sûreté nucléaire, 2003a).

Five power plants out of 13 that were exempted from thermal discharge limits used the exemptions. Of those five power plants, four were nuclear: Tricastin, Bugey, Gofech, and Cattenom as shown in Table 25. Tricastin consistently discharged water into the Rhone River at 2˚C or more above upstream temperatures between August 14th and August 27th. Bugey used it twice while Golfech used it 12 times (MacLachlan, 2004). Golfech heated the Garonne by 0.4˚C to 0.8˚C, potentially significant since, the Garonne is already one of France's hottest rivers (MacLachlan, 2003c).

Table 31. France's inland reactors and sites issued thermal release waivers.

Site Name (# units)	Cooling Source	Series	Waiver 2003	Waiver Used?	Waiver 2006
Le Blayais (4)	Garonne	CP1	3 ˚C	No	3 ˚C
Bugey (4)	Rhône	CP0	3 ˚C	Yes	3 ˚C
Belleville (2)	Loire	P'4	NA	NA	NA
Cattenom (4)	Moselle	P'4	1.5˚C	Yes	1.5˚C
Chinon (4)	Loire	CP2	NA	NA	NA
Chooz (2)	Meuse	N4 series	NA	NA	1.5˚C
Civaux (2)	Vienne	N4 series	NA	NA	NA
Cruas-Meysse (4)	Rhône	CP2	1˚C	No	NA
Dampierre-en-Burly (4)	Loire	CP1	NA	NA	NA
Fessenheim (2)	Rhine	CP0	NA	NA	NA
Golfech (2)	Garonne	P'4	1˚C	Yes	0.3˚C
Nogent-sur-Seine (2)	Seine	P'4	1.5˚C	No	1.5˚C
Saint-Alban (2)	Rhône	P4	3 ˚C	No	3 ˚C
Saint-Laurent-des-Eaux (2)	Loire	CP2	NA	NA	NA
Tricastin (4)	Rhône	CP1	3 ˚C	Yes	3 ˚C

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These measures were criticized by environmentalists and led many to wonder whether waivers for thermal discharges would become a regular summer feature if the July-August heat wave is indicative of climate change on a western European scale (MacLachlan, 2003b). The following summer DGSNR issued a permanent order allowing

EDF to modify thermal discharge limits by 1˚C to 2˚C at the Bugey, Golfech and Nogent reactor sites and by up to 3˚C at Tricastin between July 1st and September 30th of each year. The order requires EDF to justify discharging the hotter effluents into the rivers by the explicit needs of the national grid or of the Eurodif gaseous diffusion enrichment plant. The permanent order also imposed additional measures including increased monitoring of plant systems and the environment. The order helped during the summer of 2005, although production at Tricastin had to be temporarily lowered due to high temperatures in late June (MacLachlan, 2005b). EDF had also used the 2003 experience to license higher temperature limits for some nuclear plant rooms and cooling ponds (MacLachlan et al., 2006). However, these measures were not sufficient during the 2006 heat wave.

During the 2006 heat wave, temperatures in central and western Europe were 7˚C above historical maximums (MacLachlan et al., 2006). Black-outs were avoided by taking actions much the same as the measures implemented in 2003. EDF bought power on the European market and as a preventative measure purchased approximately 2,000 MW on the wholesale market prior to the heat wave (MacLachlan et al., 2006). Nuclear power plant maintenance outages were postponed, EDF used the right it has in some contracts to interrupt supply, and customers were asked to conserve. French power demand was about 3% higher than historical levels for the month of July.

The Institute of Radiological Protection and Nuclear Safety (IRSN) determined that the high temperatures had not posed any safety risk at France's nuclear installations; however, the temperatures were close to the design limits of certain equipment important for safety demonstration. In addition, the Loire River was the only French river with nuclear plants where temperatures had reached limits in the operating rules set by EDF and approved by safety authorities (MacLachlan et al., 2006). The high temperatures were determined to be compatible with the operation of Belleville, Dampierre, St. Laurent and Chinon; moreover, the 12 reactor units at those sites were monitored daily during the 2006 heat wave (MacLachlan et al., 2006).

The French government published an executive order on July 22nd 2006 allowing EDF to raise river water temperatures downstream of all its riverine nuclear plants if necessary to preserve the stability of the national grid and maintain power supply (MacLachlan et al., 2006). The ministerial order, valid until September 30, was signed by the ministers responsible for industry, environment and health. The order concerns plants located on the Garonne, Rhone, Seine, Meuse and Moselle Rivers, at sites that host 28 of EDF's 58 power reactors. The order doesn't specify absolute temperatures for each river downstream of power plants, as the 2004 order did, but only the acceptable change between the temperatures of river water at plant intake and discharge stations. The order allows a change in temperature of 0.3˚C for Golfech on the Garonne, 1˚C for plants equipped with cooling towers along the Rhone, and 1.5˚C for plants on the Meuse, Moselle and Seine. Those without cooling towers, like Tricastin and Saint Alban, can discharge water 3˚C hotter than the intake temperature. The nuclear plants on the Garonne (Golfech) and on the Rhone (Tricastin, St. Alban, Cruas, Bugey), whose production is necessary to balance electricity demand and supply were already operating under the limits set in 2004 (MacLachlan et al., 2006). The 2004 order had allowed EDF to discharge thermal effluents from Golfech into the Garonne up to a downstream temperature of 32˚C (89.6˚F). By mid-July the Garonne was already so hot that EDF had no margin for discharges. The 2004 order allowed discharge from Tricastin to heat the Rhone up to 29˚C (84.2˚F), but during the heat wave the Rhone was already at 29˚C upstream of the nuclear plant site (MacLachlan et al., 2006).

Further relaxation of thermal discharge limits was dependent on EDF accepting three conditions. First, EDF must show an imperative necessity of keeping a given plant on line, by proving it's needed to maintain grid stability. Second, the allowed temperature increase was lower than what EDF had requested, for example 0.3 degrees for the Garonne compared to 1 degree requested by EDF. Finally, the ministry asked EDF to release water from dams upstream of Golfech, for the benefit of aquatic species. An additional clause requires EDF and the French government to inform Belgium and Germany, which are downstream of France on the Meuse and the Moselle Rivers, before the utility makes use of the temperature exemptions (MacLachlan et al., 2006). Fortunately, the authorization was unnecessary as none of the reactors utilized the 2006 waiver (Autorité de sûreté nucléaire, 2006). Regardless many actions taken in 2006 were repeats of 2003 despite the benefit of prior experience. The rivers on which the nuclear plants sit were already at or near the normal limit of 28˚C during the heat waves, making it difficult for the plants to comply with discharge limits even if their cooling water isn't excessively warm (Hibbs, 2003).

An exceptional thermal release monitoring committee was set up to supervise the impact of thermal releases on the watercourses. From the environmental viewpoint, the limits stipulated in the orders aim to prevent changes to aquatic life, and ensure acceptable health conditions if water intake for human consumption takes place downstream. These limits may differ according to the environment and the technical characteristics of each plant (Autorité de sûreté nucléaire, 2004). No exceptional fish mortality was observed downstream of the nuclear power plants following the 2003 heat wave which was thought to be due to the differences in temperature during day and night or because fish were able to find deep cooler waters (Autorité de sûreté nucléaire, 2004; MacLachlan, 2003c). In addition to fish mortality, no specific impact on ecosystems was found to have occurred in the vicinity of plants as determined by oxygen concentration and algae development (Parey & Aelbrecht, 2005). However, the ASN felt that caution was important regarding the long-term effects on the aquatic life (Autorité de sûreté nucléaire, 2004).

In 2003, 17 events concerned release temperature overshoots, most of which were linked to the summer heat wave. Bugey in particular had trouble with release temperatures during the heat wave of summer 2003 (Autorité de sûreté nucléaire, 2003a). The decision to base thermal limits on relative temperature change in particular raised criticism from environmental groups. Furthermore, a note published by the environment ministry in 1999 stated that large fish begin to leave the area around the Bugey nuclear station when the Rhone reaches 25˚C and that at a river temperature of 29˚C certain species collapse (Hibbs, 2003). Large fish run the risk of asphyxiation in water over 27˚C, but generally leave the area if it gets too hot for them. Several important waterways including the Garonne reached 31˚C during the 2003 summer (MacLachlan, 2003b).

The effects of the heat wave may not be obvious or immediately apparent. Most ecological studies look at gradual increase in temperature; however, Mouthon & Daufresne (2006) evaluated the ecological consequences of the European 2003 heat wave based on real long-term data. They found a significant progressive change in the mollusc community structure of the Saone upstream of Lyon during the period from September 1996 to July 2003 probably due to increasing temperature over the same period. Moreover, a sudden change in the structure of mollusc communities occurred during the

2003 heat wave with a significant decrease of species richness and density of gastropods and bivalves. During 2004, mollusc density remained dramatically low. Similar observations were performed at four other sites along the Saone and in the lower reaches of its two main tributaries. These findings suggest that the resilience of the mollusc populations to the heat wave is low. If the frequency of heat waves increase, as predicted by climate models, more than half the mollusc species currently inhabiting the Saone, Doubs and Ognon, and likely other large rivers in France may be directly threatened with extinction (Mouthon & Daufresne, 2006).

While the environmental impact of the heat wave and thermal release waivers are debated several lessons have been learned from the experience. For instance, EDF's "Climate Uncertainty Plan" includes a gradual modification of schedules for refueling and maintenance outages to keep coastal plants on line in summer (MacLachlan, 2005a). In earlier years, four or five of the 14 coastal PWRs were off line for scheduled maintenance simultaneously in summer, the new goal is to have no more than two reactors off-line at a time. Coastal reactors do not have the same thermal constraints, since coastal waters remain cool even during heat waves. Other lessons include: the importance of enhancing commercial deals with big consumers for reducing loads, early communication to the public, and crisis training for staff (Parey & Aelbrecht, 2005).
In 2005, in compliance with requests for changes to the general operating rules, EDF reassessed the maximum temperature limits allowable in premises containing equipment important for safety. The renewal of the discharge and water intake license for the Nogent-sur-Seine nuclear power plant at the end of 2005 was an opportunity to include the possibility of higher temperature discharges in certain climatic and power demand conditions, as with the Bugey, Golfech and Tricastin nuclear power plants (Autorité de sûreté nucléaire, 2005).

During episodes of heat wave and drought, it became clear that some of the physical limits used in the design of nuclear power plants or stipulated in their general operating rules had been reached. Therefore, in 2006 ASN undertook a review of the heat wave reference documentation to assess the operation of installations in conditions harsher than those included in the design for the CPY series sites. ASN is expected to give a decision on the entire documentation in 2008. These reference documentation systems are still being drafted by EDF for the other plant series (Autorité de sûreté nucléaire, 2007). French safety authorities require EDF to study the impact of extreme temperatures and drought on nuclear plants as part of the periodic safety reviews the utility must prepare for each of its reactors every 10 years. Since 2003, requirements have been strengthened and DGSNR asked for an in-depth assessment of facility design to see if further measures should be taken to make the plants more resistant to extreme climate conditions (MacLachlan et al., 2006).

