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Louisiana's suitability for a low-level radioactive waste storage facility

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LOUISIANA'S SUITABILITY FOR A LOW-LEVEL RADIOACTIVE
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This thesis is dedicated to my grandfather, Charles A. Wilson Jr.

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ABSTRACT

Radioactive waste is an inevitable outcome of using radioactive elements in research, education, medicine, energy, and weapons production. Low-level waste (LLW) makes up 85% of the radioactive waste produced in the United States. In 2010, over 2 million ft^3 of LLW were shipped to disposal sites. Despite efforts from several states and government agencies, the options for disposing of LLW are very limited. It is the intention of this project to design a GIS based method to determine suitability of potential disposal sites based on the Code of Federal Regulations (CFR) requirements and criteria as well as supporting literature and reports. The goal of this project is to apply this method to Louisiana as the initial screening process to locate regions suitable for further evaluation as prospective disposal sites. Criteria were derived from 10 CFR part 61.50's 10 minimum requirements, the Nuclear Regulatory Commission's Regulatory Guide 0902, and a study of experiences at existing sites. A suitability formula was developed allowing for weighting factors and normalization of all criteria to a 100% scale. Data were collected and compiled into Geographic Information Systems (GIS) data sets and analyzed on a cell grid of approximately 14,000 cells (70,000 square miles) using the suitability formula and the state of Louisiana as a region of interest. Requirements were analyzed for each cell using multiple sub-criteria and surrogates for unavailable datasets. Additional criteria were added when appropriate. The method designed in this project was sufficient for initial screening tests in determining the most suitable areas for prospective disposal sites. The top 10%, 5%, and 1% include respectively 404, 88, and 4 cells suitable for further analysis. With these areas identified, the next step in siting a low-level radioactive waste storage facility would be on-site analysis using additional requirements as specified by regulatory guidelines. GIS provides an efficient and cost effective means of analyzing areas for siting LLW storage facilities and has great potential for use in other states where sufficient GIS data exist.

CHAPTER 1 INTRODUCTION AND LITERATURE REVIEW

1.1.   Statement of the Problem

The processes and methods for identifying suitable locations for low-level radioactive waste (LLW) storage facilities have become increasingly more complex since the first site was established in the United States in 1962 (Gerrard, 1994). The disposal of any sort of waste, particularly radioactive waste, must take into account political, social, economic, and environmental issues. These considerations complicate site selection, further requiring the process to be scientifically sound. Despite the difficulties in siting a LLW storage facility, LLW waste continues to be produced and the generators (any persons or groups producing LLW) have few options when deciding how and where to dispose of LLW. Between 1999 and 2003, LLW disposal volumes increased over 200% (GAO-04-604). In 2010, over 2 million cubic feet of LLW was shipped to disposal sites (MIMS). Current options available to generators include on-site storage and a limited number of disposal facilities, most of which are far from the generators' location (Figure 1). In 1980, United States Congress passed the Low-Level Radioactive Waste Policy Act (LLRWPA) in order to help encourage states to handle LLW on a regional level. The purpose of this study is to alleviate some of the difficulties in LLW storage site selection, to expedite the initial site selection process by using modern computer technologies, and to help improve site selection such that the United States might increase the number and availability of LLW storage facilities towards the original 1980 goal that each compact would have its own local storage facility.

Geographic Information Systems (GIS) offer the user the ability to analyze multiple sets of location specific data as layers on a geographic map. GIS can provide comparative analyses to identify locations meeting specific criteria on the city, state, compact, or even national level. This

thesis presents a method for using GIS to categorize sites for use as potential LLW storage sites. In addition, the suitability of Louisiana as a potential host region (region of interest) for a near ground LLW storage facility was assessed. The purpose of an analysis such as this one, for siting a facility with possible public risk, is to increase the likelihood of making a good selection (Keeney, 1980).
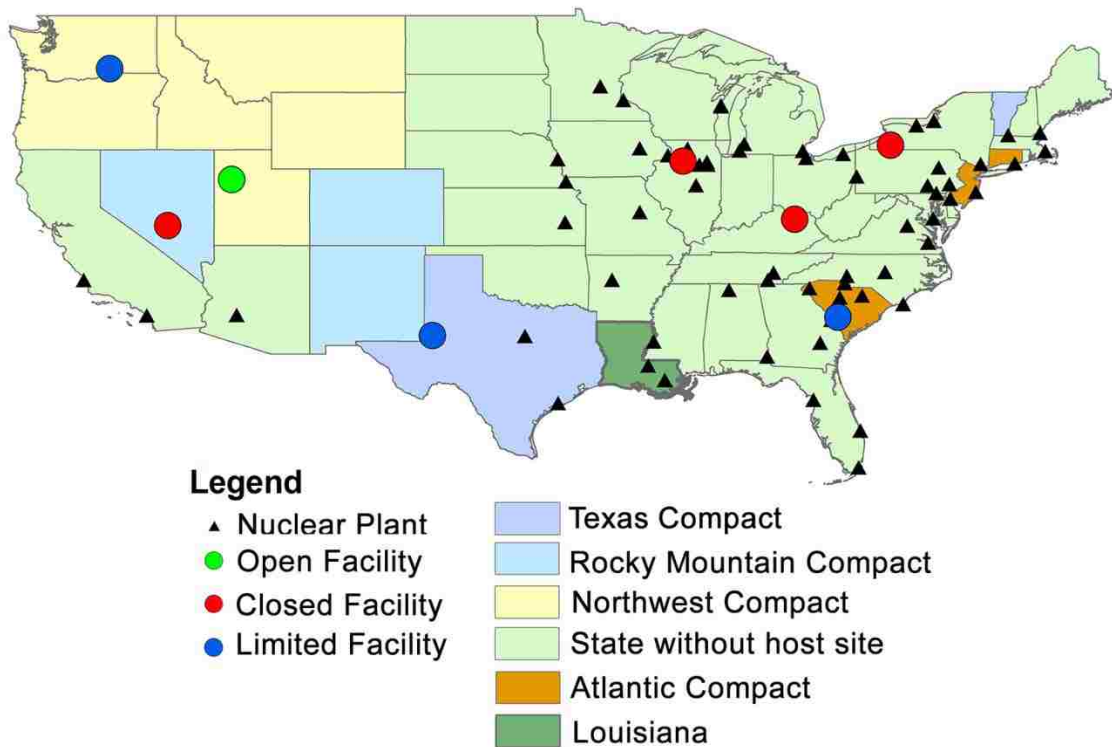
Figure 1 - Commercial (non-DOE) LLW facilities and nuclear power plants in the United States.

The United States' current federal nuclear regulatory guidelines for site selection indicate the value of using maps to describe the different criteria (NUREG 4.19). In this thesis Louisiana is used as an example to demonstrate how to collect and analyze available data layers and other

geo-referenced maps for the first two steps of site selection and demonstrate how to use the new GIS tools to analyze many of the criteria simultaneously.

1.2. Background Information

1.2.1. Types of Radioactive Waste

Radioactive wastes are typically classified into five categories: 1) High-level radioactive waste (HLW) which is waste resulting from the reprocessing of nuclear fuel and weapon production. These wastes are often produced by the U.S. Department of Energy (DOE) facilities and nuclear power plants. They must be stored in a final repository for thousands of years. 2) Uranium mill tailings which are residues from physical and chemical processing of uranium ore that have low specific activity but large quantity. 3) Transuranic wastes (TRU) which are wastes resulting from fuel assembly and weapon fabrication; they are alpha emitters with a half-life of over 20 years and must be in concentrations greater than 100 nCi/g and an atomic number greater than 92. 4) Mixed wastes are wastes that do not fit into the above three categories and are not LLW. They are radioactive, but also contain some other hazard or toxin. 5) Low-level waste (LLW) is waste that does not fit into any of the above categories (Murray, 1994).

The main generators of LLW are commercial nuclear power plants (Brookins, 1984); however almost any industries using radioactive material produce LLW. Examples of these industries include research, education, medicine, energy, and weapons production. The name LLW is somewhat misleading. While the category does not include high activity wastes that are specifically categorized in 1 to 4 above, it does in fact include isotopes such as cesium-137, cobalt-60, and iodine-131 which may be present in high activities in LLW. These isotopes are used for their high effectiveness and exposure for medical treatment. LLW also accounts for the

largest portion of radioactive waste generated (Brookins, 1984). It comprises 85% of all radioactive wastes in the United States (Chuang, 2004).

The approach used in this thesis could be applied to the disposal requirements for any of the above types of waste as it relates to site selection. Many of the requirements will be similar, but more stringent. However, this report only focuses on the specific requirements and criteria for site selection of near surface LLW storage.

1.2.1.1. Classes of Low-Level Radioactive Waste

There are four classes of LLW, Classes A, B, C, and Greater Than Class C (GTCC). While the classes are sometimes generalized using radioactive half-lives, the true distinction is described by the NRC in 10 CFR 61.55. Class B is governed by more rigorous requirements than Class A to ensure safety and stability. Class C has even more rigorous requirements than class B. GTCC wastes must be disposed of in a long term geological repository such as those designed for Yucca Mountain rather than in a near surface LLW facilities used to dispose of Classes A, B, and C.

The classes of LLW are categorized through a series of tables published by the NRC. To determine the class, one must use the ranges outlined in Tables 1 and 2. The classification depends on the type and concentration as outlined in 10 CFR 61.55.

1.2.1.2. Methods of Disposal of Radioactive Waste

Long-term storage for any forms of radioactive waste requires an "As Low As Reasonably Achievable" (ALARA) balance between cost-effectiveness and safety (10 CFR 20.1003). While engineering can provide a multitude of options to approach perfect (no risk)

disposal, it will inevitably interfere with the ALARA requirements due to the cost becoming too high.

Table 1 - Concentration Limits of long-lived nuclides for specifying LLW class (10 CFR 61.55).

Radionuclide	Concentration Ci/m^3
C-14	8
C-14 in activated metal	80
Ni-59 in activated metal	220
Nb-94 in activated metal	0.2
Tc-99	3
I-129	0.08
Alpha emitting transuranic nuclides with half-life greater than 5 years	[1]100
Pu-241	[1]3,500
Cm-242	[1]20,000

Table 2 - Concentration limits of short-lived nuclides for specifying LLW class (10 CFR 61.55).

Radionuclide	Concentration, curies per Ci/m^3		
	Col. 1	Col. 2	Col. 3
Total of all nuclides with less than 5 year half-life	700	([1])	([1])
H-3	40	([1])	([1])
Co-60	700	([1])	([1])
Ni-63	3.5	70	700
Ni-63 in activated metal	35	700	7000
Sr-90	0.04	150	7000
Cs-137	1	44	4600

[1] There are no limits established for these radionuclides in Class B or C wastes. Practical considerations such as the effects of external radiation and internal heat generation on transportation, handling, and disposal will limit the concentrations for these wastes. These wastes shall be Class B unless the concentrations of other nuclides in Table 2 determine the waste to the Class C independent of these nuclides" (10 CFR 61.55).

There are two steps in radioactive waste disposal, treatment and storage. Many methods have been developed to treat different types and levels of radioactive waste; however the main determining factor is cost-effectiveness. The general rationale of radioactive waste management is that long-term storage requires stabilization of radioactive waste into a form which will neither react nor degrade. While there are many advanced options for disposal, not many are cost-effective, particularly for LLW. The common types of treatment include concentration, transfer, and transformation (Murray, 1994).

The first option, concentration, reduces the waste volume. It accomplishes this by compaction or evaporation of the waste material. This allows for waste to be stored more efficiently, taking up less space. Transfer, the second option, removes the radioactive material from the waste stream and transfers it to another medium by methods such as filtration or ion-exchange. Transformation changes the waste's physical form. Examples of this are incineration, synroc, and vitrification. Vitrification is mixing waste sludge with small bits of borosilicate glass, heating the mixture to about 1200 degrees Celsius and pouring the molten glass into a stainless steel canister. Once it cools the radioactive material is trapped (Murray, 1994). Synroc, similar to vitrification, immobilizes the waste but uses a synthetic rock. According to the World Nuclear Association, "It is basically a ceramic made from several natural minerals which together incorporate into their crystal structures nearly all of the elements present in high level radioactive waste" ("Synroc Wasteform", 2011).

Once the waste is treated it still needs to be properly disposed. There are very limited options for the actual storage and disposal of the wastes. Some of the options that have been considered are deep final repositories such as sea-based or deep borehole disposals, transmutation, re-use, space disposal, above ground disposal, a national LLW management

program, and illegal dumping (Murray, 1994). Out of the current options, above (or near) ground disposal is the most cost-effective one. Interim storage is not a long term option, but is chosen for wastes that have no current disposal site. Once the radioactive material is stored for several hundred years most of the waste will no longer be considered radioactive and can be disposed of (if necessary) as normal waste. The time required is dependent on the isotope and the initial activity, but typically ten half-lives achieve an activity of less than 0.1% of the original activity. This can occur in about twenty to thirty years (Dreilinger, 2010).

Other countries such as France and Sweden have been successful in taking different approaches in site selection for facilities to store LLW. Their success though is recognized by the public's general belief that nuclear waste will be managed safely as well as a greater dependence on nuclear power. The United States does not have as much trust in government and corporate managers regarding nuclear power. Some of these countries are also using an approach that allows areas to volunteer land, in exchange for jobs and other benefits (McCabe, 1993). One of the major difficulties in siting a potential storage facility will be a need to educate the general public on the advantages of hosting a facility as well as the possible risks which are likely to be misperceived before social culture.

1.2.2. Policy Act and Compacts for Low-Level Radioactive Waste

In 1980, Congress passed the Low-Level Radioactive Waste Policy Act (LLRWPA) putting the responsibility of LLW disposal on the states. "Each state is responsible for providing the availability of capacity either within or outside the state for disposal of low-level radioactive waste generated within its borders (excluding defense or other federal wastes). Low-level radioactive waste can be most safely and efficiently managed on a regional basis." It was

encouraged that states may enter into compacts with their neighbors under congressional authorization. This act was amended in 1985 because little progress had been made. The amendment had the purpose of keeping the three commercial disposal sites open for use by all states, to push deadlines for ratifying compacts, selecting host states, developing plans, and submitting license applications for sites. It also required the DOE to assist states and compacts in achieving local disposal facilities. As of 2012, it seems very few of the goals have been reached. Figure 2 shows the current compacts in the continental United States as of May 2010. Very few states are in ideal neighboring compacts. Some compacts stretch halfway across the country, arguably defeating the purpose of managing waste on a regional level and keeping costs down. One of the only compacts that appears ideal, the Northwest Compact, has two disposal sites within its borders.

1.2.2.1. Current Facilities in the United States

While there is some disagreement about the urgency of available storage (Pasternak and GAO-04-604), it is agreed that the current production of LLW in the United States will eventually exceed current storage capacities and facilities will not be able to meet the disposal demands from the generators (S. HRG. 108–756).

Since the 1980's, LLW storage facilities were configured around compact agreements. In the United States, as of 2012, there are currently only four active LLW storage facilities. Ideally, each of the compacts would have its own LLW disposal site as described below. One of the four active facilities, Barnwell, South Carolina, accepts Classes A, B, and C, but only from the Atlantic compact. The facility in Barnwell was originally a national LLW storage site, however, the South Carolina legislature decided to restrict disposal to its compact states (GAO-04-604).

Richland, Washington also accepts all three classes, but serves the Northwest and Rocky Mountain compacts only (Pasternak, 2006). These restrictions are appropriate according to the original design of compacts, where each set of states would have a local host state with a disposal site. Clive, Utah currently accepts Class A wastes from all states outside of the Northwest and Rocky Mountain compacts, but cannot accept sealed sources or tissues (Pasternak, 2006). Although they facility has proposed to also accept Class B wastes, only Class A wastes are allowed (S. HRG. 108–756). This facility is unfortunately far away from many of the generators that are along the east coast and will likely be filled to capacity within the next 50 years (MIMS). A fourth facility that accepts Classes A, B, and C LLW and a few more specific wastes from other categories such as uranium mill tailings (NRC, "Frequently asked questions about Land Disposal") has opened in Andrews County, Texas. This site is currently limited to the Texas compact which includes Texas and Vermont.

Closed LLW facilities include: Sheffield, Illinois; West Valley, New York; Maxey Flats, Kentucky; and Beatty, Nevada. While each of these closed for different reasons, they typically involved public pressure and/or design issues. The facility in Sheffield, Illinois was filled to its capacity of about 90,000 m^3. The operator had initiated the process for license renewal; however, after political pressure they withdrew their request and are now closed. The West Valley, New York facility was closed due to unknown possible public risk. This risk was caused when normal precipitation infiltrated the soil used to cap the trenches. The water table in the waste-containing trenches eventually rose. However, no elevated radioactivity was found. Maxey Flats, Kentucky, was closed because of on-site elevated radioactivity that was caused when water from the waste filled trenches escaped into permeable sandstone (Brookins, 1984). Beatty, Nevada,

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was closed due to political complications and public pressure after the Three Mile Island incident and changes in the LLRWPA (Gerrard, 1994).

1.2.2.2. Litigation

Several other states have spent millions of dollars in attempts to site a LLW storage facility (Alcott et al., 2002). Litigation, politics, and public opposition have made progress very difficult. Many politicians take the "Not in My Term of Office" (NIMTO) response as well as the public's "Not in My Backyard" syndrome (NIMBY) opposition (Visocki and Bremen, 1993). By 2002, a proposed North Carolina site had cost the compact over $120 million (Alcott et al., 2002).

Other states, including Pennsylvania and New York, have been assessed for suitability to host a LLW storage facility. Pennsylvania was analyzed in the late 1980's and early 1990's using GIS and a three-phase disqualifying criterion system to determine the suitable areas to be considered (Cargin and Dwyer). Around the same time, New York used a similar strategy, which included both exclusionary and preference criteria over four stages to go from statewide to five potential sites for further study (National Research Council, 1996). Neither state made it far past the evaluation stage. In New York, some residents found inaccuracies within the GIS data (Monmonier). In Pennsylvania, no final site was recommended after the state reduced its annual waste volumes and continued storing at current facilities. At the time, South Carolina was still accepting waste and was the easiest solution to the problem despite millions already spent on-site analysis (DiBiase, 2008). California had also located a potential site, but it was eventually blocked by public response and law (Pasternak, 2006). Nebraska and North Carolina were both sued by their local compacts for failure to provide a disposal site (Alcott et al., 2002).

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The locations of open, closed and limited access facilities across the continental United States are illustrated in Figure 1. It also includes the location of non-Department of Energy (DOE) nuclear power plants that produce LLW for storage in the above referenced facilities. DOE nuclear power plants are not shown because the DOE has its own LLW disposal sites, although they can use commercial sites. In addition, Figure 1 illustrates existing compacts with designated host states with active facilities. The exception is the Rocky Mountain compact whose host site is in the Northwest compact; because they are still neighboring states, this appears to be in line with the 1980's LLRWPA. Approaching the end of the license renewals of several nuclear power plants, decommissioning will drastically increase the amount of LLW to be disposed (Pasternak, 2006).

1.2.3. Site Selection

There are four major steps for the near surface radioactive waste storage site selection process outlined in the Nuclear Regulatory Commission (NRC) regulatory guide (NUREG) 4.19. These are identifying regions of interest, identifying candidate areas, identifying candidate sites, and identifying proposed sites. Each of the major steps is a more refined and detailed step than the preceding one, until the final step where the interested party seeks the NRC's approval to develop a site. The proposed analysis in this work focuses on the first two steps, although, it may be utilized in any of the four site selection steps.

The purpose of the first step, identifying regions of interest, is to eliminate unfavorable areas and identify candidate areas for further consideration. This is done by collecting regional or state data to identify areas that are not suitable. The proposed analysis can complete the majority of this step. The method suggested by NUREG 4.19 for this step is collecting published and open

file documents on generalized land use, transportation, and geophysical information. It specifically suggests identifying areas of steep terrain, surface waters, wetlands, geologic faults and fracture zones, and karst areas.

The second step evaluates the regions of interest to identify potential candidate sites. This requires more in-depth analyses of the geophysical data from information through federal, state, and local government agencies. The analysis developed here includes several of the criteria for this step, but does not go into the detail necessary to complete this step. This thesis provides an initial analysis, but does not include analysis of aerial photographs as suggested in the NUREG 4.19.

The goal of the third step is to evaluate the candidate sites in order to identify the proposed site. This step requires on-site analysis which is beyond the scope of this project. On-site analysis involves soil and surface-water samples, low-level aerial photos, on-site photos, air analysis, windshield surveys, reevaluation of data described in the previous two steps, and investigation into meteorological conditions and frequency. Once the specific proposed site is determined, the final step of evaluating site specific data can begin.

The final step requires fulfillment of all requirements including 10 CFR Part 61.50 performance objectives, a successful screening process, and final preparation of reports. The final step is objective is to determine if the site can be licensed. If this stage is successful, licensing will be approved for near surface disposal of LLW. The NRC provides guidance for this step in NUREG-0902, NUREG 4.18, and NUREG-1199.

1.2.3.1. Geographic Information Systems

Geographic Information Systems (GIS) are a set of programs for storing, managing, and displaying locations and attributes of spatial data. GIS applications and their use have expanded significantly since digital mapping was developed in the 1960's. GIS was applied to LLW site selection in the 1990's with limited success. Two of the major causes for community concern in similar attempts of analysis were lack of access to data layers and that the software was not accessible (Monmonier). In NUREG-0902 (1988), the U.S. Nuclear Regulatory Commission also suggested ways to incorporate GIS for siting a LLW facility. However, at the time this was suggested, the general purpose was to narrow down localized potentially feasible areas during the third step.

With the abilities offered by mapping systems, the Census Bureau produced the Topologically Integrated Geographic Encoding and Referencing System, commonly known as TIGER (Chang, 2010), which is one of the most important socio-economic spatial data sets in use today. Today, the software and data layers are, for the most part, readily available from government, research, and education websites including TIGER and the United States Geological Survey (USGS). Due to the advances in software and technology, over the past several years GIS has evolved to where many average computer users can combine and analyze several detailed layers on a map. This offers a solution to the issues from the attempts in the 1990's (Monmonier). With today's technology, GIS can be used at the initial stages of siting to help increase the chance of a successful choice when siting a facility and decrease evaluation costs even before on-site analyses are begun.

It should be noted that the accuracy of a GIS layer depends upon the data used to populate the layer. There are spatial data accuracy standards that range from less than meters,

such as LIDAR, to many kilometers, such as from older digitized maps that are dependent on the scale and the source of the map. However, the major source of possible error is the difficulty in projecting three dimensional data onto a two dimensional map. This makes each cell not necessarily equal in area and therefore densities may be somewhat misleading (Chang, 2010). Other possible causes for inaccuracies are data source and entry coding or transcription errors.

1.2.4. Louisiana

In 1977, northwest Louisiana's Vacherie dome was preliminarily assessed through test borehole drilling as a proposed long term radioactive waste repository. Soon after testing began, Citizens Against Radioactive Storage was formed by both a Democrat and a Republican. They succeeded in turning the governmental opinion against the salt dome project. In 1978, DOE promised Louisiana Governor Edwin Edwards, in a signed agreement, that no radioactive waste would be committed to Louisiana without the state's consent. In 1981, Governor David Treen vetoed a bill to ban geological testing. While this facility was not for LLW but HLW, it was an indication of the public response that could be received even during testing as well as the importance and value of off-site analysis (Carter, 1988). Louisiana belongs to the Central Compact whose host state, Nebraska, withdrew from the compact as of July 17, 2004. Unable to provide a disposal site, Nebraska had to pay a settlement to the Central Compact of $151 million (Alcott et al., 2002).
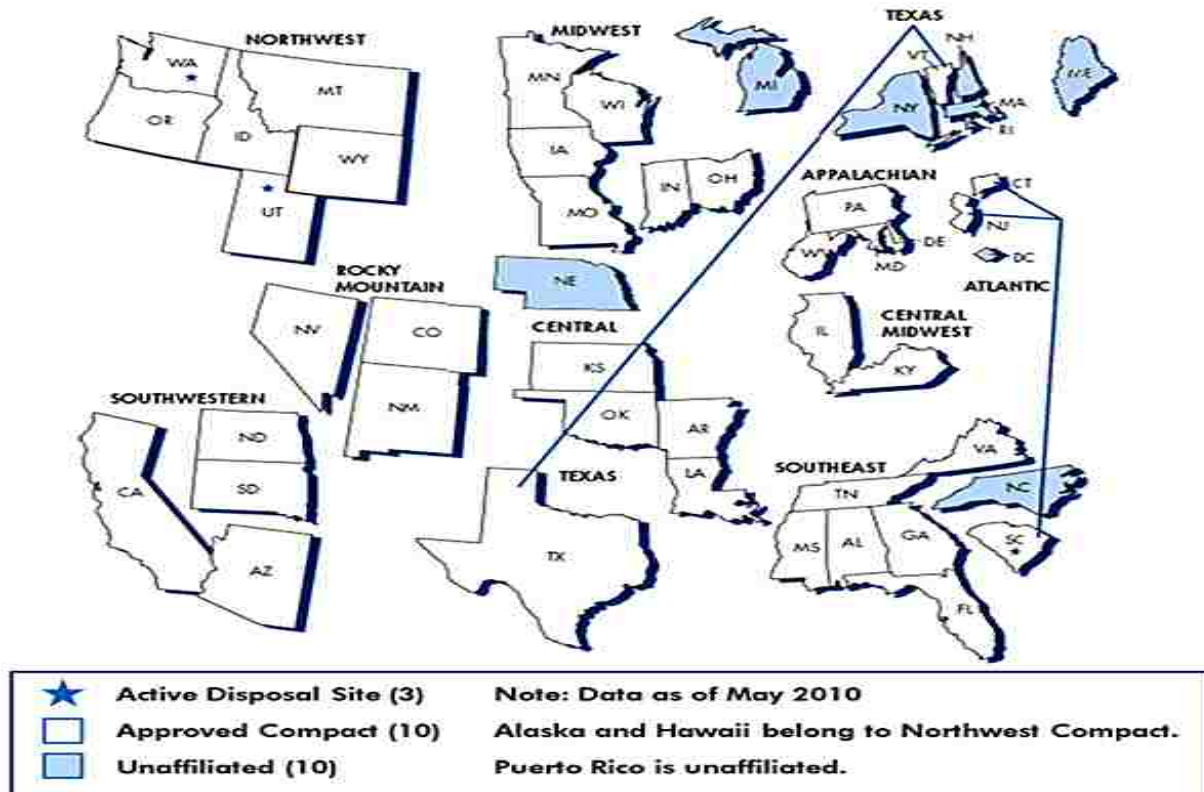
Figure 2 - Compact groups of the continental United States as of April 2012 (NRC, 2010)

While Louisiana is used here only as an example of how to use GIS to identify feasible LLW storage sites, it could be to the State's benefit to establish an LLW site. As a national disposal site, it could compete with the site in Texas if it pursues out of compact agreements, by being much closer to the majority of the generators on the east side of the Mississippi River. Even as a regional compact disposal site, it could still be profitable, follow the LLRWPA ideals, and help our local generators save money in waste management.

