

# **MGIS CAPSTONE PROJECT**

## **GIS-Based Site Suitability Analysis for an Artificial Surf Reef on Delaware's Atlantic Coast**

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## I. ABSTRACT

While surfing has increased along Delaware's coast, availability of surfable conditions has not. Certain beach management activities have decreased this availability, including beach replenishment and other practices. Coastal management efforts in Delaware should consider structures that both meet beach stabilization needs and enhance surfing conditions; one such structure is an artificial surfing reef (ASR). For this study, spatially referenced weighted overlay techniques using a geographic information system (GIS) were employed, considering ASR design and surfing-related criteria, to complete a suitability analysis to identify suitable ASR sites. Results included identification of sites with the highest level of ASR suitability. High suitability was based on several criteria, including optimal natural conditions, beaches with higher surfer numbers and sites in close proximity to current surfing breaks. Low and intermediate suitability were associated with study area sites furthest away from existing surf break locations and where natural conditions were least favorable. Unsuitable sites were located along stretches of the coastline where restrictions on surfing exist, including beaches where ownership is private and access is restricted to the public. Although the methods and data used allowed for the identification of suitable sites, future analyses should consider improvements in methods and data, including stakeholder input and higher resolution data, to produce a more effective depiction of suitability. An important implication is that planners and the surfing community will use results to make informed decisions regarding where to enhance surfing and plan beach management in Delaware. A successful ASR serving multiple purposes could provide multiple economic and social benefits for the local community, including an expansion in the local surfing industry and reduced coastal erosion.

### *Keywords*

Artificial surfing reef, ASR, Delaware, surfing, geographic information system, GIS, site suitability, weighted overlay, Analytic Hierarchy Process, AHP

## II. INTRODUCTION

Coastal regions are among the most important and valuable places on earth. In the United States, approximately 54% of the population lives within 50 miles of the coastline (DNREC, 2004a). Additionally, every year approximately 189 million people travel to coastal areas for tourism (NOPC, 2015). One particular coastal state where tourism and leisure activities are major sectors of the economy is Delaware. In 2013, approximately 7.5 million people visited Delaware, and during Delaware's Fiscal Year 2013, GDP from tourism alone totaled an estimated \$2.9 billion, generating \$451 million in state and local taxes and fees (VisitDelaware.com, 2013).

Recreational watersports have become popular activities in coastal communities across the globe. In particular, one watersport that has become an important activity in coastal areas is surfing. Surfing is defined as "the activity or sport of riding ocean waves on a special board (called a surfboard)," though sometimes surfing is considered more generally as riding an ocean wave in any way possible, using a surfboard, or other type of board such as a bodyboard or "boogie" – board (Merriam-Webster, 2015). In the U.S.A. alone, it has been estimated that over 3.5 million people participate in surfing every year (Lazarow *et al.*, 2009). The global industry of surfing, including various sectors such as surfcraft manufacturers and distributors, surf clothing retailers (i.e., Quiksilver, Billabong), sporting events, and domestic and international surf tourism, has been estimated to generate up to \$130 billion annually (Martin, 2013). Besides the economic value in surfing, it can be argued that many people value surfing for the connection it allows between a person and the marine environment. This connection can be seen as spiritual by some, for others a connection based on the enjoyment it offers, and for others still, a way of life (Lazarow *et al.*, 2009). It has also been found that surfers are one "frontline to environmental activism" for marine-related issues, especially given the growth of organizations like the Surfrider Foundation (Martin, 2013). Though, whether surfing is defined in terms of recreational value or economic value, it is clear that surfing is an important activity in coastal areas.

Beginning in the early 1960s, surfing in Delaware has evolved into a mainstream recreational activity (DE SRF, 2014). Although Delaware only has approximately 25 miles of Atlantic Ocean coastline, there is certainly an established surf community in Delaware. The state has been featured in surf videos, hosted several Eastern Surfing Association (ESA) contests, and has a growing Surfrider Foundation chapter that is actively involved with regional surfing events, environmental issues, and policies (Warshaw, 2005). A survey conducted in 2013 by the Surfrider Foundation, Point 97, The Nature Conservancy, Monmouth University, and the Mid-Atlantic Regional Council on the Ocean (MARCO) found that 66.7% of respondents participated in surfing while in Delaware (Surfrider Foundation, 2014). Though, as participation in surfing has increased since the 1960s, availability of "surfable" conditions has not, and certain beach management activities have decreased this availability (DE SRF, 2014).

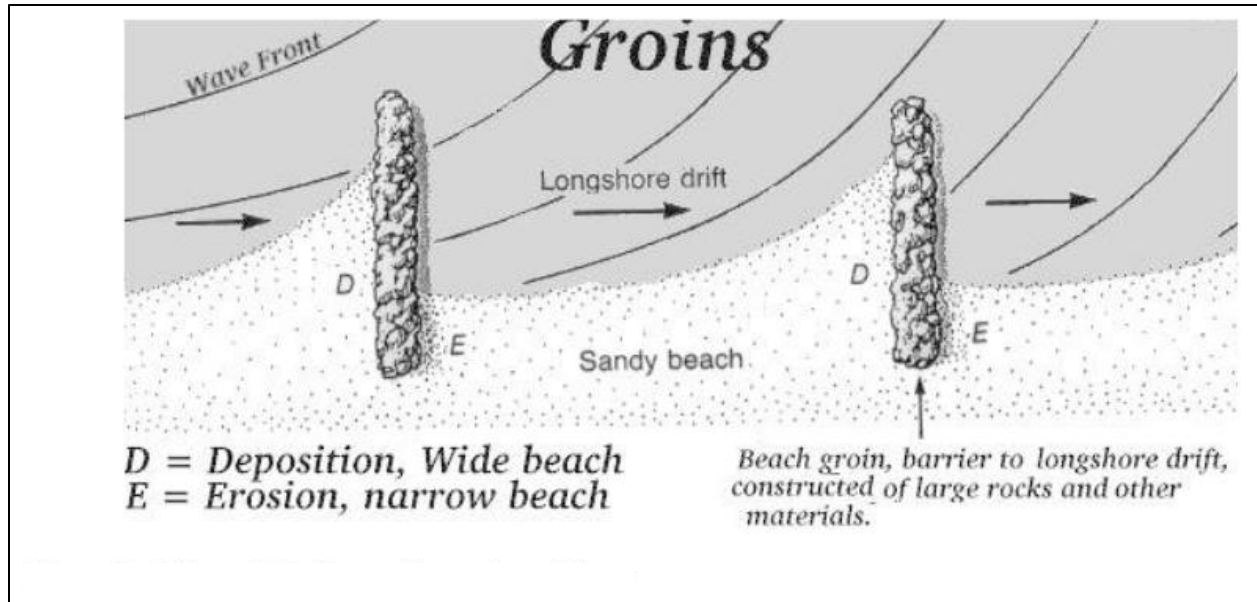
While naturally occurring coastal erosion and shoreline migration are natural processes, the need to manage their impact is essential in the Delaware coastal region (Daniel, 2001). These processes intensify as a result of storms, such as hurricanes and nor'easters in the eastern U.S., causing the movement of sand along the shoreline and its removal from beaches, but since humans have built infrastructure so close to the shoreline, the natural degradation of beaches poses a significant socio-economic threat (Daniel, 2001). To mitigate the negative effects on man-made infrastructure adjacent to shorelines from coastal erosion and shoreline migration,

coastal engineers in Delaware have traditionally considered two different responses. The first response is “hard stabilization,” where physical structures, such as seawalls, offshore submerged breakwaters, or jetties and groins, are placed on beaches or the nearshore zone of the ocean to reduce the energy of crashing waves and the longshore transport of sand along the shoreline (Daniel, 2001). In Delaware, hard stabilization techniques have traditionally been implemented to control coastal erosion and shoreline migration. Structures such as stone jetties and groins were a popular choice in the 1970’s, and the most surfable waves in Delaware were located directly adjacent to these jetties and groins, at beaches like Cape Henlopen and Indian River Inlet (DE SRF, 2014). Table 2.1 and Figure 2.1 list the type of surf break bottom type feature at each Delaware beach, as well as show how incoming waves and longshore sand movement are affected by groins, respectively. The localized breaks in sand movement and resulting shoreline offsets caused by the jetties or groins create surfable conditions (DE SRF, 2014). As the sand accumulates against these structures, a bathymetric “wedge” feature is created, and as the crest of

**Table 2.1 – Delaware Surfing Areas by Break Type.** Table lists the surf breaks found in Delaware, organized by the type of coastal management structures found at each beach. The majority of these breaks contain either jetty or groin structures. ©2014 DE SRF. All rights reserved. Reproduced here for educational purposes only.

<b>Historic Delaware Surf Breaks by Bottom (break) Type</b>		
<b>Stone Inlet Jetties</b>	<b>Stone/Timber Erosion Control Groins</b>	<b>Sand bottom without any Shoreline Management Structures</b>
Indian River Inlet North	Cape Henlopen Herring Point	Dewey Beach
Indian River Inlet South	Cape Henlopen Gordon’s Pond	Delaware Seashore (Tower Road)
	Rehoboth Beach	Fenwick Island
	Bethany Beach	

a wave converges on the jetty, a peak in wave height is created and the wave breaks in a peeling manner along the wedge feature as it approaches the shoreline (Scarfe *et al.*, 2003a). Though, these hard structures tend to have some negative outcomes for the beaches where they are located. In the case of seawalls, not all of the wave energy is absorbed by the wall, causing either sand in front of the wall to be eroded by reflected wave energy, or sand on adjacent unprotected beaches to be eroded by deflected wave energy (Daniel, 2001). Offshore breakwaters also only protect and widen a localized portion of beach, so when the wave energy is dispersed by these structures, the longshore transport of sand is interrupted, and downdrift beaches are starved of sand that would have been supplied by longshore drift (Daniel, 2001). Jetties and groins also interrupt the longshore movement of sand, though these structures have more of a blocking effect, where sand accumulates on the updrift sides of the structures in an attempt to widen the beach, while exaggerating erosion of sand on the downdrift sides, affecting other recreational functions and the aesthetics of beaches (Daniel, 2001). The second response to coastal erosion is “soft stabilization,” with the major technique being beach replenishment, or nourishment (Daniel, 2001). This technique involves pumping sand from a ‘borrow’ area, such as offshore from the ocean floor, onto the beach to create a wider buffer of sand between the water and



**Figure 2.1 – Effect of Groins on Longshore Sand Movement and Waves.** This diagram shows how groins, commonly used in Delaware, placed on beaches can affect the movement of sand along the shoreline, as well as how they interact with waves. ©2014 DE SRF. All rights reserved. Reproduced here for educational purposes only.