During the 2006 heat wave, ASN asked EDF for an analysis of the impact of a theoretical continued rise in the temperature of the Loire river on the safety of the Belleville, Chinon, Dampierre and Saint-Laurent reactors. One of the consequences of these studies led EDF to increase the capacity of certain heat exchangers. This was completed at the end of June 2007 (Autorité de sûreté nucléaire, 2007). Other potential fixes include operating measures, and plant modifications that might be implemented in the 2010-2020 timeframe. The flow rate of the Vienne River is low; therefore, the Civaux site continues to operate with the use of a special cooling tower that cools down drainage from the main cooling towers before it is released into the river. This measure may be implemented at other sites. In order to improve its ability to deal with such problems, ASN organised a number of meetings with EDF and the General Directorate for Energy and Raw Materials at the Ministry for Ecology, Sustainable Development and Spatial Planning (MEDAD), before the summer of 2007. Furthermore, in a memo addressed to the MEDAD, ASN defined its role in the event of a heat wave and also set up a heat wave situation decision-making process (Autorité de sûreté nucléaire, 2007). In addition, DGSNR is looking for suggestions on a 30 year climate plan for France nuclear plants. However, EDF was unable to find any other utility in the world that has thought about the influence of climatic conditions on their facilities over the next 30 years (MacLachlan, 2005a).

7.3. Drought and Heat Waves in the United States

The effects of heat waves and droughts on reactors in the United States have been less remarkable in part because the U.S. is not as dependent on nuclear for meeting energy needs. Moreover, heat waves of the spatial extent, duration, and intensity that have hit Europe have not yet manifested in North America. Typically, regional droughts and heat waves have posed problems rather than a single climatic event impacting the entire country.

Deratings or reduction of power generation due to the temperature of cooling waters is not uncommon; however, it does not typically pose a significant problem since thermal limits can often be maintained by reducing power generation by a small amount at a couple of units in a single region. Nonetheless, the drought and heat wave in 1988 caused significant problems for U.S. nuclear power plants, necessitating deratings, technical specifications waivers, and a pursuit for alternative cooling water sources at plants in the Midwest, Northeast and the Southeast (Baker, 1988a). For instance, at the Waterford-2 nuclear power plant, located along the Mississippi in Louisiana, the operator considered plans to bring in a few hundred thousand gallons of fresh water per day to meet the plant's demand for makeup water if the local water supply becomes tainted with salt water (Baker, 1988a). Salt water contamination had occurred in communities 30 miles to the south of Waterford. Also in Louisiana, the cooling water intake pipes for the River Bend plant were extended to insure that the intakes stay far enough below the level of the Mississippi River to operate effectively (Baker, 1988a).

In the Northeast, three nuclear plants were forced to derate due to the heat. Hudson River water temperatures reached 87˚F in August, forcing Indian Point-2 and Indian Point-3 to reduce power for short periods. Both Indian Point plants requested and received temporary waivers for technical specifications relating to maximum intake water temperature in early August. Indian Point-3's final safety analysis report has also been recalculated based on the new higher water temperatures. High water temperatures in Lake Ontario reduced condenser efficiency, causing deratings of up to 20% in July and August at the Fitzpatrick site (Baker, 1988b).

Half of the nuclear reactor sites in the eight Midwestern states that make up Region III were affected by heat waves with an average derating of 10% due to a combination of high service water temperatures, low river levels, and high ambient temperatures (Baker, 1988b). From July 6th to July 17th of 1988, the two 833-MW BWRs at Quad Cities in Illinois were limited to an average of 80% power and short-term deratings have forced the reactors to less than 25% power on some days. At Dresden also in Illinois, the two 832-MW BWRs have been limited to an average of 84% power over the same period, with the units being forced as low as 75% power at some times (Baker, 1988a). In August, the situation worsened and Quad Cities and Dresden stayed at or below 50% power most of the time (Baker, 1988b).

A combination of low-flow rates and high water temperatures in the Mississippi River forced the Monticello 580-MW BWR, in Minnesota to go to a partially closed recirculation mode during July and August. The Mississippi usually has flow rates of from 2,000 to 4,000 cubic feet per second (cf/s) during the summer months in the area of Monticello. During the summer of 1988, flow rates were down to 700 to 900 cf/s and water temperatures averaged 10 to 15 degrees F (5.5 -8.3˚C) above normal. Permits restrict the percentage of river flow the site can use and during recirculation mode some condenser water is rerouted back through the condenser a second time to reduce the amount of river water needed for cooling. Power reductions stemming from this varied, but at times Monticello was limited to 86% power (Baker, 1988a). Furthermore, new problems with scaling in the unit's condensers caused by increased silt levels in intake water developed in August (Baker, 1988b).

A heat wave of the spatial extent and duration that occurred in 1988 has not occurred since in the United States. Nonetheless, drought and battles over water in regions with nuclear power plants have been ongoing. In particular, Georgia, Alabama, and Florida have feuded since 1989 over water with the recent drought worsening the problem (Manuel, 2008). Alabama and Florida successfully sued Georgia over a state plan for withdrawing water from Lake Lanier, the main source of drinking water for the Atlanta metro region. In addition, Lake Lanier feeds the Chattahoochee River, whose flow is necessary for the survival of endangered species such as freshwater mussels and sturgeon, and supplies water to towns in Alabama and Florida, and the 1,776-MW Farley nuclear plant in Alabama (Manuel, 2008).

The US Court of Appeals for the District of Columbia Circuit overruled a lower court on the question of whether the state of Georgia, the Army Corps of Engineers and hydropower and water stakeholders in Georgia could reallocate 22% or more of the water storage at the Lake Lanier reservoir for local consumption. The appellate court concluded that a reallocation of 22% of the water storage definitely would be a major operational change requiring congressional approval (Electric Power Daily, 2008a).

This court decision does not signal the end of water battles in this region, or an end to tough decisions on water allocation. For instance, Georgia senators and congressional representatives introduced a bill to amend the endangered species act, so that it may be suspended during periods of drought. The suspension would take effect if a drought was a threat to the health, safety, or welfare of the population that is located in the region. The suspension period would terminate at the end of the drought as determined by the Secretary of the Army (acting through the Chief of Engineers) or the Governor of the State ("A bill to amend the Endangered Species Act of 1973 to provide for the suspension of the act during periods of drought," 2007).

Georgia, Alabama, and Florida are not the only states battling over water in regions with nuclear power plants. North Carolina and South Carolina are currently battling in the Supreme Court over water in the Catawba River basin. The question under review in the Supreme Court is whether, "North Carolina's interbasin transfer statute is invalid under the Supremacy Clause of the United States Constitution and the constitutionally based doctrine of equitable apportionment because North Carolina, pursuant to that statute, has authorized and continues to authorize transfers of water from the Catawba River in excess of its equitable share of the waters of that interstate river, thereby harming South Carolina and its citizens" (State of South Carolina vs. State of North Carolina, 2007). In 1991, North Carolina enacted an "interbasin transfer statute" that claims to authorize the transfer of large volumes of water from one river basin in North Carolina to another basin in that State. Under that statute, North Carolina has authorized the transfer of at least 48 million gallons per day from the Catawba River Basin, with the most recent such transfer authorized in January 2007. South Carolina contends that past transfers and pending transfers exceed North Carolina's equitable share of the Catawba River. The Catawba River is an interstate river that originates in the mountains of North Carolina and flows through a series of lakes including Lake Wylie, where it enters South Carolina. The Catawba River is essential to the generation of hydroelectric power, provides cooling water to Duke Energy's Catawba Nuclear Power Plant and McGuire Station, and is vital for economic development, commerce, and recreation. Yet the Catawba River is subject to severe periodic fluctuations in water level that can render its volume inadequate. North Carolina and South Carolina have issued drought advisory warnings for the Catawba River Basin and both states agree that moderate drought conditions currently exist. The most recent prior drought lasted from 1998 through 2002 (State of South Carolina vs. State of North Carolina, 2007).

In the Catawba Basin, McGuire Station has been impacted by the latest drought.

From July to September 2007 the average rainfall in the system was 4.55 inches compared to 12.02 inches for a long-term average. Full pond elevation at Lake Norman is 760 feet above mean sea level (Duke Energy, 2007b). Critical elevation for Lake Norman was determined to be 750 feet MSL due to thermal limitations associated with McGuire Nuclear Station. McGuire needed a system modification to operate to 745 ft MSL which was scheduled during a 2008 outage. At the time of the identification of critical elevations the modification and schedule were thought to not be a problem because probability of having a drought worse than 1988-2002 drought seemed low (Duke Energy, 2007c).

The water of Lake Norman is used in two ways to provide electricity. Lake Norman is a cooling water source for not only McGuire Nuclear Station, but also for Marshall Steam Station and powers the generators at Cowans Ford Hydroelectric Station. In addition, the lake provides a dependable supply of water to Lincoln County, Mooresville and Charlotte-Mecklenbury and provides 40 percent of the total usable water storage in the eleven-lake system; furthermore, Lake Norman (along with Lake James) serves as a vital "shock absorber" to the lake system to lessen the impacts of drought and high water events on the other reservoirs (Duke Energy, 2007b).

Adding new piping and valves to a back-up system at McGuire Nuclear Station will allow the plant to operate at lower lake levels. Cost of this work is considered part of normal operating costs and minor since the power plants in the basin generate about 9000 megawatts of electricity (Duke Energy, 2007a). Modifications on McGuire Nuclear Station intakes have been completed allowing the minimum Lake Norman elevation needed to operate McGuire to return to the License Application's Critical Elevation. The work added approximately 3 feet of available storage in Lake Norman, which represents approximately 11 percent of the Total Usable Storage of the Project (Duke Energy, 2008).

The North Anna reactor in Virginia was also impacted by the 2002 drought and as a result modifications were made at this site. On August 9, 2002 the North Anna Power Station declared a Notification of Unusual Event (NOUE) due to Lake Anna level decreasing to less than 246 feet above mean sea level (Landis, 2002). The lake level is related to providing adequate water for normal operating and long term cooling of safety related equipment. Long term cooling (at least 30 days) is provided by the Service Water

Reservoir at the site with Lake Anna providing long term makeup to the Service Water Reservoir via the Screen Wash pumps. The licensee determined that approximately six additional months of continued drought would be required before it became necessary to shutdown both units at Lake Anna level of 244 feet. Operating Technical Specifications for the reactors at the site allow continued plant operation as long as Lake Anna level remains above 244 feet (Landis, 2002; Twachtman, 2002b).