The goal of this project was to design a method for site selection suitability analysis using the criteria and requirements based on 10 CFR and expanded within the NUREG 4.19 and 4.18. Additional criteria were added when determined to be necessary or useful. Once designed, the method was applied to the candidate area of Louisiana. The entire state was analyzed for

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comparison and visual analysis, with the expectation that the area of emphasis would be

Northern Louisiana.

1.2.5. Goal and Aims

It is the intention of this project to design a GIS based method to determine suitability of

potential disposal sites based on the Code of Federal Regulations (CFR) requirements and

criteria as well as supporting literature and reports. The goal of this project is to apply this

method to Louisiana as the initial screening process to locate regions suitable for further

evaluation as prospective disposal sites. The aims of this project are to assess the requirements

from 10 CFR 61.50 to determine appropriate criteria for each requirement, to determine the GIS

data sources that can be used to assess each criteria, and to determine a suitability score from the

criteria for each requirement using Louisiana as an example region.

CHAPTER 2 – METHODS AND EVALUATION CRITERIA

Suitability was determined by using a grid overlapping the region of interest. Each cell within the grid was analyzed with every feasible criteria derived from the 10 CFR requirements. Because of the number of criteria with different methods for this analysis, the evaluation criteria are presented below along with the methods used to analyze them.

2.1. Grid System

A grid was created covering the region of interest (Louisiana) that was 0.035 decimal degrees on each side of a cell. Although decimal degrees were used for cell creation, one could also make a grid for an equal area projection to use a more classic unit of measurement such as length in miles or kilometers. 0.035 decimal degrees was chosen as a reasonable medium between number of cells and the size of a cell taking into consideration the current size of Barnwell, South Carolina's facility. The facility is 235 acres according to the South Carolina Department of Health and Environmental Control, which is around 0.4 square miles (SC DHEC, 2007). A cell of 0.035 decimal degrees, depending on the projection system used, converts to about 5.0 ± 0.1 square miles per cell within the region of this map using a Louisiana centered projection. This allows for more than twelve unique options, the size of Barnwell's facility, within each cell for actual placement of a facility. If the cells were too close to the size of an ideal facility, the results could be overly sensitive to grid placement, however if the cells are too large the analysis loses its spatial sensitivity, with potential invalidation of regions where the affecting criteria are substantially fare away. The grid is shown in Figure 3. Cells beyond the boundaries of the region of interest (Louisiana) were removed from the grids database.

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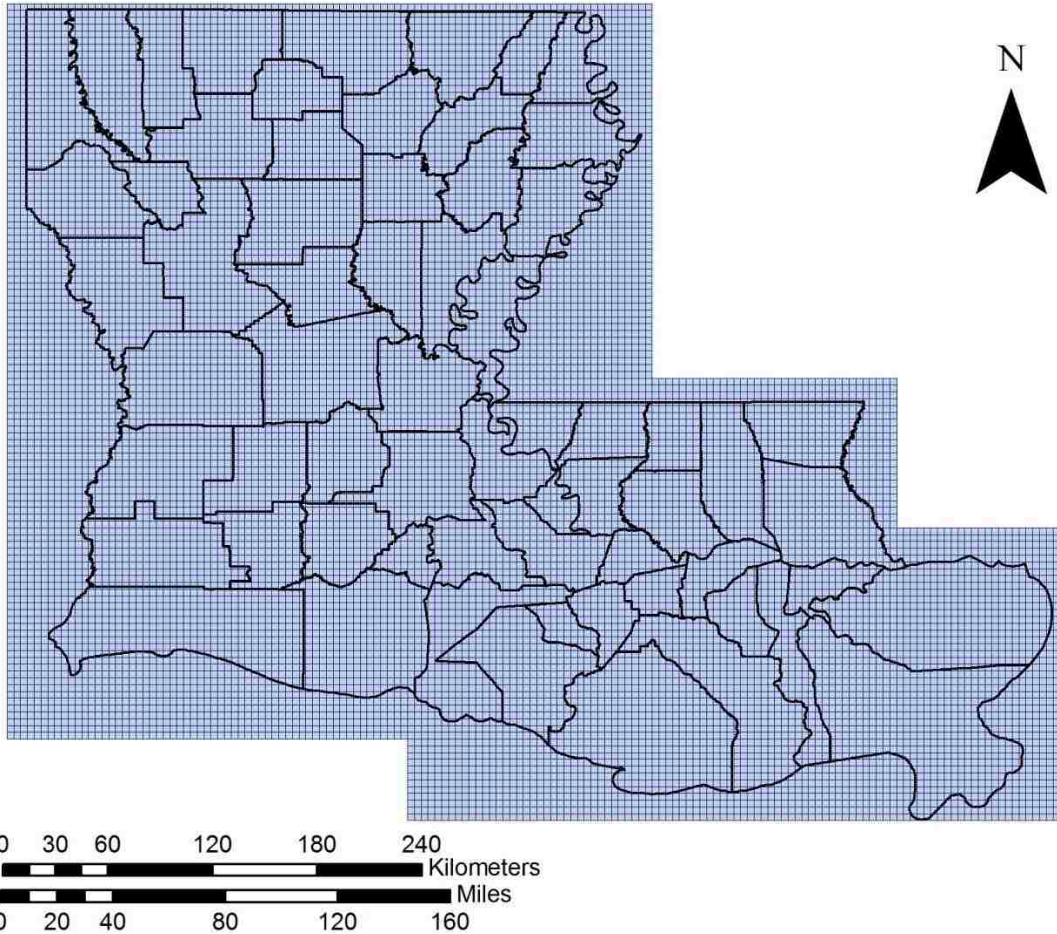
Figure 3 - Base cell grid used as template for the suitability analysis. Grid cells outside of the region of interest (the state boundary) were excluded.

Each criterion was converted into a usable format using built-in tools or a GIS add-on called Hawthe's Tools to form individual polygon analysis. For each cell (which is considered a polygon), Hawthe's Tools or GIS analyzed the data within that cell. There were three general types of analysis performed: polygon in polygon analysis, point in polygon analysis, and line in polygon analysis. GIS 10 became available during this project and its newer built-in tools were also utilized. Polygon in polygon analysis has a few specific options that can be tailored to individual requirements. Within each grid polygon, the polygon(s) that it analyzes can create a field (or combination of fields) based on the area weighted mean, the sum of any values within the cell, the maximum value within a cell, the minimum value within a cell, or the count of

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different polygons within the cell, as well as an area based calculation that determines the area of coverage within the cell. This latter area weighted mean (AWM) coverage data were chosen for most of the analysis done by polygon in polygon and others were used when necessary. Line in polygon analysis was typically analyzed using GIS 10 by summing lengths of all lines within a cell. Points, and lines converted to points, were analyzed by counting the number of points within the cell grid. This count was put into a new field (attribute table column) for each cell.

GIS offers tools to convert points into buffered points which create new polygons and can be analyzed by polygon in polygon analysis. This was valuable for certain criteria where general proximity was a better way of measuring suitability than specific location. For example, road access to a facility could be measured using this method. Another method analyzed point data by using a spatial join in which the polygon took the value of interest for the closest point. This analysis was valuable for criteria that were not densely concentrated or when density was not of interest. There were many occurrences where raster data needed to be analyzed. Raster data is data that is not points, lines, or polygons, but actual images with positional and value data (Chang, 2010). For the purpose of this report, raster data was usually converted into polygon data. Polygon data created from a raster file is extremely large and can be difficult for a computer to analyze. Raster data that consisted of multiple criteria was simplified into displaying only one criterion to simplify it for polygon in polygon analysis. For example, USGS land coverage raster was separated into subcategories such as wetlands (grouped with other categories). Wetlands could then be analyzed independently of other data by this method. When GIS 10 tools were sufficient for analyzing the raster directly, this was done because it made the analysis much quicker. For example, zonal statistics were used to describe average or dominant values of the raster within each cell.

2.2. Equation for Suitability

LLW site suitability requirements are outlined in 10 CFR Part 61 "Requirements for Land Disposal of Radioactive Waste" specifically in Part 61.50 "Disposal Site Suitability Requirements for Land Disposal." This part specifies ten requirements that the NRC describes as the minimum characteristics a site must have to be considered acceptable. The requirements are general and therefore are explained in the NRC's Regulatory Guide 4.19 "Guidance for Selecting Sites for Near-Surface Disposal of Low-Level Radioactive Waste" and explained in more detail in NUREG 0902 "Site Suitability, Selection and Characterization." Criteria were chosen from these regulatory guides and used to design the analysis. To be used in the analysis each criterion was required to be directly or indirectly measurable, available for use, and in a format that was compatible or could be converted for use by the GIS software.

The regulatory guides suggested multiple criteria that were included in the analysis. Additional criteria were included based upon discussions with personnel at current waste facilities and more recent natural disasters. The measurable criteria were designated as absolute, scalar, or a combination of the two. Absolute criteria were criteria that must meet a certain requirement and are either acceptable or fail to meet the requirement. If the criterion was not met, the site was not suitable for any further analysis and failed as a potential location. For example, wetlands cannot be considered as potential sites. Therefore no areas that were identified as wetlands were suitable after this criterion was analyzed and the areas would not be candidate sites. A similar method of screening is exclusionary screening (DiBase, 2008). Scalar criteria were criteria that have a most and least ideal value for suitability; scalar criteria do not result in complete exclusion, instead representing a continuum of potential degree of suitability. A combination of both absolute and scalar criteria results in a site where all absolute criteria are

acceptable and the scalar criteria contribute proportionally to the final assessment. For example, karst terrain is unacceptable, but certain areas may only be partially covered with karst terrain. This absolute criterion would reject sites that are predominantly karst, but a scalar criterion could allow partially karst terrain with the degree of suitability depending on the proportion of karst to other terrain. Similarly, a minimum elevation could be required above sea level; higher elevations would be considered more suitable because they are further from sea level, and elevations just above the cutoff would be considered marginally suitable. Thus, the minimum elevation is an absolute criterion, while elevation above the minimum is a scalar criterion.

      Suitability for a specific cell (x, y), in Equation 1, was calculated as the sum of all scaled criteria for that cell divided by the number of criteria. To scale each criterion, the criterion's least suitable (min), most suitable (max), and the value of the cell being calculated are necessary. The min is not necessarily the lowest value for that cell.

Equation 1

$$Suitability_{cell:\, x,y} = \frac{1}{n} \sum_{i}^{n} \left(\frac{Cell_{x,y_{Ci}} - \min(C_i)}{\max(C_i) - \min(C_i)} \right)$$

These formulas can be modified to include weighting factors if appropriate (Equation 2). If an argument can be made that one scalar requirement is more important than another then appropriate weighting factors could be assigned. Similarly, weighting factors can be used to balance each of requirements from 10 CFR 61.50. A modification factor would need to be included to accomplish this since requirements did not contain an equal number of criteria. For example, Requirement 1 had three criteria and Requirement 3 had nine; a weighting factor could be used to make the 3 criteria each count 1/3 as much. For the analysis, this was accomplished by using the modified formula for each requirement individually and then averaging the suitability

scores for all requirements to obtain final cell suitability. Thus the modification factors were used to ensure that all major requirements were equally treated and weighting factors could have

Equation 2

been used if one requirement or criterion is proven more significant than another. This project only used modification factors with one necessary exception explained in 2.3.4.2. Note that not all possible criteria were included for each requirement for this analysis. Non-quantitative criteria were excluded. Also, if data for a measurement were not available and no indirect measurements were available, the criterion was excluded. Finally, some criteria were found during the analysis to have negligible contributions to the suitability score and were removed to simplify the score calculations. Any excluded criteria could conceivably be included in later steps of site selection.

$$Weighted\ Suitability_{cell:\ x,y} = \frac{1}{\sum W_i} \sum_{i}^{n} \left(W_i \frac{Cell_{x,y_{Ci}} - \min(C_i)}{\max(Ci) - \min(C_i)} \right)$$

2.3. Suitability Requirements

Some of the Requirements in 10 CFR 61.50 refer to subpart C of part 61, performance objectives. These are the general performance objectives for all near surface disposal sites. The requirements can be summarized as follows: the facility must be sited and run so that exposure to humans are well within established limits; there must be protection to minimize risk of individuals inadvertently intruding; the facility should be sited and run to minimize need for ongoing maintenance; and the facility should use ALARA practices in all steps of its existence (10 CRF 61.40-44).

Data for each criterion are stored in a GIS database under fields representing the requirement and criteria. They fields are named RxCryz where x indicates the requirement

number, y indicates the criterion number, and z indicates multiple replacements for individual criteria. Most figures used a Jenks classification system unless otherwise specified. Jenks classification uses natural breaks in the data to determine the ranges for each group (ESRI, 2009).

2.3.1. Requirement 1

"The disposal site shall be capable of being characterized, modeled, analyzed and monitored." (10 CFR 61.50 Line 2)

The first requirement for site suitability is interpreted by NUREG 0902 as two important criteria that are difficult to measure directly: the site should be geologically and hydrologically simple. While the first requirement says the site "shall be capable," it was not considered an absolute criterion. As a site becomes more geologically and hydrologically complex, it is more difficult to characterize, model, analyze and monitor. The issue with these two criteria is that there is no direct means of measuring simplicity. The measurement must be made indirectly. As described in NUREG 4.19, sites that are geologically and hydrologically simple and contain processes that occur at consistent and definable rates are preferred over complex sites. Geological simplicity was measured as the second derivative of elevation, rate of change of slope, or curvature, within a cell. This was chosen because while neither elevation nor slope can truly indicate modeling complexity, the amount of change in slope within a certain area was considered a logical surrogate.

Similar decision issues arise with measuring hydrology. The most reasonable substitution based on the data layers available seemed to be a combination of two measurements. The first was the density of water wells in a cell and the second was the total length of streams and water

bodies within a cell. Arguably this could also include surface water, however that was included later as an absolute criterion (one that makes the cell not suitable). NUREG 4.19 indicates that site characterization is not necessary for the initial screening steps, but our GIS method makes it possible to include in the initial screening. By analyzing the rate of change in slope, or curvature, as well as the water well density and length of water bodies, this surpasses the required initial screening and presumably increases the chance of a good selection.

2.3.1.1. Elevation

The procedure for analysis of the curvature criterion for Requirement 1 was as follows. Elevation raster data (USGS) was analyzed to produce a curvature raster dataset. ArcMap 10 (ESRI Software, Redlands California) was used to perform raster in polygon zonal statistics which was exported into table form and then joined to the grid system in column R1Cr1. Because a negative curvature is equally as suitable (or unsuitable) as a positive curvature, the absolute value of all cells was taken. Each cell had a mean raster value used as its cell value. These data were then analyzed using the scalar method with the most suitable value being 0 and the least suitable value was the highest curvature within a cell. The result is shown in Figure 4.

2.3.1.2. Water Wells and Water Bodies

Water well density data was compiled from the USGS dataset to allow for point in polygon analysis. This was used as the first surrogate to indicate consistent measurable
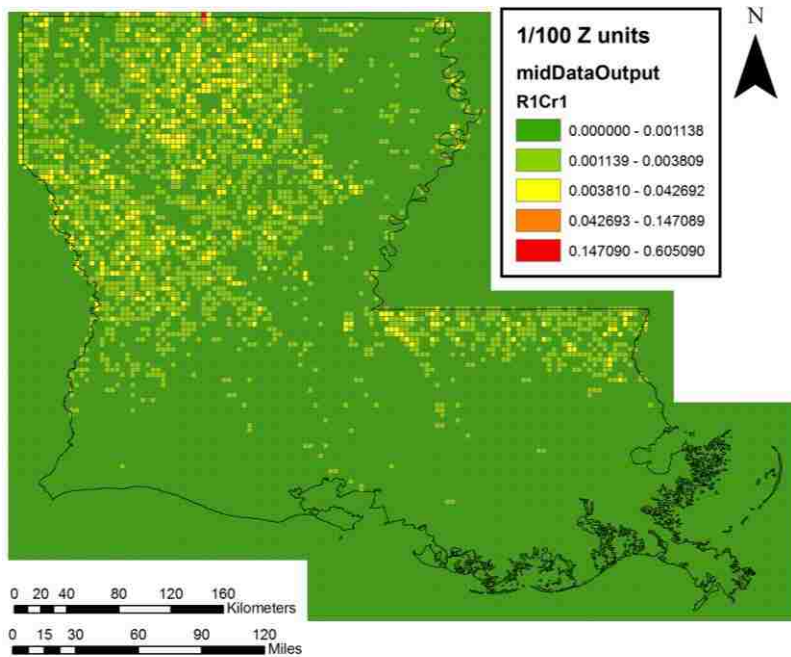
Figure 4 – Curvature throughout Louisiana was used as a surrogate for geological complexity. According to GIS, expected values for hilly areas have a magnitude of 0.5 (ESRI, 2009).
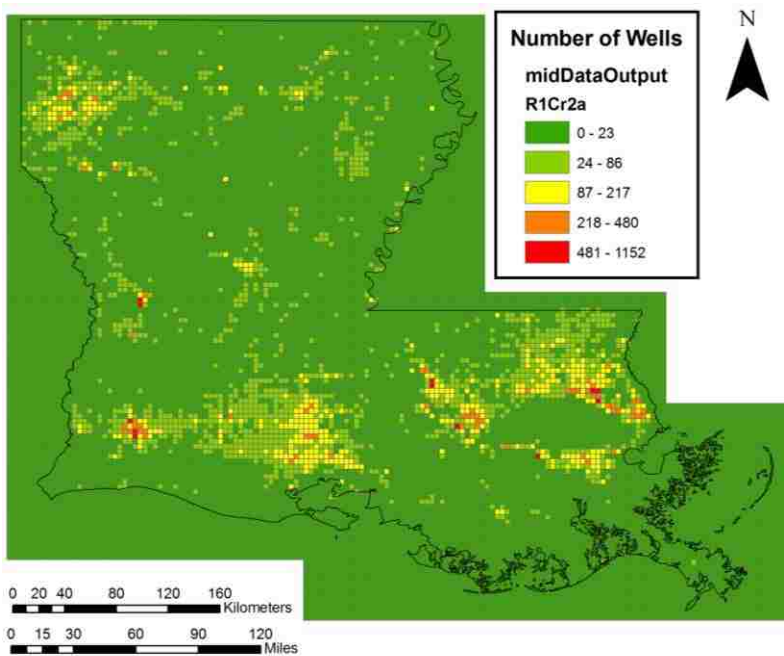
Figure 5 - Water well density data throughout Louisiana were used as one indicator of hydrological complexity. According to this criterion, areas colored red are the least suitable for a LLW storage facility.

hydrological rates. The data were compiled into attribute table column R1Cr2a and analyzed as a

scalar criterion with a most suitable value of 0 wells and the least suitable being the number of

wells in the highest density cell (Figure 5). The streams and water bodies' data were the second

surrogate for hydrological complexity and were also compiled from the USGS. These data were

analyzed using line in polygon analysis. Each cell value is a measurement of total length in

distance of streams and water bodies in the cell. The highest values are least suitable. The data

are stored in R1Cr2b and shown in Figure 6.
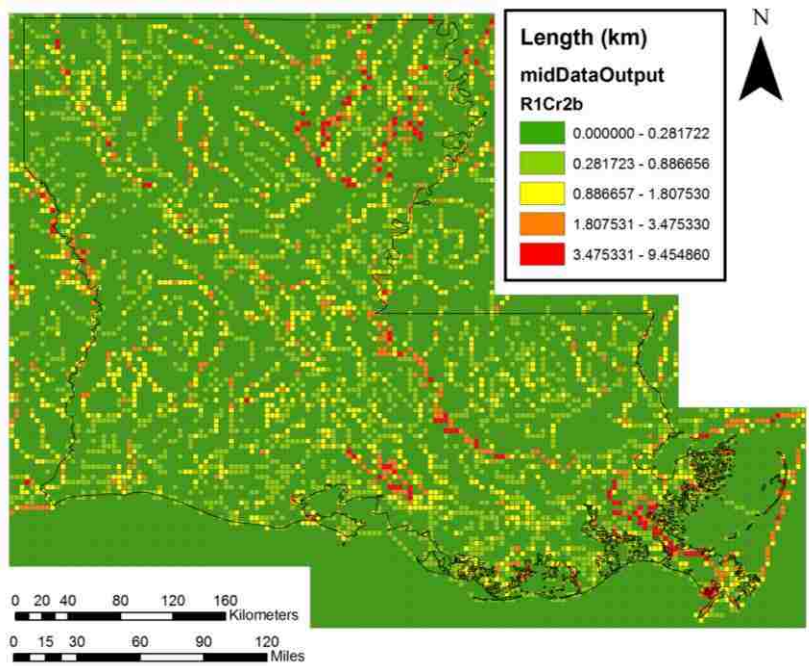
Figure 6 - Relative length of water bodies throughout Louisiana used as the second indicator for hydrological complexity. The most suitable areas, under this criterion, will have no water bodies.

2.3.2. Requirement 2

"Within the region or state where the facility is to be located, a disposal site should be

selected so that projected population growth and future developments are not likely to affect the

ability of the disposal facility to meet the performance objectives of subpart C of this part." (10 CFR 61.50 Line 3)

The second requirement is to investigate the local population in different ways to make sure that the facility can minimize population risk in the short and long term. Criteria derived when taking into consideration the NUREG 4.19 are: low population, low population density, low population growth, two kilometers from residential limits, no planned highway, and sufficient road access. While some of these seem repetitive each was decided to provide valuable and unique data. However, they are not independent data. There were multiple options for how to analyze the data for these criteria which are discussed below in each criterion's section.

"Subpart C" of 10 CFR 61 (as referred to in Requirement 2 above) is the reasonable expectation included in 10 CFR 61 as the baseline for how to properly maintain the facility. These performance objectives outline the maximum annual dose to the general public as well as requirements for methods to be used to minimize this dose. It also gives the timeline for these performance objectives to be met over the total lifetime of the facility (before and after construction and operation).

2.3.2.1. Low Population

Low population is an important requirement because the lower the local population the less risk to the general public (per person risk). One should also consider a balance of population because a facility needs a supply of local workers. There were several options for methods to directly measure population. Population data were available on the parish level (a parish is a county equivalent). Population could also be measured on the cell block level. Cell blocks (or census blocks) are much smaller then parish polygons and census tracts, but neither cell blocks

nor parish polygons were aligned with the grid system designed for this analysis. Population

could also be measured by land use cover data. This dataset organizes areas with high, medium,

and low density structures on a level more precise than the cell grid generated. When choosing

which method to use one must take into consideration that there are other similar criteria

(density, growth, and residential limits). It was decided that the best way to analyze this would

be to use the basic population data and include the density structure data as a surrogate when

dictated as necessary by the low population density criterion (see section 2.3.2.2.). The scalar

method was used for polygon in polygon analysis of population data per parish into R2Cr1

(Figure 7). The most suitable value for this criterion would be the lowest population and the least

suitable is the highest population.
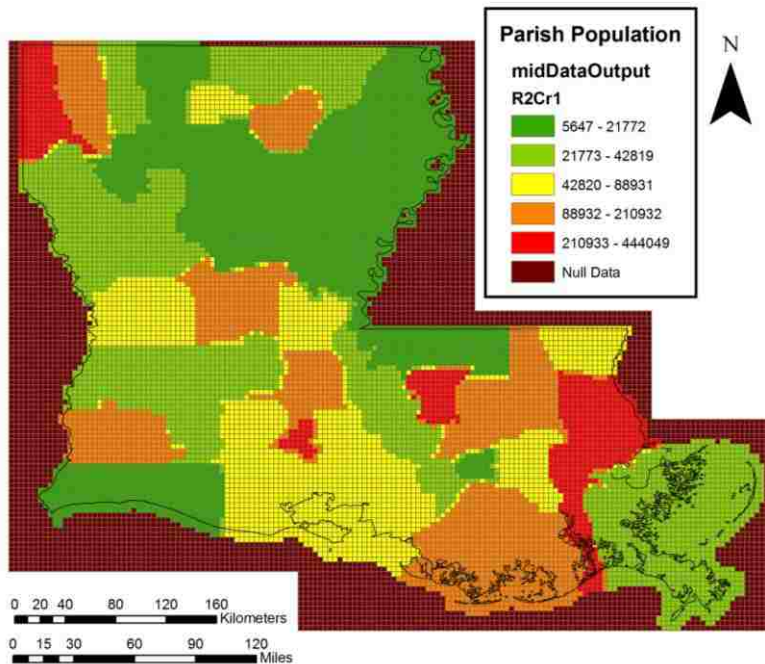
Figure 7 – Parish population throughout Louisiana used as a measurement of possible risk to
population. The most suitable areas, under this criterion, have the lowest population.