property lines (Daniel, 2001). Beach replenishment has been the most preferred method of maintaining beaches along the Delaware coastline in recent years (Table 2.2). While certainly a quick response to beach erosion, replenishment of beaches with sand from the submerged, nearshore areas negatively affects the surf conditions. The pumping of sand onto beaches buries groins in sand and increases the height of beaches relative to the adjacent body of water, steepening shoreline slopes, causing waves to break directly on the shore (DE SRF, 2014). Additionally, as the sand is pumped onto beaches and the width of the beach increases seaward, troughs between naturally occurring sandbars and the shoreline become filled (Shane, 2012). These sandbars are what create surfable conditions on beaches with little or no “hard” beach management structures, such as Ocean City, MD and Fenwick Island, DE (Shane, 2012). Normally these sandbars would also reduce wave energy farther offshore, though after replenishment eliminates the sandbars, waves breaking near the shore are more powerful, creating potentially more dangerous conditions for swimmers and surfers alike (Chesler, 2013). Data collected by the United States Lifesaving Association (USLA) showed increases in major medical beach injuries the same year or the year following a beach replenishment project suggesting replenishment caused these increases (Chesler, 2013). In 2006, a year when beach replenishment took place in Ocean City, there were 87 surf-related major medical injuries on Ocean City beaches, while the following year had 345 injuries. In 2010, another replenishment year, 233 major medical injuries occurred, while 306 occurred the following year (Chesler, 2013). Furthermore, along the Delaware coastline, coastal erosion rates have historically ranged from 2 to 4 feet of sand eroded from the shoreline per year, and traditional beach preservation methods, such as beach replenishment and dredging activities, have only been able to produce 1 to 3 year beach life spans before the beaches lose their storm protection and recreation functions (Daniel, 2001). The combined effect of beach replenishment on reducing a beach’s surf-

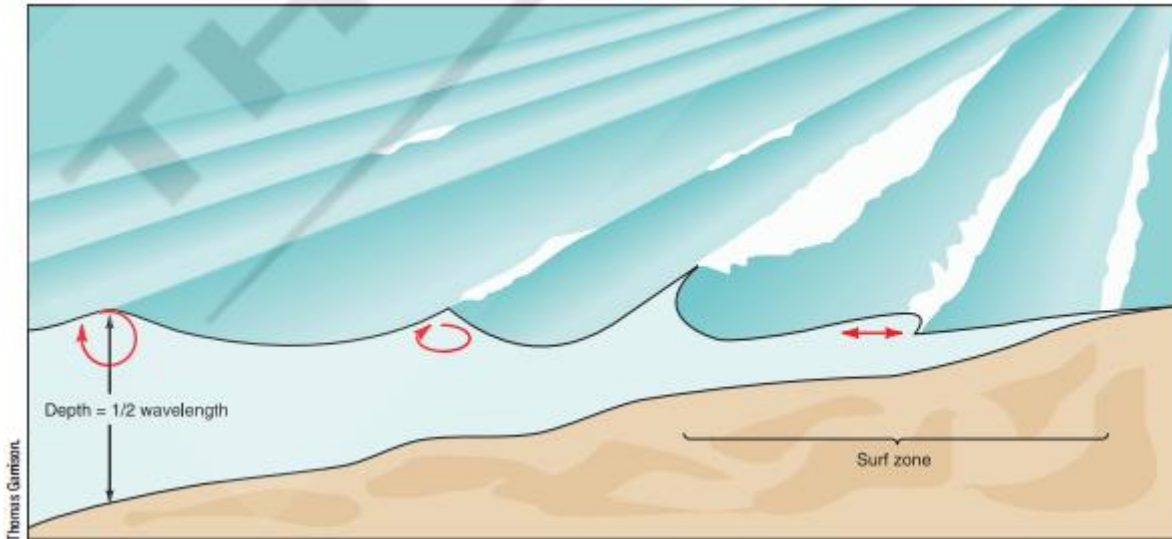
**Table 2.2 – Delaware Beach Replenishment Projects Since 1960’s.** Table lists the many beach replenishment projects completed in Delaware since the early 1960’s; a popular beach management activity in Delaware. ©2014 DE SRF. All rights reserved. Reproduced here for educational purposes only.

Community	Years of Beach Nourishment Projects – Source: DE DNR
Fenwick Island	1962, 1988, 1994, 1998, 2004, 2008, 2011 2013
South Bethany Beach	1962, 1989, 1994, 1998, 2008, 2011 2013
Bethany Beach	1961, 1962, 1989, 1992, 1994, 1998, 2008, 2009, 2011, 2013
Indian River Inlet	1957, 1962, 1963, 1972, 1975, 1978, 1982, 1990, 1992, 2013
Dewey Beach	1962, 1993, 1994, 1998, , 2005, 2009, 2011, 2013
Rehoboth Beach	1962, 1998, 2005, 2011, 2012, 2013

enhancing physical features and only serving as a temporary solution to coastal erosion makes it seem an ineffective solution, especially with regards to the recreational activity of surfing.

Moving forward, coastal management efforts in Delaware should consider the addition of structures that can have a positive effect on the recreational activity of surfing. One such structure is an artificial surfing reef (ASR). An ASR can be described as a submerged breakwater structure that can serve the primary purpose of improving surf conditions, such as wave quality, as well as providing secondary benefits, such as reducing coastal erosion (Ranasinghe *et al.*, 2006). Unlike emergent beach management structures, such as groins and breakwaters, that tend to have negative impacts on beach amenity and aesthetics, submerged structures like ASRs can provide similar erosion control effects without reducing amenity and aesthetics (Ranasinghe *et al.*, 2006). To understand how ASRs function in creating surfable waves, it is necessary to understand how waves form and break as they approach shallow, near-shore waters. As ocean waves approach the shoreline, they begin to ‘feel bottom,’ where the wave crest will move forward while the wave base drags on the bottom, resulting in the wave crest curling forward, or breaking (Hyndman & Hyndman, 2006). Waves will begin to feel bottom when seafloor depth is equal to half the wavelength, the distance between crests of two successive waves leading to an increase in wave height, called shoaling, and eventual breaking (Figure 2.2) (UDel, n.d.). This breaking will commonly occur when wave height is equal to local water depth (UDel, n.d.). Refraction occurs when wave crests bend while passing over a portion of seafloor with varying depths, where the portion of wave moving across shallower water slows down, causing the deeper water portion of wave to catch up and become more parallel with the shoreline (UDel, n.d.; Phillips *et al.*, 2003). This is common when waves approach the shoreline at an angle rather than perpendicular (Figure 2.3). Refraction changes a wave’s peel angle ( $\alpha$ ), “defined as the angle between the trail of the broken whitewater and the crest of the unbroken wave as it propagates shoreward” (Figure 2.4) (Scarfe *et al.*, 2003a). Ranging from 0° to 90°, lower angles create faster waves and higher angles create slower waves, where a peel angle of 0° results in a ‘closeout,’ or a wave that breaks all at once across its entire along-shore length (Scarfe *et al.*, 2003a). Peel angle is argued to be the most important wave parameter for distinguishing between a surfable and non-surfable wave, and the function of a surf break is to “increase peel angles to within surfable limits” (Scarfe *et al.*, 2003b). Waves of good surfability will break in a “peeling



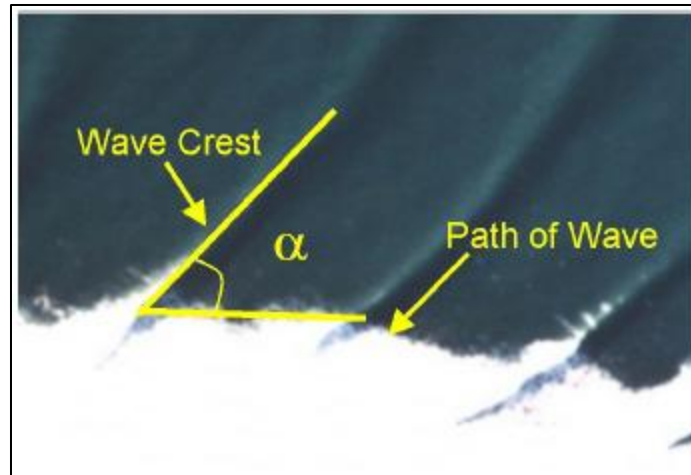


**Figure 2.2 – Wave Interaction with Nearshore Bathymetry.** This diagram shows how waves start to ‘feel bottom’ when approaching the shoreline, occurring when depth is approximately half the wavelength distance, eventually breaking in the surf zone as the top of the wave moves forward faster than the bottom (Hyndman & Hyndman, 2006). ©2006 Thomson Brooks/Cole. All rights reserved. Reproduced here for educational purposes only.



**Figure 2.3 – Wave Refraction on California Shoreline.** This diagram shows how waves refract when approaching shoreline at an angle, causing a bend in wave crests. In this example, waves approaching a headland are breaking in a peeling manner, where the shallow-water portion of wave breaks first, causing the deeper portion of wave to ‘catch up’ and break as it becomes parallel with the shoreline (Phillips *et al.*, 2003). ©2003 Inter’l Surf Reef Syspm. All rights reserved. Reproduced here for educational purposes only.

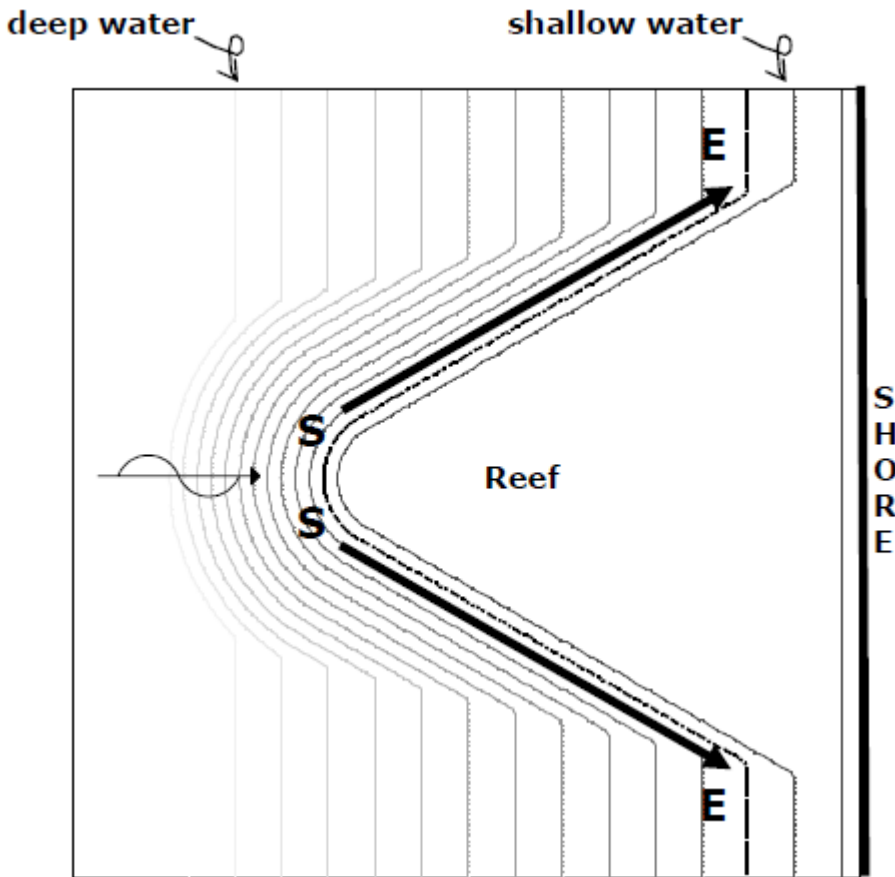
manner,” meaning the breaking section of the wave “translates laterally across the wave crest,” where the best position for a surfer is the area adjacent to the breaking crest of the peeling wave, called the “pocket,” allowing the surfer to ride for the longest possible time (Mead, 2003).