Company engineers looked into positioning a couple of service water pumps lower into the man-made lake. Putting the pumps in deeper water would ensure availability of cooling water even if the lake levels continue to fall. The company also examined putting in a dam-like structure on the discharge canal to ensure the proper water level differential exists between the discharged warm water and the cooler water that the plant takes in. The change is needed to maintain a strong flow of water through the condenser (Twachtman, 2002a). The modifications would allow the two North Anna units to operate even if the lake drops several feet below the 244-foot mark. The changes did not need NRC approval, but did require updating North Anna's final safety analysis report (Twachtman, 2002a). A total of 15 inches of rainfall in October and November allowed Dominion to terminate the unusual event on November 18th (Twachtman, 2002c). The lake fell as low as 245.1 feet during the drought and had to rise to at least 246.5 feet before Dominion could exit the unusual event. The lake's water level at full pond is 250 feet (Twachtman, 2002c).

A third unit is currently planned for the North Anna site. The issue of cooling a future unit 3 was raised by citizens and officials with the Virginia Department of Environmental Quality (DEQ) and other agencies, which were concerned about the environmental impacts on the lake (Weil, 2006). Dominion submitted a supplement to its early site permit (ESP) application to NRC that contained plans for cooling a potential third unit at North Anna through a combination of dry and wet cooling towers (Weil, 2006). The earlier application said that a new third unit would use once-through cooling. A potential unit 4 would use a dry cooling tower system. Revising the cooling approach for a unit 3 would cost the company more than $200-million, but the cooling tower system would remove the heat impacts and substantially reduce the additional water consumption of Lake Anna (Weil, 2006). The third unit would use two operating modes, either "energy conservation" or "maximum water conservation" (MWC), depending on the lake water levels. Two-thirds of the cooling is still done through wet cooling in MWC mode. When the lake levels were at or above 250 feet mean sea level (MSL), the energy conservation mode would be used, and this would be the situation most of the time. The water conservation mode consumes about 11 MW more energy than the energy conservation mode. The water would flow through the dry tower system before moving through the wet tower system; however, fans usually would not be turned on in the dry system. The fans would operate when lake levels remained below 250 feet MSL for seven days (Weil, 2006).

Drought concerns and the need for adaptive measures have also impacted reactors in the Midwest. In 2005, the governor of Montana and the Army Corps of Engineers warned that the Missouri River faced low levels during the summer months due to drought, which could impact three nuclear plants and 22 coal-fired plants that use water from the river for cooling. The reduced snow pack was of particular concern, since Montana received less snow that winter compared to any of the last seven years of drought. Moreover, dry soil conditions due to persistent drought absorb much of the runoff before it reaches the Army Corps' reservoirs. The primary concern was that with reduced flows it would be difficult to maintain energy production without violating thermal permits (Electric Power Daily, 2005). Thermal issues forced a summer production cut at the 801-megawatt (MW) Cooper Nuclear Station near Omaha. The plant's operator, Nebraska Public Power District, bought as much as 25 MW of replacement power; a significant amount since this region is accustomed to being a net power exporter (Wagman, 2005). Channel degradation from the self-scouring action of the Missouri River worsens the drought situation by increasing the exposure of intake pipes. For instance at Kansas City, the river bed is 11-12 feet deeper than 30 years ago, helping to drop water levels below intake structures (Wagman, 2005). Along the Missouri River, utilities are investing millions of dollars for items such as trash rakes and traveling screens to keep water intakes clean, pumping systems to draw river water into existing intake systems, and wellfields to pump water out of the ground and into power plant cooling systems, and cooling towers (Wagman, 2005). Many of these measures have not only construction costs, but also substantial operational costs particularly in the case of cooling towers.

While nuclear power plants in the south already have cooling towers in place to handle heat waves and droughts, the increased frequency at which the plants must use cooling towers does have consequences and sometimes even these actions are not enough to keep plants on-line. Throughout the summer of 2007, Browns Ferry and Sequoyah nuclear plants frequently used cooling towers requiring a substantial amount of power that the utility would have otherwise sold (Electric Power Daily, 2008b; *TVA Regional Resource Stewardship Council Meeting Minutes*, 2007). Running cooling towers reduces the power output by less than two percent of the average net power output of the facility during normal conditions, but during heat waves the reduced output increases to 4 percent of the facility's net output (U.S. Department of Energy, 2008). For the Tennessee Valley Authority (TVA) this small percentage can be significant because the TVA generates 30 percent of its power at nuclear plants and sells electricity to 8.7 million people in seven states (Weiss, 2008). In addition, the drought and heat wave forced the TVA to regularly and systematically cut power production (Power Markets Week, 2007). The mountain reservoirs, which typically keep the water temperature downstream within normal limits were at a historic low of an average 19 feet below normal (Power Markets Week, 2007). Furthermore, the drought conditions in the area were more severe in 2007 than any time previous in Browns Ferry's operational experience (U.S. Nuclear Regulatory Commission, 2008a).

Meanwhile the heat wave was causing record demands for energy. The peak demand was a record 33,499 MW on August 16th, while the previous record of 33,334 MW was reached on August 8th. Demand was near but slightly below the record after industrial customers and distributors were asked to reduce usage (Power Markets Week, 2007). The TVA tried to control the temperature of the river by cutting back power at all three units at the Browns Ferry site, but ultimately was forced to shut down Unit 2. The plant's other two units were scaled back to 74% production on August 16 and August 23 (Power Markets Week, 2007).

At the Browns Ferry Nuclear Plant and the Cumberland Fossil Plant 24-hour sampling was required during the heat wave. Browns Ferry was shutdown because the Tennessee River exceeded 90˚F average over 24 hours (*TVA Regional Resource Stewardship Council Meeting Minutes*, 2007). However, the potential for tough decisions in the future became evident. According to the TVA, the first priority during a drought is to first guard health and safety of the public and not let intakes become exposed and next to protect water quality and downstream habitat (*TVA Regional Resource Stewardship Council Meeting Minutes*, 2007).

The U.S. NRC determined that the drought conditions that existed in the Tennessee Valley during 2007 were a likely contributor to a large fish kill and resulting event at Brown's Ferry in January 2008. A large number of Threadfin shad were drawn into the intake structure at Browns Ferry and caused clogging and damage of the traveling water screens. This reduced the Condenser Circulating Water (CCW) flow and resulted in an unplanned power reduction (U.S. Nuclear Regulatory Commission, 2008a). Threadfin shad may experience shock when there is a water temperature change of greater than 2˚F in a 24-hour period or when water temperature falls below 45.5°F. The fish stun began during the morning hours of January 2nd, 2008 when river temperature fell to 45.5°F. Shortly thereafter, the temperature reached the greater than 2°F change in 24 hours. While the exact cause for the thermal shock cannot be determined, TVA River Operations had significantly varied river water flows for several days prior to the event to support meeting peak power demands. A rapid increase in river flow could result in a temperature drop sufficient to result in thermal shock; however, the thermal shock could have occurred naturally. Unusually cold weather can cause the water temperature to fall to 45.5°F or to be cooled 2°F in 24 hours and such conditions did exist prior to the event (U.S. Nuclear Regulatory Commission, 2008a). Nonetheless, the drought established conditions where an increase in river flow could result in a more extreme change in temperature. Moreover, this event demonstrates that planning and operating nuclear power plants during drought is a complicated task with many factors to consider.

7.4. Biological Fouling in Canada and the United States

Many forms of aquatic life or debris can cause problems with the cooling water intake system at nuclear power plants. *Cladophora* algae are of particular concern since problems with algae have arisen multiple times at the same reactors particularly in the Great Lakes. While *Cladophora* is a problem throughout the Great Lakes, the thermal discharges of nuclear power plants create a local environment that is thermally enriched compared to other areas, thus potentially enhancing algae growth locally (Ontario Power Generation, 2007). An algae bloom in itself is not enough to cause a problem with the intake system. A strong wind that breaks the attached algae away from rocky substrates is also necessary. Ontario Power Generation (OPG) recognizes that climate change could worsen this problem. Increase in water temperature in Lake Ontario would lead not only to warmer intake water temperature, but also increased algal and zebra mussel growth and alteration of fish communities. In addition, extreme weather events would result in greater disturbance of algae leading to greater quantities of algae becoming detached (Ontario Power Generation, 2007).

The severe weather resulting from hurricane Isabel on September 19, 2003 caused algae to accumulate in the Pickering B screenhouse. Unit 7 was proactively shut down to reduce the cooling water load and avoid tripping multiple units, but was able to return to power within two days (CNSC, 2004). A more problematic event occurred in 2005. On August 19, Pickering B shut down three of the four operating units due to wind conditions that resulted in a large influx of algae to the screen house. Fouling of the screens temporarily reduced the intake flow of cooling water for the turbine condensers, causing the turbines to trip. A review of the event determined that the three units were shut down before a standby generator and a high-pressure emergency core coolant pump were started (CNSC, 2006). As a result, for approximately two hours, no power would have been available to the high-pressure emergency core coolant pumps that were necessary to ensure fuel cooling in the event of a loss of coolant accident and loss of off-site power to the remaining operating reactor (Unit 7). A simultaneous loss of coolant accident and loss of off-site power is deemed to be unlikely; however, following the shutdown of three units, the probability of a loss of off-site power was higher than normal (CNSC, 2006). Also in 2005, OPG's Darlington Generating Station reduced its electrical output as a result of algae and silt blockage in its water intake system. High winds and stormy lake conditions caused an abnormally large amount of algae and silt to enter the station's water intake systems. To protect equipment, Darlington personnel safely shut down Unit 1 which was affected by blockage (OPG, 2005). In 2007, an incident involving algae clogging of the intake cooling water system at the Pickering station necessitated unit de-ratings, one unit forced outage, and a delayed unit restart. OPG has tried to take corrective actions by installing a diversion net by the water intake and improving upon mitigating operating procedures, but these changes have not been completely effective (CNSC, 2008).

OPG estimates that *Cladophora* fouling of cooling water intakes at the Pickering and Darlington nuclear power plants along Lake Ontario has cost the company more than $30 million in lost power generation in the last 12 years (Hamilton, 2007). Therefore, potential solutions are being explored by OPG. Current operations dictate that pumps are shut down and reactor power levels are reduced if there is a perceived threat of algae intrusion. In the event that intake water flow is considerably restricted by aquatic plants, and the mechanical rakes and traveling screens cannot re-establish or maintain sufficient flow, reactor power would be reduced due to reduced cooling water availability (Ontario Power Generation, 2007). A long-term option would be to draw deeper, cooler water rather than water from the littoral zone where the highest densities of *Cladophora* occur. This long-term option offers additional advantages including reduced silt, less fish impingement and a reduction in the temperature of intake water. OPG and the Regions of York and Durham have commissioned a study at the University of Waterloo to assess the sources of the algae affecting the lake in the vicinity of the Pickering site. The study will propose preventative or ameliorative measures (Ontario Power Generation, 2007).

On several occasions, the FitzPatrick nuclear power plant, located on the U.S. side of Lake Ontario, has encountered problems with algae intrusion at the circulating water intake structure causing blockage of the Traveling Water Screen (TWS) (U.S. Nuclear Regulatory Commission, 2008a). Traveling screen blockage has the potential to lead to a cascade of events. Failure of a single screen can lead to multiple screen failures which can cause a loss of the Circulating Water System, loss of inlet cooling water for the plant, and eventually can cause loss of the main condenser (U.S. Nuclear Regulatory Commission, 2008a). Because of these events, Fitzpatrick has responded by reducing power in order to take a circulating water pump(s) off line to reduce water velocity and thus algae adherence to the TWS (U.S. Nuclear Regulatory Commission, 2008a).