2.3.2.2. Low Population Density

Population density is arguably equal to or more important than actual population. Like population data, there were multiple options to measure it. While population density could be accounted for using high, medium, and low density structures, this would be somewhat incomplete for not giving good indication of parish wide information. Population density was analyzed by using parish (county) wide population census data divided by the area within a parish. The unit of area does not matter as long as all parishes are analyzed using the same unit of measure, because relative scales are used in the suitability formula. Square miles were used in this analysis. Population density was analyzed by polygon in polygon analysis and stored in column R2Cr2 (Figure 8). For this criteria's scalar analysis, the cells with lower values are more suitable for a storage site.
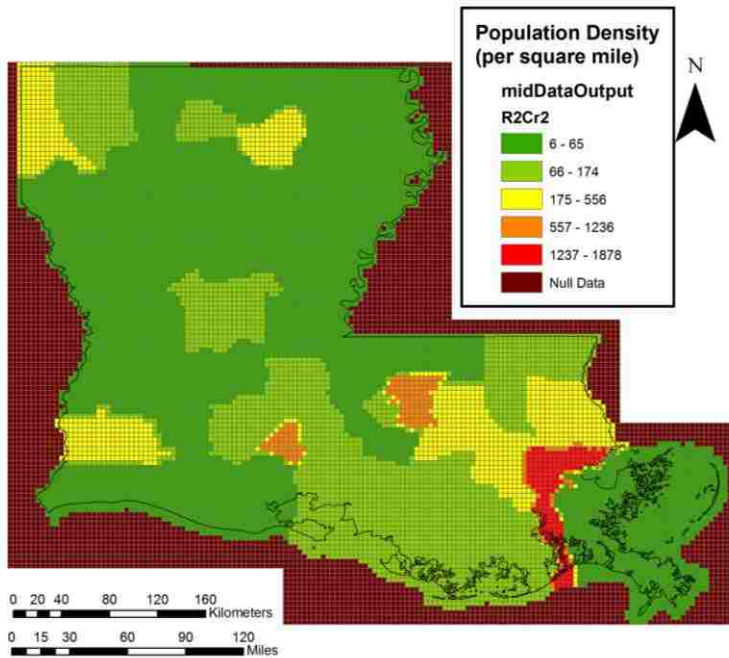
Figure 8 – Parish population density throughout Louisiana used as a measurement of possible risk to population. The most suitable areas, under this criterion, have the lowest density.

2.3.2.3. Low Population Growth

Predicting the population growth in the region of interest is also an important step in minimizing possible future risk. While an area may not be highly populated at present, by studying historic populations and growth patterns one can predict the possibility of the region to be densely or highly populated in the future. Just as in the previous sections, different resolutions of data were available. The data for this criterion were collected in two ways, a direct field category from census datasets and, (which also allowed for an accuracy check) a calculated the population percent change in the past 5 and 10 years. Alternatively, the Population 2030 estimates, or any future estimates, could be used. However, these data are typically based upon the census population growth model; it would be a duplicate measure of the census datasets. Polygon in polygon analysis was performed and the data are stored in column R2Cr3. For this criterion, the most negative value is most suitable and the most positive value is least suitable (Figure 9).

2.3.2.4. Residential Limits

The LLW storage facility cannot be built within 2 kilometers of residential limits because this would increase the possibility of encounters with way-warders as well as increase possible person risk. The population proximity data were determined using the structure density data as an absolute criterion. If any cells contain any the high, medium, and low density structures they were not suitable for a LLW facility and therefore were excluded from remaining analysis. The three datasets, low, medium, and high intensity structures, were taken from the 2001 USGS Louisiana Land Cover Data Set (USGS). Each set was analyzed by polygon in polygon area analysis. Each resulting value could have a maximum of 0.001225 square decimal degrees.
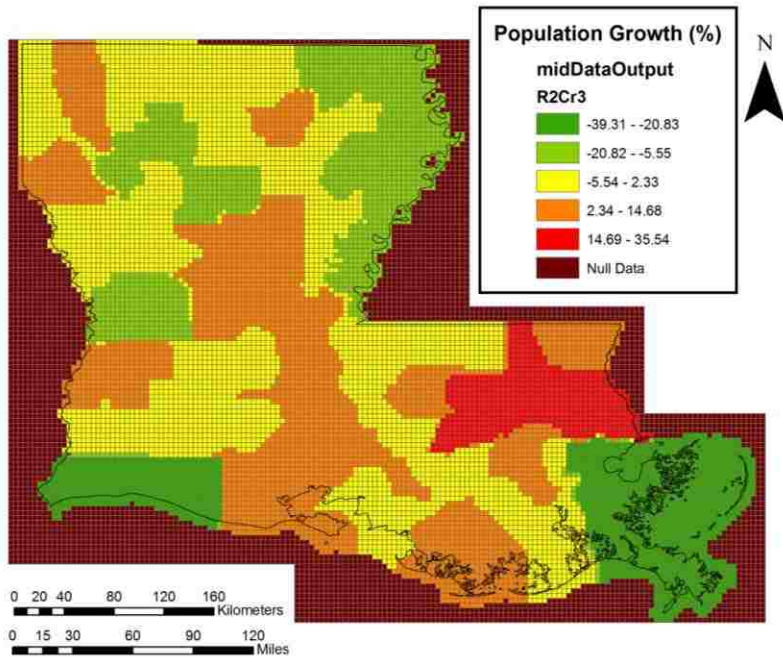
Figure 9 – Parish population growth throughout Louisiana used as a measurement of possible future risk to the population. The most suitable areas, under this criterion, have the lowest (most negative) population growth percentage.
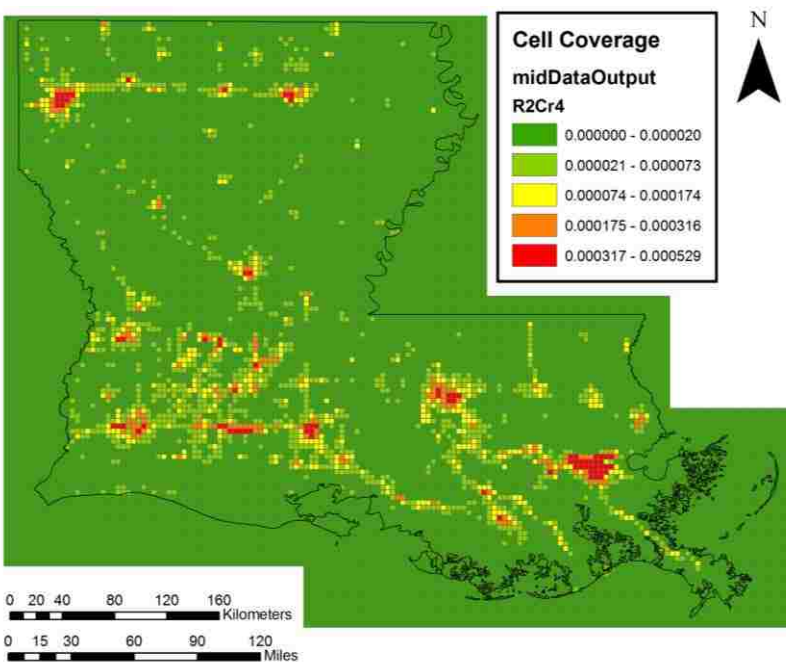
Figure 10 – High, medium, and low population structures throughout Louisiana used as a measurement of possible risk to the population. The most suitable areas, under this criterion, have none of these structures.

These values were summed and then divided by three into a final column R2Cr4 and can be seen in Figure 10. If there was any value greater than 2% (0.02) for R2Cr4, then the cell was ineligible for site selection and removed as a potential cell site, values less than this were analyzed as a scalar criterion.

2.3.2.5. No Planned Highway

"No planned highway" is not a criterion that is easily applicable to this analysis. Although a data layer could be created, major planned highways are not easy to validate if they are not in the final stages of planning. Long term predictions for highway planning would be almost complete guesswork so the criterion was not used. One could use this criterion only if discussion regarding a new highway is in progress at the time of the analysis, or if reasonable guesses for future developments could be made, such as extension of existing highways.

2.3.2.6. Sufficient Road Access

The final criterion of Requirement 2 is sufficient road access. Road access is important to the facility for obvious reasons such as transportation of waste and supply of workers. While roads could easily be built to a facility, total facility cost is reduced if new roads are not necessary. A dense road system likely correlates to a densely populated area, but this was accounted for by another criterion. The road access criterion uses the scalar analysis method with the highest density as the most desirable. The data layers were readily available through transportation databases and other sources. This was analyzed with ArcGIS 10 by measuring the lengths of clipped segments of roads within each cell (Figure 11). Alternatively, this criterion could be analyzed by only using major roads of the region of interest or time by road to the

closest major road; one could use the proximity feature within GIS. While this method would not

give direct road access, it would indicate proximity to major roads which should be valuable.

The density data were stored in column R2Cr5 (Figure 11).
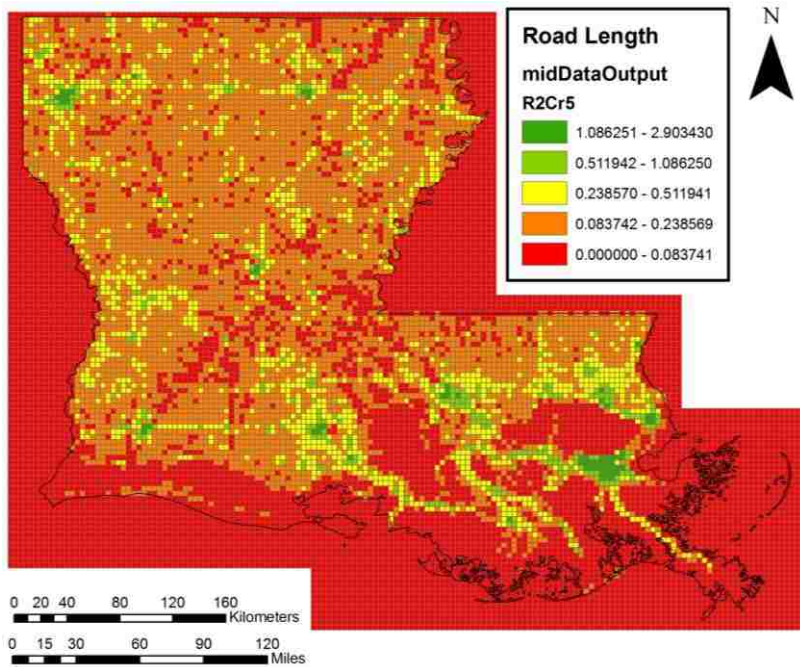
Figure 11 – Total road length within each cell as an indicator of road access. Higher road access allows for easier means of shipping and increases suitability.

2.3.3. Requirement 3

"Areas must be avoided having known natural resources which, if exploited, would result

in failure to meet the performance objectives of subpart C of this part." (10 CFR 61.50 Line 4)

The current production and availability of natural resources are indicators of both

regional needs and future resource harvesting that could change the ability of a site to meet the

performance objectives. When deciding what natural resources to investigate, one must consider

those which would sustain the local culture as well as those that would support future endeavors.

Areas having known natural resources may in the future be sought for their value. If this could

cause problems with the integrity of the storage facility, the location is not ideal. This

requirement assesses the presence of valuable resources in the vicinity of the storage site that could possibly cause issues if exploited. In general, this step would identify areas where harvestable natural resources are not in a significant concentration such that people would likely harvest them, and potentially affect the facility. Resources cannot be fully evaluated without being onsite, but a preliminary analysis based upon available data can help narrow down possible areas and minimize potential risk. NUREG 4.19 offers a more descriptive explanation of the criterion, "areas should be avoided if they contain natural resources in quantities or of such quality that future exploitation could affect waste isolation." The best analysis of this criterion may require national comparisons. For example, when looking at geothermal activity, the majority of Northern Louisiana has greater potential than Southern Louisiana to be used for energy production. However, on a national scale Louisiana is likely a much less desirable location for geothermal resources overall. All appropriately formatted data were analyzed as either polygon or point data. Many of the layers were point data layers with points for current mines such as oil. This is not a direct measurement of future harvesting, however it is an indication of current and past production. Preference should be given to layers available in polygon form if available, because they are likely to provide indication for future harvesting of the natural resource.

2.3.3.1. Metallic and Non-Metallic Minerals and Ores

Metallic minerals and ores make up the first criterion group derived from this requirement. The USGS has compiled much of the available metallic and non-metallic mineral and ore data in a GIS compatible format. The resources included within the region of interest were: aluminum, barium-barite, calcium, clay, geothermal (discussed below) gypsum-anhydrite,

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halite, limestone, manganese, perlite, phosphorus-phosphates, salt, sand and gravel, crushed

stone, sulfur, halite, titanium pigment, and germanium. The data include past and present

producers of these resources as well as sites that have had essentially no resource seeking

activity. No sites were removed from the analysis despite some not serving any current purpose.

The most suitable cell is the cell with the lowest value. The point in polygon data were stored in

column R3Cr1 and can be seen in Figure 12.
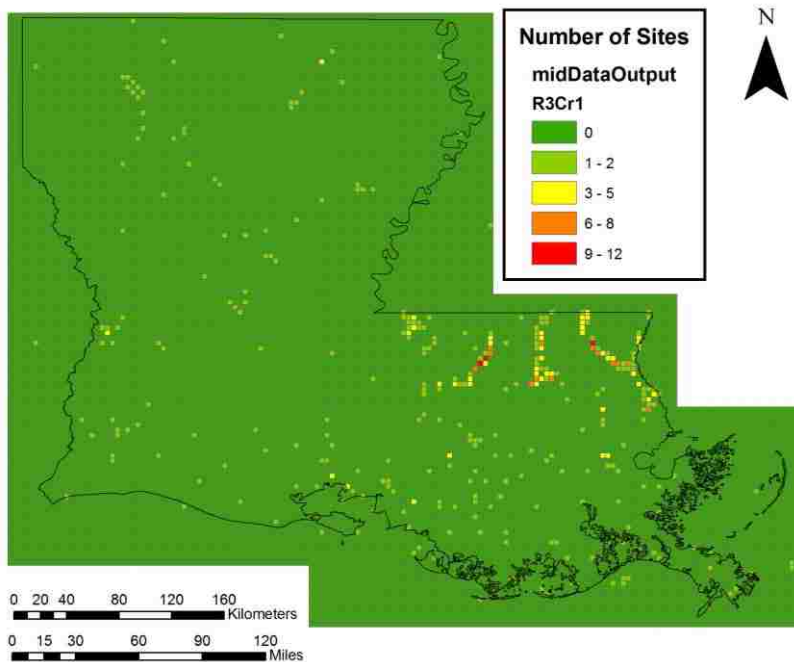
Figure 12 – Minerals and ores sites throughout Louisiana as an indicator of resources that may be desirable in the future. Low values are more suitable than high values and are green.

2.3.3.2. Fuels: Peat, Lignite, and Coal

Fuels such as peat, lignite, and coal are important resources due to the demand for energy

from modern society. If the facility were sited where that resource could be exploited, it could

jeopardize the physical reliability of the facility and cause the facility to fail to meet the

performance objectives. The resources, as all resources within this requirement, would have to be

in a level that could plausibly be worth harvesting in the lifetime of the facility.

Peat is decayed vegetative matter that can be used for fuel. According to the World Energy Council's survey of resources, peat is rarely used for energy purposes outside of Europe (World Energy Council, 2007). Although it may not be greatly used now, it could possibly be a source of energy within the lifespan of the storage facility and should still be analyzed. The data used was from Louisiana Geologic Survey which categorized areas of Louisiana in shapefile form by aerial geologic map codes. Those categories that included peat were analyzed. Because it was polygon data, an area weighted mean was taken so cells with 100% coverage would have the maximum value, and areas with 0% coverage would have a minimum. In this case, the minimum would be the most suitable. It was not an absolute criterion because the existence of peat does not make a site impossible but it could be less desirable. However, peat is also an indication of wetlands so it is likely the less suitable cells will not pass the wetlands criterion below. The data are stored in column R3Cr2a and can be seen in Figure 13.

Lignite is another natural resource available to be used as fuel. It is a low grade of coal but still could be exploited as a resource. Two sources had valuable data when analyzing this criterion. The first was the Louisiana Geologic Survey. The second was the National Atlas's "Coal Fields of the United States" (USGS). The first source goes into more detail and is more precise regarding the polygons selected. The second is more conservative and gives three general areas within Louisiana that have lignite. Two of these areas are considered potentially mineable, while the third can be considered for other uses. The first dataset was chosen due to its greater accuracy and definition. The data are stored in column R3Cr2b and shown in Figure 14.

Coal was the final fuel resource to be analyzed. In Louisiana, the majority of coal exists as lignite. Because of this, coal was not analyzed separately.
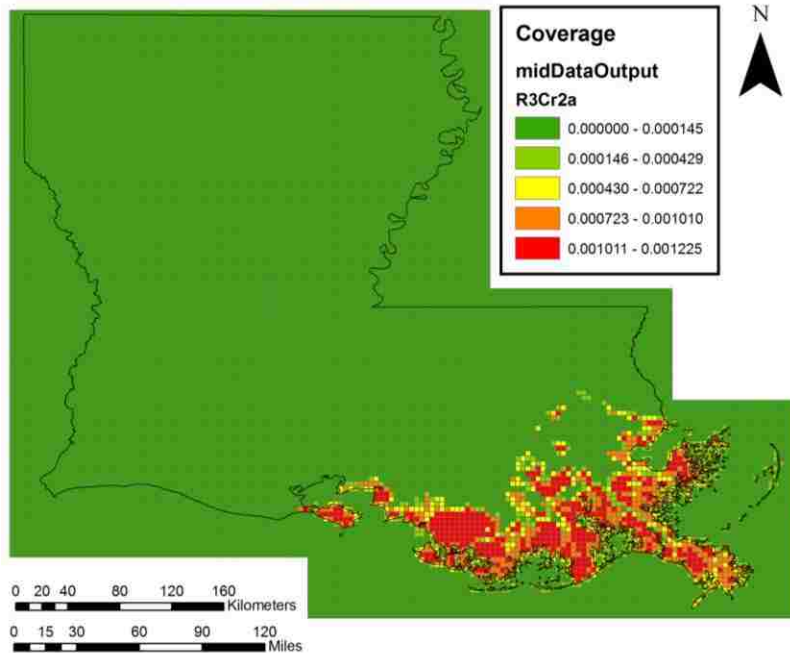
Figure 13 – Cell coverage of areas likely to contain peat. As a potential indicator of wetlands and a potential resource for fuel, areas with high coverage are less suitable.
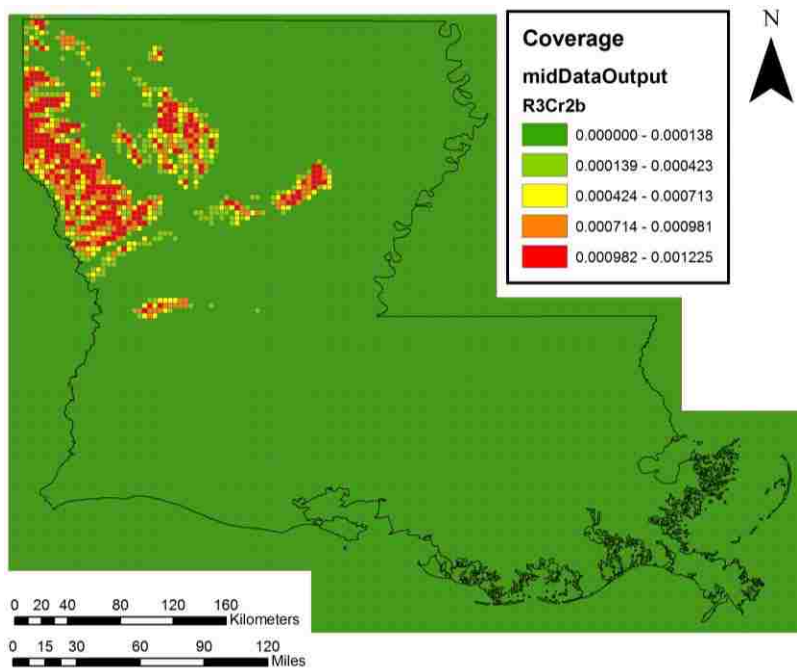
Figure 14 – Coverage of areas likely to contain lignite coal. As a potential indicator of mineable resources for fuel, areas with high coverage are less suitable.

2.3.3.3. Hydrocarbons

The next category of resources to be analyzed was hydrocarbons. This included gas, oil, tar sands, and asphalt. Similar to the above, these meet an obvious demand for multiple purposes including fuels and consumer products.

Oil and gas were available in two possible point layers as well as one polygon layer. All three were from the Louisiana Department of Natural Resources. The first was points that were centered on oil and gas fields. The second was points for each oil and gas well. The third option was active oil and gas leases in Louisiana in polygon form. The second option was chosen for its increased precision as well as the third option because it may provide a better long term indicator of use. The well data file included oil, gas, and injection wells which were analyzed using point in polygon analysis. The cells with the highest count were considered least suitable. The lease data were analyzed using polygon in polygon analysis. All leases were considered equally valuable, although Hawthe's tools allow for area weighting based on a value (such as cost per acre); cells were analyzed by area of lease within a cell divided by area of the cell. Cells with higher coverage approaching 0.001225 square decimal degrees were considered less suitable. Because oil and gas were provided together, they were analyzed simultaneously. To account for analyzing oil and gas twice (once polygon and once point) these criteria were modified to each contribute 50% to the final suitability. However, these are Louisiana's top resources and could be weighted more heavily in the final suitability if desired. The point data were stored in column R3Cr3a and the polygon data were stored in R3Cr3b see (Figures 15 and 16).

Tar sands are another form of hydrocarbon, also known as oil sands. Similarly asphalt deposits can be an indication of underground oil bodies. Because neither of these are directly available, shale datasets were used. Because of its physical properties, tar sands are more

difficult to change into useable products but as oil increases in cost the need for harvesting tar

sands may increase. Louisiana had recently found a new shale play, the Tuscaloosa shale play,

which made several shale play maps out of date. However, the U.S. Energy Information

Administration had a data layer conservatively including both Louisiana shale plays (US EIA).