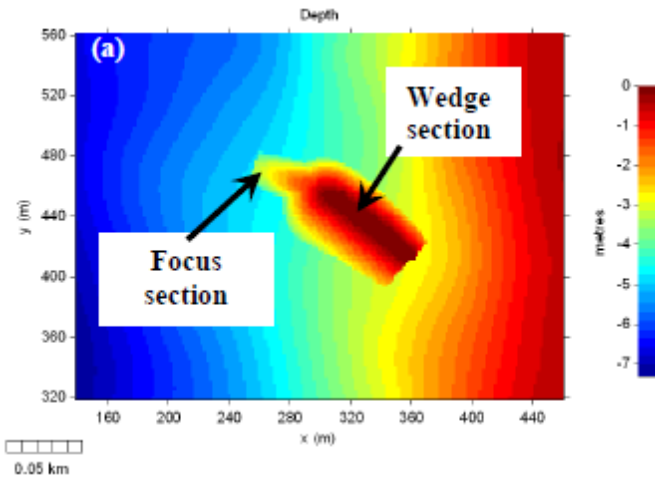
**Figure 2.4 – Wave Peel Angle.** This diagram shows the peel angle ( $\alpha$ ) of a wave; as angles become greater than  $0^\circ$ , the more surfable waves become (Scarfe *et al.*, 2003a). ©2003 Scripps Institution of Oceanography. All rights reserved. Reproduced here for educational purposes only.

ASRs attempt to create these peeling wave conditions, creating optimal surfability for surf breaks that generally have low surfability or un-surfable conditions. The ASR design that has been the most widely employed revolves around a V-shaped design, where the apex points seaward and the two ‘arms’ of the V serve to create a left- and right-peeling wave, in relation to the shoreline (Black & Mead, 2009; Cáceres *et al.*, 2010; Loomis, 2003). The apex of the ASR is meant to function as a focus feature drawing wave energy onto the reef causing a peak in wave height that allows for easier take-off by surfers (Mead *et al.*, 2010; Scarfe *et al.*, 2003b). The arms of the ASR then act as wedge features, or planar elements, that cause waves to break in a peeling manner by raising the bathymetry and causing refraction through their downward tilted offshore orientation (Scarfe *et al.*, 2003b). From the surfer’s perspective, the left arm of the reef would cause a left-hand peeling wave to break and the right arm would cause a right-hand peeling wave to break. Though other factors such as the orientation of the reef to the predominant swell direction and wind speed and direction would have a significant effect on the peel angle and breaking intensity (Mead *et al.*, 2010). Figures 2.5 and 2.6 show how a surfer would ride a wave breaking over an ASR and the focus and wedge sections of the Boscombe, England multi-purpose reef, respectively.

The multiple advantages ASRs can offer are increasingly recognized in coastal communities where both recreational function and protection of beaches are important. Several ASR and other multi-purpose AR construction projects have been completed at various beaches around the world including three sites in New Zealand, four sites in Australia, three sites in the United Kingdom, two sites in California, and one site in India (Scarfe *et al.*, 2009). In addition there have been over 20 feasibility studies completed for ASRs at other international sites (Scarfe *et al.*, 2009). One such project was at Narrowneck beach near Surfers Paradise, a prominent surfing community on the Gold Coast of Queensland, Australia (Jackson *et al.*, 2002). The artificial reef structure (Figure 2.7), constructed of large (3- 4.5 m diameter, 20 m long) geotextile containers filled with sand, was installed with the primary purpose of coastal erosion control for the

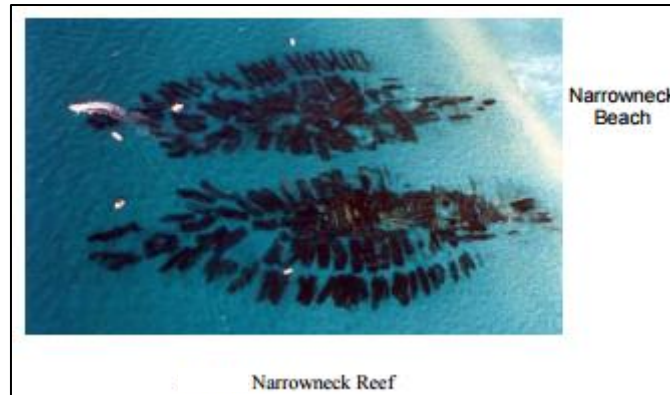


**Figure 2.5 – Surfing a Conventional Surf Reef.** This diagram shows how a surfer would ride a wave refracting on an ASR, where **S** is the surfer take-off point, **E** the end of a ride, and dashed line the breaker line (Van Ettinger, 2005). ©2005 TUDelft. All rights reserved. Reproduced here for educational purposes only.



**Figure 2.6 – Focus & Wedge Sections of Boscombe Reef.** This diagram shows how the Boscombe multi-purpose reef is oriented, with focus and wedge sections that create potentially surfable conditions (Mead *et al.*, 2010). ©2010 Coastal Engineering. All rights reserved. Reproduced here for educational purposes only.

adjacent nourished beaches but was also designed to enhance surfing, swimming, diving, fishing, and habitat conditions (Jackson *et al.*, 2002). This multi-functional reef was continuously monitored starting in 1999 during installation of the geotextile containers, ending in July of 2002, to assess performance of the reef and facilitate improvements in its design (Jackson *et al.*, 2002). After several years of monitoring and 13 major storm events, Jackson *et al.* (2002) reported a 20-30 m widening of the beach in the lee of the submerged reef structure, an overall improvement in surfing conditions across various structure depths, and the establishment of a diverse marine habitat. The widening of the beach was in relation to adjacent, unnourished beaches to the north and south of the reef beach, though these unnourished beaches still accreted approximately 10-20 m of sand during this time (Jackson *et al.*, 2002). Figure 2.8 shows photos of the beach at Narrowneck Beach several years before (1996) and after (2002) beach nourishment and reef installation were completed. The changing depth of the top, or “crest” of the reef structure, due to a combination of natural seabed changes and intentional alterations to the reef, allowed for various surf conditions favored by a wide range of surfcraft and rider skill levels (Jackson *et al.*, 2002). The shallower the crest ( $\leq -0.5$  m LWD [low water datum]), the better the waves were for shortboard and bodyboard riders, while deeper crest positions



**Figure 2.7 – Narrowneck Beach Reef.** This picture shows the geotextile sand containers of the Narrowneck AR, arranged for erosion management, surfing, fishing and diving purposes (Jackson *et al.*, 2004). ©2004 ICCE. All rights reserved. Reproduced here for educational purposes only.



**Photo 2. Narrowneck 1996**



**Photo 3. Narrowneck 2002**

**Figure 2.8 – Narrowneck Beach Pre- and Post-Beach Nourishment/Reef Installation.** This photos show Narrowneck beach before (Photo 2, '96) and after (Photo 3, '02) beach nourishment and artificial reef installation, where significant beach widening was achieved (Jackson *et al.*, 2002). ©2002 ICCE. All rights reserved. Reproduced here for educational purposes only.

(< -1.5 m LWD) resulted in waves better for longboard riders (Figure 2.9) (Jackson *et al.*, 2002). Though, other oceanographic processes and properties have significant effects on how waves break, including tide level, wave height, and wind speed and direction (Scarfe *et al.*, 2003b). This project provides an example of how informed design and site assessment can lead to a successful implementation of an artificial reef (AR) that meets the needs of multiple stakeholders.



**Figure 2.9 – Breaking Wave Types Under Various Swell Conditions at Narrowneck Beach AR.** These photos show the different types of breaking waves observed under various swell conditions at the AR at Narrowneck Beach (Jackson *et al.*, 2002). ©2002 ICCE. All rights reserved. Reproduced here for educational purposes only.

Another example of a successful implementation of an AR designed for multiple purposes was the Boscombe multi-purpose reef in Bournemouth, England. The company ASR Ltd., commissioned to design the reef, conducted several field studies at the proposed site, including bathymetry surveys, wave climate data collection via buoy and metered instrumentation, as well as tide and wind monitoring (Mead *et al.*, 2010). After completion of post-construction monitoring, it was found that the reef produced surfable conditions as was intended in design, and also resulted in salient development in the reef's lee (Mead, *et al.*, 2010). Though, many local surfers in Bournemouth believed the reef failed to meet expectations, producing inconsistent waves (Mull, 2014). Dr. Shaw Mead, co-founder of ASR, stated that expectations for ASRs to create perfect waves all the time ultimately leads to them being perceived as failures, as they are not designed to produce such conditions (Mull, 2014). Nevertheless, this reef

project is indicative of how careful planning of an AR for recreational and other purposes is necessary to obtain results anticipated during design stages.

In contrast to the Boscombe and Narrowneck reef projects, Pratte's Reef at El Segundo, California did not have as successful a result. This reef was constructed to mitigate the loss of quality surfing conditions present in the area prior to Chevron's construction of the "El Segundo Groin" (Slotkin *et al.*, 2008). This AR was the first of its kind, an AR designed specifically for enhancing surfing conditions, so the design of Pratte's reef did not have the benefit of basing specifications on other constructed ASRs (Loomis, 2003). Though, through wave modeling following Kirby and Dalrymple's (2002) REF/DIF1 wave model, it was determined the best design for this reef was a V-shape structure constructed of 185 4'x7'x10' sand bags, smaller than Narrowneck and Boscombe reefs, and placed on the proposed site where the shallowest portion of the reef would be three feet below mean low water level (Loomis, 2003; Richmond *et al.*, 2011). It was found from post-construction monitoring that reef elevation was not maintained, surf conditions were poor compared to historically popular adjacent surf spots on the same days and deterioration of installed sand bags occurred (Loomis, 2003; Richmond *et al.*, 2011). Furthermore, the co-author of the reef's Comprehensive Monitoring Program study indicated that no numerical modeling, wave climate analysis, or beach surveys were completed for the reef's site before design stages (Slotkin *et al.*, 2008). The poor performance of the reef led to its removal from the site where the structure's sand bags were removed in two phases costing an estimated \$550,000 (US) (Richmond *et al.*, 2011). While mitigation for El Segundo's loss of surfing amenity was a priority, the feasibility of an ASR as a means of mitigation may not have been the best solution for that particular location. Table 2.3 lists the design specifications and parameters for some of the more notable constructed and proposed ASR projects around the world. These design parameters can serve as an effective starting point for determining suitability of sites in the Delaware study area for ASR deployment.