Algae intrusion events requiring shut down or down power occurred at FitzPatrick nuclear power plant on September 12th, October 13th, October 28th, and November 16th, 2007. During the September 12th event, the algae caused an overload condition to the traveling screen system beyond their design capacity. The downstream TWS buckets were pushed into the concrete by increased water velocity. The water velocity was increased by a lower lake level combined with upstream screen debris loading induced flow restriction. This concrete impact increased the rotation resistance which contributed to shear pin failure and/or fluid coupling slippage (Deretz, 2007).

Operators responded appropriately by reducing reactor power, inserting a manual scram and placed the plant in a stable condition. In order to restore the traveling screen system to service it was necessary to cooldown and depressurize the plant. During the cooldown, the feed water startup flow control valve operated sluggishly. Operators were challenged by control room feedwater flow instrumentation that does not provide adequate range or resolution for monitoring the control valve response at low flow rates (Deretz, 2007). Reactor level lowered to the scram initiation setpoint, but was subsequently restored and the cooldown completed satisfactorily (Deretz, 2007).

Changes in operating procedure and strategy were in place after the September event; however, these actions were inadequate on October 13 when high winds led to clogging of the Traveling Water Screens. Once clogged the TWS motors were unable to maintain continuous operation. The increasing differential pressure resulted in the TWS shear pins shearing off to protect the TWS motors. Once the TWS became stationary the continuing suction from the plant circulating water pumps resulted in further plugging of the TWS such that the only means available to maintain the Ultimate Heat Sink level was to reduce power and secure circulating pumps (Deretz, 2007).

Once the TWS were clogged and stopped the only means to lower the differential pressure across the TWS and allow movement of the TWS was to take the plant to cold shutdown and secure all CW pumps. By securing the suction from the back side of the screen the TWS motors were able to lift the TWS out of the water to be cleaned. These events made apparent the need for both equipment upgrades and procedural changes (U.S. Nuclear Regulatory Commission, 2008a). Equipment upgrades include: higher strength shear pins, downstream screen guide rails, larger motor on screen drive train enabling higher speed operation, screen wash diversion troughs, and fire hoses available for cleaning. Procedure Changes and Detection/Mitigation strategies include: a lowered setpoint for screen differential pressure alarm, added guidance for use of fire system sprays on screens, installed web cam at fish basket, training of operators on shear pin installation, and additional guidance for power reduction based on weather forecast. Trigger points are used to change operational procedures. For instance if severe weather causes sustained winds greater than 20 mph (32 km/hr), or if other conditions that could cause a rise in the amount of debris in intake water exist or are expected, then the following actions will be performed: the traveling screens will be put into continuous mode, and the traveling screen performance and debris basket quantity will be frequently monitored. If significant lake debris is incoming, then screen performance, debris basket quantity and screen differential level will be continuously monitored. If there is indication of a rising screen differential pressure then the fire houses are used to clean the screens. In addition, FitzPatrick has also taken steps to minimize *Cladophora* by using divers to harvest the algae in areas of high concentration (U.S. Nuclear Regulatory Commission, 2008a).

The U.S. NRC did not consider the algae problems at FitzPatrick a performance indicator because the situation was not foreseeable. Until the Traveling Water Screen improvements are complete, additional power reductions due to algae intrusions of this magnitude will not to be counted by the U.S. NRC as a performance indicator as long as proactive procedures to lessen the severity of the event have been implemented by the licensee. After the Traveling Water Screen improvements are complete, algae intrusions of this severity will be counted as a performance indicator (U.S. Nuclear Regulatory Commission, 2008a).

According to an NRC special inspection report, Kewaunee along Lake Michigan has also experienced problems with *Cladophora* fouling. Inspection of the 'A' safety injection pump lube oil cooler during a scheduled quarterly inspection on January 15th, 2004 revealed silt and *Cladophora* accumulation at the tube pass inlets (S. A. Reynolds, 2004). The licensee identified that 17 of 20 tubes in each pass were blocked. The flow was measured between 3 and 3.8 gallons per minute (gpm), while after cleaning flow was measured between 5.95 and 6.05 gpm. This finding prompted an investigation into the condition of the 'B' safety injection pump lube oil cooler. Seventeen of 20 tubes in each pass of this cooler were also blocked and tests revealed that there was no flow in the 17 tubes. Plant operators declared both trains of the high pressure safety injection system inoperable at 12:20 am on January 16th and a plant shutdown was commenced 1 hour later in accordance with Technical Specifications (S. A. Reynolds, 2004).

Significant fouling of the safety injection pump lube oil coolers with *Cladophora* was identified as early as 1992 when the coolers were first opened and inspected. On October 2001 both coolers were inspected. Eighty percent of the tubes on both passes were found blocked with *Cladophora* and silt on the 'B' safety injection pump lube oil cooler. All of the tubes on both passes were found blocked on the 'A' safety injection pump lube oil cooler. The condition evaluation discussed five possible corrective actions; however, no corrective action was implemented. In May 2002 the licensee wrote an engineering work request to evaluate a modification to replace the existing coolers with a different design having larger diameter tubes to minimize fouling (S. A. Reynolds, 2004).

The inspectors noted that the assessment did not mention any consideration of the actual amount of tube plugging which would also affect the heat removal capability of the coolers. In May 2003, the licensee completed a review of abnormal plant conditions or indications that could not be easily explained. The licensee identified that the fouling of the safety injection pump lube oil coolers was widely known issue which had not been pursued, had existed for a long period of time, and had the potential to affect an important piece of safety-related equipment. It did not appear that the licensee had identified the fouling as a significant condition adverse to quality and did not routinely document the results in the corrective action program for evaluation, trending and early identification of problems. There were no condition reports specifically associated with the results of recent safety injection pump lube oil cooler inspections in May 2003 and October 2003. The inspectors were concerned that the licensee had missed many opportunities to correct the problem sooner because the licensee had not correctly evaluated the longstanding degraded condition (S. A. Reynolds, 2004).

Currently attentive monitoring is the best strategy to deal with biological fouling; however, even with monitoring shutdown and power reductions are necessary to maintain safe operations. Similarly, maintaining adequate flood protection requires vigilant attention to changing conditions, in particular, whether design basis flood levels determined during plant construction remain adequate today. Upgrades to flood protection and intake adjustments incur considerable costs. These financial investments are small compared to the costs associated with alternative cooling systems that are needed to deal with drought and heat waves. In addition, nuclear power plant operation impairs the ability of natural and human systems to adapt as indicated by the thermal release waivers issued in France during heat waves, and the water battles in the southeastern United States.

8. Discussion

According to considerable scientific evidence, we are now experiencing the impacts of anthropogenic climate change. While societies have a long record of managing the impacts of climate events, additional adaptation measures will be needed to reduce the adverse impacts of projected climate change and variability, regardless of the level of mitigation achieved over the next few decades (IPCC, 2007b). Nuclear power has the potential to mitigate for climate change because it does not produce greenhouse gas emissions during the generation of electricity. However, mitigation measures must also adapt to climate change and the mitigation measure might in turn impair the adaptation of systems to climate change. Adaptation and mitigation have both tradeoffs and synergies, but little research has been done to explore the problems and the opportunities between the two measures. The criteria developed here to evaluate the Adaptation-Mitigation Dilemma are applied to nuclear power, but could be used to evaluate any mitigation measure.

The first part of this chapter reviews the criteria and compares nuclear power operation at both inland and coastal sites. The summation of this work answers the question: Is nuclear power a practical solution to climate change? The second part of the chapter addresses the adaptation-mitigation dilemma by looking specifically at adaptation problems pertaining to energy supply and by suggesting strategies in using the criteria to evaluate other mitigation projects.

8.1. Evaluation of Nuclear Power

8.1.1. Interrupted Operation

Extreme climate events interrupt operation at both inland and coastal sites. However, the consequences of interrupted operation at inland sites are more severe compared to coastal locations. While reactors often need to shut-down during coastal storms, typically the reactors are able to resume power generation soon after storms have passed. Storms cause considerable damage to the transmission system, and these damages delay restart of nuclear power plants after storms more than damage sustained at the nuclear power plant itself. In addition, during severe storms evacuations occur and therefore demand for energy is low.

In contrast, heat waves threaten continued operation at a time of peak demand. A combination of low-flows due to drought and warmer temperatures in summer months raises the temperature of cooling waters prior to the onset of heat waves. Due to physical constraints related to the Carnot efficiency nuclear reactors produce less energy with an increase in the temperature of cooling water. When heat waves hit, and nuclear power plants must reduce power to comply with thermal release regulations, the supply shortage becomes even greater. Consequently, power needs to be supplemented from other sources that potentially emit greenhouse gases.

8.1.2. Financial Costs

The measures needed to adapt to climate change require considerable financial cost whether at inland or coastal sites. The cost for certain adaptation measures are deemed minor for existing nuclear power plants because of the economic importance of maintaining the supply of energy and the high costs associated with building a new power plant. For instance, flood protection and intake adjustments are absolutely necessary for continued operation and expenses for these modifications are generally cost efficient. In contrast, the expense of upgrading cooling systems to use less water can be cost prohibitive and deemed unpractical for aging nuclear power plants. While flood protection has high construction costs, alternative cooling systems have both high construction and operating costs.

Cost overruns continue to afflict nuclear power plant construction, and additional costs necessary to adapt to climate change could make some sites economically unfeasible. For dry cooling to become more widely accepted in the future, there needs to be better data on the performance penalty of these systems under a range of climatic conditions and also on the additional capital and operational costs associated with implementing these systems (Micheletti & Burns, 2002). The high costs, and uncertainty of exact costs, prevent the adoption of dry cooling systems unless there is pressure from stakeholders outside the utility companies. For instance, at the North Anna site the issue of cooling a future third unit was raised by citizens and officials from state agencies; subsequently, the utility changed their plans from once-through cooling to a hybrid system that uses both dry and wet cooling at an additional cost of $200 million (Weil, 2006).

Climate change means that the past can no longer be used to predict the future; however, uncertainty in predicting climate continues to cause problems in planning. For example, at the McGuire nuclear power plant in the United States, critical elevations for the reservoir were identified and the modifications and schedules were thought not to be a problem: the probability of having a drought worse than the drought from 1988-2002 seemed low. The adjustments were planned for a 2008 outage but had to be moved to an earlier date, because what was previously considered improbable had occurred. The inability to predict climate impacts can increase costs substantially when adjustments necessitate unscheduled shutdowns.

8.1.3. Adaptation Impairment – Human Systems

The financial resources needed to protect nuclear power plants from coastal impacts could in itself impair the adaptation of human systems. Nuclear power plants can not be abandoned; therefore, coastal locations will need to spend money on improving coastal defenses. The money spent protecting nuclear facilities means less money is available to finance the protection of other coastal developments. In addition, the protection of one piece of shoreline can increase erosion further along the shore. For example, losses of beach area have been noted near the San Onofre nuclear power plant. Damages to the coast and impairment of human systems are not immediately apparent, but models demonstrate future impacts to the coast. These models serve as an important tool in planning for future developments.