The data layer appears to overestimate the actual size of the Haynesville shale play. The data

were analyzed using polygon in polygon analysis with the most suitable areas having the lowest

coverage of shale play. The data are stored in R3Cr3c (Figure 17).
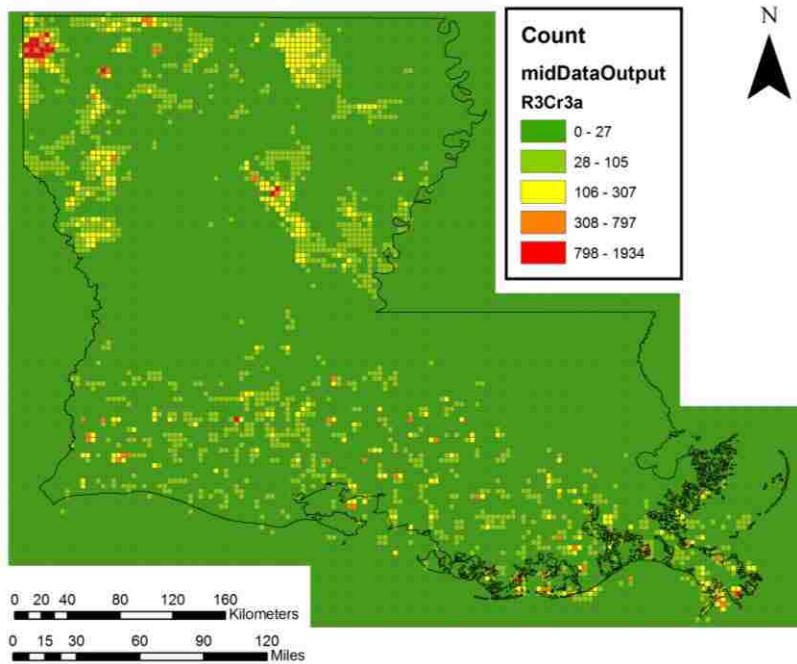
Figure 15 – Oil and gas wells throughout Louisiana as an indication of increased risk to the facility. While it is possible these resources can be sought without affecting a nearby storage site, they contribute to lower suitability by definition.
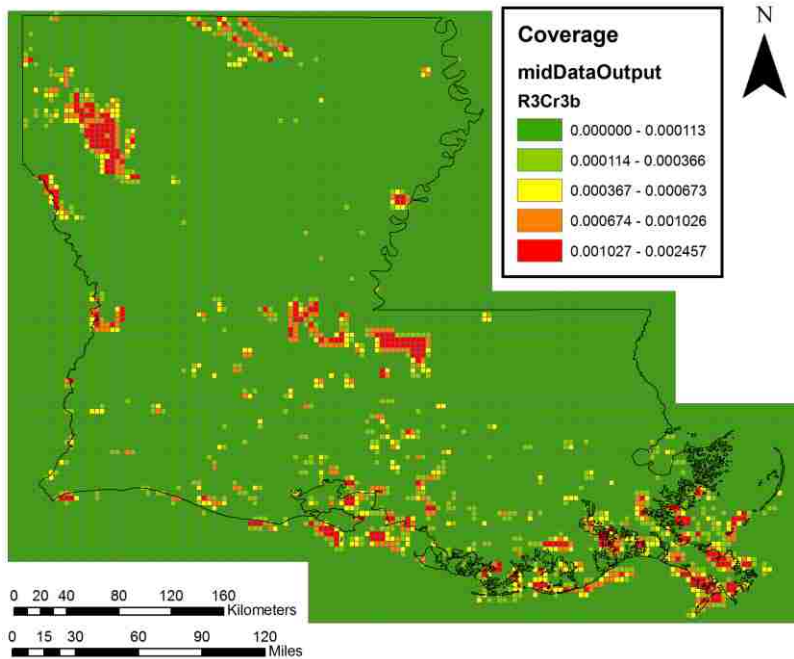
Figure 16 – Oil and gas leases throughout Louisiana as an indication of increased risk to the facility. While it is possible these resources can be sought without affecting a nearby storage site, they contribute to lower suitability by definition.
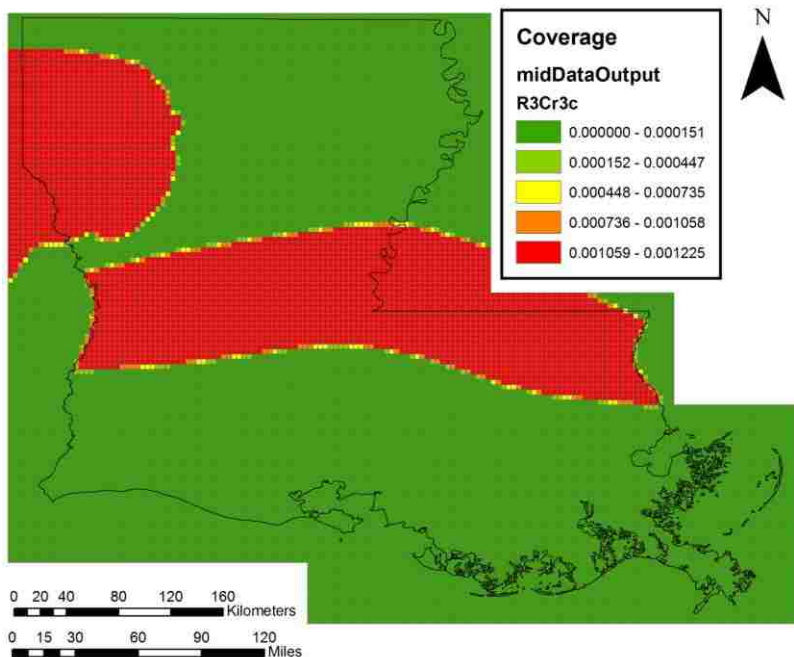
Figure 17 – Haynesville and Tuscaloosa shale plays of Louisiana. Cells covered by the shale plays are less suitable for site selection. While it is possible these resources can be sought without affecting a nearby storage site, they have lower suitability by definition.

2.3.3.4. Geothermal Potential

Geothermal resources are another possible source of energy. There were three sources of data for this criterion. The first set of data describing US geothermal resource potential did not include Louisiana as a region of interest. The second was the same USGS point data layer used above in metallic and non-metallic minerals and ores. This data layer suggested there are a few geothermal "unnamed prospects." However, it is more likely these projects are positioned for research and information due to the category definition suggesting they have shown no significant resources since first placement. A third source was a data layer indicating worldwide geothermal potential based off of underground heat flow. This data would be ideal however it was not available in GIS form. The data were available in Google maps form however and were converted into a GIS data file. This is not ideal due to uncertainties in conversion accuracy; however it was the best available surrogate for a direct measurement to indicate geothermal potential. The data are stored in column R3Cr3d and were ranked 1 to 8, with 8 as the highest potential and therefore the least suitable. The data can be viewed in Figure 18.

2.3.3.5. Agricultural Resources and Surface Water Resources

Agricultural ground and surface water resources were analyzed by using 2007 agriculture census data by the National Agricultural Statistics Service (USGS). Parish-wide data were analyzed by polygon in polygon analysis. The data were total cropland as a percentage of land areas in acres (Figure 19). This could be replaced with data from sales of value if one felt the socioeconomic data was more important. Because this was parish wide data, cells that overlapped multiple parishes were given the maximum value within the cell. The data are stored in column R3Cr4 see (Figure 19).
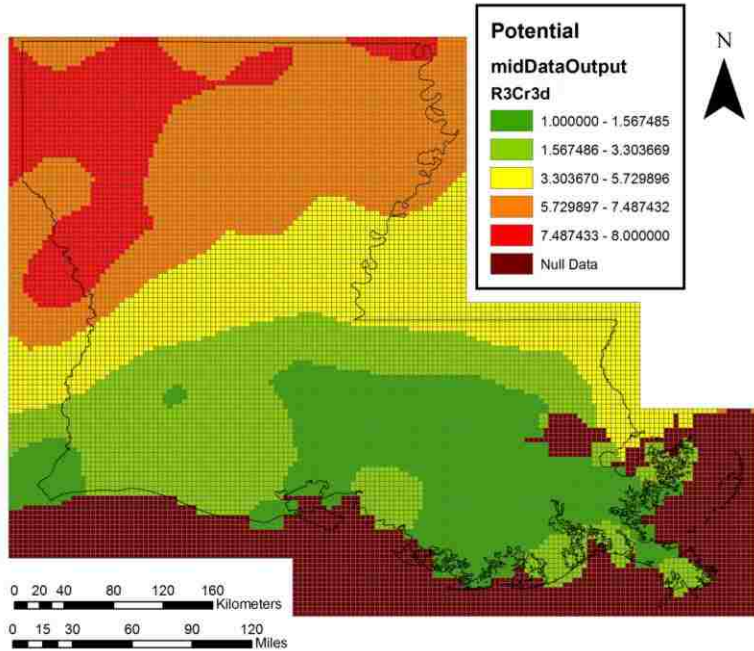
Figure 18 – Geothermal potential throughout Louisiana. Green areas indicate low potential. Red areas indicate the highest potential.
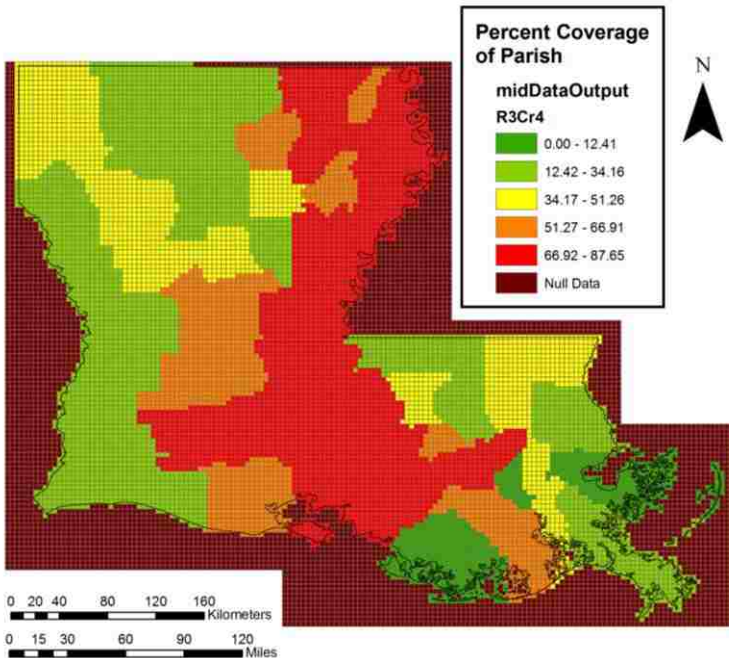
Figure 19 – Parish cropland as a percentage of parish area. The most suitable areas have low crop coverage.

Surface waters should also be analyzed beyond its agricultural uses. Due to the problems of previous and closed LLW storage facilities regarding water intrusion, it is important to avoid

areas that are at risk of flooding. While there are advantages to being near waters, such as delivery by barge, being too close greatly increases risk of failure to meet the performance objectives. Analysis of surface water is further discussed with land cover data for Requirement 6.

2.3.3.6. Industrial Minerals

Industrial mineral are any resource such as sand, gravel, clay, aggregate sources, shales, and building stone that are mined for industrial purposes other than fuel or metals. These were analyzed in previous steps (mostly in metallic and nonmetallic minerals and ores); however, if unique resources were present, it would be suitable to include them.

2.3.4. Requirements 4 & 5

"The disposal site must be generally well drained and free of areas of flooding or frequent ponding. Waste disposal shall not take place in a 100-year flood plain, coastal high-hazard area or wetland, as defined in Executive Order 11988, Floodplain Management Guidelines. Upstream drainage areas must be minimized to decrease the amount of runoff which could erode or inundate waste disposal units" (10 CFR 61.50 Lines 5 & 6).

Requirements 4 and 5 are grouped together due to their similarity of concept. Some of the major issues that provoked political response in the previous LLW facilities originated from poor water control. These issues can be caused from physical slope and position relative to the coast. The criteria derived by NUREG 4.19 for requirements 4 and 5 are: the facility cannot be within the 100-year floodplain; it cannot be in a coastal high hazard area; and it cannot be in an area where flood velocities could damage the facility. The guide generalizes the requirements by

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suggesting to avoid placing the facility in an area where the design of complex hydrologic features would be needed.

2.3.4.1. Wetlands

While wetlands is a considered a generic term by the USGS, it typically describes areas of frequent collected surface waters by pooling from surface waters or ground water discharge. Wetlands are also considered a culturally significant area. Because of these reasons it is best not to consider any cells dominated by wetlands as potential sites. The USGS put Louisiana wetlands into two categories (although there are more categories, Louisiana data only uses two). The two categories are woody wetlands and emergent herbaceous wetlands. The raster data were converted into individual polygons and then the two types of wetlands coverage's were summed. If the cell was 90% or more covered by wetlands areas, it was considered not suitable for further analysis. The data are stored in R4Cr1 and can be viewed in Figure 20. This criterion is also evaluated in Requirement 7.

2.3.4.2. 100-Year and 500-Year Flood Zones

When considering the greatest threats to a LLW facility, flooding is certainly among them. Therefore one must minimize the risk as much as reasonable. A 100-year flood zone is an area that has an annual 1% chance to be inundated by flood. Similarly, a 500-year flood zone is an area that has an annual 0.2% chance to be inundated by flood. For Louisiana, there are three generations of flood zone maps. The first is the original paper maps, some of which have been digitized but few provide complete parish wide datasets. The second generation of data are called

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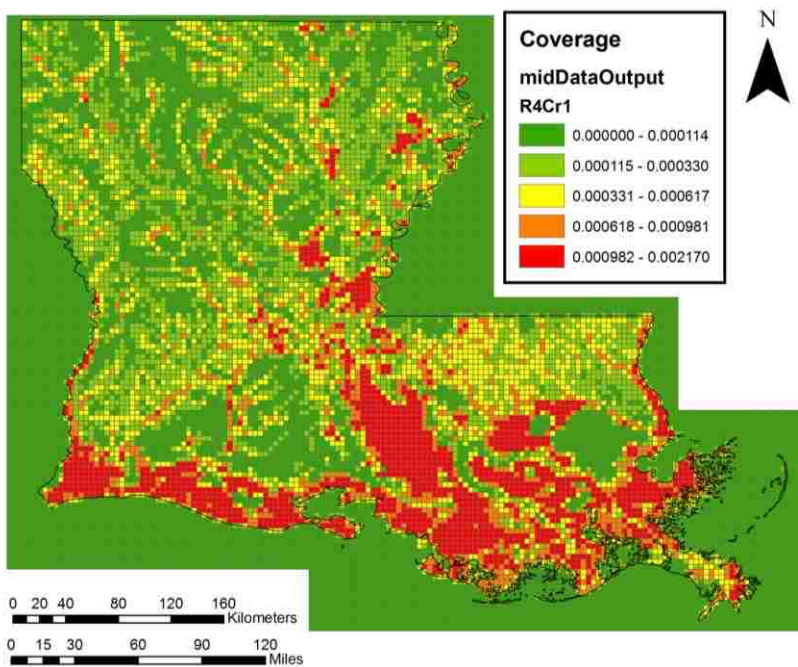
Figure 20 – Cell coverage of wetlands throughout Louisiana. Cells approaching full coverage are unsuitable for further analysis. Cells with no coverage are most suitable according to this criterion.

Q3 Data, mostly digitized mosaics from the paper maps, but many of which were improved. This set of data is incomplete for Louisiana. The most recent generation of data is called DFIRM and includes very modern elevation datasets as well as accurate levee measurements. Unfortunately this dataset, like the Q3, is somewhat incomplete, and due to recent hurricanes is still undergoing revisions. FEMA provides most of these data sets, particularly for the Q3 data.

The DFIRM data was used when finalized, but this is only a few parishes. This caused issues when trying to find a data layer suitable for analysis that would include the 100-year flood plain data. Furthermore, the zone categorization had changed between the generations of maps. The 100-year floodplain should be considered as an absolute criterion, making this a very valuable dataset to analyze. Regarding the lifetime of the facility, one should also consider the 500-year flood plain data. When doing this one can use the 100-year floodplain data as an

absolute criterion, and the 500-year as a scalar criterion. If the cell is within the 500-year but outside of the 100-year floodplain, it was considered 50% as suitable as if it was completely out of both 500-year and 100-year flood plains. The data provided 3 categories in the region of interest. Category X was outside both the 100-year and 500-year floodplains, Category A was inside the 100 year floodplain, and Category X500 was outside the 100-year floodplain but within the 500-year floodplain. The best solution to the problem presented by lack of data was to use the most recent data available, to exclude unsuitable cells, and not to perform analysis for this criterion on unavailable parishes (they were neither excluded nor increased in suitability). To accomplish this the data were split into three unique polygons (one for each category A, X, and X500) and analyzed twice, first as an area weighted mean on the value of the zone, then again as an area weighted mean for the area covered. If the area covered was less than 50% it was considered not enough data to analyze. If the coverage was greater than 50%, the area was analyzed by its dominant zone. If category A was the dominant zone and covered more than 75% of the cell, it was considered unsuitable. Otherwise, if category X500 covered the majority of the cell a weighting factor of 50% was assigned for the suitability analysis, or if X covered the majority of the cell its coverage was used for the suitability. The most suitable cell would be completely dominated by the highest coverage of X. The weighting factor was necessary because X500 cannot be considered as good as X. The data layers representing zones A, X, and X500 are shown in Figures 21, 22, and 23 respectively.

2.3.4.3. Coastal High Hazard Areas

According to FEMA, a coastal high-hazard area is "an area of special flood hazard extending from offshore to the inland limit of a primary frontal dune along an open coast and any
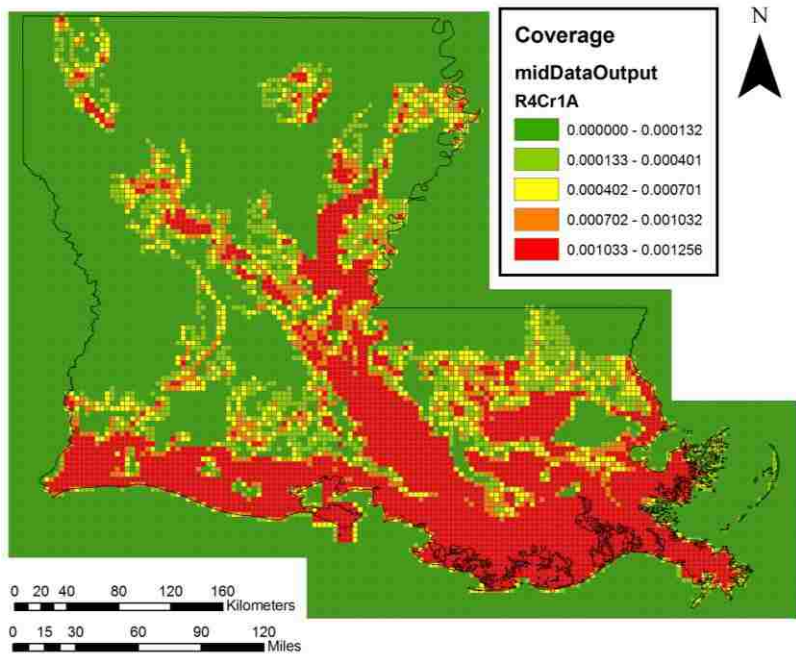
Figure 21 – Cell coverage of areas categorized as Zone A on flood insurance rate maps. Cells dominated by this category in red are unsuitable for further analysis.
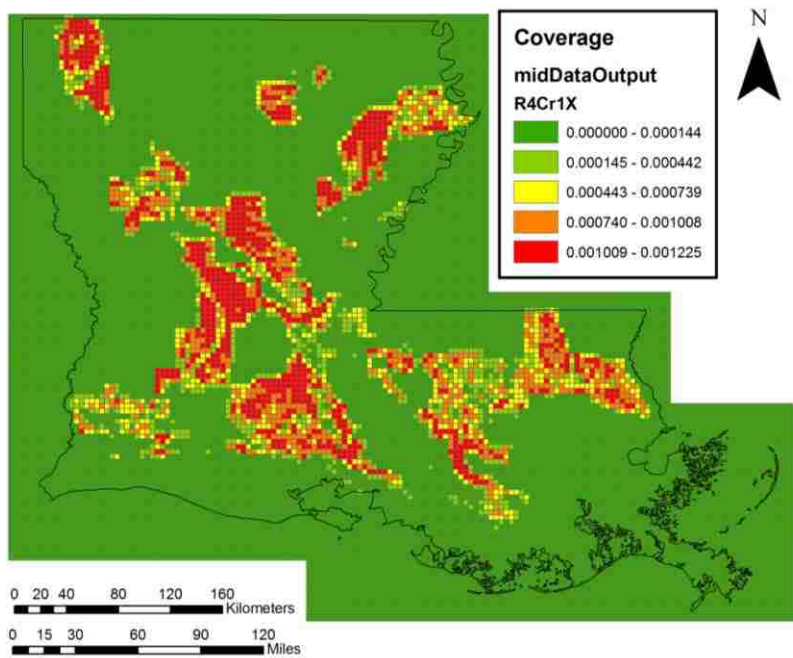
Figure 22 – Cell coverage of areas categorized as Zone X on flood insurance rate maps. Note red indicates favorable cells for this figure.
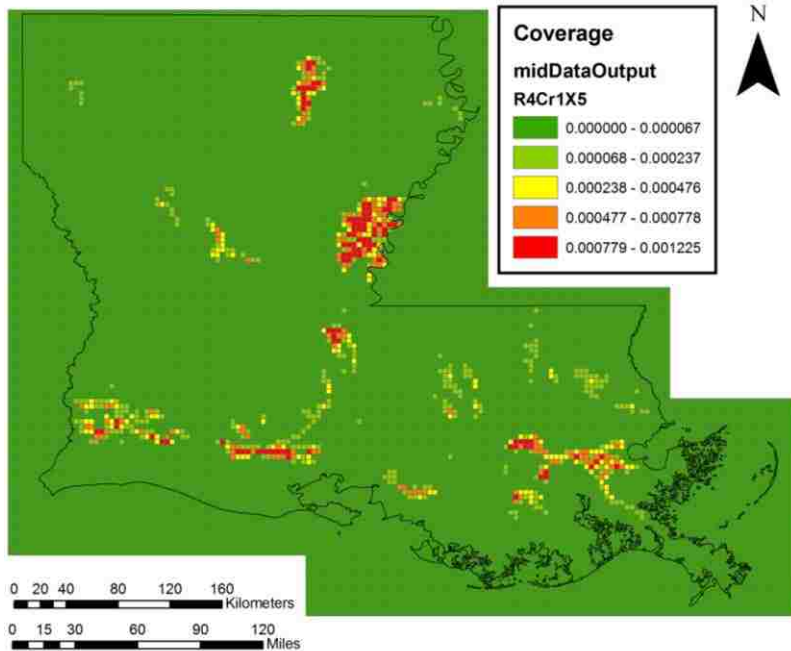
Figure 23 – Cell coverage of areas categorized as Zone X500 on flood insurance rate maps. Note red indicates favorable cells for this figure.

other area subject to high velocity wave action from storms or seismic sources. The coastal high

hazard area is identified as Zone V on Flood Insurance Rate Maps (FIRMs). Special floodplain

management requirements apply in Zones V including the requirement that all buildings be

elevated on piles or columns" (FEMA, 2010). This is a large risk for coastal sited facilities,

however once wetlands are taken into consideration, few areas of risk remain in Louisiana; Zone

V areas are in parishes along the coast. Zone V areas are treated as absolute criteria and any cell

within that parish would not be suitable. Unfortunately, the current dataset did not include any

areas with this categorization. Newer datasets currently under development may include Zone V

(or equivalently categorized) areas.

2.3.4.4 Steep Slope

The criterion of no steep slope has the purpose of avoiding areas where flooding can cause rapid water runoff. This is similar to the criterion regarding projected land uses, but does not require any assumptions. In an area where the ground is steep, intense weathering could occur to damage the disposal facility. This criterion was analyzed by using GIS's analysis tools to calculate the slope using an elevation raster data layer. The original elevation data set was a Digital Elevation Map (DEM) from the Louisiana Department of Environmental Quality (LDEQ, 2004). The GIS analysis feature created a second raster providing slope values and allowed raster in polygon analysis. Each cell was represented by the average slope within it using the zonal statistics feature in GIS. The most suitable cell would be one with a low average value indicating low incline and hence low chance of runoff from above. A high value would indicate lower suitability. One would not want to site a facility on an extreme incline because more digging would have to occur to level the facility. Because of this, the higher values are not impossible to build on, but still less suitable. Data were stored in column R4Cr2 and can be seen in Figure 24.

2.3.4.5 Runoff from Projected Land Uses

Future land use that affects runoff is another criterion that must be analyzed in steps following the initial screening. The difficulty in creating a data layer that analyzes the projected land uses, such as urbanization, conflicts with the purpose of the initial GIS analysis. While the criterion should be analyzed it is not appropriate at this stage without making a generalization such as a constant slope would allow the area to drain efficiently. Because of this, no steep slope

is used as a surrogate for this criterion with an appropriate modification factor because it is analyzed twice.
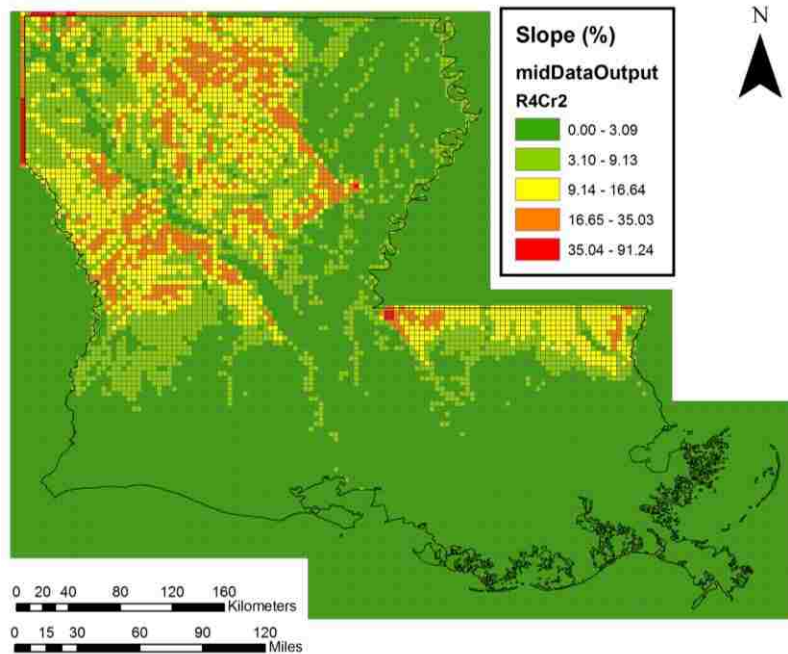
Figure 24 – Slope (change in elevation) as a percentage throughout Louisiana. Steep slopes are considered less suitable than shallow slopes.

2.3.4.6 No Need for Extensive Design

Similar to the first requirement of geological and hydrological simplicity, "no need for extensive design" cannot be directly measured. The method of analysis is to again analyze the rate of change in slope within a cell (curvature). This was done by using the GIS tools to calculate curvature, the second derivative of elevation, followed by polygon analysis. No modification factor is needed for this second use because it is for a different requirement. Figure 4 shows the results from this criterion.