Black and Mead (2009) indicate that ASRs are holistic systems where each component (i.e., depth, arm length, orientation, etc.) is linked to every other component. Black and Mead (2009) argue that for expectations to be met and maximum surfing potential realized, each ASR component must be designed for the specific physical environment where it is to be placed (Black & Mead, 2009). Environmental factors, in addition to other social and location-based factors (e.g., surfing regulations, beach access), need to be considered as part of the holistic reef system to ensure successful implementation of an ASR. Informed planning and site analysis accounting for the necessary criteria for an ASR is necessary to determine suitable locations for ASR deployment.

Geographic information systems (GIS) are especially equipped with tools to complete this location-based suitability analysis, bringing together various spatial data layers representing different site and design criteria to determine spatial relationships. The values in the data layers are ranked and weighted to denote relative importance using GIS software functions, where certain spatial data values are assigned higher ranking and weighting values to signify more favorable conditions (Briney, 2014). The ranking and weighting of data layer values to represent varying levels of suitability also allows the user to visualize 'next-best' sites for the proposed feature in case the most suitable sites identified through GIS are not feasible (Briney, 2014).

**Table 2.3 – Existing and Proposed ASR Project Design Specifications.** Table lists some of the more notable constructed and proposed ASR projects around the world, and their associated design specifications. These design parameters can serve as a starting point for determining site suitability for an ASR in Delaware.

Reef Name	Location	Size (L)	Size (W)	Size (H)	Depth at Reef	Seabed Slope at Reef	Avg. Significant Wave Height (H <sub>s</sub> )	Tide Range	Distance from Shoreline	Intended Results Achieved?	Reference
Mount Maunganui (Mount Reef)	Bay of Plenty, New Zealand	90 m	80 m	3 m	3 - 4 m	~ 1° (1:50) - 3° (1:20)	1.5 m	2 m	250 m	Yes/No	ASR America, 2008; Bay of Plenty Times, 2014; Black & Mead, 2009; Jackson & Corbett, 2007; Mull, 2014
Opunake	Opunake, New Zealand	99 m	30 m	3.5 m	1.8 - 3 m	??	??	> 3 m	200 m	No	Jackson & Corbett, 2007; Keith, 2011
Lyall Bay	Wellington, New Zealand	160 m	115 m	??	4 - 5 m	??	??	??	250 m	Proposed	deepfried.tv, 2005; Phillips <i>et al.</i> , 2003
Cable Station	Perth, Australia	70 m	140 m	2 - 3 m	3 - 6 m	3° (1:20)	2 m	0.8 m	400 m	Yes	ASR America, 2008; Bancroft, 1999; Jackson & Corbett, 2007
Narrowneck	Gold Coast, Australia	350 m	600 m	??	1.5 - 10 m	1° (0.02)	1 m	2 m	150 m	Yes	Bancroft, 1999; Jackson <i>et al.</i> , 2004; Jackson & Corbett, 2007; Ranasinghe & Turner, 2006
Bargara	Queensland, Australia	??	??	??	??	??	< 1 m	3.7 m	??	Yes	Jackson & Corbett, 2007
Pratte's	El Segundo, CA, USA	30 m	60 m	2.15 m	4.6 m	2° (~0.03)	< 1 m	1.6 m	80 m	No	ASR America, 2008; Bancroft, 1999; Jackson & Corbett, 2007; Nelsen, 1996
Oil Piers	Ventura, CA, USA	110 m	100 m	6.5 m	~ 6 m	??	??	??	~ 200 m	Proposed	Barlow & Plascencia, 2011; Kasey, 2010; Surfing Magazine, 2003
Cocoa Beach	Cocoa Beach, FL, USA	175 m	122 m	??	??	~ 0.5° (1:120)	1.1 m	1.06 m	244 m	Proposed	Hearin, 2009
Boscombe	Bournemouth, England	120 m	~ 60 m	??	3 - 5 m	< 3° (~1:20) - 4° (~1:15)	1 m	1.76 m	225 m	Yes/No	Black & Mead, 2009; Fletcher <i>et al.</i> , 2011; Mead <i>et al.</i> , 2010; Mull, 2014
Kovalam	Kovalam, India	110 m	40 m	??	??	??	??	??	100 m	Yes/No	Ananthakrishnan, 2010; Kasey, 2010; Mull, 2014

Regarding the deployment of coastal management structures, such as ARs, adequate planning and site selection is argued to be the most important task in the deployment process, as it is the most common cause of unsuccessful ARs when insufficiently executed (Barber *et al.*, 2009; Tseng *et al.*, 2001). Much of the literature on using GIS in site selection analysis is in relation to AR siting for the purposes of enhancing or creating marine habitats (Barber *et al.*, 2009; Erfteimeijer *et al.*, 2004; Kennish *et al.*, 2002; Tseng *et al.*, 2001). ASR deployment needs to take into account similar criteria types as habitat-related ARs in site selection analysis, though how these criteria influence suitability and priority rankings for proposed study sites will vary. For example, in site selection for a habitat-related AR, Tseng *et al.* (2009) used water depth in the range of 20-30 meters as the optimum depth for the AR, as these depths would avoid impeding shipping lanes and the destroying effect of waves. In site selection analysis for an ASR, shallower depths would be considered optimum, as these depths are where wave action exists, a necessity for an ASR to function properly. To distinguish between optimum and least favorable conditions in site selection analysis priority rankings or weights are assigned to each input

criterion. Assigning relative levels of priority to each criterion is an important step in this type of analysis, as any change to these rankings or weights can significantly alter analysis results (Barber *et al.*, 2009; Tseng *et al.*, 2001).

Tseng *et al.* (2001) found a hierarchical “weights of criteria” GIS site selection method that considered criteria such as water depth, bottom type (geology), sea-bottom slope, distance to coast, and distance to fishing ports, an effective means of locating a habitat-enhancing AR (Table 2.4). Most of these criteria would seem pertinent in locating an ASR though factors such as proximity to ports, as a means of measuring the accessibility to the ARs, would not be very applicable. The methods adapted by Tseng *et al.* (2001) employed the Analytic Hierarchy Process (AHP) to calculate the relative weights assigned to each criterion for spatial analysis, where the AHP model is comprised of a goal, criteria, and many levels of subcriteria. The AHP process is used to extract a relative weight, or each criterion's level of importance to the overall goal of analysis, through “pair-wise comparisons” of each criterion to every other criterion (Tseng *et al.*, 2001). Figures 2.10 and 2.11 show the layout of an AHP decision matrix and hierarchy chart of weights assigned to each criterion.

Tseng *et al.* (2001) indicated weight values assigned to analysis criteria could change due to decision-makers subjectively altering criterion scores obtained through the decision matrix when assigning relative importance of alternatives for each criterion. They further argued that assigning criteria scores objectively in the decision matrix improves AHP analysis accuracy and reliability (Tseng *et al.*, 2001). While the AHP method is subjective, it also demonstrates the flexibility in allowing the decision-maker to assign criterion scores in these importance comparisons that suit the specific study. The AHP method and Environmental Systems Research Institute's (Esri) ArcGIS (2015a) Spatial Analyst and map algebra functions allowed Tseng *et al.* (2001) to identify optimal sites for AR deployment, where higher scores in the final suitability map represented more suitable sites. Employing the raster data format, where data layers are displayed as a regular grid of cells, with each cell storing a single data layer value, allows comparisons between data layers to easily be made as a specific cell will exist in the same location for each data layer. It was also found that the majority of existing habitat-related ARs in the study area coincided with more suitable areas, lending support to the effectiveness of the methods used. Furthermore, Tseng *et al.* (2001) states that using this AHP method in conjunction with GIS software can allow for quick changes in the criteria weighting when new or better data become available. Additionally, while it was found the collection and digitizing of a few of the data layers used comprised the most time of any task in the project, they argued the success of the GIS-based methods highly depended on the completeness of data used (Tseng *et al.*, 2001).

In a study on deployment of a habitat-related AR in Massachusetts Bay, MA, Barber *et al.* (2009) found exclusion mapping and criteria importance weighting to be effective in selecting suitable sites for an AR. The exclusion mapping model included substrate (i.e., bottom sediment type), bathymetry, and proximity to a study area pipeline as the suitability criteria (Barber *et al.*, 2009). After reclassifying the substrate and bathymetry criteria data layers in proximity to the pipeline feature with new suitability values (e.g., prime – 2, potential – 1, unsuitable – 0) and conversion to raster format, ArcGIS's Raster Calculator tool was used to multiply the layers together to produce a suitability layer (Barber *et al.*, 2009). After producing this suitability layer, Barber *et al.* (2009) collected data in the field for each of the identified suitable sites, as they argued simple exclusion mapping methods fail to incorporate the “physical and biological data



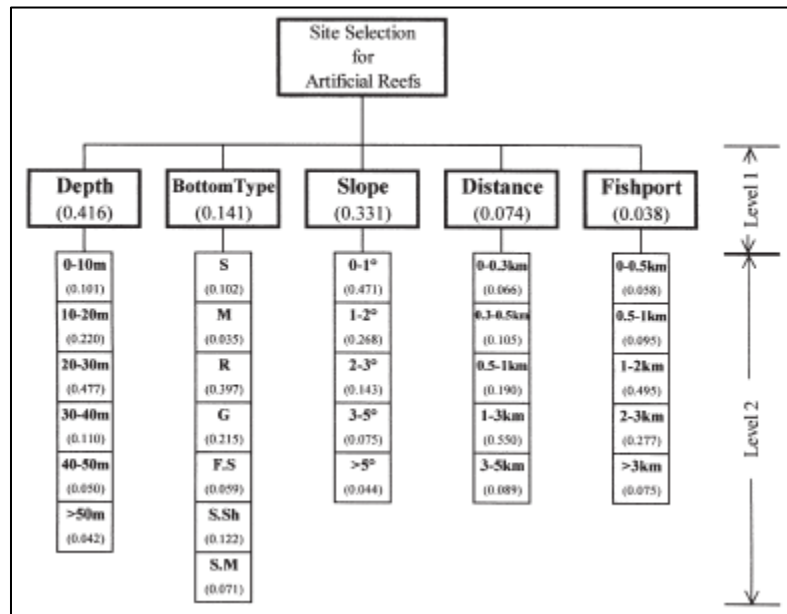
**Table 2.4 – Site Selection Criteria for Habitat-Related AR Deployment.** Table lists the criteria used by Tseng *et al.* (2001) to select suitable areas for habitat-related AR deployment, where the “Optimum” conditions for the AR were given higher weights in analysis. ©2001 Fisheries Science. All rights reserved. Reproduced here for educational purposes only.