While adaptation at coastal locations involves planning for the future, recent events demonstrate that operations of nuclear power plants at inland locations have already impaired the ability of human systems to adapt. States with nuclear power plants, specifically in the southeastern U.S., are waging legal battles for water indicating the challenges for these regions to adapt to drought. Another area of serious concern is the vulnerability of nuclear power to heat waves. In terms of lives lost, heat waves are the most dangerous of extreme climate events; therefore, reliability of the energy grid is essential to assure public safety. Thus far blackouts during heat waves have been avoided, but this has often come at the expense of natural systems.

8.1.4. Adaptation Impairment – Natural Systems

Coastal habitats must adapt to a rise in sea level; however, development along the coast leads to a loss of coastal habitats as the land types are not able to "move" inland to accommodate to rising seas. Restricting development along the coast remains the best strategy to reduce loss of coastal habitat. Sites for nuclear power plants must be suitable for 100 years; therefore, planned retreat is no longer an option at these locations. Moreover, preventing erosion by building hard defenses reduces the sediment supply needed to build valuable habitats (Cronin et al., 2003). While loss of coastal habitat occurs slowly, over time the cumulative losses become substantial.

Similarly, the impacts of thermal pollution during heat waves might not cause large fish-kills and thus are not immediately apparent. However, the combination of higher temperatures from climate change and the warm effluent from nuclear power can cause serious changes to ecosystems. In France easing of environmental regulations has become a permanent feature due to the issuance of a permanent order in 2004 allowing higher thermal releases during summer months. The mollusc communities in France's rivers have shown low resistance to changes in water temperature and extinction of several species is likely to occur due to high water temperatures (Mouthon & Daufresne, 2006).

Likewise, during a drought water needs must be prioritized. For example, the Tennessee Valley Authority places priority in not letting intakes becoming exposed during a drought, while maintaining water quality and quantity for aquatic ecosystems is secondary. Unless real solutions to climate change are deployed, indications are that these choices will need to be made more often as the frequency and duration of droughts and heat waves increase. For instance, in the United States a bill has been introduced in the house and the senate by Georgian senators and congressional representatives to waive the Endangered Species Act during times of drought.

8.1.5. Other Environmental Problems

Nuclear power has the potential for catastrophic accidents and consequently widespread environmental damage, unlike any other form of energy. Therefore the possible costs of not adapting nuclear operations to climate change are exceptionally high. Safe operation during extreme climate events remains a challenge. Yet, the response to climate change by many utility companies and nuclear regulators has been slow. France has taken the lead in addressing climate change because of problems encountered with floods and heat waves. Electricité de France is working on a 30 year plan that addresses how climate will impact power generation, but they have been unable to find any other utility in the world developing similar plans. As well, the nuclear safety authority in France is working with the IAEA on developing guidance on floods and climate change that will be ready next year.

The uncertainty in predicting climate change poses a problem for safety. Historical flood levels are no longer an adequate predictor of future floods. As seen in France, recent floods have exceeded design basis levels. The 1999 Le Blayais flood led to the examination of design basis flood levels for other nuclear power plants in France and the implementation of additional flood protection measures. In contrast, despite the threat of a change in hurricane intensity and sea level rise, the U.S. NRC is using a method that derives lower surge levels than previously used methods. While the old method was determined to be obsolete, additional margins should be included in design basis estimates to account for climate change. NOAA's refusal to release the model that contradicted other studies and demonstrated appreciably greater surge heights makes analysis of this situation much more difficult. Interviewing those involved in developing surge models could arrive at a more definitive answer on the accuracy of each of the models and constitutes an area of future work.

Regardless of design parameters, storms at coastal locations continue to be a problem because they often lead to the failure of multiple systems, and despite previous experience failures in alarm and communication systems continue to occur. In addition, experiences are often not shared between sites. Nuclear power plant operators at different locations encountered similar problems that could have provided learning opportunities, but these opportunities have been missed. For instance, multiple sites in the Great Lakes region in both the United States and Canada have encountered problems with biological fouling due to *Cladophora*; yet, a coordinated effort to deal with the problem has not occurred.

In certain cases, licensees have shown a low awareness of potential problems caused by external events; as a result, the response to problems has not been adequate.

Biological fouling of the safety injection pump lube oil coolers was identified as a problem requiring monitoring after significant fouling occurred in 1992 at Kewaunee along Lake Michigan; yet, inadequate monitoring lead to an accumulation of silt and *Cladophora* necessitating shutdown of the reactor in 2004. Moisture buildup leads to equipment failure; nonetheless, a licensee at one site did not recognize the problem as something requiring preventative and corrective measures. In addition, after a hurricane had passed a site in Florida, the missile shield doors that protected safety related equipment were found open. The licensee stated that the doors could have been open for several years. These examples indicate that licensee's do not always take proper action in dealing with external events; moreover, they are not prepared for the issues that will arise due to climate change.

8.1.6. Is Nuclear Power A Practical Solution To Climate Change?

Questions abound around nuclear power about impaired operations, potential high costs of adaptation, impairment to other forms of adaptation, and other environmental problems. Nevertheless full evaluation of climate impacts remains difficult. Security issues related to nuclear power operation pose the most important barriers. In addition, utility companies are secretive about power purchase agreements that arise when nuclear power plants are not operating. Providing the details on the costs and the sources of power is viewed as hindering the companies' competitiveness. Moreover, those utilities that had to make adjustments to intake structures do not report the costs of adjustments. Regardless, climate impacts to nuclear power clearly hinder safe operation and cause financial repercussions.

According to estimates, nuclear power capacity must be tripled to make a significant reduction in greenhouse gas emissions. Taking into consideration the replacement of aging reactors this means approximately 1000 reactors will need to be constructed worldwide (MIT, 2003; Socolow et al., 2004). Siting nuclear power plants requires consideration of regional climate impacts. Constructing nuclear power plants at existing sites is the quickest option, but existing nuclear power plants are already vulnerable to climate impacts. Many regions of the world are already experiencing water shortages which will only become worse with climate change. For instance, the Hadley Centre Global Climate Model predicts that the proportion of the land surface in extreme drought will increase from 1% for the present day to 30% by the end of the twenty-first century (Burke et al., 2006). Seasonal changes in precipitation, such as reduced snow pack and drier summers, pose problems for operation as well. Appropriate inland sites for nuclear power plants will be more limited in the future because of diminished water resources. Restrictions on coastal developments are already in place; therefore, the lack of suitable sites at inland locations can not be addressed simply by locating nuclear power plants along the coast.

The high risk and high investment associated with nuclear power necessitates an all or nothing approach to nuclear power expansion. Addressing concerns regarding waste, proliferation, and safety requires considerable financial investment. Nuclear power competes for limited research money that could be used to expand solutions that exploit the synergies between adaptation and mitigation. The few regions where nuclear power will work do not justify the financial investment required for new reactor designs. A practical solution to climate change manages both mitigation and adaptation. While some tradeoffs between mitigation and adaptation will likely be necessary, one can not be sacrificed for the other. Nuclear power meets all the criteria identified as problematic characteristics of purported solutions for climate change, and thus it can not be considered a practical solution for climate change.

8.2. The Adaptation-Mitigation Dilemma

Nuclear power is not the only mitigation measure that has consequences for adaptation, and it is not the only form of energy vulnerable to climate change. The IPCC 2007 report stressed that it is essential to look at how the various components of the energy-supply chain might be affected by climate change. Moreover, a robust predictive skill is required to ensure that any mitigation programs adopted now will still function adequately if altered climatic conditions prevail in the future (Sims et al., 2007). A diverse energy portfolio which considers climate vulnerability is essential to adaptation. For instance, the heat waves in Europe occurred during a time of drought; therefore, hydro power production was low. The lack of cooling water affected both nuclear and coal, and wind power production was low because the air was still. While solar power is potentially vulnerable to climate change due to increased cloud cover (Sims et al., 2007), it is not vulnerable to heat waves. One important first step towards incorporating solar power into the energy supply system would be to use it at public institutions that are used as cooling centers, such as hospitals, or private facilities, such as shopping malls. This would provide relief during heat waves, without increasing demand from those sources of energy that are vulnerable to heat waves, and would therefore serve as both an adaptation and mitigation strategy.

The supply side of the energy equation is not the only area that must be addressed. Measures that address both adaptation and mitigation should be deployed first, such as reducing energy demand. For instance, insulating homes would keep homes cooler during heat waves thus supporting adaptation, while the reduction in energy consumption serves as a mitigation strategy (Bosello, 2005). In developing countries, decentralized renewable energy addresses critical climate change adaptation needs, particularly in rural areas where people have no access to electricity, while also addressing mitigation objectives (Venema & Cisse, 2004). In developed regions, moving towards a decentralized energy system would mitigate for climate change by reducing transmission losses and allowing for the use of more intermittent sources of energy such as wind and solar (Butler, 2007; Sims et al., 2007). Additionally, a decentralized system is an adaptation strategy because it reduces the congestion of transmission systems during times of peak-demand. Furthermore, the transmission infrastructure sustains considerable damage during storms as indicated by past hurricanes. A simpler transmission system reduces the number of areas that need repair after storms, thus fulfilling another adaptation strategy.

Options that address both adaptation and mitigation are not limited to energy supply. Planting trees mitigates climate change and trees in urban locations provide relief during heat waves by reducing the heat island effect (Klein et al., 2005). The criteria developed and used in this thesis are limited in that they only address trade-offs to adaptation and do not evaluate the synergies between adaptation and mitigation. However, the criteria could easily be expanded to consider synergies. This would be particularly helpful in evaluating those mitigation measures that impair adaptation in some regions, while improving adaptation in other regions. For example, if conservation tillage practices are pursued to sequester carbon, the rotation length and choice of agricultural crop could differ from the rotation length and crop most adaptable to climate change (Wilbanks et al., 2003). In this case the mitigation project would impair adaptation. However, conservation tillage can also lead to better soil moisture retention (Blevins et al., 1971). Therefore in this example, mitigation also acts an adaptation strategy, particularly in mid-continental areas that are projected to experience summer drying.

Climate change is not going to be solved by one simple solution that can be applied everywhere. It is a global problem, but the impacts are felt regionally. Therefore, addressing climate change must be based on regional needs and impacts. The criteria set forth here elucidate consequences of mitigation and can be used to decide on a strategy that is the best fit for a particular region. Ignoring adaptation in the search for mitigation solutions will produce mistakes with serious consequences.