2.3.5 Requirement 6

"The disposal site must provide sufficient depth to the water table that ground water intrusion, perennial or otherwise, into the waste will not occur. The Commission will consider an exception to this requirement to allow disposal below the water table if it can be conclusively shown that disposal site characteristics will result in molecular diffusion being the predominant means of radionuclide movement and the rate of movement will result in the performance objectives of subpart C of this part being met. In no case will waste disposal be permitted in the zone of fluctuation of the water table. (10 CFR 61.50 Line 7)"

As further described by NUREG 4.19, areas which are characterized by a high water table should be avoided, and a disposal site should be well above the water table so that no water intrusions should occur. This set of criteria will require on-site analysis to fully investigate, however geographical data can help indicate areas more likely to be suitable. While the requirement directly states that it will consider exceptions, the purpose of this analysis is to find the most suitable site which takes into consideration the simplest and most cost effective areas based on the ALARA principles.

2.3.5.1 Surface Waters

While water based storage has been discussed as a potential option, and previously used, it is currently not a desirable choice. Water is considered a good shielding material; however, the threat of intrusion of water to damage the facility and waste material is a substantial risk. For these reasons, surface water must be treated as an absolute criterion. If a cell has more than 80% coverage, it is not suitable. If it has less than 80% coverage it was analyzed using scalar analysis with the most suitable cells having the lowest value. The data were available from the USGS

land cover data set. The open water data was converted to a single polygon for analysis and stored in R6Cr1 (Figure 25).

2.3.5.2 Water Bodies

The same data used in Requirement 1 was re-analyzed as a surrogate indicator of the water tables. Rivers, streams, and water bodies were clipped and measured using GIS. The values are provided in length form (see also Requirement 1). It can be assumed that the presence of water bodies may indicate ground water as well. These were stored in R1Cr2b (Figure 6).
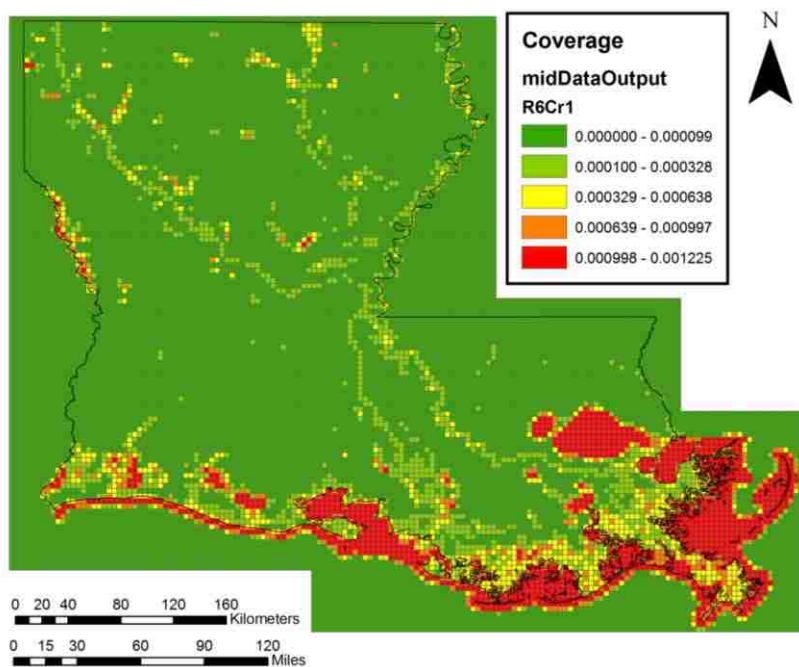
Figure 25 – Open (surface) water of Louisiana. For this analysis, water based storage is not considered. Therefore, any cells covered by water are not suitable. Cells with no coverage are the most suitable.

2.3.5.3 Water-Level Data (Well Depth)

Water well data were collected from the USGS data maps; the amount of wells with level data was significantly more limited than that of well concentrations used above. The importance of using water wells is to ensure that the main method of radioactive waste movement is limited to mostly molecular diffusion if the water table is well below the facility and to decrease the likelihood of selecting a cell where fluctuations of the water table would cross the facility itself. It was analyzed by using a spatial join, where the closest point to the polygon was used to represent that polygon's level data. The data are stored in R6Cr3 and can be viewed in Figure 26.
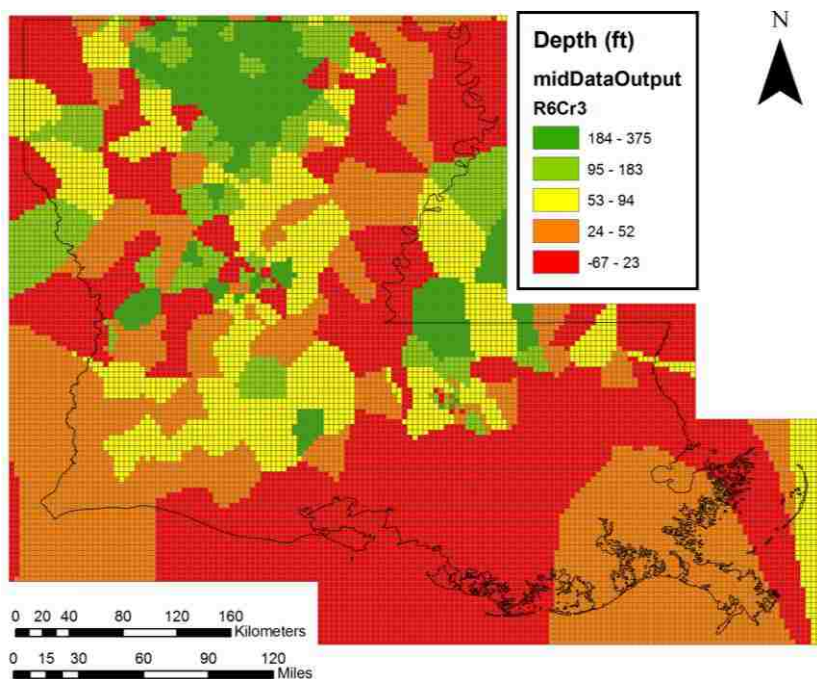
Figure 26 –Water well depth throughout Louisiana. Used as a surrogate for estimating underground water tables. The deeper the well, the more suitable the cell.

2.3.5.4 Elevation

Elevation data was used as an indicator of likelihood to be within fluctuations of the water table. The areas may also have increased flood risk. The data were collected from the

Louisiana Department of Environmental Quality (LDEQ, 2004) and were analyzed by raster in

polygon analysis. For this analysis, the greater the elevation value the more suitable the cell.

While this is not always true, one must take into consideration the other criteria being analyzed

and the goal of this criterion, to avoid water (Figure 27). Alternatively, a benchmark could be set

at a certain distance above sea level, such as 30 meters with all cells above this value as equally

suitable; any values below 30 meters would be considered not suitable and not included for

further analysis. This would be repetitive with other criteria that are categorized by low elevation

however. The data are stored in Colum R6Cr4 and can be seen in Figure 27.
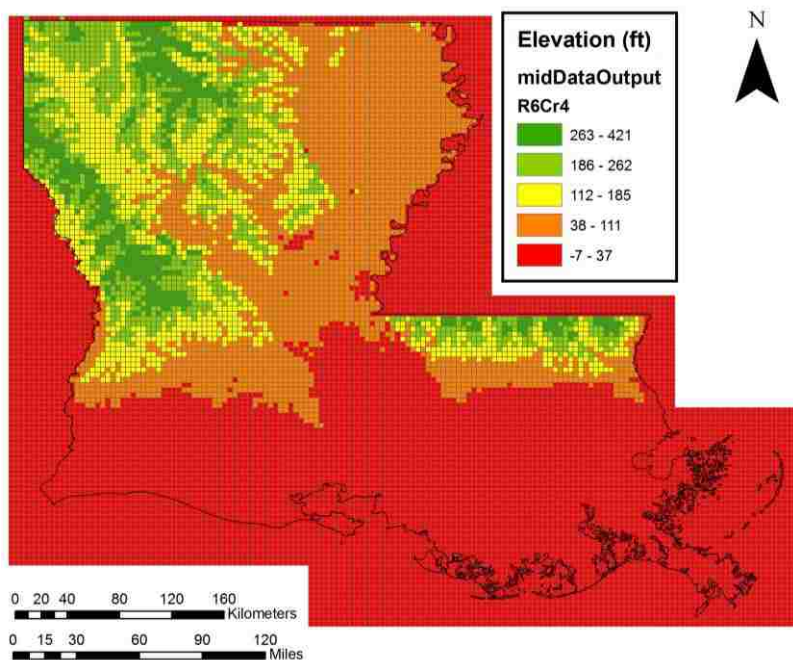
Figure 27 – Elevation throughout Louisiana. The higher elevations were considered more
suitable for site selection.

2.3.6 Requirement 7

"The hydrogeologic unit used for disposal shall not discharge ground water to the surface

within the disposal site. (10 CFR 61.50 Line 8)"

The suggested criteria for this requirement from the NUREG are springs, seeps, swamps and bogs. These were all analyzed to assess this requirement. The basic goal of this requirement is to ensure that no water movement occurs to increase risk by methods of radioactive escape. In Louisiana, the two criteria of swamps and bogs can be summarized with an important additional requirement by the EPA's definition in their regulations listed at 40 CFR 230.3; these criteria can be replaced with a new one, which is that the facility should not be built in the presence of wetlands. The importance of wetlands extends beyond its physical implications to the stability of the facility, to include its cultural and natural resources weights.

2.3.6.1 Springs and Seeps

Both spring and seeps are potential means of groundwater discharge; they decrease the possible stability of the facility. While engineering of the facility could compensate for this feature, it would increase the construction cost of the facility and make it less suitable according to the ALARA model. There were two sources of spring data, both in point form from the National Hydrography Dataset (NHD). Both sources were used as the most conservative option. Areas with the presence of springs and seeps are less suitable due to the possible risk to fail to meet the performance objectives of the facility. The cell with the highest number of springs will be treated as the least suitable for this criterion. The NHD categorized both springs and seeps the same. The data are stored in R7Cr1 (Figure 28).

2.3.6.2 Swamps and Bogs

Swamps and bogs were found in polygon form from wetlands datasets. Areas with 90% to 100% coverage would not be considered suitable for the entire analysis, areas with less than

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90% were considered less suitable. Similar to the above criterion this dataset was used for two suggested criteria and a modification factor could be applied. This is unnecessary as both sets account for two criteria. The data were already stored in R4Cr1 and can be viewed in Figure 20.
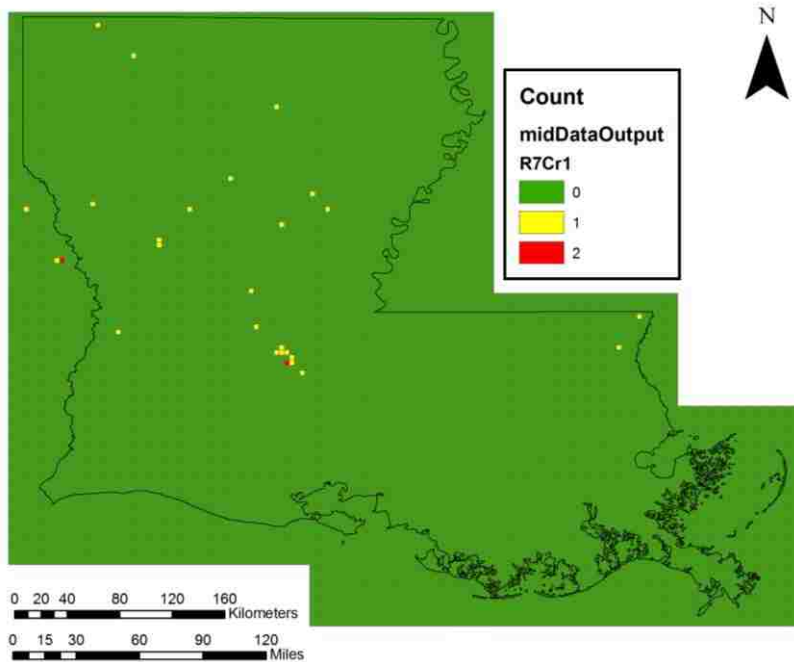
Figure 28 – Springs and Seeps throughout Louisiana. These can increase the chances of radioactive escape and should be avoided when determining where to place a facility.

2.3.7 Requirements 8 & 9

"Areas must be avoided where tectonic processes such as faulting, folding, seismic activity, or volcanism may occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives of subpart C of this part, or may preclude defensible modeling and prediction of long-term impacts. Areas must be avoided where surface geologic processes such as mass wasting, erosion, slumping, land sliding, or weathering occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives of subpart C of this part, or may preclude defensible modeling and prediction of long-term impacts. (10 CFR 61.50 Lines 9 and 10)."

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GIS again allows for many of the criteria to be analyzed without being onsite. However, some of the criteria might be characteristic of areas significantly smaller than the cell and should be revisited as a criterion to choose between the final sites.

2.3.7.1 Volcanism

Volcanism poses an obvious threat to the stability of the radioactive material in a facility. Although a storage facility could be built to withstand most natural disasters, this increases cost. Any volcanic activity should be taken into account; however Louisiana has no active volcanoes. Because of this, this criterion does not need to be analyzed for the region of interest. If the region of interest includes active or historical volcanoes a buffer should be added to the point data. This buffer can be based on likelihood or magnitude of eruption or distance. This would be then analyzed using polygon in polygon analysis similar to the method used for 100-year flood plains in Requirements 4 and 5.

2.3.7.2 Faults

Active fault lines are available from the USGS for most states. This dataset is national and can be analyzed using line to point in polygon analysis. Louisiana, Alabama, and parts of Texas are a small exception to this because of the Gulf margin normal fault. This fault line is composed of hundreds of fault lines. While there are several fault lines, the hazard is considered very low. All of Louisiana is considered "Class B." According to USGS, Class B structures have low seismic activity and threat from significant ground ruptures cannot be determined due to the ground makeup (Wheeler and Heinrich, 1998; Crone and Wheeler, 2000). Since there is low risk, this does not make any cells unsuitable for the analysis. Also, because all of Louisiana is equally

"Class B" it does not need to be evaluated for the comparison. It would add equally to all cells. This data set was used to produce the United States seismic risk shape file which can be seen in Figure 29. One can easily see how low the risk is for the Louisiana area.
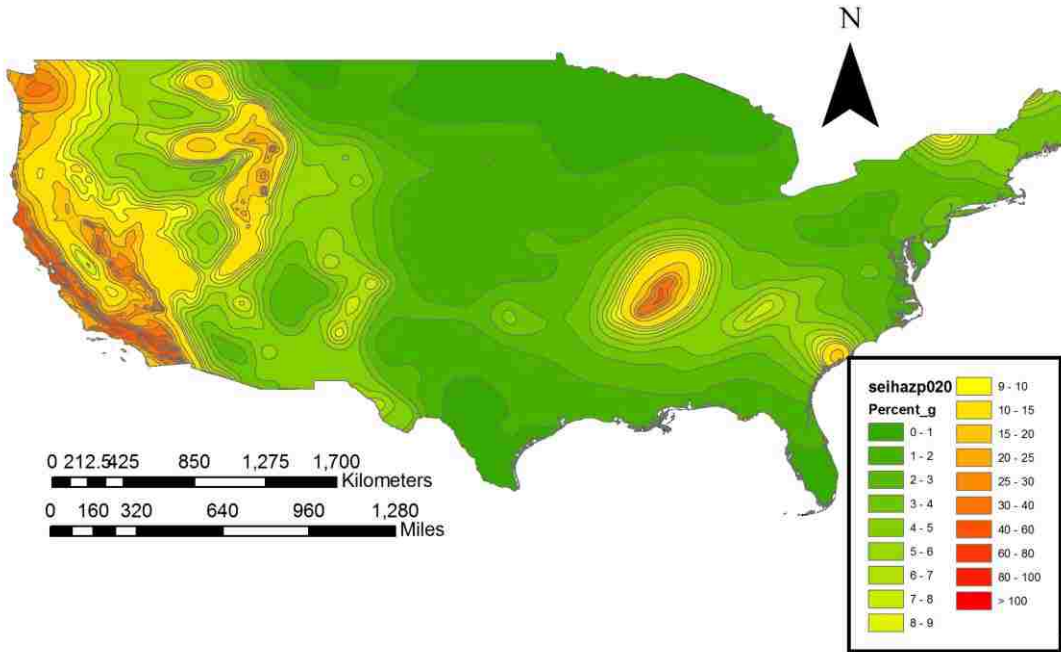
Figure 29 – USGS Seismic risk in relative percentage. Values are determined as a 10% probability in the next 50 years that an earthquake will reach the listed percentage of gravity. Louisiana is between 0-3%.

2.3.7.3. Earthquake Incidence

Earthquake incidence, like fault lines, is an important criterion to analyze due to the natural risk to the storage facility. While fault lines help with the estimation of suitability based on physical characteristics, earthquake incidence allows for a prediction based on actual occurrences. A large enough earthquake can cause significant damage to buildings that are very well built. However, if the risk is known the facility can be built to withstand it. This increases cost which causes areas of high frequency to be less suitable. Louisiana has had very few significant earthquakes. The USGS data were collected in point form and analyzed using a spatial join. The distance from the closest point was used as the representative variable. Longer

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distances from the point of the earthquake indicate more suitable cells. The data are stored in R8Cr1 and can be seen in Figure 30.
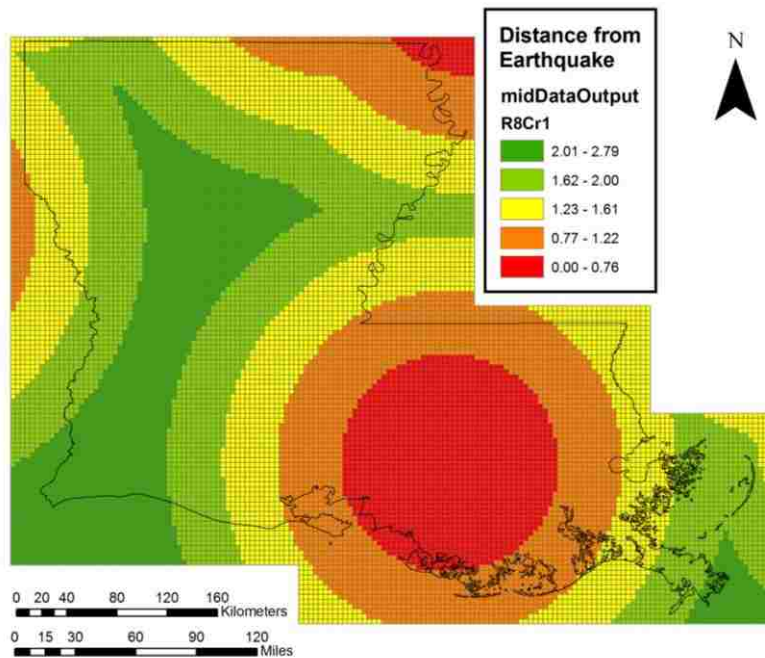
Figure 30 – Distance to closest earthquake in Louisiana.

2.3.7.4. Karst Terrain

Areas of karst terrain often indicate voids underground that can cause sink holes and disappearing streams. The danger these can pose to the storage facility is similar to earthquakes causing shifts beneath or adjacent to the facility. The data were available from USGS in polygon form and analyzed using the polygon in polygon analysis. Areas with 90-100% coverage were considered not suitable for any further analysis; this is because of the direct concern pointed out in NUREG 4.19. After areas with high coverage are removed, areas with less than 90% coverage are considered least suitable and areas with 0% coverage were considered most suitable for this criterion. The data are stored in R8Cr2 (Figure 31).
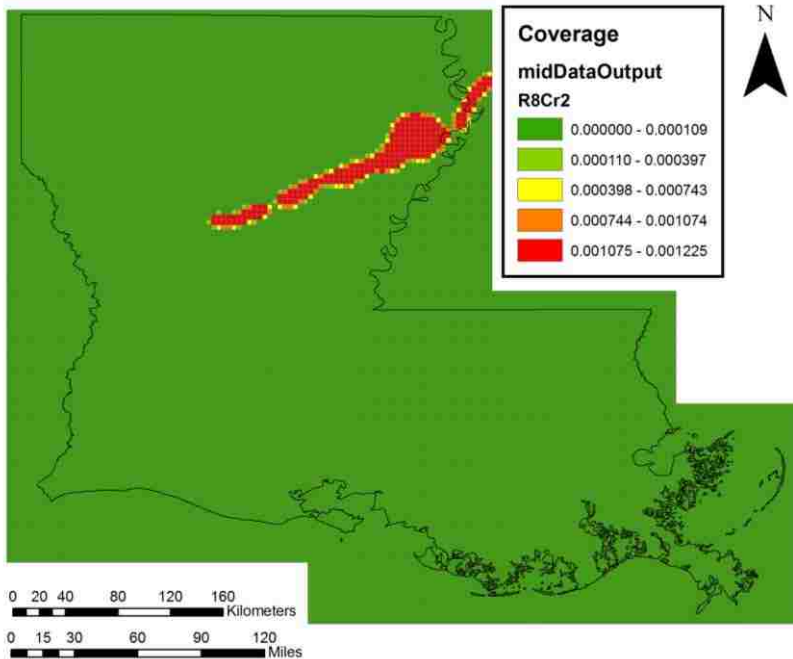
Figure 31 – Louisiana karst terrain. Areas of high coverage are unsuitable for a LLW storage facility.

2.3.8. Requirement 10

"The disposal site must not be located where nearby facilities or activities could adversely impact the ability of the site to meet the performance objectives of subpart C of this part or significantly mask the environmental monitoring program. (10 CFR 61.50 Line 11)"

NUREG 4.19 suggests that state and local land use plans should be evaluated for future uses that may impact the disposal site. As described earlier, future uses are better analyzed once the initial screening is complete. Facilities that would impact the disposal sites monitoring program are facilities that are also using radioactive materials in quantities that could pose a threat to the surrounding area. These could include power plants (both nuclear and coal), research institutions, hospitals, weapons facilities, and other facilities that use, produce, or store radioactive materials. Using GIS, coal and nuclear power plants as well as USGS resource locations that mine or use radioactive materials were compiled into one data set. These data

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points were given a buffer around them converting them into polygons. Distance from the facility could also have been used but seemed unnecessary beyond of the radius chosen. Louisiana has two nuclear power plants, River Bend Station and Waterford Stream Electric. Mississippi also has a reactor within a few kilometers of the Louisiana border. The data used included three nuclear reactors, six coal plants, and nine phosphorus mines (or occurrences). Each were given a 20 km radius buffer chosen based on the evacuation area from the Fukushima disaster (Niiler, 2012). The data were stored in R10Cr1 and were the product of the area covered by polygons and the number of polygons that intersected with the cell border. It can be viewed in Figure 32.
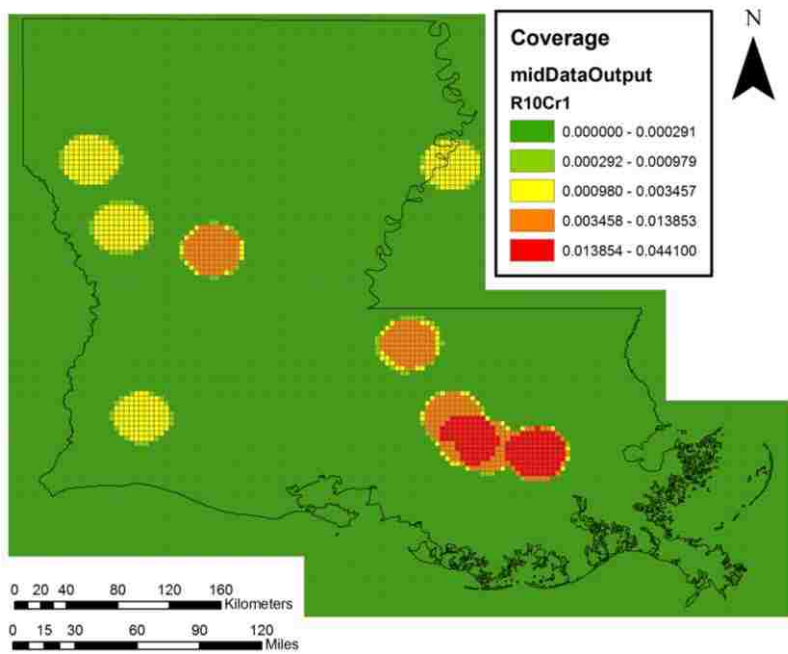
Figure 32 - Buffered locations of facilities that may affect the monitoring program for a LLW storage site.

2.3.9. Non-Mandatory Requirements

After the evaluation of the 10 requirements listed in 10 CFR 61.50, further criteria were added. These criteria were based on obvious need, discussion with experts, observance of similar facilities, additional NUREG 4.19 suggested criteria not within the 10 CFR requirements, and recent natural disasters. They were categorized into three groups: software boundary clarification, other significant (such as culturally) areas, and weather and natural disasters.