Criterion	Optimum	Consideration
Depth (m)	20–30	20 m clearance for shipping channel
Slope	Flat topography	Avoid collapse of reef structures
Bottom type	Hard or solid rock	Avoid sinking into the sea-floor
Distance to natural reef (nautical miles)	>0.5	Effects effectiveness
Estuary and pollutant	Far away	Away from areas of lower water quality
Current velocity (knots)	<1.5	Avoid the scraping effect by strong currents
Distance to coast		Reduce wave effect
Distance to fish ports		Convenient to fishing or research

Chang<sup>2</sup>; D’itri<sup>2</sup>; Wright *et al.*<sup>2</sup>

$$M = \begin{pmatrix} 1 & C_{12} & \dots & C_{1n} \\ C_{21} & 1 & \dots & C_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{n1} & C_{n2} & \dots & 1 \end{pmatrix}$$

**Figure 2.10 – AHP Decision Matrix.** This diagram shows the decision matrix used to derive weights for each analysis criterion (Tseng *et al.*, 2001). ©2001 Fisheries Science. All rights reserved. Reproduced here for educational purposes only.



**Figure 2.11 – AHP Weights Hierarchy Chart.** This diagram shows the hierarchy chart of criteria and subcriteria weights used in site selection analysis (Tseng *et al.*, 2001). ©2001 Fisheries Science. All rights reserved. Reproduced here for educational purposes only.

necessary to understand the ecology of a prospective site for AR development.” Though, the exclusion mapping method can help in reducing the amount of additional data collection and analysis necessary, as only identified suitable areas would require field data collection and analysis rather than the entire study area. Barber *et al.* (2009) then used weighting and ranking analysis to assign numerical scores to each criteria from the data collection process based on how well each site met the selection criteria. These numerical values were then multiplied by weights indicating the relative importance of each criterion to the project goals (Barber *et al.*, 2009).

Using GIS methods and the chosen suitability criteria, Barber *et al.* (2009) was able to exclude 80% of prospective reef area for AR deployment. Furthermore, Barber *et al.* (2009) indicated that a lack of spatial data for some of the selection criteria limited the use of GIS in exclusion mapping and field data collection revealed some of the existing GIS data layers had incorrect information, such as bathymetry and substrate data. This exemplifies the need for further data collection efforts in coastal regions to more effectively plan for coastal management structures, such as ARs and ASRs, using spatial analysis methods.

Other projects where GIS was used for AR deployment included that of Kennish *et al.* (2002) for selecting suitable sites in the Hong Kong area for an AR, where a qualitative prioritization technique was used to rank potential sites. Kennish *et al.* (2002) argued not using numerical weights to assign importance to each input criterion ensured no one criterion exerted “undue bias” on the selection process. As their methods compared criteria from areas of differing types (i.e., environmental, socio-economic, cost-efficiency), the absence of criteria weights ensured no one interest was seen as more important than another (Kennish *et al.*, 2002). Erfteimeijer *et al.* (2004) also argued that based on insufficient scientific findings or input from decision makers, weights of criteria were not seen as appropriate for assigning relative importance, and thus were not applied in their study on AR GIS site selection in Bahrain.

ASR site selection analysis should also consider the use of exclusion mapping and weighting overlay techniques, given the prevalence in AR suitability literature. Scarfe *et al.* (2009) argue overlay techniques through GIS, considering various ASR design criteria such as bathymetry, bottom sediment grain size, tidal and wave data, can lead to a better understanding of the coastal environment where ASRs are placed to enhance surfing conditions. Other criteria that should be considered relevant for ASR studies includes wind patterns, surfer numbers and seasonal variations, precise locations of surfing rides, and the number of surfable days per year (Scarfe *et al.*, 2009). These and other types of coastal region data, such as beach accessibility, other coastal amenities (e.g., parking, bathroom facilities), and regulations on recreational activities such as surfing are also pertinent in determining suitability for an ASR. This project will discuss the methods for identifying sites suitable for ASR deployment in the Delaware coastal region.

### III. GOALS AND OBJECTIVES

The primary goal for this study is to identify locations most suitable for the deployment of an ASR along Delaware's Atlantic coastline. To accomplish this goal, the following objectives are outlined:

- Identify common design measures and environmental criteria considered in design and construction of completed and proposed ASR projects,
- Identify study area-specific social, legal and environmental considerations related to activity of surfing,
- Apply geographic information system (GIS) technology to analyze study area-specific data layers storing data associated with the identified ASR design and surfing-related considerations to reveal suitability patterns,
- Classify a GIS-produced suitability output to describe varying levels of suitability, and
- Locate the study area sites with the highest suitability rankings.

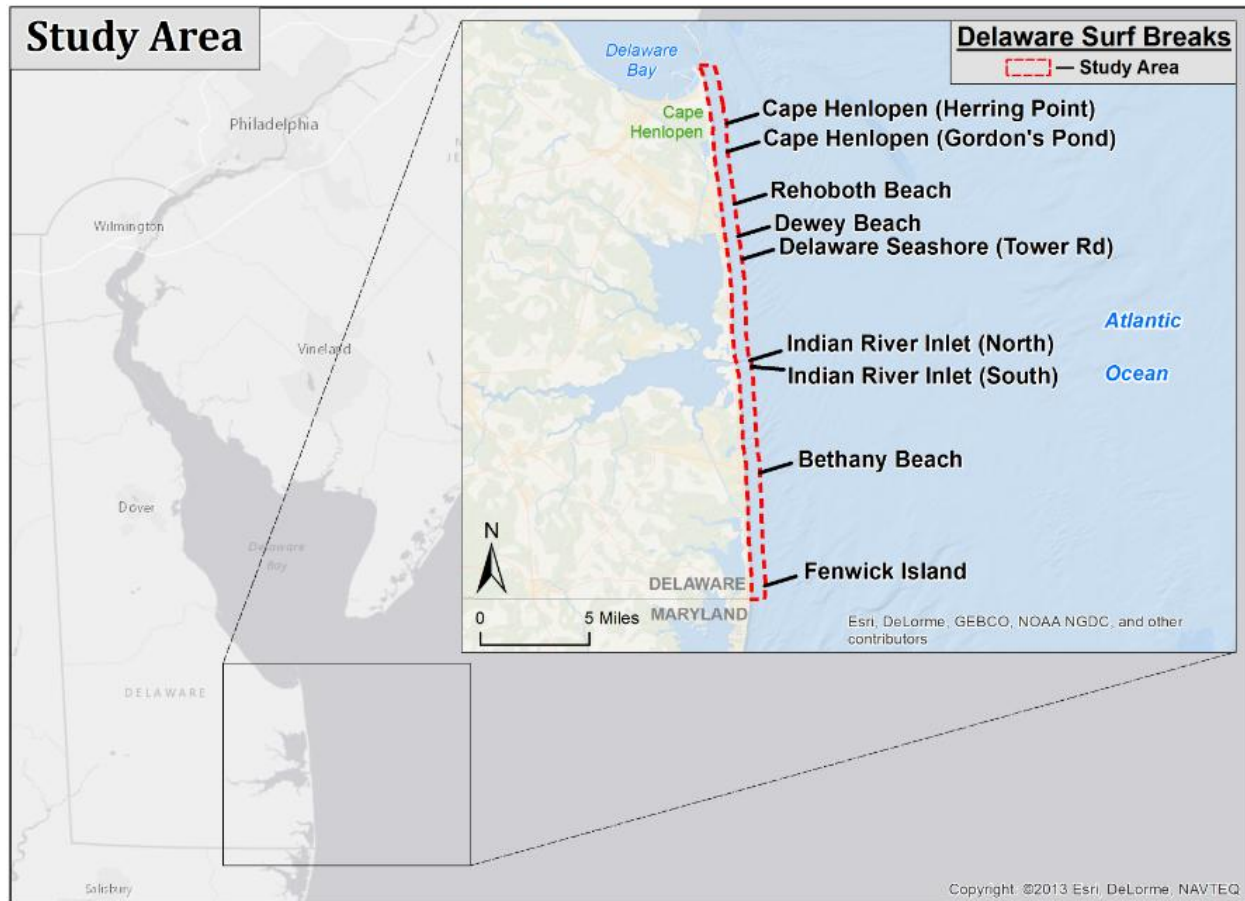
Employing GIS for this site suitability analysis, the goal is to develop an informed spatial analysis approach that will be used for identifying suitable ASR sites in the study area and that may be applicable in other domestic and international locations. The following objectives are given to achieve this aim:

- Identify analysis methods used in other related GIS-based AR and ASR site selection studies, including analysis concepts and specific software operations performed,
- Identify the most current, publicly available spatial data layers to represent the identified ASR design and surfing-related criteria,
- Delineate an approach for processing the identified data layers in a GIS environment to produce a single suitability analysis output,
- Present an applied framework for future GIS-based ASR suitability analyses to adapt and improve upon,
- Identify the advantages and drawbacks of the GIS analysis techniques used and how they may be improved upon for future analyses,
- Identify any spatial accuracy, resolution, and insufficiency issues as well as criteria and associated data layers not incorporated that would enhance the analysis, and
- Describe the considerations for applying this study's analysis in other domestic and international settings.

## IV. METHODS

### 4.1 Study Area

The study area encompasses the 25 miles of Delaware's Atlantic Ocean coastline from Fenwick Island in the south to the northern most point at Cape Henlopen (Figure 4.1). Also identified in Figure 4.1 are the beaches on Delaware's shoreline where surfing has historically taken place as indicated by DE SRF (2014) in Table 2.1.



**Figure 4.1 – Study Area and Delaware Surf Breaks.** This map shows this project's study area, encompassing the 25 miles of Atlantic coastline from Fenwick Island at the DE/MD line to the northern most point on Cape Henlopen. Labeled are the beaches along Delaware's Atlantic coast where surfing has historically taken place, as indicated by DE SRF (2014) in Table 2.1. Created with Esri ArcGIS/ArcInfo Desktop 10.2.1. ©2014 Esri. All rights reserved. Produced here for educational purposes only.