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Appendix 1. Fission and Nuclear Power Plants

Fission is possible for only a few isotopes of uranium and plutonium: ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu. The fissionable nuclide in thermal reactors is ^{235}U. Natural uranium consists of 0.7% ^{235}U and 99.35% ^{238}U. Uranium enrichment is necessary for reactors that require a higher fraction of ^{235}U than is found in natural uranium. Several different methods of enrichment exist including gaseous diffusion, centrifuge separation, aerodynamics processes, electromagnetic separation, and laser enrichment; however, only gaseous diffusion and centrifuge operate on a commercial scale (Bodansky, 2004; World Nuclear Association, 2008e).

The energy of the neutrons inducing fission constitutes one of the major classes of nuclear reactors. Reactors can be classified as either thermal or fast reactors, although a large majority of reactors are thermal. A thermal reactor has a moderating material either light or heavy water, or carbon in the form of graphite or beryllium. A good moderator has a low atomic number, a large scattering cross section, and a small absorption cross section. A large scattering cross section indicates that it is able to reduce the kinetic energy of the neutrons. Neutrons that are absorbed by the moderator would decrease the number of neutrons available for fission. Therefore, the moderator must reduce the energy of the neutrons, while not reducing the actual number of neutrons by a substantial amount. A large portion of the core of the nuclear reactor is composed of the moderator.

Fission begins when a fissionable nucleus captures a thermal neutron. Capture upsets the internal force balance between neutrons and protons in the nucleus. The nucleus splits into two lighter nuclei, and an average of two or three neutrons is emitted. The emitted neutrons are fast neutrons, some are not slowed, and thus do not result in fission. If one of the neutrons emitted is captured by another fissionable nucleus a second fission occurs similar to the first. Nuclear power depends on a self-sustaining chain reaction: that is each fission reaction must continue to trigger one more fission reaction.

Fast neutrons have many fates. Surrounding the reactor cores is either a reflector or blanket. The reflector prevents neutrons from leaking out by reflecting the neutrons back to the core, whereas a blanket captures neutrons leaking from the core. A good reflector has the same characteristics as a good moderator (Foster & Wright Jr., 1977).

The blanket and reflector are surrounded by a shield to minimize radiation that leaves the area.

While a self-sustaining chain is necessary to produce nuclear power, the reaction must always remain under control. Control materials are needed to regulate reactor operation and provide a means for rapid shutdown. Removing neutrons from the reactor core will decrease the power and reaction rate. Boron and cadmium are good control materials because of their high cross sections for the absorption of thermal neutrons. Typically the control material is in the form of control rods with either boron carbide or cadmium in a silver-indium alloy. Boron may also be introduced into the circulating cooling water to regulate reactor operation (Bodansky, 2004).

Coolants should have a high specific heat, high conductivity, good stability, good pumping characteristics, and low neutron absorption cross section (Foster & Wright Jr., 1977). Liquid metals have a high boiling point and therefore can be used at low pressures; however, metals must be preheated prior to reactor startup (Foster & Wright Jr., 1977). Coolant is contained within a pressure vessel because the most efficient transfer of heat occurs under pressure. Water is typically kept at 340˚C, since steam is not an effective coolant, and above 375˚C liquid water cannot exist. When gases or liquid metals are used as reactor coolants the coolant can reach a much higher temperature because the liquid-gas phase transition is not a concern as it is in water. Moreover, dry superheated steam at 540˚C allows smaller, less expensive, turbines to be used permitting higher thermal efficiencies (Shultis & Faw, 2008).

Appendix 2. Reactor Types

While a reactor is classified as either fast or thermal, the type of nuclear reactor is further categorized according to the coolant, moderator, and fuel utilized by the reactor. The majority of reactors currently in operation and under construction use water as a coolant and a moderator as shown in Table 1. This may be due to technical and economic advantages or because of historical and commercial forces (Bodansky, 2004). Reactors that use light water as the coolant and the moderator include pressurized water reactors (PWR) and boiling water reactors (BWR). Nevertheless, all current reactors depend on cooling water. The steam or heated gas that moves the turbine must be cooled by water in order to be used in another cycle of energy generation.

Table 1. Nuclear power plants in operation and construction according to type. Data obtained from PRIS database (IAEA, 2008b).

Reactor Type	Coolant	Moderator	Fuel	Operational		Construction	
				Units	MW(e)	Units	MW(e)
Pressurized Water	Water	Water	Enriched Uranium	265	243178	25	22096
Boiling Water	Water	Water	Enriched Uranium	94	85044	2	2600
Pressurized Heavy Water	Heavy Water	Heavy Water	Natural Uranium	44	22362	4	1298
Gas-Cooled	CO2	Graphite	Natural/Enriched Uranium	18	9034	0	0
Light Water Graphite	Water	Graphite	Enriched Uranium	16	11404	1	925
Fast Breeder	Liquid Sodium	None	Uranium or Plutonium	2	690	2	1220

Pressurized water reactors have two water loops. The primary loop is pumped through the reactor to remove the thermal energy produced by the core. Water in the primary loop is held at a high pressure to prevent water from boiling. The water is passed through a steam generator where the secondary-loop water is heated creating high pressure steam that turns the turbines. The boiling water reactor has a single loop and the cooling water boils while passing through the core. The steam passes directly to the turbine and the low pressure steam leaving the turbine is condensed and pumped back to the reactor.

The heavy water reactor has two loops with the primary loop containing pressurized heavy water that is used to cool the core. The fuel is contained in pressure tubes through which the heavy water coolant passes. Pressure tubes pass through the moderator vessel, which is also filled with heavy water. The heavy water in the primary loop then passes through steam generators to boil the secondary-loop light water. A hybrid design of the heavy water reactor also exists where heavy water is used as the moderator only and light water is used as a coolant with only a single loop.

In a gas cooled reactor carbon dioxide or helium gas is used as the core coolant by pumping it through channels in the solid graphite moderator. The fuel rods are placed in these cooling channels. The heated gas then passes through steam generators where water is heated to produce steam which in turn drives the turbines. In high-temperature gas cooled reactors the fuel is packed in many channels in graphite prisms. Helium coolant is pumped through channels bored through the graphite prisms and the hot helium goes to a steam generator.

Fuel is placed in fuel channels in graphite blocks that are stacked to form the core in light water graphite moderated reactors. Vertical pressure tubes are also placed through the graphite core and light water coolant is pumped through these tubes and into an overhead steam drum where the two phases are separated and the steam passes directly to the turbine.

In a fast reactor, the chain reaction is maintained by fast neutrons. Moderator material cannot be used in the core, so to avoid materials of low atomic mass; the core coolant is a liquid metal such as sodium or a mixture of potassium and sodium. Sodium becomes radioactive when it absorbs neutrons and also reacts chemically with water. To keep radioactive sodium from interacting with the water/steam loop, an intermediate loop of non-radioactive sodium is used to transfer the thermal energy from the primary sodium loop to the water/steam loop. Fast reactors can be used to produce fissile fuel exceeding that which is consumed during the chain reaction. In these reactors ^{238}U is converted to fissile ^{239}Pu or ^{232}Th into fissile ^{233}U.

Appendix 3. Ultimate Heat Sink

The following heat loads must be taken into consideration regarding the ultimate heat sink: reactor core decay heat from radioactive decay and shutdown fission, spent fuel decay heat, stored heat, heat rejected from items important to safety, and other accident-related heat sources such as chemical reactions (IAEA, 1981). Groundwater offers a potential alternative cooling water source for systems and components important to safety, even though it has not been commonly used for this purpose. However, the sustained yield of the aquifer must be determined if groundwater is to be used; in addition, the effect on connected surface water bodies, potential land subsidence, groundwater supply interruptions and seismic effects should be considered (IAEA, 1984). Relevant regulations or laws concerning environmental protection may dictate or prohibit use of certain available heat sinks; therefore, it may be necessary to request an exemption from these regulations or laws, on the grounds that the heat sink is needed for safety purposes, and that its use would be limited to infrequent situations of limited duration (IAEA, 1981).

Sharing of the ultimate heat sink between reactors at a multi-unit site is found to be permissible providing that the following conditions are met: the simultaneous safe shutdown and cool down of all the reactors they serve and their preservation in a safe shutdown state; the dissipation of heat following an accident in one reactor, plus the simultaneous safe shutdown and cool down of all remaining units and their preservation in a safe shutdown state. Furthermore, where heat transport systems directly associated with the ultimate heat sink are shared, account should be taken of the greater potential consequences of failure of the system (IAEA, 2004).

In establishing the maximum heat rejection rate, the most severe combination of individual heat loads should be identified for all postulated initiating events for which the system is called upon to perform a normal operation or a safety function (IAEA, 2004). In particular for the ultimate heat sink, the need for make-up of heat transport fluids should also be examined. Where a limited quantity of heat transport fluids is stored on site, the capability for make-up should be ensured by either: providing an adequate quantity of such fluids to allow time to repair the damaged part of the make-up system, or by protecting the make-up system from an external event. In case the make-up facilities cannot be fully protected, they should at least be dispersed or protected in such a way that a minimum capacity remains immediately available after any external event (IAEA, 2003a).

Appendix 4. Evaluating Sites for Nuclear Power Plants

The availability of large amounts of water is not the only factor considered in site selection. The selection of an appropriate site is an important process since local circumstances can affect safety. Choice of site may be approached in a prescriptive manner, although more generally the choice of site is a balance between competing factors including economic interests, public relations and safety (IAEA, 1999). In terms of nuclear safety, the main objective in site evaluation for nuclear installation is to protect the public and the environment from the radiobiological consequences of radioactive releases due to accidents (IAEA, 2003e). The IAEA (2003e) outlines three aspects that must be considered in the evaluation of the suitability of the site for a nuclear installation: the effects of natural or human induced external events occurring in the region of the particular site; the characteristics of the site and its environment that could influence the transfer to persons and the environment of radioactive material that has been released; and the population density, population distribution and other characteristics of the external zone in so far as they may affect the possibility of implementing emergency measures.

The likelihood of significant external events and their possible effects on nuclear power plant safety must be determined from investigations of local factors. Moreover, the hazard evaluation associated with extreme events has been extended from the siting of the plants to the whole lifetime of the plant, including design, construction, operation and decommissioning (IAEA, 2003b). Local factors that could adversely affect the safety of the plant include geological and seismological characteristics, the potential for hydrological and meteorological disturbances, and human induced factors such as aircraft impact and explosions (IAEA, 1999, 2003e). In order to evaluate their possible extreme values, the following meteorological variables must be documented for an appropriate period of time: wind, precipitation, snow, temperature and storm surges. As well, meteorological phenomena including tornadoes, tropical cyclones, blizzards, sand storms, drought, icing and hail must be considered in the evaluation (IAEA, 2003d, 2003e). Geotechnical hazards including: slope instability, collapse, subsidence or uplift of the site surface, soil liquefaction (engineering solutions), behavior of foundation materials, groundwater regime and chemical properties of the groundwater (IAEA, 2003e).

Historical data concerning phenomena that have the potential to give rise to adverse effects on the safety of the nuclear installations, such as volcanism, sand storms, severe precipitation, snow, ice, hail, and subsurface freezing of subcooled water (frazil), shall be collected and assessed (IAEA, 2003e). Installations that may give rise to wind-generated missiles of any type that could affect the safety of the nuclear installation must be evaluated. As well, potential effects of electromagnetic interference, eddy currents in the ground and the clogging of air or water inlets by debris shall be evaluated (IAEA, 2003e).