2.3.9.1. Within the Area of Interest

Due to the geometry of the grid, all areas outside of Louisiana needed to be removed. The first additional criterion is simply for software correction and is that the facility must be sited within the area of interest. The purpose of adding this requirement is to instruct the software to not include any cells outside of the area of interest since the cell grid which is originally rectangular must extend beyond the area of interest. Some cells also have area both within and outside of the region of interest. Therefore any cell that is less than 90% covered by Louisiana is considered not suitable. This criterion must be analyzed as an absolute criterion. The data are stored in RACr1 and can be viewed in Figure 33.

2.3.9.2. Other Significant Areas

When siting a facility one should also take into consideration the culturally significant areas. Failure to do this could lead to additional public resistance. For this reason, data layers were collected as a sample of some culturally significant areas that should also be analyzed. National parks were readily available in polygon form from Louisiana Department of Wildlife and Fisheries data portal (LAGIC) and were created by the National Park Service.
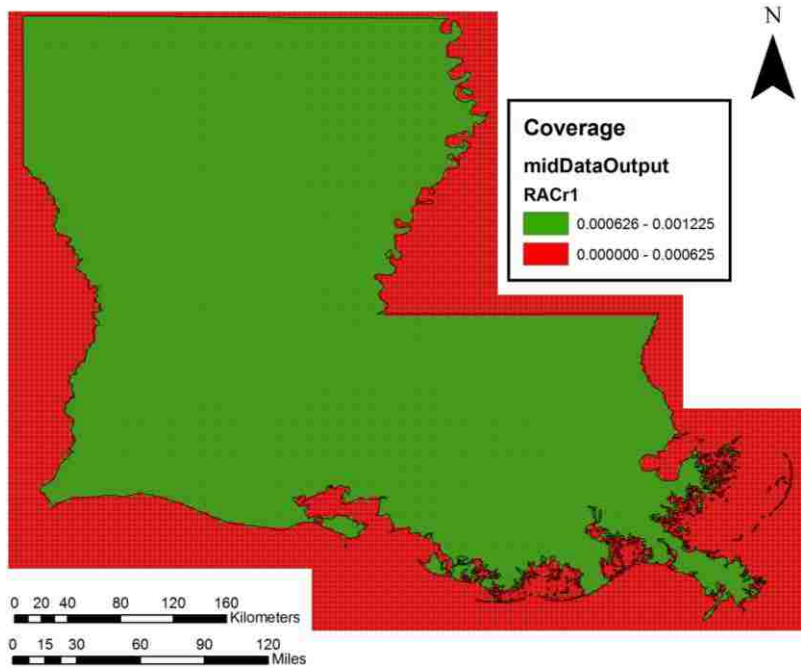
Figure 33 – Areas outside of the region of interest, but within the cell grid had to be removed from the suitability analysis.
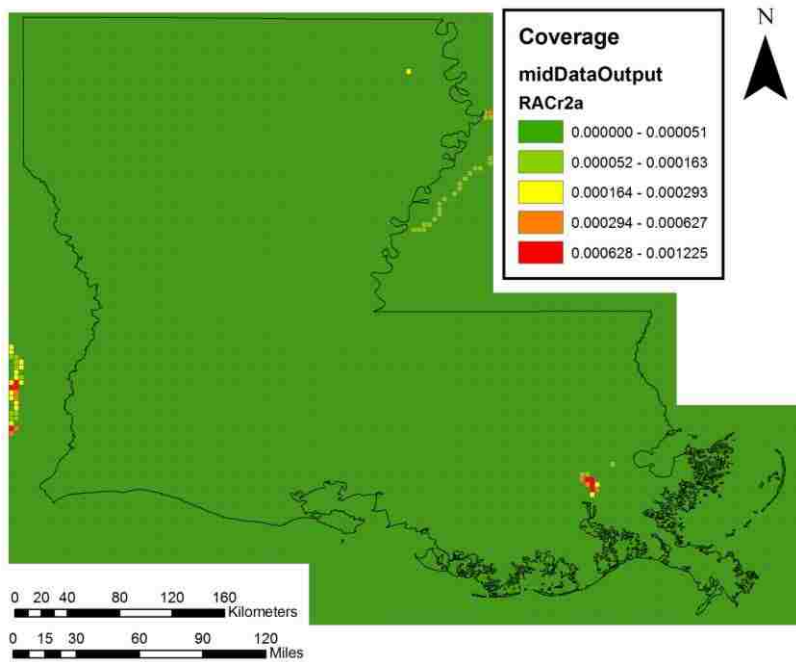
Figure 34 – National parks of Louisiana are culturally significant and lower suitability.

These were analyzed using the polygon in polygon analysis and area weighted mean. The cell value is dependent on the amount of national park coverage within the cell. When a cell is completely filled by a park it is no longer considered suitable. Anything below 90% is still considered available but 0% is viewed as most suitable. The data are stored in RACr2a and can be viewed in Figure 34.

State parks were only available in point form (LDOTD, 2007). To compensate for the actual size, a two mile radius buffer was placed around each point as a conservative estimate of its size; even if they were not two miles in diameter the increased traffic would increase the chance of random encounter. This created a polygon suitable for polygon in polygon analysis. Similar to national parks, any cell completely covered by a park is not considered suitable for analysis. Cells were considered most suitable with no coverage. The data are stored in RACr2b and can be viewed in Figure 35.
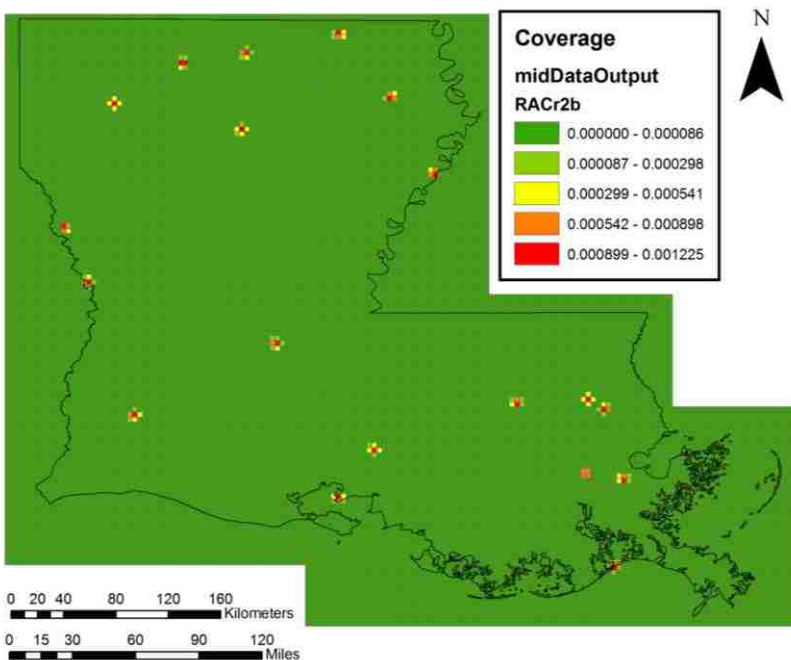
Figure 35 – State parks of Louisiana lower suitability for a LLW site. Because no polygon was available for these data, buffered points were used as a surrogate.
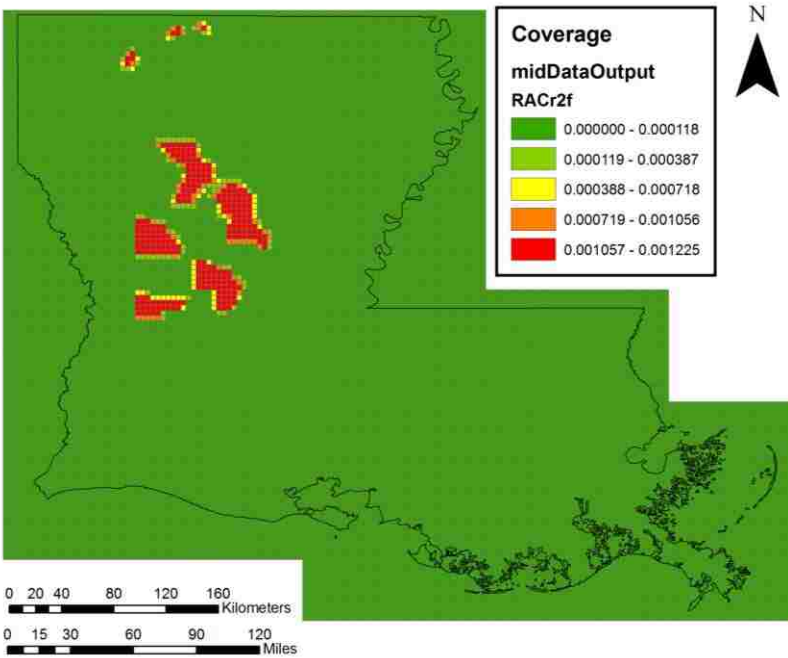
Figure 36 – National forests of Louisiana. Areas of higher coverage indicate lower suitability.

National Forest data were drawn from the United States Department of Agriculture (USDA, 1998) and were available in polygon form. The cells were analyzed using scalar analysis where the most suitable cell would have the least coverage of national forest; the resultant data are illustrated in Figure 35. Kisatchie National Forest covers a large area of Louisiana and is the main national forest of interest. The data are stored in RaCr2f (Figure 36).

Native American lands of Louisiana, when available, were taken into consideration for their cultural significance. The data were analyzed using polygon analysis where the most suitable cell would have no coverage and the least suitable has complete cell coverage. The data are stored in RACr2d and can be viewed in Figure 37.

2.3.9.3. Military Land

Military bases data were available in polygon form from LAGIC and developed by the Military Surface Deployment and Distribution Command Transportation Engineering Agency. Because the land would not be available for a storage facility, it was analyzed by polygon in polygon analysis and considered as an absolute criterion. The data are stored in "RACr4" and can be viewed in Figure 38.
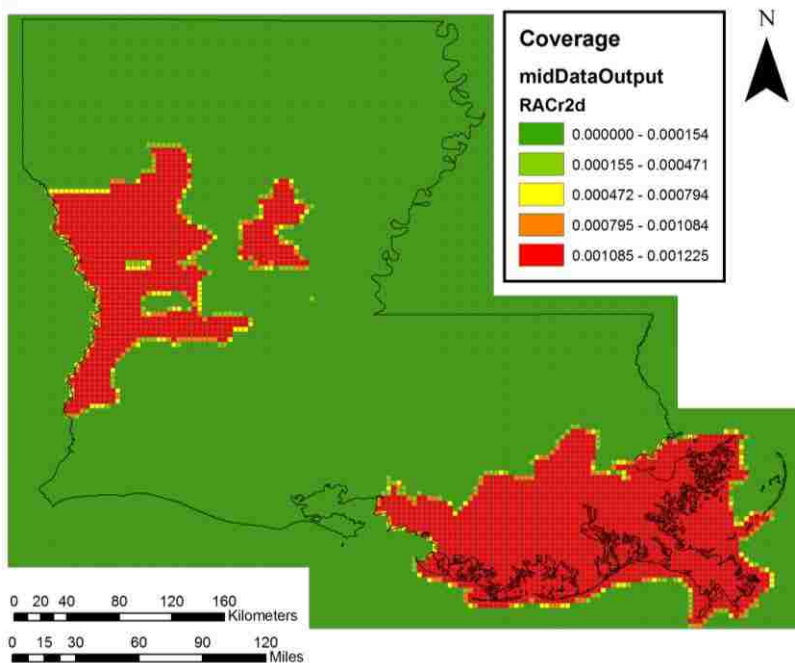
Figure 37 – Native American lands of Louisiana. These areas indicate cultural significance and lower suitability.

2.3.9.4. Wildlife Refuges

National Wildlife Refuge and Hatchery Boundaries were found from the US Fish and Wildlife Service (USFWS, 1998) in polygon form. Similar to the above requirements it is not acceptable to site a facility within a wildlife refuge. Any cell with more than 90% coverage was considered unacceptable. The data are stored in RACr2c and can be viewed in Figure 39.
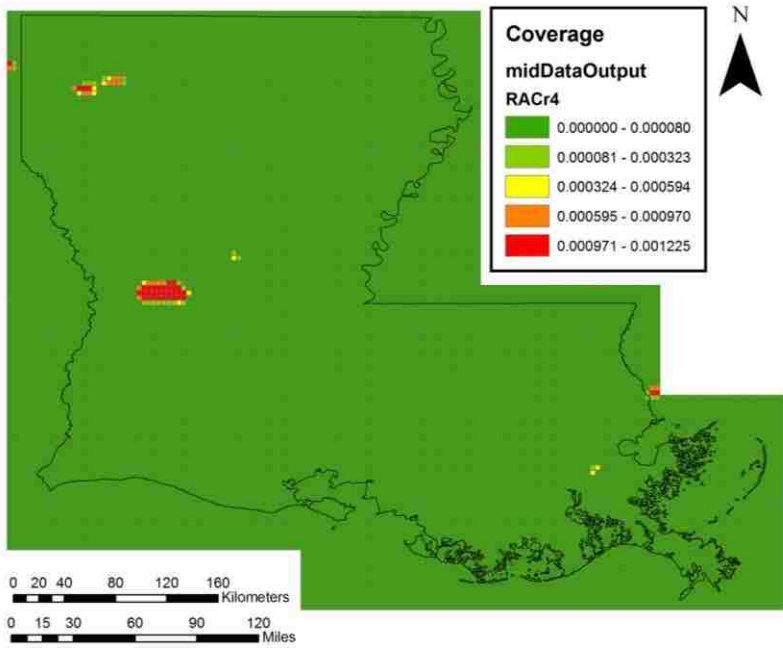
Figure 38 – Military owned land of Louisiana was considered not suitable for analysis.
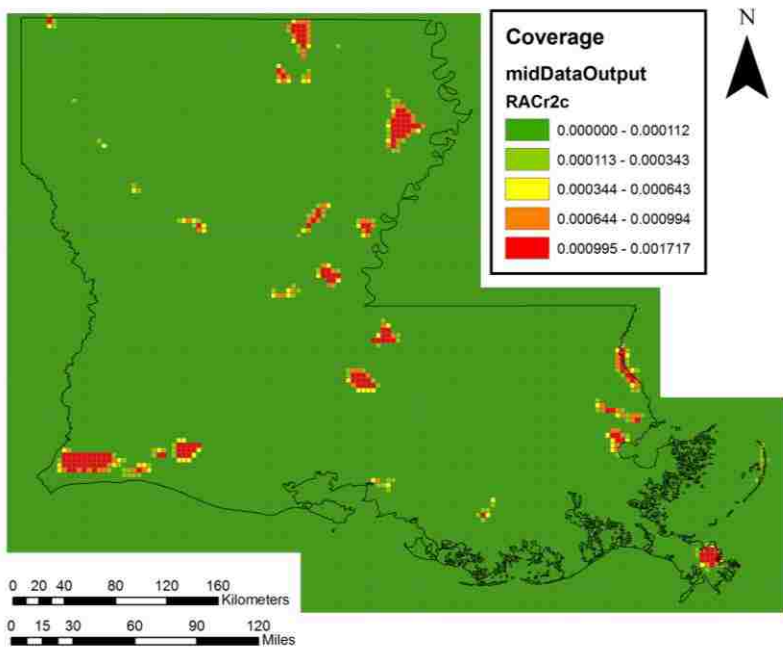
Figure 39 – Wildlife refuges throughout Louisiana are culturally significant and lower suitability.

2.3.9.5. Wildlife

Unique wildlife such as endangered species or culturally significant species should also be incorporated for this analysis. Louisiana Black Bear Breeding Areas were provided by the Louisiana Department of Wildlife and Fisheries (LDWF, 2005). These were marked as scalar criteria using polygon in polygon analysis. Areas with the most cell coverage were considered the least suitable. The data are stored in RACr2e and can be viewed in Figure 40.
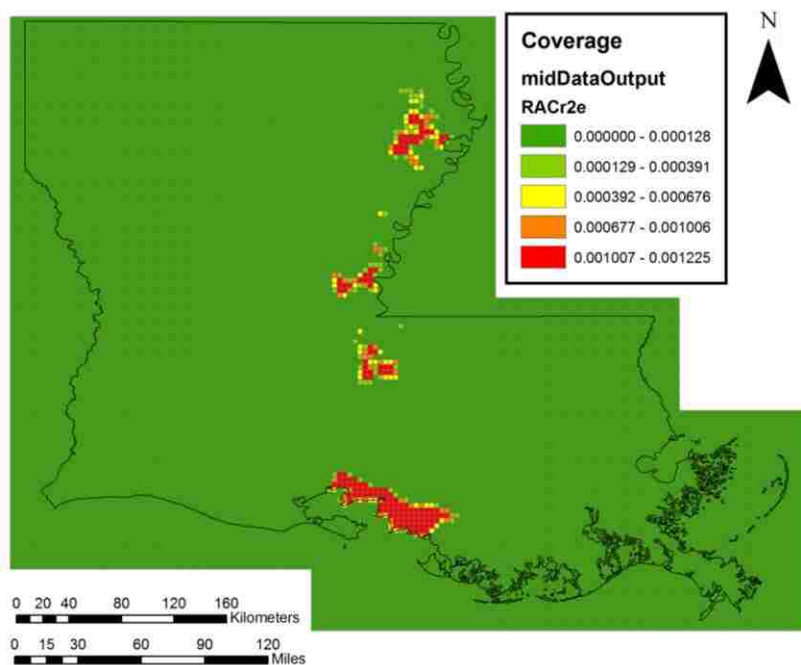
Figure 40 – Bear breeding locations in Louisiana were considered to be culturally significant and high coverage lowers suitability.

2.3.9.6. Natural Disasters

Natural disasters are additional criteria worth analyzing. After the tsunami incident in Fukushima, Japan, the dangers of natural disasters to any radioactive waste generating or storage

facility were highlighted. For this reason hurricane tracks, tornados, tsunamis, and average rainfall were analyzed.

Tornados in point form (National Atlas) were given a buffer of 5 miles. The coverage was multiplied by the count of polygons within the cell to give the suitability value. The data are stored in RACr3a and can be viewed in Figure 41.

Hurricanes were analyzed using a line buffer in polygon analysis. The area coverage was multiplied by the number of polygons within the cell to give the hurricane value. The data are stored in RACr3b and can be viewed in Figure 42.
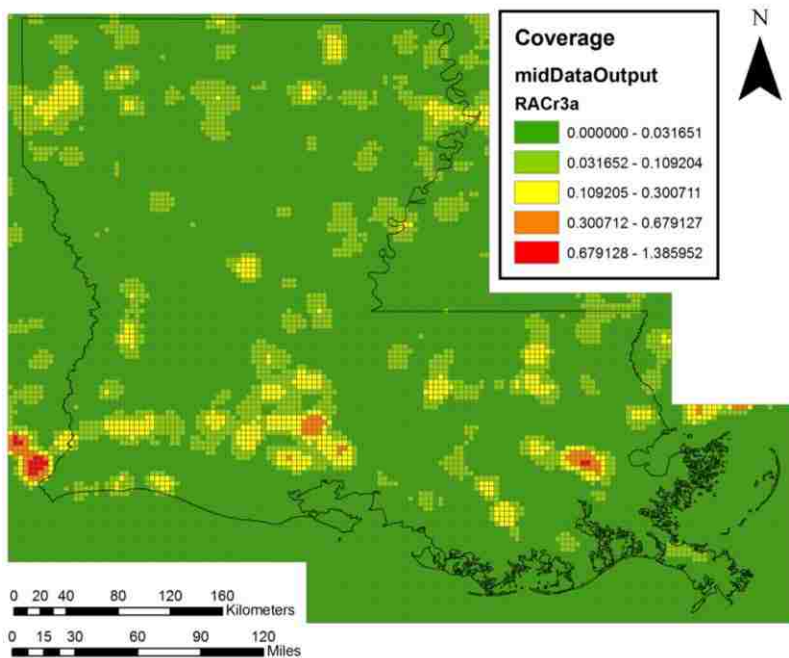
Figure 41 – The product of tornado coverage and frequency throughout Louisiana. Areas of higher coverage indicate lower suitability.

While Louisiana is a coastal state, its risk for tsunamis is minimal since there is very little tectonic activity within the region (see 2.3.7.2). While it is feasible create a data layer with

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distance from the shore, this threat is arguably negligible and should not affect the placement of a storage facility.
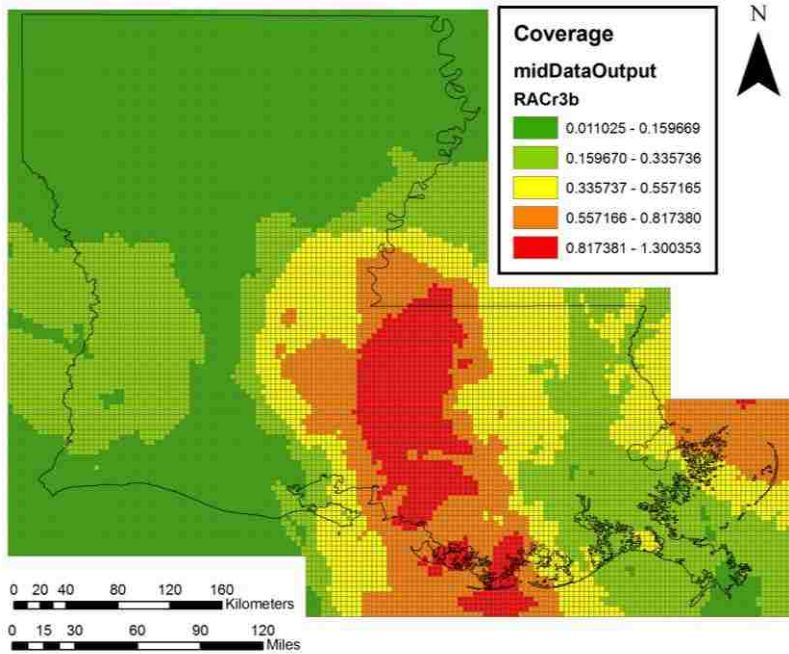
Figure 42 – Product of Hurricane coverage and frequency throughout Louisiana. Areas of higher coverage indicate lower suitability.

Average rainfall was a suggested criterion within the NUREG. An increase in water when not properly accounted for with engineering barriers can decrease the stability of the facility. Because normal precipitation caused issues in previous (now closed) storage sites, areas were analyzed based on the polygon data available (National Atlas); the higher the average rainfall within a cell the lower the suitability for a LLW storage site. The data are stored in RACr3c Figure 43.

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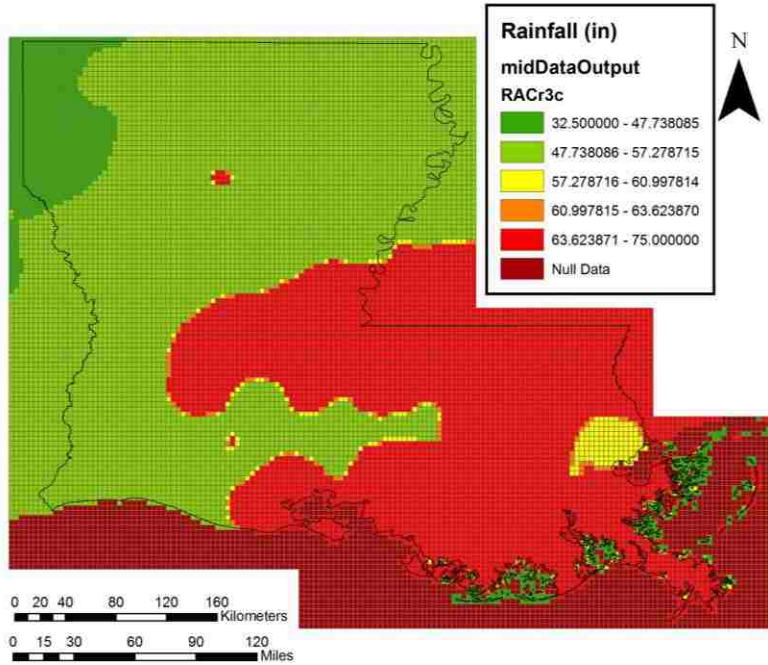
Figure 43 – Precipitation in Louisiana. Due to study of previous facilities, increased precipitation lowers sit suitability.

CHAPTER 3 RESULTS

Each requirement was analyzed separately to produce individual maps for suitability study using individual criteria data from Chapter 2. To analyze each requirement null values (typically indicated as -999) had to be removed. The final map that resulted from all requirements and additional criteria was generated. If any cell received a suitability of "-1" for any criterion, it was removed from the final analysis. The value 0.001225 square decimal degrees represent full coverage of a cell and appears often within the formulas. Suitability for each requirement is expressed on a relative scale with 0 as completely unsuitable and 1 as completely suitable.

3.1. Results

3.1.1. Requirement 1 Results

For the first requirement, geologic and hydrologic complexities were equally weighted. This resulted in the two criteria that analyzed hydrologic complexity needing a modification factor of ½ each. The result was stored in column R1F and can be seen in Figure 44. No cells were removed from the final analysis due to this requirement. Modification factors were necessary for the two criteria used as surrogates for hydrological complexity.