### 4.2 Analysis Criteria and Data Layers

The criteria used for identifying suitability for ASR deployment were defined so the appropriate spatial data layers representing each criterion could be selected. Table 4.2.1 lists the general criteria that are pertinent in regards to ASR design and deployment, as well as study area specific criteria deemed important for this analysis. These criteria were chosen for several reasons. The

water depth where an ASR is placed will determine how waves breaking over the ASR will form and how far away from the shoreline waves will break, thus, near-shore water depth will need to be considered as a criterion for this analysis (Barber *et al.*, 2009; Scarfe *et al.*, 2009; Tseng *et al.* 2001). Depths too great can have the effect of waves not breaking over the ASR, but depths too shallow may create dangerous conditions for surfers. Near-shore seabed slope needs to be considered because differing slopes can create waves of varying surfability (Black & Mead, 2009). Slopes less than 4 degrees can create waves of an average surfability difficulty level, and slopes greater than 5 degrees may be unsuitable for reef stability (Barber *et al.*, 2009; Black & Mead, 2009). Substrate types should be considered because differing substrates have varying levels of support for ASR materials (Barber *et al.*, 2009; Scarfe *et al.*, 2009; Tseng *et al.* 2001). The presence of waves is certainly a requirement for an ASR to produce surfable waves. Cáceres *et al.* (2010) found that generally wave heights should exceed 0.35 meters for waves to be surfable. Wind conditions can affect the surfability of waves at a given location, and should also be considered for determining suitability for an ASR (Phillips *et al.*, 2003; Scarfe *et al.*, 2009). The locations where the activity of surfing is currently practiced should also be considered important for the deployment of an ASR as these locations will draw the highest numbers of surfers, both local and visiting (Scarfe *et al.*, 2009). Though, certain surf breaks in Delaware have coastal management structures already in place (e.g., jetties and groins) that may already produce surfable conditions, so the priority for an ASR may not be as high as other surfing locations without structures in place (DE SRF, 2014). The numbers of surfers at certain locations should also be considered a criterion, where locations with higher numbers of surfers should be considered more suitable for ASR deployment (Scarfe *et al.*, 2009).

Proximity of potential ASR deployment locations to public parking amenity needs to be considered as a suitability criterion. Proximity to public parking facilities can determine the accessibility to an ASR for the general public, especially visiting surfers, where parking options for non-residents during the summer season can be limited (Beachapedia, 2013; Hearin, 2009). Beach access to sites where an ASR may potentially be located is also important for determining suitability. Proximity to a higher number of beach access points, such as dune crossings, can equate to higher beach accessibility (Beachapedia, 2013). Additionally, restrictions on watersports such as surfing and recreational conflicts with other user groups on beaches should be considered important for determining suitability. Various beaches along Delaware's coast have regulations on watersports, including surfing, during summer months, in addition to certain beaches being closed to the public (Beachapedia, 2013; DNREC, 2004b). Certain user groups on Delaware beaches may also have conflicting activities on beaches, such as the beaches where the activity of surf fishing is allowed (DNREC, 2014). Fishing lines cast by surf fishing participants can affect the ability of surfers to access the water and ride waves.

With the pertinent suitability criteria outlined, appropriate spatial data layers were selected to effectively represent these criteria. Table 4.2.2 lists the data layers used for each analysis criterion, with the spatial data format type (e.g., vector, raster), the source of the data, the date of creation and representation, accuracy and resolution, and initial GIS processing steps taken to prepare the data for subsequent GIS suitability analysis steps.

**Table 4.2.1 – ASR Site Suitability Analysis Criteria.** Table lists the criteria used in this study’s site suitability analysis. These criteria include both general criterion related to ASR deployment, as well as a few study area specific criterion.

Criterion	Description	Reference
<i>General</i>		
Depth (Bathymetry)	Seafloor depth will determine how waves will break over a proposed ASR. Depths too great will avoid wave action needed for ASR to function. ASRs need to be located within or adjacent to existing surf zones.	Barber <i>et al.</i> , 2009; Scarfe <i>et al.</i> , 2009; Tseng <i>et al.</i> , 2001
Slope	Determines the hollowness and speed of wave, and thus, the skill level required to ride wave. ASRs producing average difficulty waves should be located on seabed gradients lower than 1:15 to 1:20, or approx. 3° to 4°. Steep slopes (>5°) unsuitable for reef stability.	Barber <i>et al.</i> , 2009; Black & Mead, 2009
Substrate	The type of substrate found on ocean floor will determine the stability and degree that reef materials may sink into ocean floor.	Barber <i>et al.</i> , 2009; Scarfe <i>et al.</i> , 2009; Tseng <i>et al.</i> , 2001
Wave Climate	Presence of waves with adequate heights will determine effectiveness of ASR. Wave heights exceeding 0.35 m are required for waves to be surfable.	Cáceres <i>et al.</i> , 2010; Scarfe <i>et al.</i> , 2009
Wind	Wind direction and speed can affect surfability of waves.	Scarfe <i>et al.</i> , 2009
Existing Surfing Breaks	Determines level of usage and exposure of ASR.	Scarfe <i>et al.</i> , 2009
Surfer Numbers	Historically higher numbers of surfers at surf breaks may equate with potentially more use of proposed ASR	Scarfe <i>et al.</i> , 2009
Parking Amenity	Proximity to parking can determine level of access to ASR location by general public, especially visitors, given limited parking options in Delaware coastal towns/cities.	Beachapedia, 2013; Hearin, 2009
Beach Accessibility	Access to beaches a requirement for ASR suitability. Proximity to higher numbers of beach access points (e. g., dune crossings) would be more suitable for ASR deployment.	Beachapedia, 2013
<i>Study Area Specific</i>		
Restricted Areas on Surfing	Various beaches along Delaware coast have restrictions in place (during summer months) for not allowing activity of surfing, in addition to privately owned beaches.	Beachapedia, 2013; DNREC, 2014
Recreational Conflicts	Various beaches allow for activities such as surf fishing, and may negatively affect or interfere with activity of surfing.	DNREC, 2014; Kennish <i>et al.</i> , 2002

## GIS-Based Site Suitability Analysis for an Artificial Surf Reef on Delaware's Atlantic Coast

**Table 4.2.2 – Analysis Criteria Data Layers.** Table lists the data layers used for each analysis criterion, specifying the data layer's name, spatial data format, source, date of creation and representation, spatial reference information, accuracy and resolution, and initial GIS processing tasks completed to prepare each data layer for site suitability analysis.

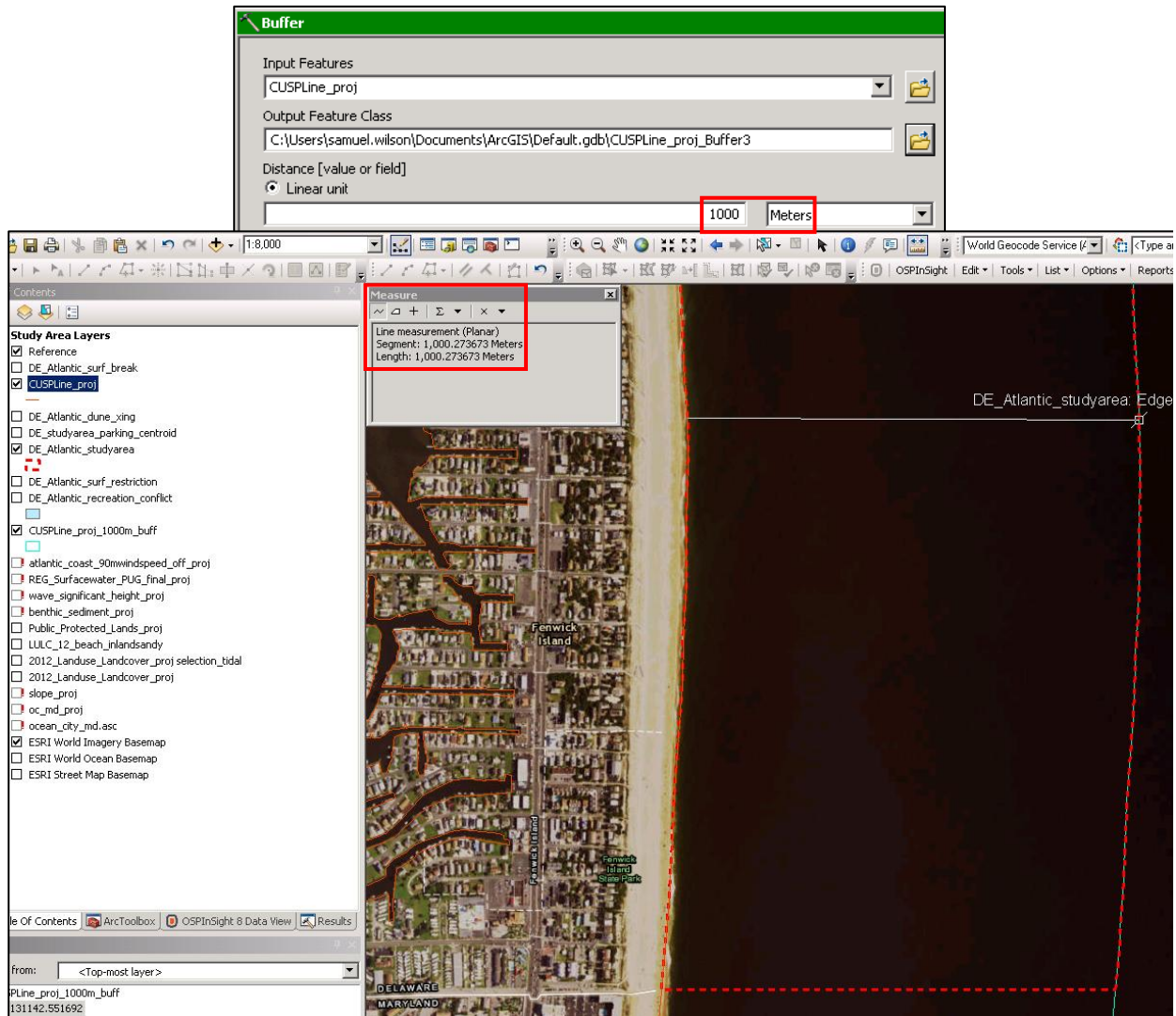
Criterion	Data Layer	Format	Source	Date of Creation / Representation	Spatial Reference	Accuracy & Resolution	Initial GIS Processing
<i>General</i>							
Depth (Bathymetry)	"Ocean City, MD/VA/DE 1/3 arc-second MHW DEM"	Raster (ESRI Arc ASCII)	Grothe <i>et al.</i> , 2010	Oct. 2009	Horizontal Datum: WGS 84; Vertical Datum: mean high water (MHW, meters)	Horizontal Acc.: 10 - 10's m; Vertical Acc.: 0.1 m - 5% water depth; Resolution: 1/3 arc-second (~10 m)	- project to NAD 83 Delaware State Plane projected coordinate system - clip to study area - resample to common analysis grid resolution (cell size) - create Slope raster surface
Slope	derivation of above DEM	Raster	Grothe <i>et al.</i> , 2010; this study	Creation: Jan. 2016; Representation: Oct. 2009	NAD 83 State Plane Delaware FIPS 0700 (m)	"	- derived from above DEM data layer
Substrate	"Sediment Grain Size"	Vector Polygon (.shp)	The Nature Conservancy, 2010	Creation: 2010; Representation: 2005	WGS 84 Web Mercator Auxiliary Sphere	Original point data interpolated using Kriging method in ArcGIS to raster grid of 500 meter cell size	- re-project to NAD 83 Delaware State Plane coordinate system - extrapolate data to within study area boundaries - clip to study area - convert to raster format & resample to common analysis grid resolution
Wave Climate	"Significant Wave Height"	Vector Polygon (.shp)	NREL, 2011	Creation: Oct. 2011	WGS 84	Resolution: data aggregated to grid of polygons approx. 1/15 degree of latitude (~7400 meters) in size	- project to NAD 83 Delaware State Plane projected coordinate system - extrapolate data to within study area boundaries - clip to study area - convert to raster format & resample to common analysis grid resolution
Wind	"Atlantic Coast 90m Windspeed Offshore Wind"	Vector Polygon (.shp)	NREL, 2012	Creation: Sep. 2009; Representation: Sep. 2009	WGS 84	Resolution: shapefile polygons produced from merging of 200 m resolution rasters	- project to NAD 83 Delaware State Plane projected coordinate system - extrapolate data to within study area boundaries - clip to study area - convert to raster format & resample to common analysis grid resolution
Existing Surfing Breaks	Digitized point locations of surf breaks/beaches	Vector Point (.shp)	This study	Creation: Jan. 2016; Representation: Present	NAD 83 State Plane Delaware FIPS 0700 (m)	Digitized at scale of 1:1,000 using ESRI World Imagery basemap	- digitize points representing locations of surf breaks/beaches (at shoreline) - create proximity polygons (Buffer Tool) - convert to raster format & resample to common analysis grid resolution
Surfer Numbers	"Surface Water-Based Activities"	Vector Polygon (.shp)	Point 97 <i>et al.</i> , 2013	Representation: Jul. – Dec. 2013	WGS 84 Web Mercator Auxiliary Sphere	Accuracy: data supplied by survey participants, grouped to 1x1 km grid	- clip to study area - convert to raster format & resample to common analysis grid resolution
Parking Amenity	"2012 Landuse, Landcover" / digitized	Vector Polygon / Point (.shp)	DE OSPC, 2012	Creation: Jan. 2016; Representation: 2012	NAD 83 State Plane Delaware FIPS 0700 (m)	Accuracy: digitizing performed per 2 acre min. mapping unit/digitized at scale of 1:1,000 using ESRI World Imagery basemap	- select LULC polygons for parking areas - derive centroids/digitize point locations - create proximity polygons (Buffer Tool) - convert to raster format & resample to common analysis grid resolution
Beach Accessibility	Digitized point locations of dune crossings	Vector Point (.shp)	This study	Creation: Jan. 2016; Representation: Present	NAD 83 State Plane Delaware FIPS 0700 (m)	Digitized at scale of 1:1,000 using ESRI World Imagery basemap	- digitize points representing locations of dune crossings - create proximity polygons (Buffer Tool) - convert to raster format & resample to common analysis grid resolution
<i>Study Area Specific</i>							
Restricted Areas on Surfing	"Public Protected Lands" / digitized	Vector Polygon (.shp)	DNREC PR, 2015a / this study	Last Modified: Jun. 2015/Creation: Jan. 2016; Representation: Present	WGS 84	N/A / Digitized at scale of 1:8,000 using ESRI World Imagery basemap	- project to NAD 83 Delaware State Plane projected coordinate system - extrapolate data to within study area & select land not in public polygons - clip to study area - convert to raster format & resample to common analysis grid resolution
Recreational Conflicts	Digitized areas representing recreation conflicts	Vector Polygon (.shp)	This study	Creation: Jan. 2016; Representation: Present	NAD 83 State Plane Delaware FIPS 0700 (m)	Digitized at scale of 1:8,000 using ESRI World Imagery basemap	- digitize polygons representing areas of recreational conflict - convert to raster format & resample to common analysis grid resolution