Appendix 5. External Events and Nuclear Power Plant Design

Design must assure the protection of components vital to safety and continued removal of heat from the core regardless of climate events. In the design of systems for long term heat removal from the core, site related parameters, such as the following should be considered: air temperature and humidity, water temperatures, available flow of water, minimum water level and the period of time for which safety related sources of cooling water are at a minimum level, with account taken of the potential for failure of water control structures (IAEA, 2003e). A loss of off-site power should be assumed coincident with any extreme design basis external event if a direct or indirect causal relationship cannot be excluded (IAEA, 2003a). Potential natural and human induced events that could cause a loss of function of systems required for the long term removal of heat from the core shall be identified, such as the blockage or diversion of a river, the depletion of a reservoir, or an excessive amount of marine organisms (IAEA, 2003e). Redundant paths, screens, or other provisions should be made to prevent the entrainment of debris which might obstruct air and water intakes (IAEA, 2003a, 2004). Alternative intakes might not suffice to prevent the blockage. For such events, a diverse ultimate heat sink or intake system should be provided (IAEA, 2003a). In addition, an inspection regime should be established which takes due account of the need for passive or active control measures and consideration of the rate of growth of the biological matter (IAEA, 2003 a).

The long term capacity of the ultimate heat sink is ensured by means of designs that provide immediate access to inexhaustible natural bodies of water or to the atmosphere. For sites with such access, it should be demonstrated that sufficient capacity exists to accept the heat load until the heat sink can be replenished. Consideration should be given to factors that could delay the replenishment process such as: evaporation, human induced events, plant accident conditions, and the availability of interconnections and the complexity of the procedures for replenishment (IAEA, 2004). The locations and sizes of intake and discharge structures should be carefully evaluated in terms of yearly temperature excursions, and the recorded patterns and effects of biofouling and of the buildup of sand and silt on the effectiveness and performance of the proposed design. Depending on the site characteristics, the need for a backup ultimate heat sink should be carefully assessed (IAEA, 2004).

The associated systems to the reactor coolant system must also be considered in the design basis accident. The connected and associated systems mitigate the consequences of design basis accidents and hence they are considered safety systems. Associated systems are systems that are essential for the reactor coolant system and connected systems including the component cooling water system, intermediate cooling circuits, and essential service water system (IAEA, 2004). The system should be so designed and laid out that no external event or internal hazard considered in the design has the potential to prevent it from performing its intended safety functions (IAEA, 2004).

The design of the reactor coolant system and associated systems is influenced by external events such as fires, earthquakes, wind-generated missiles, floods and other natural phenomena, since these events could lead to a postulated initiating events (IAEA, 2004). Floods in particular have the potential to affect water intakes and thereby affect safety related items. Flood considerations include sedimentation of the material transported by the flood, erosion of the front water side, blockage of intakes by ice, biological fouling by animals, and salt corrosion (IAEA, 2003c).

The design basis flood is derived from the analysis of all the possible flooding scenarios at the site (IAEA, 2003c). The design basis flood is a series of parameters that maximize the challenge to plant safety. For coastal sites the flood hazard is related to the most severe among the following types of flood: probable maximum storm surge, maximum tsunami (earthquake or landside), maximum seiche, wind and wave either independent or in combination. A conservatively high reference water level is considered for each of the cases to allow for tides, sea level anomalies, river flow, and surface runoff (IAEA, 2003c). The expected average level of the seawater for the lifetime of the plant should be appropriately documented with its confidence interval (IAEA, 2003d). Upstream water control structures must also be analyzed to determine whether the nuclear installation would be able to withstand the effects resulting from the failure of one or more of the upstream structures (IAEA, 2003e). The potential for flooding due to one or more natural causes should also be determined. Parameters to characterize the hazards due to flooding shall include the height of the water, the height and period of the waves, the warning time for the flood, the duration of the flood and the flow conditions

(IAEA, 2003c, 2003e). In addition to food analysis, a preliminary investigation should be undertaken to determine whether there is a potential for instability of the shoreline or riverbank since erosion over the lifetime of the nuclear power plant could affect items important to safety. Erosion maps and tidal current maps, aerial photographs and satellite images are very useful and should be used where possible for studying erosion over large areas (IAEA, 2003c).

Several options exist for flood protection and each should be evaluated. All items important to safety should be constructed above the level of the design basis flood, which can be accomplished by locating the plant at a sufficiently high elevation or by means of construction arrangements that raise the ground level at the site (the 'dry site' concept). In addition, permanent external barriers such as levees, sea walls and bulkheads may be constructed. The barriers should be considered features important to safety; therefore, care should be taken that appropriate design bases are selected for the barriers and that periodic inspections, monitoring and maintenance of the barriers are conducted (IAEA, 2003c). Sea walls, breakwaters, and revetments should be properly designed to prevent soil erosion, flooding and structural failures which may jeopardize the safety of important facilities. Potential failure of these structures from external events must be assessed. If hazardous effects are expected, appropriate countermeasures should be taken to protect the facility or otherwise the site layout should be reconsidered (IAEA, 2004).

As a redundant measure against flooding of the site, the protection of the plant against extreme hydrological phenomena should be augmented by waterproofing, and by appropriate design of all items necessary to ensure the capability to shut down the reactor and maintain it in a safe shutdown condition. All other structures, systems and components important to safety should be protected against the effects of a design basis flood (IAEA, 2003c). Special operational procedures should be specified on the basis of real time monitoring data on the identified causes of the flooding. A warning system should be available that is able to detect potential flooding of the site with sufficient time to complete the safe shutdown of the plant together with the implementation of adequate emergency procedures. The warning system and all other items important to safety should be designed to withstand the flood producing conditions (IAEA, 2003c).

In order to provide additional defense to the basic forms of protection, active or administrative measures based on forewarning can also provide safety benefits for some external events. For instance, the installation of additional barriers or the closure of watertight gates in anticipation of flooding, or the inspection of drainage channels may be utilized. The reliability of such measures should be balanced with the reliability of the monitoring, forecasting equipment and the operator (IAEA, 2003a). In designing for additional protection, it should be borne in mind that barriers can introduce difficulties for inspection and maintenance, while a greater spread in plant layout may require more staff to handle the increased task of surveillance (IAEA, 2003a).

A safety classification is in place to ensure that those features needing extra protection are protected in a design basis event. In addition to the safety classification, the external event (EE) classification is a process that associates an external event category to any plant item according to its required performance during and after a design basis external event (IAEA, 2003a). Safety limits specified in safety classification represent the design basis conditions for the items. Exceeding safety limits challenges plant safety and therefore a plant shutdown is required with precise post-event revalidation. Limits and conditions for normal operation should be identified in the hazard evaluation phase to ensure prompt action (IAEA, 2003a).

Systems that should be classified as EE-C1 include: the reactor system containment structure or the external shielding structure; structures supporting, housing, or protecting items important to safety; structures protecting the plant from external events; the power and instrumentation and control cables relevant to safety related items; the control room or the supplementary control points; systems or portions of systems that are required for monitoring, actuating and operating those parts of systems protected against design basis external events; the emergency power supplies and their auxiliary systems necessary for the active safety functions and the post-accident monitoring system. Systems that should be classified as EE-C2 are those components whose continued functionality is not required, but whose failure could reduce the functional capability of any plant features specified as EE-C1 or could result in incapacitating injury to occupants of the control room. Systems that should be classified as EE-C3 include: components for spent fuel confinement; spent fuel cooling systems; systems for the containment of highly radioactive waste in gaseous, vapor, liquid and/or solid form. The EE classification can exclude items not affected by any design basis external event, for instance items located an elevation higher than the flood level in the cases of a design basis flood (IAEA, 2003a).

The classification determines the level of protection given to each item. EE-C1 items should be designed, installed and maintained in accordance with engineering practice for nuclear applications, for which appropriate safety margins should be established according to the associated consequences. For any item in Category 1, an appropriate acceptance criterion should be established (e.g. functionality, leaktightness and maximum distortion) according to the required safety function (IAEA, 2003a). EE-C2 items have a more simplified and less conservative criteria for design, installation and maintenance may be used, and in some cases a lower intrinsic safety margin than for EE-C1 items and in relation to their probability of being the initiator of an accident. Often, experience based walk downs are implemented in response to this concern (IAEA, 2003a). EE-C3 items should be designed, installed and maintained in accordance with engineering practice for nuclear applications, but generally the criteria are less conservative than those defined for EE-C1 (IAEA, 2003a).

Rare meteorological events such as lightning, tornadoes, and tropical cyclones must be evaluated for the site (IAEA, 2003e). The potential for occurrence of tornadoes is assessed on the basis of detailed historical and instrumentally recorded data for the region. The hazards associated with tornadoes are expressed in terms of rotational wind speed, translational wind speed, radius of maximum rotational wind speed, pressure differentials and rate of change of pressure, and potential wind-generated missiles. The following data on the storm parameters for tropical cyclones should be collected: maximum central pressure, maximum wind speed, horizontal surface wind profile, shape and size of the eye, vertical temperature and humidity profiles within the eye, characteristics of the tropopause over the eye, positions of the tropical cyclone at regular preferably six hourly, intervals, and sea surface temperature (IAEA, 2003d, 2003e).

Appendix 6. New Reactor Design and Research Goals

Reactors are categorized by generation. The first generation was advanced in the 1950s and 60s in the early prototype reactors. The second generation began in the 1970s in the large commercial power plants that continue to operate today. Reactors in the third generation were developed more recently in the 1990s and promise advances in safety and economics. These reactors have been built primarily in East Asia. Advances to Generation III have resulted in Generation III+ reactors that are actively under development and deployable in the near-term. Plants built between now and 2030 will be chosen from Generation III+ reactors. Generation III+ reactors include: several types of advanced boiling water and pressurized water reactors, advanced heavy water reactors and gas cooled reactors such as the Gas Turbine–Modular High Temperature Reactor and Pebble Bed Modular Reactor (PBMR).

Argentina, Brazil, Canada, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom, and the United States joined together to form the Generation IV International Forum (GIF) to develop future-generation nuclear energy systems that can be licensed, constructed, and operated in a manner that will provide competitively priced and reliable energy products while addressing concerns pertaining to nuclear safety, waste, proliferation, and public perception (U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, 2002). The objective for Generation IV nuclear energy systems is to have them available for international deployment by the year 2030, when many of the worlds' currently operating nuclear power plants will be at or near the end of their operating licenses. The GIF decided to focus on research and development of six reactors: Gas-Cooled Fast Reactor System (GFR), Lead-Cooled Fast Reactor System (LFR), Molten Salt Reactor System (MSR), Sodium-Cooled Fast Reactor System (SFR), Supercritical-Water-Cooled Reactor System (SCWR), and Very-High-Temperature Reactor System (VHTR). The reactors chosen include those with closed fuel cycles, open fuel cycles, or both. In an open fuel cycle discharged fuel is sent directly to disposal, while in a closed fuel cycle waste products are separated from unused fissionable material that is recycled as fuel into reactors. The GIF ranked each reactor according to goals in the categories of sustainability, economics, safety and reliability, and proliferation resistance.