Requirement 1 variables were:

$R1F_{i,j}$ – Requirement 1 Final Suitability for cell i,j

0.60509 – Least Suitable cell value for Requirement 1 Criterion 1 from R1Cr1

0 – Most suitable cell value for Requirement 1 Criteria 1, 2, and 3 from R1Cr1, R1Cr2a, and R1Cr2b

1152 – Least suitable cell value for Requirement 1 Criterion 2 from R1Cr2a

9.45486 – Least suitable cell value for Requirement 1 Criterion 3 from R1Cr2b

R1Cr1 – Average curvature

R1Cr2a – Number of wells

R1Cr2b – Length of water bodies

The Requirement 1 cell suitability formula was:

$$R1F_{i,j} = \frac{\dfrac{R1Cr1 - 0.60509}{0 - 0.60509} + \dfrac{1}{2}\dfrac{R1Cr2a - 1152}{0 - 1152} + \dfrac{1}{2}\dfrac{R1Cr2b - 9.45486}{0 - 9.45486}}{2}$$

All unspecified values and variables in the remaining requirements were analogous to the above

description.

Figure 44 – Requirement 1 suitability. A value of 1 indicates complete suitability while 0
represents complete unsuitability.

3.1.2. Requirement 2 Results

The second requirement was criteria measuring population by different means. The result

was stored in column R2F and can be seen in Figure 45. 1397 cells were concluded not suitable

for the final analysis. No modification factors were necessary for this requirement.

Requirement 2 variables were:

R2Cr1 – Population by parish

R2Cr2 – Population density by parish

R2Cr3 – Population growth by parish

R2Cr4 – High population density structure data

R2Cr5 – Road length

The Requirement 2 cell suitability formula was:

$$if\ R2Cr4 > 2\%\ 0.001225\ then\ R2F_{i,j}\ suitability = -1$$

$$else\ R2F_{i,j} = \frac{\left(\left(\frac{R2Cr1b - 444049}{0 - 444049}\right) + \left(\frac{R2Cr2 - 1878}{0 - 1878}\right) + \left(\frac{R2Cr3 - 35.55}{-39.31 - 35.542}\right) + \left(\frac{R2Cr5 - 0}{2.90343 - 0}\right)\right)}{4}$$

Figure 45 - Requirement 2 suitability. A value of 1 indicates complete suitability while 0 represents complete unsuitability.

3.1.3. Requirement 3 Results

Requirement 3 concerned the resources of the region of interest. Its complexities due to the categories were equally accounted for with modification factors according to topic. The result was stored in column R3F and can be seen in Figure 46. No cells were removed from the analysis. Modification factors of ½ for peat and lignite, $\frac{1}{6}$ for the two oil and gas datasets and $\frac{1}{3}$ for the oil and gas data were necessary for each of the sub-categories of fuel. Requirement 3 variables were:

R3Cr1 – Metallic and non-metallic minerals and ores

R3Cr2a – Fuels peat

R3Cr2b – Fuels lignite

R3Cr3a – Oil and gas point data

R3Cr3b – Oil and gas polygon data

R3Cr3c – Shale plays

R3Cr3d – Geothermal potential

R3Cr4 – Agricultural resources percent land covered area by crops

The Requirement 3 cell suitability formula was:

$$R3F_{i,j} = \left(\left(\frac{R3Cr1 - 12}{0 - 12} \right) + \left[\left(\frac{1}{2} \right) \left(\frac{R3Cr2a - 0.001225}{0 - 0.001225} \right) + \left(\frac{1}{2} \right) \left(\frac{R3Cr2b - 0.001225}{0 - 0.001225} \right) \right] \right.$$

$$+ \left[\left(\frac{1}{6} \right) \left(\frac{R3Cr3a - 1934}{0 - 1934} \right) + \left(\frac{1}{6} \right) \left(\frac{R3Cr3b - 0.002457}{0 - 0.002457} \right) + \left(\frac{1}{3} \right) \left(\frac{R3Cr3c - 0.001225}{0 - 0.001225} \right) \right.$$

$$+ \left(\frac{1}{3} \right) \left(\frac{R3Cr3d - 8}{0 - 8} \right) \right] + \left(\frac{R3Cr4 - 87.65}{0 - 87.65} \right) \right) \left(\frac{1}{4} \right)$$

Figure 46 - Requirement 3 suitability. A value of 1 indicates complete suitability while 0 represents complete unsuitability.

3.1.4. Requirements 4 & 5 Results

Requirements 4 and 5 regarded flooding and water risk were confounded due to the incomplete flood zone data. The data can be seen in Figure 47. 2861 cells were removed from the final analysis due to these requirements. A modification factor was necessary for the slope data since it was used as a surrogate for a second criterion regarding runoff. A second modification was also necessary to fix the relationship between X and X500 data. Requirements 4 and 5 variables were:

R4Cr1 – Wetlands

R4Cr1A – Zone A flood zone coverage

R4Cr1X – Zone X flood zone coverage

R4Cr1X5 – Zone X500 flood zone coverage

R4Cr2 – Average slope

R1Cr1 – Geological simplicity

The Requirements 4 and 5 suitability formula was :

If $R4Cr1 > 0.9 * 0.01225\ OR\ R4Cr1A > 0.75 * 0.01225\ then\ R45F_{i,j} = -1$

else if $R4Cr1A + R4Cr1X + R4Cr1X5 > 0.01225 * 0.95\ then$:

(If the sum of the three flood zone coverage's was equal to 95% of the total area of a cell it was

considered to have enough data to analyze it including flood zone data)

$$R45F_{i,j} = \left(\left(\frac{R4Cr1 - 0.00217}{0 - 0.00217} \right) + \left[\left(\frac{R4Cr1X - 0}{0.001225 - 0} \right) + \left(\frac{R4Cr1X5 - 0}{0.001225 - 0} \right) * 0.5 \right] + (2) \left(\frac{R4Cr2 - 91.24}{0 - 91.24} \right) \right.$$

$$\left. + \left(\frac{R1Cr1 - 0.60509}{0 - 0.60509} \right) \right) \left(\frac{1}{5} \right)$$

$$Else: R45F_{i,j} = \frac{\left(\left(\frac{R4Cr1 - 0.00217}{0 - 0.00217} \right) + (2) \left(\frac{R4Cr2 - 91.24}{0 - 91.24} \right) + \left(\frac{R1Cr1 - 0.60509}{0 - 0.60509} \right) \right)}{4}$$
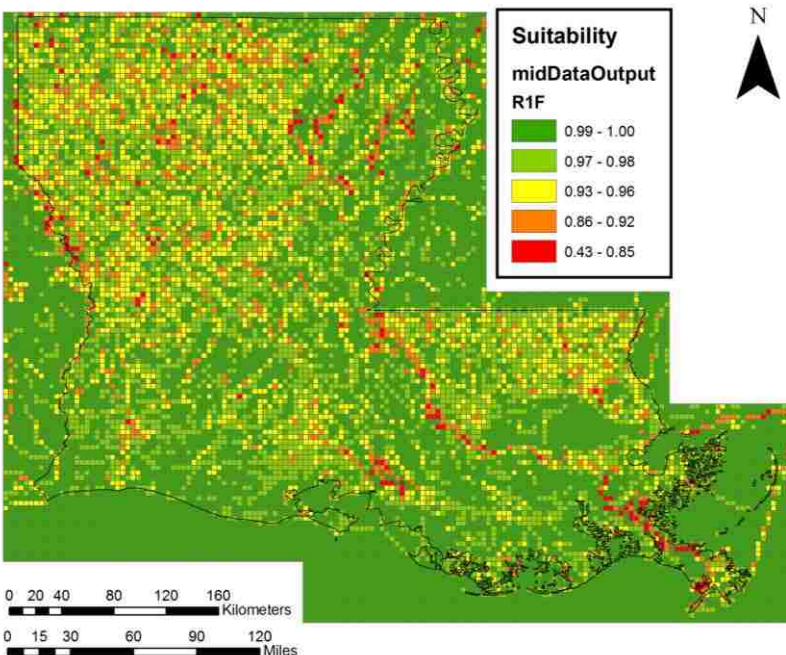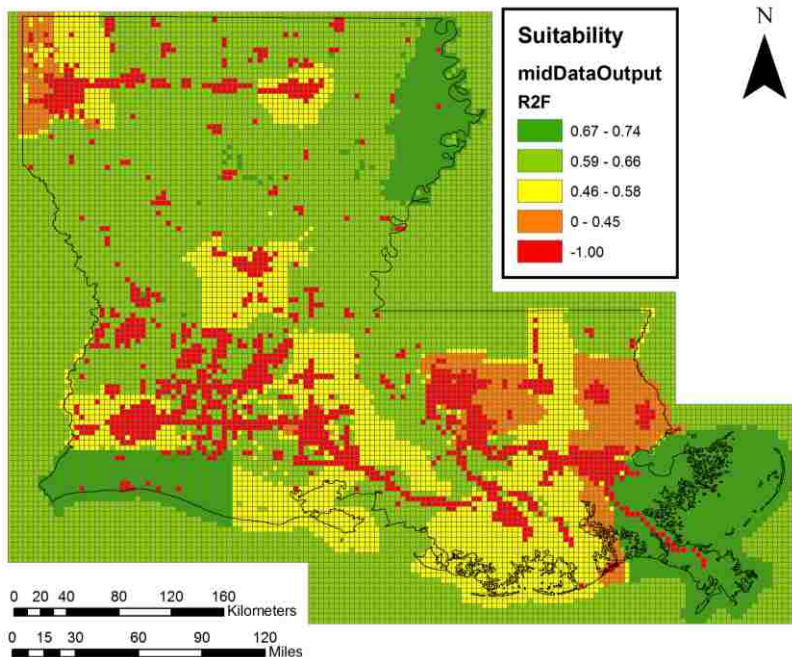

Figure 47 – Requirements 4 and 5 suitability. A value of 1 indicates complete suitability while 0 represents complete unsuitability.

3.1.5. Requirement 6 Results

Similar to requirements 4 and 5, requirement 6 focused on effects of water with a focus on the water table. The result was stored in column R6F and can be seen in Figure 48. 846 cells were removed from the final analysis. No modification factors were necessary for this requirement.

Requirement 6 variables were:

R6Cr1 – Surface water

R1Cr2b – Water body length

R6Cr3 – Well depth

R6Cr4 – Majority elevation

The Requirement 6 suitability formula was:

$$\text{If R6Cr1} > 0.9 * 0.01225 \; then \; R6F_{i,j} = -1$$

$$else \; R6F_{i,j} = \left(\frac{\left(\frac{R6Cr1 - 0.001225}{0 - 0.001225} \right) + \left(\frac{R2Cr2b - 9.455}{0 - 9.455} \right) + \left(\frac{R6Cr3 - -67.3}{0 - -67.3} \right) + \left(\frac{R6Cr4 - -7}{0 - -7} \right)}{4} \right)$$

3.1.6. Requirement 7 Results

Similar to requirements 4, 5, and 6, requirements 7 focused on effects of water, but was concerned with surface discharge. The result was stored in column R7F and can be seen in Figure 49. No cells were removed from the final analysis. No modification factors were necessary for this requirement.

Requirement 7 variables were:

R4Cr1 – Wetlands (Swamps and Bogs)

R7Cr1 – Springs and Seeps

Figure 48- Requirement 6 suitability. A value of 1 indicates complete suitability while 0 represents complete unsuitability.
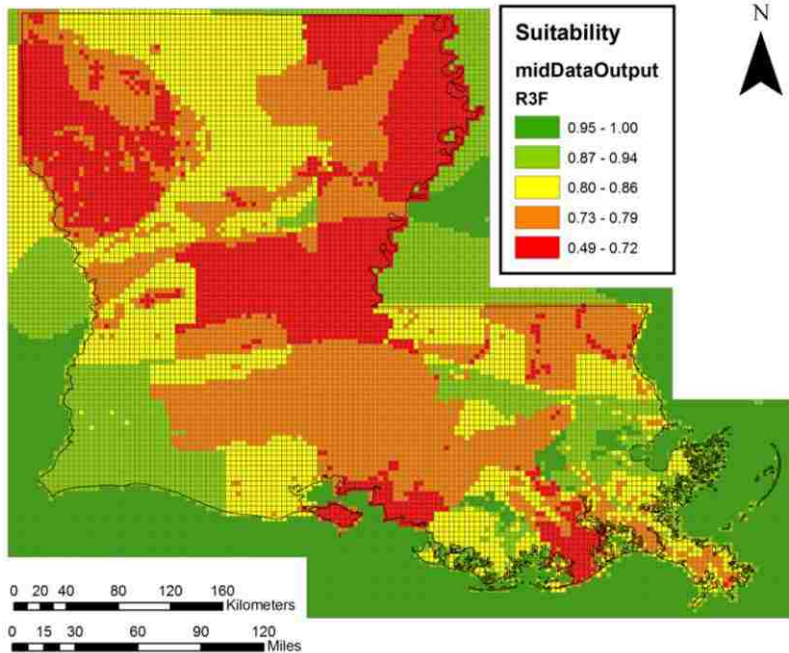

Figure 49- Requirement 7 suitability. A value of 1 indicates complete suitability while 0 represents complete unsuitability.

The Requirement 7 suitability formula was:

$$R7F_{i,j} = \left(\frac{\left(\frac{R4Cr1 - 0.00217}{0 - 0.00217} \right) + \left(\frac{R7Cr1 - 2}{0 - 2} \right)}{2} \right)$$

3.1.7. Requirements 8 & 9 Results

Requirements 8 and 9 concerned tectonic activity and stability of the site chosen. The result was stored in column R89F and can be seen in Figure 50. 192 cells were removed from the final analysis. No modification factors were necessary for this requirement.

Requirements 8 and 9 variables were:

R8Cr1 – Distance from Earthquake

R8Cr2 – Karst Terrain

Requirements 8 and 9 suitability formula was:

$$if \, R8Cr2 > 90\% \, 0.001225 \, then \;\; R89F_{i,j} \; suitability = -1$$

$$else \, R89F_{i,j} = \left(\frac{\left(\frac{R8Cr1 - 0}{2.795 - 0} \right) + \left(\frac{R8Cr2 - 0.001225}{0 - 0.001225} \right)}{2} \right)$$

3.1.8. Requirement 10 Results

Requirement 10 focused on minimizing the possible difficulties within the monitoring program. The result was stored in column R10F and can be seen in figure 51. No cells were removed from the final analysis. No modification factors were necessary for this requirement.
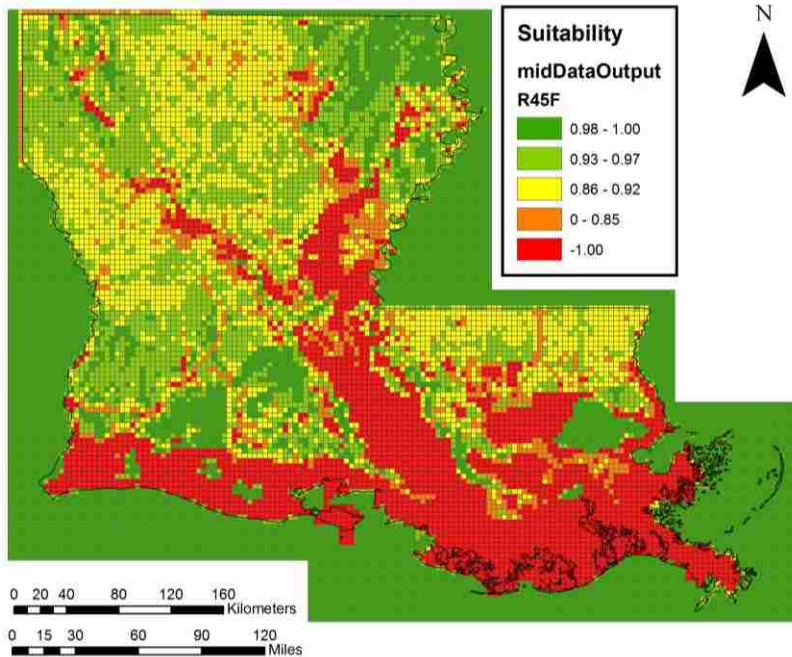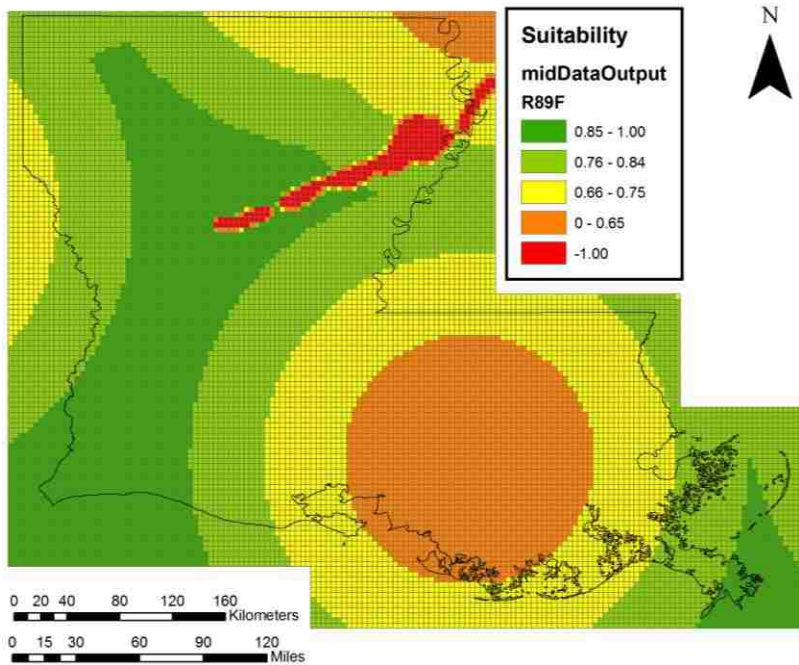
Figure 50 – Requirements 8 and 9 suitability. A value of 1 indicates complete suitability while 0 represents complete unsuitability.
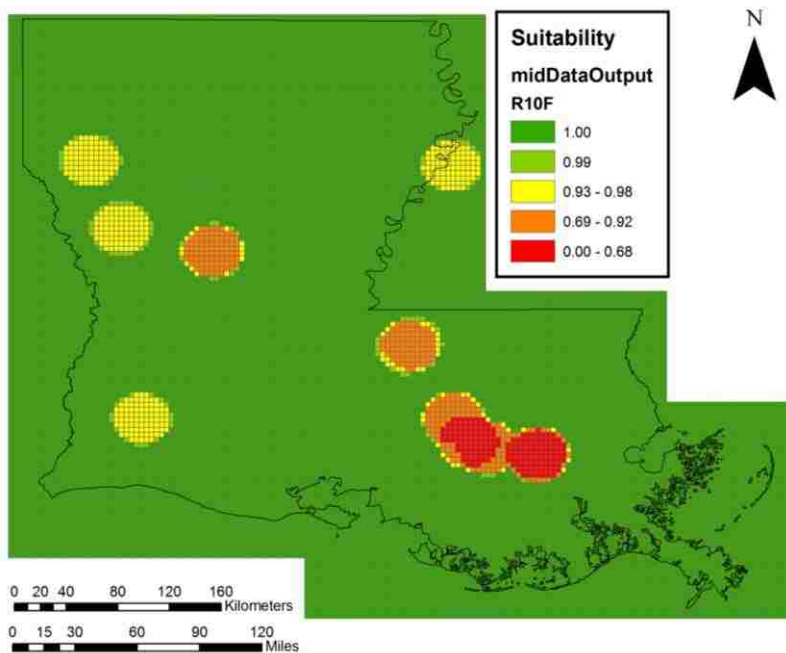
Figure 51 - Requirement 10 suitability. A value of 1 indicates complete suitability while 0 represents complete unsuitability.

Requirement 10 variable was:

R10Cr1 – Buffered point data for radiation risk facilities

Requirement 10 suitability formula was:

$$R10F_{i,j} = \left(\frac{R10Cr1 - 0.0441}{0 - 0.0441} \right)$$

3.1.9. Non-Mandatory Requirement 1 Results

The first non-mandatory requirement was to remove cells outside of the region of interest. 5161 cells were removed from the final analysis. No modification factors were necessary for this requirement.

Requirement A1 variable was:

RACr1 – Louisiana coverage

Requirement A1 suitability formula was:

$$if\, R10Cr1 < 90\%\, 0.001225\, then\,\, RA1F_{i,j}\, suitability = -1$$

No additional formula was necessary.

3.1.10. Non-Mandatory Requirement 2 Results

The second additional requirement concerned culturally significant and other areas of interest. The result was stored in column RA2F and can be seen in Figure 53. 169 cells were removed from the final analysis. No modification factors were necessary for this requirement.

Requirements A2 variables were:

RACr2a– National parks

RACr2b – State parks

RACr2c – Wildlife refuge

RACr2d – Native American land

RACr2e – Bear breeding populations

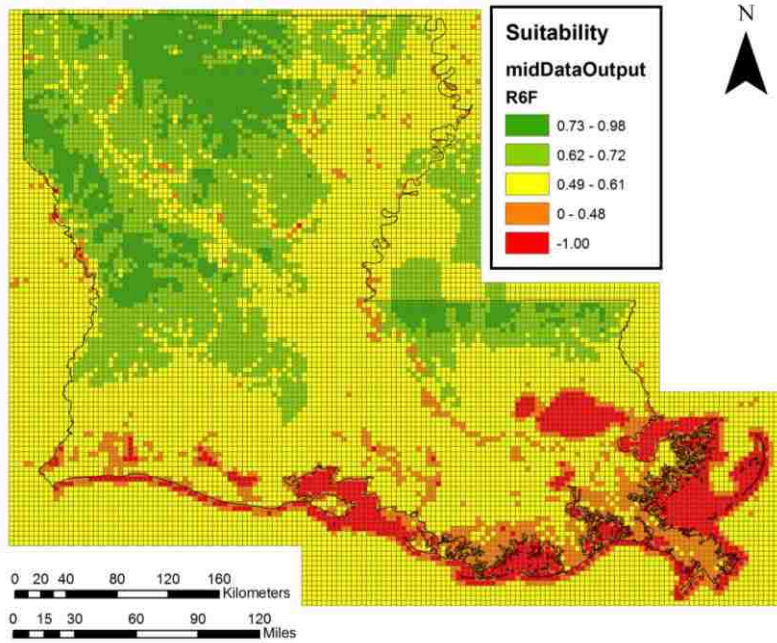*RACr2f – National Forests*

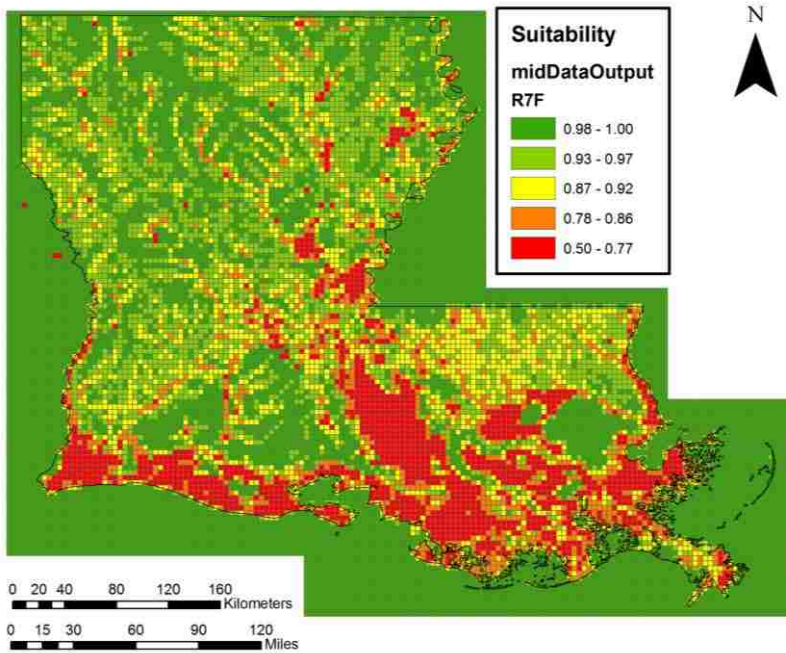*RACr4 – Military Land*
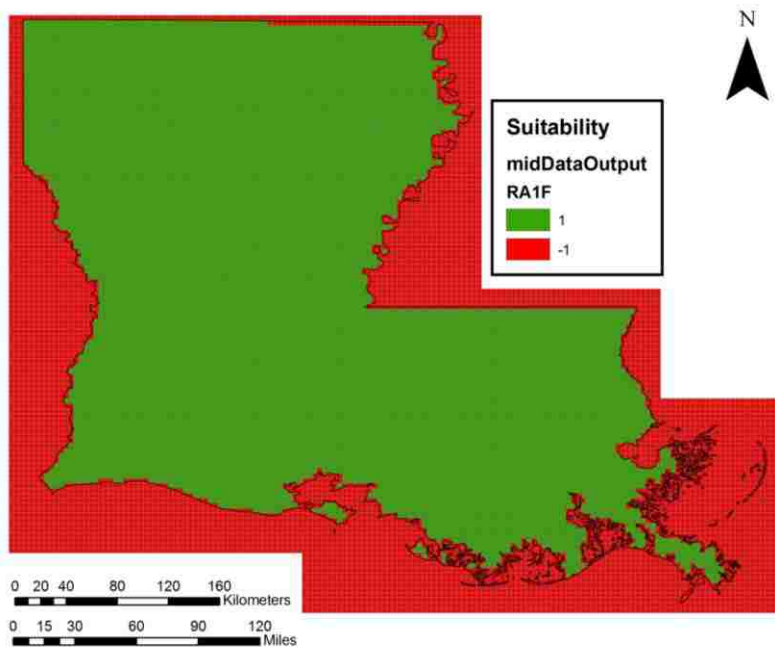
Figure 52 – Additional requirement category 1 suitability. A value of 1 indicates complete suitability while 0 represents complete unsuitability.