### 4.3 Workflow

The type of GIS analysis completed for this study was a raster data-based spatial analysis. Raster-based spatial representations of suitability criteria data layers were produced through GIS, and then overlaid through a map algebra operation to produce a single suitability output surface. Given the extensive use and discussion of overlay analysis techniques in other AR suitability studies (e.g., Barber *et al.*, 2009; Erfteimeijer *et al.*, 2004; Kennish *et al.*, 2002; Scarfe *et al.*, 2009; Tseng *et al.*, 2001), this type of analysis seemed the most effective for discovering spatial suitability. Furthermore, the ability to directly compare and combine data for the exact same locations on many different criteria input layers, reclassified to a common numerical suitability scale, made this method appealing (Randolph, 2004). Site suitability analysis encompassed several tasks to produce a final output layer for the study area. This included initial GIS software operations to manipulate each data layer in preparation for successive suitability analysis tasks, reclassification of each criterion's raster-based values to a common suitability ranking scale, the calculation of weight values to signify each criterion's importance to the overall goal of an ASR, and the creation of a suitability output surface through the combination of the ranking and weighting values.

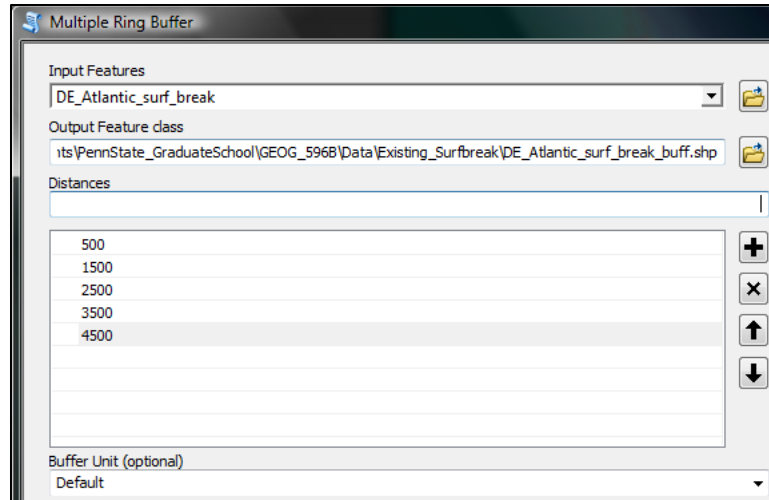
As indicated in Table 4.2.2, each data layer first underwent initial GIS software operations (i.e., GIS processing) in preparation for successive analysis tasks. Most of the existing data layers' spatial coordinate values needed to be confirmed and, if necessary, projected into a common, study-area specific planar (two-dimensional) coordinate system. Projecting a data layer's coordinate values involves applying a mathematical transformation operation in a GIS to convert three-dimensional coordinate values into two-dimensional values (Morais, 2002). Since many of these data layers had their spatial coordinate values in the WGS 84 geographic coordinate system, their coordinate values were stored in decimal degrees (e.g., three-dimensional latitude and longitude values). This made it difficult to perform accurate linear measurement operations in a GIS, such as finding the proximity (i.e., distance) of study area locations to criterion features (e.g., parking lots, existing surf breaks). Therefore, these data layers' coordinate values were projected into the Delaware NAD 83 State Plane coordinate system that uses linear units of meters. This task was performed using ArcGIS's Project (for vector data layers) (Esri, 2015b) and Project Raster tools (for raster data layers) (Esri, 2015c). Following this projection task, the study area boundary was created so that existing data layers could be restricted by the study area's extent. The study area boundary was created based on the National Oceanic and Atmospheric Administration National Geodetic Survey's (NOAA NGS) Continually Updated Shoreline Product (CUSP) spatial data layer (2011). This layer represents the most current delineation of the United States mean high water (MHW) shoreline based on several imagery, lidar and other data sources (NOAA NGS, 2011). Referencing the CUSP data layer line (hereinafter "CUSP line"), ArcGIS's Buffer tool (Esri, 2014a) was used to create a 1,000 meter buffer polygon to the seaward side (e.g., eastern side in the case of this study area) of the CUSP line (Figure 4.3.1). The distance of 1,000 meters was chosen for the reason that based on the list of existing and proposed ASRs from around the world (Table 2.3), no ASR has been placed farther than 750 meters from its respective shoreline. Rounding up from this number, 1,000 meters from the shoreline was deemed a sufficient distance that any proposed ASR would be located within in any coastal setting. This 1,000 meter buffer area was extended from the Delaware – Maryland state line in the south up to the northern most point of Cape Henlopen in the north, thus, defining the study area boundary.





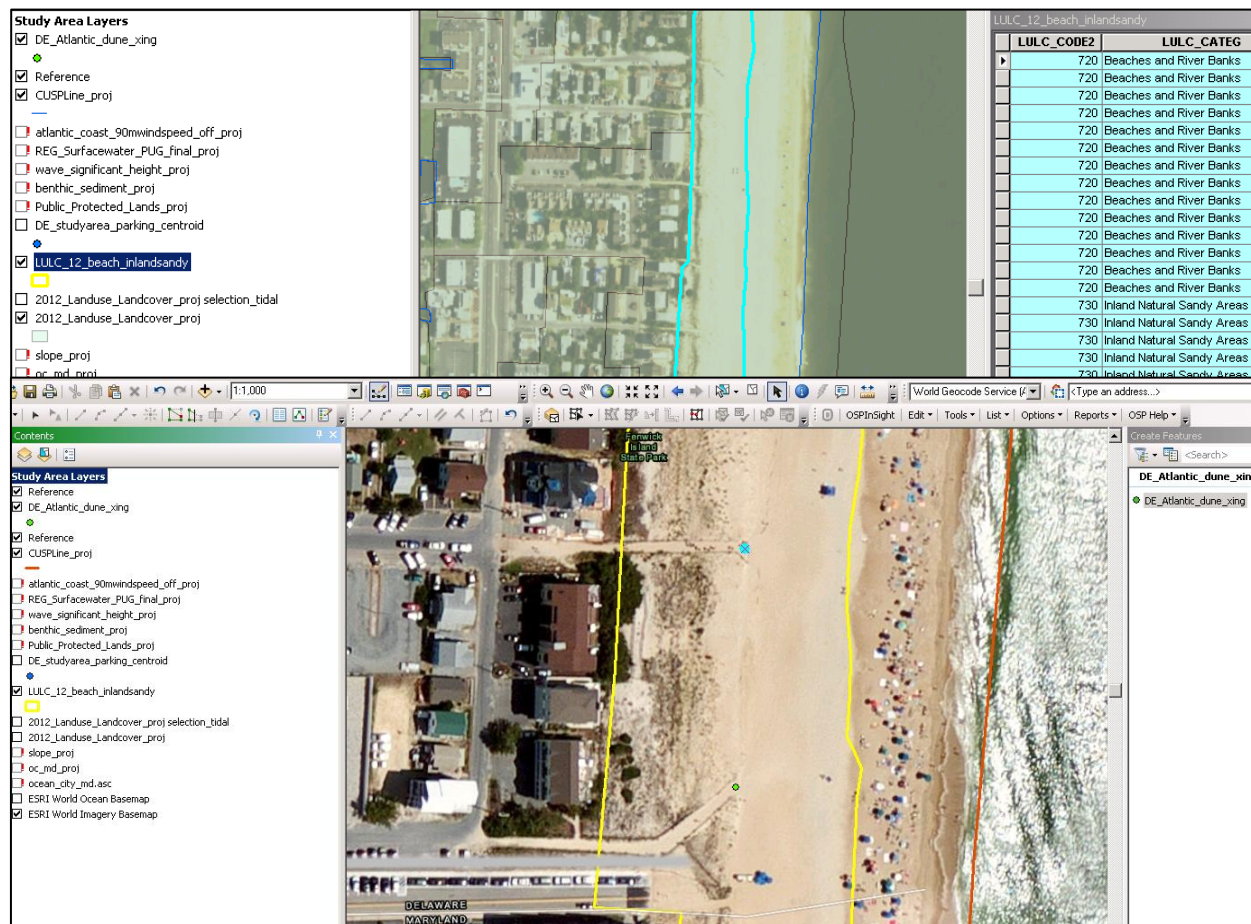
**Figure 4.3.1 – Study Area Boundary Creation.** These screenshots show the process applied to create the study area boundary, used for extracting and delineating data from each criterion data layer. The Buffer tool in ArcGIS was employed to create a 1,000 meter buffer polygon seaward from the CUSP line. Created with Esri ArcGIS/ArcInfo Desktop 10.2.1. ©2014 Esri. All rights reserved. Produced here for educational purposes only.