Table 1. Goals of Generation IV nuclear power plants (U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, 2002).

Category	Goal
Sustainability	Provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.
Sustainability	Minimize and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.
Economics	Clear life-cycle cost advantage over other energy sources.
Economics	A level of financial risk comparable to other energy projects.
Safety and Reliability	Operations will excel in safety and reliability.
Safety and Reliability	Have a very low likelihood and degree of reactor core damage.
Safety and Reliability	Eliminate the need for offsite emergency response.
Proliferation Resistance and Physical Protection	Increase the assurance that the nuclear power plants are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

In particular, actinide management is a mission with significant societal benefits because it insures both nuclear waste consumption and long-term assurance of fuel availability. Actinides are the elements produced during a nuclear reaction with atomic numbers (Z) greater than or equal to that of actinium (Z = 89). Some actinides are fissile and can be used as nuclear fuel in other reactors; moreover, many of the actinides have long half-lives, complicating the problems of nuclear waste disposal (Bodansky, 2004).

Although Generation IV systems for actinide management aim to generate electricity economically, the market environment for these systems is not yet well defined (U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, 2002). All designs include untested engineering, and also depend on the development of new materials that can resist continued high temperatures, intense bombardment by neutrons in the chain reaction, and often corrosive reagents (Butler, 2004). The uncertainty of the outcome of research and development, and the large uncertainty in projecting production and capital costs several decades into the future make the evaluation of economics for each of the reactors difficult (U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, 2002).

Appendix 7. Nuclear Power as a Mitigation Measure for Climate Change

The World Nuclear Association (2007) estimates that currently 2.6 billion tons of CO_2 per year (GtC/year) is avoided because of nuclear power. While nuclear power does not generate greenhouse gases during direct energy production, considering the entire fuel cycle leads to different estimates in the amount of emissions associated with nuclear power. The entire fuel cycle includes uranium mining, enrichment, power plant construction, and decommissioning all of which require the burning of fossil fuels. An additional source is chemical reactions particularly the production of cement and steel (Storm van Leeuwen & Smith, 2005).

One important difference in the amount of greenhouse gases generated for nuclear power is the enrichment process used. For instance, most enrichment in the United States utilizes the gas diffusion process whereas centrifuge enrichment is predominant in Europe (Andseta et al., 2000). The gaseous diffusion process consumes about 2500 kWh/SWU (separation work unit), while modern gas centrifuge plants require only about 50 kWh/SWU (World Nuclear Association, 2008e). The large difference emphasizes the importance of enrichment process efficiency in overall determination of CO_2 releases per unit electrical energy output.

Choosing more efficient enrichment processes is an important consideration in reducing the greenhouse gas emitted during the nuclear fuel cycle. The mining of uranium is another matter that could reduce the potential for nuclear power to mitigate for climate change in the long-term. Storm van Leeuwen and Smith (2005) emphasize that due to the declining ore grade over time, the CO_2 emission will rise gradually. Up until today, uranium has been extracted from easily mined and relatively rich uranium ores. The largest uranium resources of the world, however, exist in far leaner ores which are more difficult to mine than in the past. When very poor ores are to be exploited, the CO_2 emissions will rise exponentially and surpass that of gas-fired electricity generation and any fossil-fuelled power system (Storm van Leeuwen & Smith, 2005).

Therefore, in the long term (fifty to a hundred years) a significant reduction in CO_2 emissions, worldwide, via use of nuclear power, will require reactors that utilize a much larger fraction of the energy content of uranium than do most of the reactors in use today, or would require economical extraction of uranium from ores much leaner than those presently used (Perry & Weinberg, 2001). In the near term nuclear power plants could not play a significant role to reduce carbon dioxide emissions because they operate near their maximum output already and cannot provide much incremental output (Paffenbarger, 1998). For instance, in the U.S. new plants could not make a substantial contribution to reducing U.S. global warming emissions for at least two decades even under an ambitious deployment scenario (Union of Concerned Scientists, 2007). Measures that offer near-term reductions are needed such as efficiency measures, conservation, and removal of barriers to existing technologies.

In addition, nuclear power as a mitigation option shifts the focus to developing technologies that address supply, while many solutions are available on the demand side of the energy problem. Nuclear proponents point to the need for high-volume, concentrated energy sources for sustained economic growth in urban populations (Nuclear Energy Institute, 2007). However, many developing countries have an opportunity since they are not locked-in to a centralized grid. Centralized grids are inefficient and costly with energy losses of 8% along long-distance transmission lines (Butler, 2007). The grid is often congested because it relies on a few high-traffic arteries. The congestion amplifies the inefficiency because if the utility cannot redirect power from efficient sources, they have to turn to costlier, dirtier and more inefficient sources to meet peak demand (Butler, 2007). Utilizing multiple decentralized energy sources allows electricity to be generated close to the point of use, avoiding the losses and congestion that result from long-distance transmission (Butler, 2007). Technologies that aid in developing efficient grids include smart meters that provide real-time data on grid conditions, load and pricing. The meters help in the demand side by helping users consume less energy, but also in the supply side by providing better ways to handle the intermittent and distributed nature of alternative energy sources grids (Butler, 2007).

Appendix 8. Coastal Vulnerability Methods

The methods described here were used to determine relative Coastal Vulnerability in the United States by Thieler and Hammar-Klose (1999a; 1999b; 2000). The geomorphology variable expresses the relative erosion rates of different landform types. These data were derived from state geologic maps and USGS 1:250,000 scale topographic maps. The regional slope of the coastal zone was calculated from a grid of topographic and bathymetric elevations extending approximately 50 km landward and seaward of the shoreline. Relative sea level change over the past 50-100 years were obtained for 28 National Ocean Service (NOS) data stations and contoured along the coastline. Shoreline erosion and accretion rates for the U.S. were taken from the Coastal Erosion Information System (CEIS). The data in CEIS are drawn from a wide variety of sources, including published reports, historical shoreline change maps, field surveys and aerial photo analyses.

Tide range data were obtained from the National Ocean Service's 657 tide stations along the U.S. coast, and their values contoured along the coastline. Typically a large tidal range is associated with higher coastal vulnerability. This study inverted the ranking, because a small tidal range means the site is always near high tide, and therefore, always at risk of inundation from storms.

Wave height was used as an indicator of wave energy, which drives the coastal sediment budget. Hindcast nearshore mean wave height data for the period 1976-1995 was obtained from the U.S. Army Corps of Engineers Wave Information Study (WIS). The model wave heights were compared to historical measured wave height data obtained from the NOAA National Data Buoy Center. Wave height data for 151 WIS stations along the U.S. coast were contoured along the coastline.

Numerical variables are assigned a risk ranking based on data value ranges as shown in Table 1 and 2 for the Atlantic and Pacific respectively. The non-numerical geomorphology variable is ranked according to the relative resistance of a given landform to erosion. The coastal vulnerability index is calculated as the square root of the geometric mean, or the square root of the product of the ranked variables divided by the total number of variables as in the following equation:

CVI = SQRT((a*b*c*d*e*f) / 6)

where, a = geomorphology, b = coastal slope, c = relative sea level rise rate, d = shoreline erosion/accretion rate, e = mean tide range, and f = mean wave height.

Table 1. Ranking of coastal vulnerability index for the Atlantic and Gulf coasts.

	Ranking				
Variable	Very Low 1	Low 2	Moderate 3	High 4	Very High 5
Geomorphology	Rocky cliffs, fjords	Medium cliffs, indented coasts	Low cliffs, Glacial drift, Alluvial plains	Cobble beaches, Estuary, Lagoon	Barrier beaches, Sand beaches, Salt marsh, Mud flats, Deltas, Mangrove, Coral reefs
Coastal Slope (%)	>0.115	0.115 – 0.055	0.055 – 0.035	0.035 – 0.022	<0.022
Relative sea-level change (mm/yr)	<1.8	1.8 – 2.5	2.5 – 3.0	3.0 – 3.4	>3.4
Shoreline erosion/accretion (m/yr)	>2.0	1.0 – 2.0	-1.0 – 1.0	-1.1 – -2.0	<-2.0
Mean tide range (m)	>6.0	4.1 – 6.0	2.0 – 4.0	1.0 – 1.9	<1.0
Mean wave height (m)	<0.55	0.55 – 0.85	0.85 – 1.05	1.05 – 1.25	>1.25

Table 2. Ranking of coastal vulnerability index for the Pacific coast.

	Ranking				
Variable	Very Low 1	Low 2	Moderate 3	High 4	Very High 5
Geomorphology	Rocky cliffs, Fjords	Medium cliffs, Indented coasts	Low cliffs, Glacial drift, Alluvial plains	Cobble beaches, Estuary, Lagoon	Barrier beaches, Sand beaches, Salt marsh, Mud flats, Deltas, Mangrove, Coral reefs
Coastal Slope (%)	>1.9	1.3 – 1.9	0.9 – 1.3	0.6 – 0.9	<0.6
Relative sea level change (mm/yr)	<-1.21	-1.21 – 0.1	0.1 – 1.24	1.24 – 1.36	>1.36
Shoreline erosion/accretion (m/yr)	>2.0	1.0 – 2.0	-1.0 – 1.0	-1.1 – -2.0	<-2.0
Mean tide range (m)	>6.0	4.1 – 6.0	2.0 – 4.0	1.0 – 1.9	<1.0
Mean wave height (m)	<1.1	1.1 – 2.0	2.0 – 2.25	2.25 – 2.6	>2.6

Appendix 9. Coastal Vulnerability Data

Table 1 and Table 2 provide the actual values for site variables at each of the sites on the Atlantic and Pacific coasts respectively.

Table 1. Summary of coastal variables for each site on the Atlantic coast. * Indicates an average value for those sites that have two different coastal segments.

Reactor	Mean tidal range (m)	Coastal Slope %	Erosion/Accretion (m/yr)	Mean Wave Height (m)
Seabrook	2.460	0.19840*	-0.500	1.2
Pilgrim	2.990	0.19410	4.500	0.9
Millstone	0.790	0.24990	-0.700	0.9
Calvert Cliffs	0.400	0.10	-6.4	0.9
Saint Lucie (coast)	0.800	0.00108	-0.600	1.2
Saint Lucie (river)	0.800	0.00108	-0.600	1.2
Turkey Point	0.500	0.00108	-0.100	0.9
Crystal River	0.890	0.05977	-2.000	0.4

Table 2. Summary of coastal variables for sites on the Pacific coast. * Indicates an average value for those sites that have two different coastal segments.

Reactor	Mean tidal range (m)	Coastal Slope %	Erosion/Accretion (m/yr)	Mean Wave Height (m)
Diablo Canyon	1.12	1.1002	-0.30	1.3
San Onofre	1.12	1.5626*	-0.46	0.7