The Requirements A2 suitability formula was:

$$if\ RACr2a, RACr2b, RACr2c, or\ RACr4 > 90\%\ 0.001225\ than\ RA2F_{i,j}\ suitability = -1$$

$$RA2F_{i,j} = \left(\left(\frac{RACr2a - 0.001225}{0 - 0.001225} \right) + \left(\frac{RACr2b - 0.001225}{0 - 0.001225} \right) + \left(\frac{RACr2c - 0.001717}{0 - 0.001717} \right) \right.$$

$$+ \left(\frac{RACr2d - 0.001225}{0 - 0.001225} \right) + \left(\frac{RACr2e - 0.001225}{0 - 0.001225} \right) + \left(\frac{RACr2f - 0.001225}{0 - 0.001225} \right)$$

$$\left. + \left(\frac{RACr4 - 0.001225}{0 - 0.001225} \right) \right) \left(\frac{1}{7} \right)$$
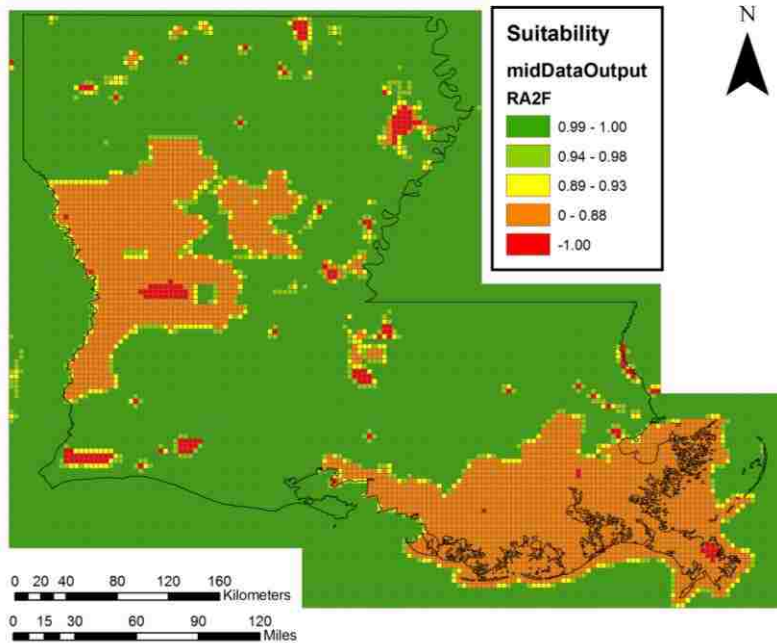
Figure 53 - Additional requirement category 2 suitability. A value of 1 indicates complete suitability while 0 represents complete unsuitability.

3.1.11. Non-Mandatory Requirement 3 Results

The third additional requirement concerned weather and weather disasters. The result was stored in column RA3F and can be seen in Figure 54. No cells were removed from the final analysis. No modification factors were necessary for this requirement.

Requirements A2 variables were:

RACr3a– Tornados

RACr3b – Hurricanes

RACr3c – Annual Precipitation

Requirements A3 suitability formula was:

$$RA3F_{i,j} = \frac{\left(\left(\frac{RACr3a - 1.386}{0 - 1.386}\right) + \left(\frac{RACr3b - 1.3}{0 - 1.3}\right) + \left(\frac{RACr3c - 75}{0 - 75}\right)\right)}{3}$$
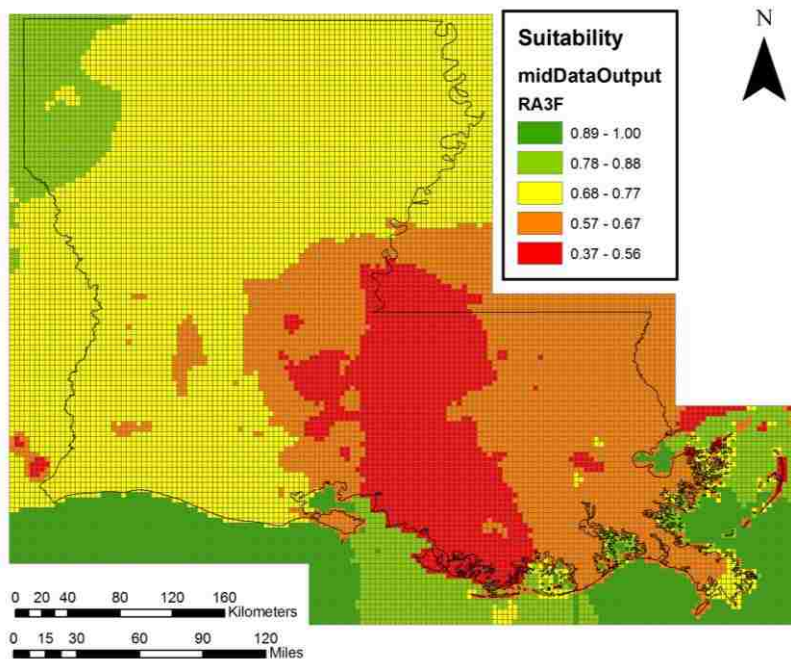
Figure 54 - Additional requirement category 3 suitability. A value of 1 indicates complete suitability while 0 represents complete unsuitability.

3.1.12. Final Suitability

The final cell suitability initially contained an "if" statement to check for any criterion with a given value of -1. If one did, then Final Suitability for that cell is = -1. If no criteria contained a valuable of -1 it was calculated as follows:

$$SuitaF_{i,j} = \frac{(R1F + R2F + R3F + 2 * R45F + R6F + R7F + 2 * R89F + R10F + RA2F + RA3F)}{12}$$

Because of the method of removing cells, the data were concentrated between 60 and 90 percent

suitable. The data were then normalized by using the original formula.

$$NSuitaF_{i,j} = \left(\frac{SuitaF - 0.66}{0.90 - 0.66} \right)$$

The range of values was between 0.66 and 0.9. For the normalized suitability, 0.66 is the least

suitable, and 0.9 is the most suitable. The final normalized map can be seen in Figure 55 and

transposed over satellite imagery in Figure 56 and the largest suitable area is enlarged in Figure

57.
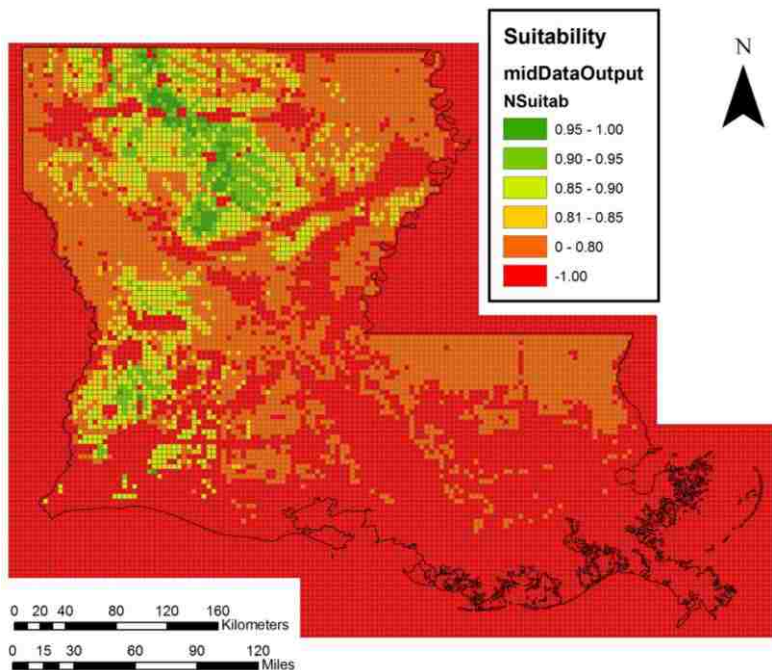
Figure 55 – Normalized final suitability for Louisiana. A value of 1 indicates complete suitability while 0 represents complete unsuitability.
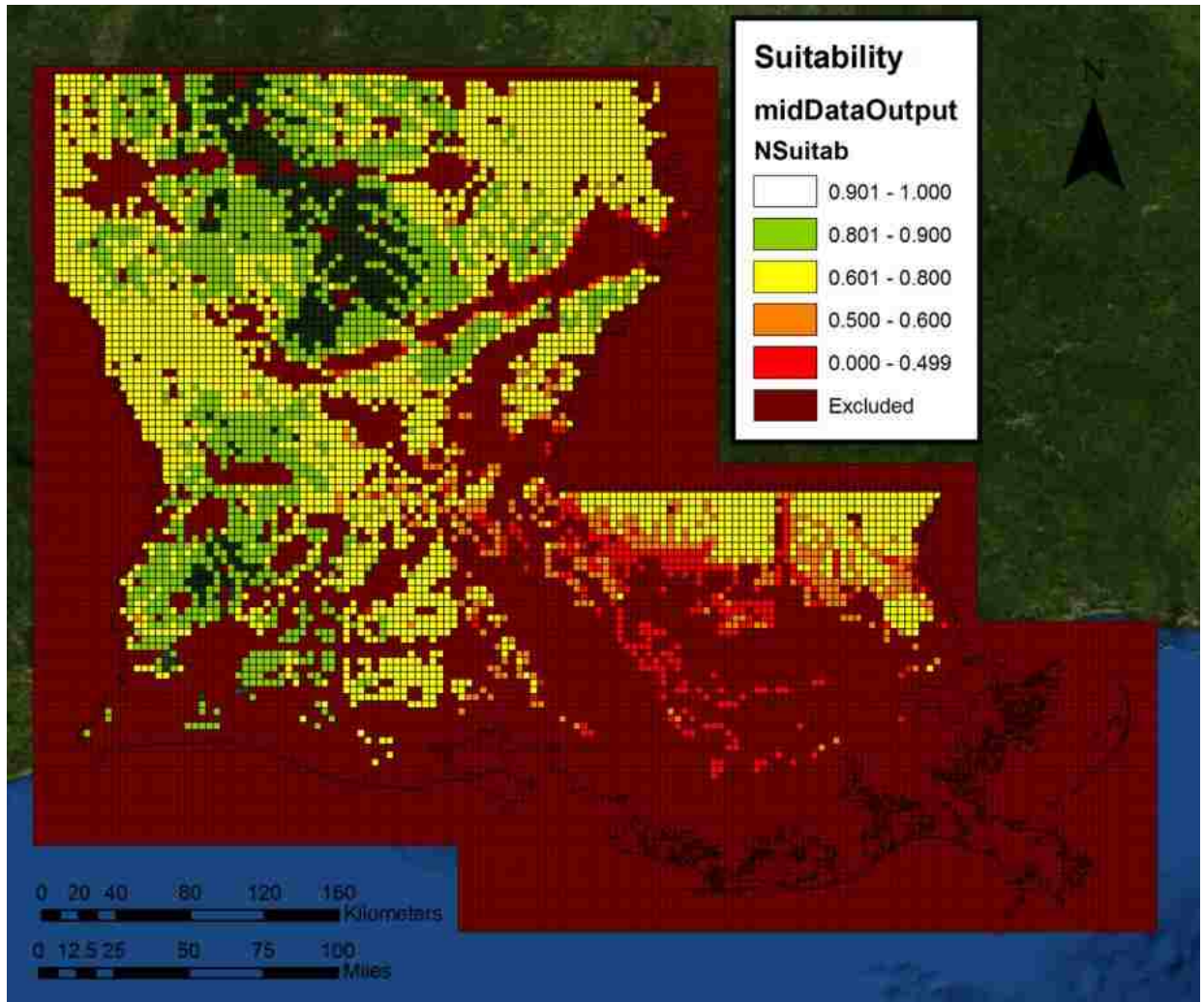
Figure 56 – Normalized final suitability for Louisiana over satellite imagery. The top 10% are transparent to see the satellite imagery below. A value of 1 indicates complete suitability while 0 represents complete unsuitability.
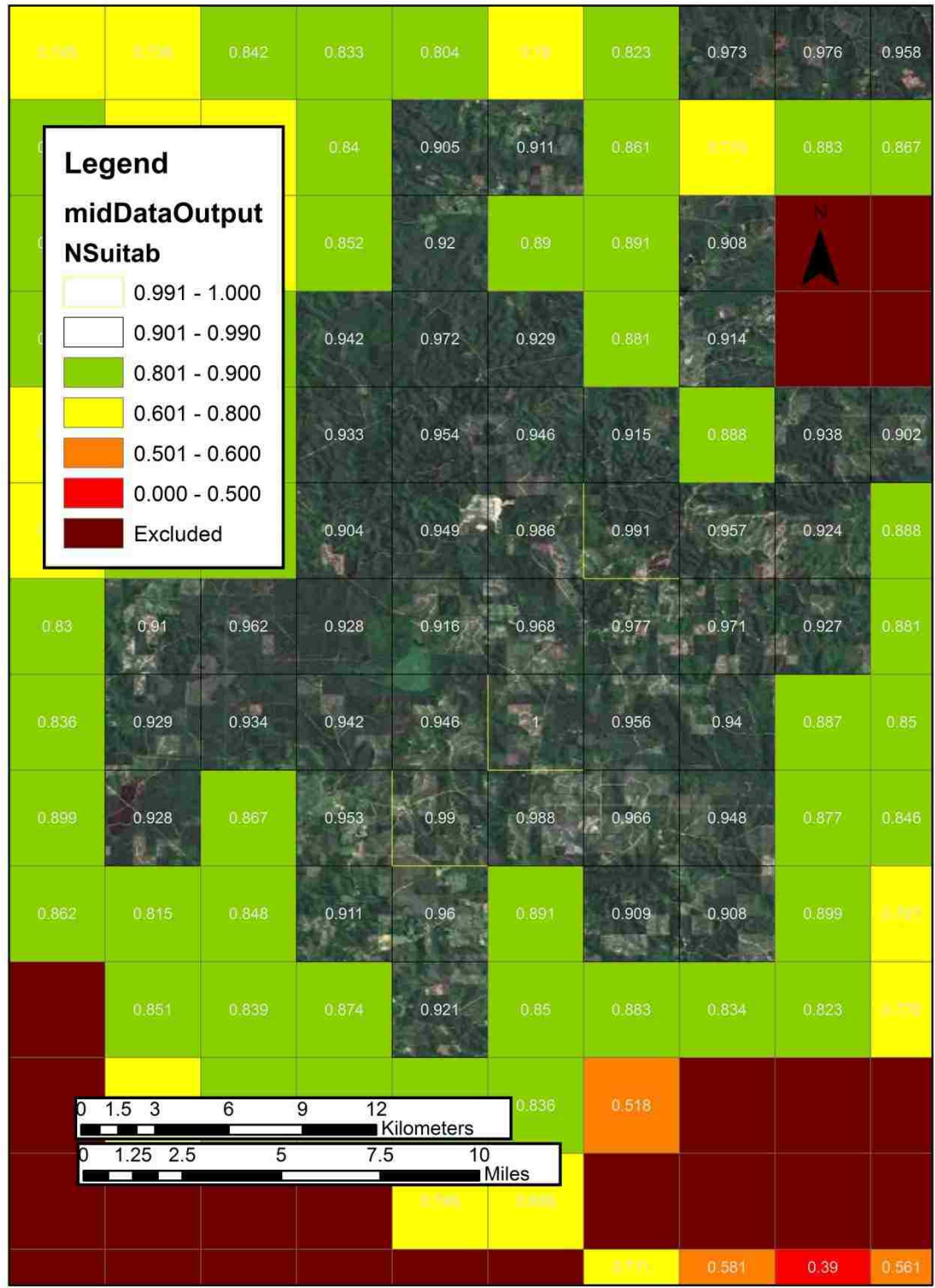
Figure 57 – Normalized final suitability for the highest potential region in Louisiana over satellite imagery. The top 10% are transparent to see the satellite imagery below. The top 3 cells are transparent with a yellow border. The normalized suitability is also shown for each cell not excluded.

CHAPTER 4 DISCUSSION AND CONCLUSION

The NRC sets initial guidelines for site selection that provide a good framework, and allows for adopting additional criteria. Furthermore, a set method of analysis would be ideal in attempting to compare all possible locations equally. The requirements provided are described as the minimum requirements and therefore it may be considered the responsibility of the investigator to include additional criteria as they see fit.

This is a pilot design for a robust, GIS based investigation of site suitability for LLW storage facilities. While similar attempts have been unsuccessful in the past, the purpose of this project is to set a framework where requirements and criteria can be equally and simultaneously compared across an entire region of interest using cells of appropriate size across a range of sizes of areas. It is difficult for all required criteria to be analyzed on a large scale using computer software primarily because of lack of data; however, the majority of the requirements can be analyzed or at least approximated. Scales previously used for GIS did not easily convey what areas were suitable and why, and weighting factors were not clear to the general public. A suitability method such as the one presented in this study uses a normalized 0-100% scale that can easily be interpreted even with little knowledge of the data. With this model, weighting factors can be added if proven to be scientifically sound and still maintain the percentage based scale.

As it relates to the application to Louisiana, this analysis found several cells suitable for further evaluation. Parishes Winn, Jackson, Claiborne, Lincoln, Bienville, Webster, Grant, Caldwell, Vernon, and Beauregard all have more than 4 cells within the parish that are above 90% suitable (after being normalized). This investigation should be refined once the new DFIRMS are released. Parishes with more than 4 cells that are 95% normalized suitable are

Winn, Jackson, Bienville, Lincoln and Claiborne, with the 99% normalized suitability cells within Winn and Claiborne parishes. The next steps besides further investigation should include social-cultural impacts to see if there is a parish or town from these listed above that would be willing to host a facility.

While several suitable locations were found, there were also several changes that could be made to better improve the analysis. Although these changes may not greatly affect the final result, they would increase the reliability of the analysis.

Ideally, these cell applications would be reduced to a smaller dimension so the region and placement of the cells would not matter. Until this happens, one of the first methods to check the data would be a ½ length and width grid shift. Although each cell has enough surface area for several unique facilities, it was a concern that the grid could possibly produce misleading information or randomly supportive information that is not characteristic of the general area. A grid shift of 0.00175 decimal degrees (half of one cell length) in the horizontal, vertical, or in both could also be made to determine if data changes significantly. This would quadruple time required for computer analysis but not overall time because the data have been collected already. Because the resultant data are in clusters of similar suitability, this is not necessary.

There are other ways that the analysis could be improved. Some apply to multiple requirements, and others are specific to one requirement and are outlined below. One possible improvement or suggestion that could be applied to many of the requirements is that the parish wide data is often available in block, block group, and tract sets. The reason to keep parish wide data was that the 2010 data was not consistently available in this format as it was still being released. In the future one could use the smaller area options and possibly increase the accuracy of the data.

Another general concern for the data was that the formula assumes linear suitability; this could cause some concern since some criteria may not have linear suitability. Some criteria may warrant an exponential or logarithmic suitability or a suitability curve that follows the distribution of the data.

Adding buffers to point data would be another way to improve the data. This method was included later within the analysis and would be the first step towards converting the analysis into a pixel instead of cell based analysis. The difficulty with this approach is determining the range of the buffer. The initial analysis that did not use this method was repeated to determine if there were significant changes when using a buffer. It was decided that the differences were not significant and that the current method was acceptable.

The last general concern is that the availability and methods will be constantly improving and changing. During the research, GIS version 10 became available that fixed several of the errors in previous analysis; however it changed some of the methods that had already been used. For example, Hawth's tools were replaced with GIS 10 for line in polygon analysis and raster in polygon analysis. While this improved the analysis, it did suggest that it might not be possible to set a specific example on how to analyze for suitability.

4.1. Review of Specific Requirements

4.1.1. Requirement 1

Since there is no direct way to measure geological and hydrological complexity, the surrogates used for Requirement 1were successful as an initial screening. However, some causes for concern appear within the data. Three cells have relatively high values. While these values

are very little compared to what one would expect for mountainous areas, they are large

compared to the majority of the region of interest. The border regions are often incorrect due to

elevation raster cutoffs. This was not an issue because the region of interest does not include

bordering cells so long as they are less than 90% covered by Louisiana. Furthermore for this

requirement, an alternate to the well density was taken as buffered well density data. The result

was not significantly different. However, it may still be a better indication of well density.

4.1.2. Requirement 2

The second requirement was to analyze population and was able to find conservative

areas with low chances of way warders or possible intrusion and risk to the population. Some of

the data could be improved such as road access data could be replaced with a time analysis using

GIS 10. To accomplish this, centroid point's time by road to the nearest highway would have to

be analyzed. While this would be ideal for future analysis, it was not necessary for an initial

screening.

4.1.3. Requirement 3

Requirement three was to avoid areas dense with resources. Some of the concerns for this

requirement included that USGS data had to be edited due to conflicting positions. Some sites

indicated that they were in a different state but were located within Louisiana boundaries.

Additionally, sites with essentially no clear current purpose were kept in data analysis because of

the potential as an indicator for future resources. Another concern within this requirement was

that when summing the wetlands data, the total area ended up being greater than 100% coverage.

It is likely that some areas may be categorized as multiple types of wetlands. This did not affect

the final outcome since any data greater than 90% coverage were removed. However it did shrink the range of this non-normalized final suitability.

4.1.4. Requirements 4 & 5

The primary concern for this project came from this set of requirements; data for the floodplains was incomplete. After meeting with experts on the new data it was decided that the best method was to analyze only what was readily available to avoid possible conflicts such as those received by New York claiming that data was not available to citizens (Monmonier). The analysis was still successful in using surrogates to avoid the areas of concern, but it is likely that some of the highly suitable southern cells will be removed once this is fully analyzed

4.1.5. Requirement 6

While Requirement 6 was considered accomplished for an initial screening, there were additional suggested criteria that could not be included due to data limitations. The seasonal fluctuation to the water table would be necessary to evaluate to assure that there are no drastic changes in the water table to account for the average water depth. This is best analyzed by periodic well data if available. However, only general data was consistently available. Similarly, stratigraphic cross were suggested by the NUREGs as another criteria. These sections are important to take into account after the potential areas have been narrowed down. They allow the best understanding of water table fluctuations as well as movements, but it was currently not feasible to integrate into GIS. Additional criteria suggested by the NUREGs include an in-depth study of the Louisiana aquifers. Vegetation maps using low-level aerial photo could also be added, but it is reasonable to analyze these after the initial screening.

4.1.6. Requirements 7, 8, & 9

These requirements were also considered completed, but could also be further investigated during the next stages, or initially if the data were available. Some suggested criteria would include hydrothermal activities, underground water movements, subsurface cavernous weathering and the Aeolian, fluvial, or colluvium processes (all of these are suggested by the NUREG).

4.1.7. Requirement 10

The purpose of Requirement 10 is to avoid areas that may affect the environmental monitoring processes. The established list did look at some of the most likely facilities to affect this. However, one could add more facilities that use radioactive material on a smaller scale.

4.1.8. Additional Requirements

The additional requirements were an initial list and should be added for further consideration with available data. Because one of the greatest difficulties in siting previous facilities was to find a community willing to host the site, it is important to take into consideration as many culturally significant factors as early as possible. Another criterion worth investigating, beyond those investigated, during a more in depth study would be the generators of radioactive wastes. LLW generators are any facilities that produce LLW. Ideally the coordinates of all the generators would be combined into one data layer and then analysis taken based on the total distance from a cell's midpoint to all of the generators. Cells closest to all facilities would have the greatest suitability for this criterion. Since nuclear power plant data was collected, and

these plants are the major generators of LLW (Brookins, 1984) this could be a reasonable substitution for the data. This requirement would contradict with requirement 10 on a small scale, but could be valuable on a larger one.

4.2. Conclusion

The purpose of this project was to develop a method to analyze LLW site preliminary suitability using GIS based on the minimum requirements of 10 CFR 61.50. To test this method, Louisiana was used as a region of interest for its suitability for hosting a potential LLW storage facility. Based on the results of this GIS analysis, there are several ideal locations within Louisiana for a LLW storage facility. Out of the 14,000 cells (70,000 mi^3) analyzed, the top 10%, 5%, and 1% include respectively 404 (2020 mi^3), 88 (440 mi^3), and 4 cells (20 mi^3) suitable for further analysis. These cells are clustered and are located primarily in northern Louisiana. If a facility were to be built in these areas of Louisiana, it would be convenient to a multitude of east coast LLW generators that do not have a local host site. It would also provide the central compact with its own host site satisfying the goals of the 1980 LLRWPA.

GIS is an exceptional tool for planning and evaluation. Recent advances in GIS make this process even easier for the user to compile the data into the proposed suitability analysis. However, the analysis is only as good as the data available and as discussed earlier, some of the data indicate minor discrepancies.

The analysis showed that the method was successfully designed to meet regulatory requirements. While not all criteria were thoroughly assessed or replaced, those not included were likely not important for a preliminary analysis. The final outcome in designing an initial screening process using GIS to locate a region which is more likely to be a good site for a LLW

storage facility was achieved. To complete the evaluation for these sites, on-site investigation would be needed. It is much more likely that the next step would involve public hearings introducing cost benefit analysis, social culture study, and/or private investment. It would also be useful for the State, perhaps through the Department of Economic Development to conduct a more comprehensive study of using LLW storage as an alternative source of local jobs and income for an economically depressed region within the state. Regardless, it is evident from the layered final maps that there are several location options to continue the next stages of investigation.

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