The next step taken was to create data layers for the criteria that did not have existing, publicly available data layers. These criteria included existing surfing breaks, beach accessibility, and recreational conflicts. Other criteria that had incomplete, but available data layers included parking amenity and restricted areas on surfing, so these criteria data layers were also partly created for this study. The first data layer created was the point locations of existing surfing breaks. For the purposes of this study, the points digitized for this data layer were representative of the precise location where surfing takes place on Delaware’s coastline, and proximity to these locations was considered an important criterion for this analysis. One point was digitized at the CUSP line for each of the nine historic surf breaks listed in Table 2.1 using ArcGIS’s Editor tools (Esri, 2013a). The surf break points were confirmed through personal knowledge and maps from two sources: the DNREC State Parks website (2015b) and Wannasurf.com (2009). ArcGIS’s Multiple Ring Buffer tool (Figure 4.3.2) was then used to create buffer polygons at the following distances from the surf break points to depict proximity across the entire study area:



**Figure 4.3.2 – Existing Surfing Breaks Proximity Distances.** This diagram shows a screenshot of the Multiple Ring Buffer tool in ArcGIS used to create buffer distances around each surf break point, where distance to the surf breaks determined suitability for an ASR. Created with Esri ArcGIS/ArcInfo Desktop 10.2.1. ©2014 Esri. All rights reserved. Produced here for educational purposes only.

500, 1500, 2500, 3500 and 4500 meters (Esri, 2014b). The next data layer created was for the beach accessibility criterion, containing the point locations of dune crossings along the coastline. To consistently digitize the dune crossing locations, the “2012 Landuse, Landcover” data layer from the Delaware Office of State Planning Coordination (DE OSPC; Table 4.2.2) was used as a reference. The land use, land cover types covering dune area along the coast were first selected from the 2012 Landuse, Landcover data layer, and these included “Beaches and River Banks” and “Inland Natural Sandy Areas” (Figure 4.3.3) (DE OSPC, 2012). At a map scale of 1:1000, points were then placed in the middle (from east to west) of the selected land use, land cover polygons at the locations of dune crossings, as observed on ArcGIS Online’s World Imagery basemap service layer (Figure 4.3.3) (Esri, 2016). This process was repeated along the entire coastline, except for the stretch of beach in the Town of South Bethany. Running along the middle of this beach’s dune area, a shoreline-parallel pathway is present that connects each dune crossing. Dune crossing points were digitized at the intersection of this dune pathway and each dune crossing, as this represented the approximate middle of the dune area land cover type. ArcGIS’s Multiple Ring Buffer tool was then used to create buffer polygons at the following distances from the dune crossing points: 500, 1,000, 1,500, 2,000 and 3,000 meters. Another data layer created for this study was for the recreational conflicts criterion. This data layer was digitized as polygons attributed with the number of recreational activities other than surfing that take place along the respective stretch of coastline. The polygons were digitized at a map scale of 1:8000 by tracing along the CUSP line and extending out to eastern study area boundary line to provide complete study area coverage. The polygons ranged in size from a street block’s length of beach up to entire stretches of state park beach, depending on where certain recreational activities are allowed. Once digitized, the polygons were populated with attributes describing which recreational activities take place in that stretch of the coast that may interfere with surfing. A “Y” (if activity takes place) or “N” (if activity does not take place) was entered for the



**Figure 4.3.3 – Beach Accessibility Criterion Data Layer Creation.** These screenshots show the process applied to create the beach accessibility criterion data layer, where points were placed at dune crossings in the east – west center of landuse, landcover polygons covering dune areas (in yellow). These dune crossing points were digitized at a map scale of 1:1000 while referencing ArcGIS Online’s World Imagery basemap service layer. Created with Esri ArcGIS/ArcInfo Desktop 10.2.1. ©2014 Esri. All rights reserved. Produced here for educational purposes only.

polygons for the following activities: surf fishing, swimming, kayaking, wind surfing, and kiteboarding. Additionally, an attribute field for the count of activities was populated with values ranging from 1 to 5, depending on how many “Y’s” the respective polygon contained.

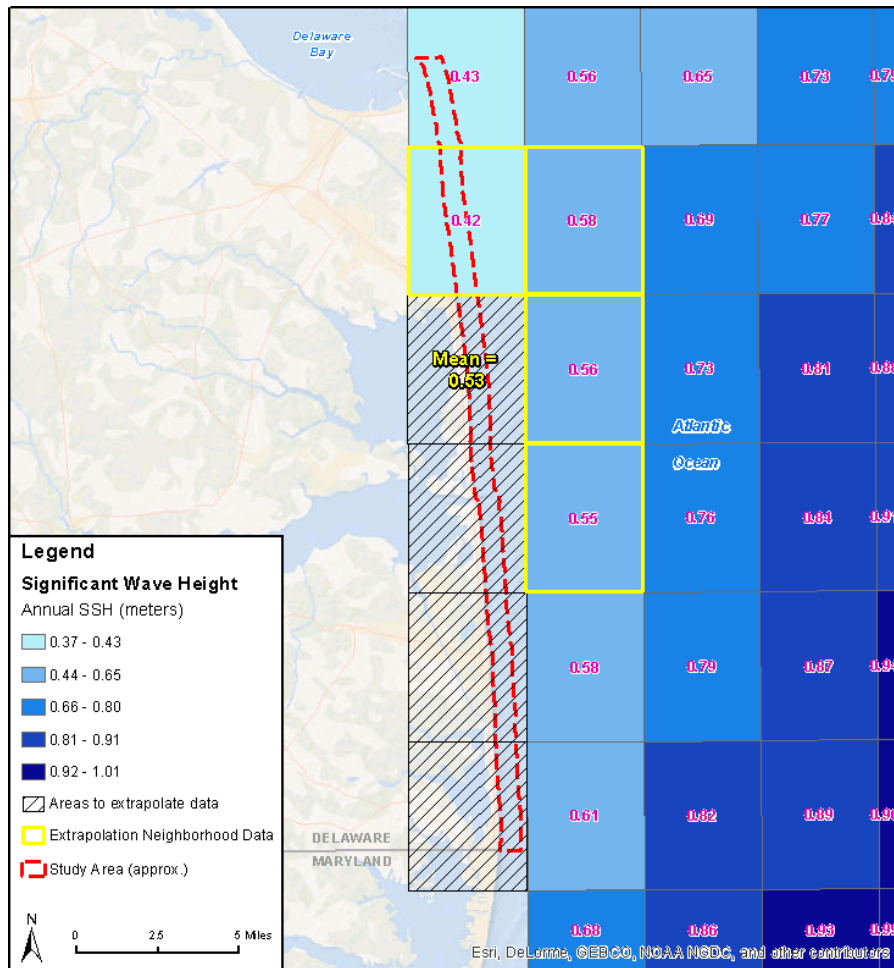
The other data layers partially created for this study, the parking amenity and restricted areas on surfing criteria data layers, were also digitized using ArcGIS’s Editor tools. The parking amenity data layer contained the point locations of public parking amenities including parking lots, metered parking, and other on-street parking. First, the 2012 Landuse, Landcover data layer from DE OSPC was used to select the polygons for parking lots on the ocean-side of Coastal Highway for the entire study area. Once these land cover polygons were selected, the ArcGIS Feature To Point tool was employed to generate a data layer containing the centroids of these polygons (Esri, 2015d). Since the 2012 Landuse, Landcover data layer’s polygons did not capture all parking areas as separate polygons, some manual digitizing was conducted. Points were added to the parking amenity data layer at places that had metered and on-street parking. The points were placed in the middle of street blocks adjacent to the beach that had these types of parking. Once completed, the Multiple Ring Buffer tool was used to create buffer polygons at the following

distances from the parking amenity points: 500, 1000, 2000, 3000 and 4000 meters. The data layer for the restricted areas on surfing criterion was created based on an existing data layer created by DNREC Division of Parks & Recreation (DNREC PR) named "Public Protected Lands" (Table 4.2.2) (2015a). Referencing this layer, the restricted areas on surfing layer's polygons were digitized, using a similar technique to that of the recreational conflicts data layer polygons, in order to provide complete study area coverage. Sections of the study area adjacent to the "public" polygons in the DNREC PR layer were attributed as "N" for no restrictions (i.e., surfing is allowed), and sections of the study area adjacent to places where no public polygons existed were attributed as "Y" for restrictions on surfing in place (i.e., surfing is not allowed).

The necessary data layers were then extrapolated to the study area's extent, depending on how data fell within the study area, and then restricted to the study area boundary. Restricting or "Clipping" data in a GIS involves extracting a subset of data from one data layer using the spatial extent of another spatially intersecting data layer (Morais, 2008). Extrapolating data in a GIS involves estimating data values at locations beyond a data layer's existing spatial boundaries using known values in the adjacent, existing data (Morais, 2013). The Significant Wave Height data layer was one of the data layers that had a spatial extent falling just east of the eastern edge of the study area boundary. Therefore, a means of extrapolating to the study area extent was used. The extrapolation technique was similar to that of the Focal Statistics functionality seen in ArcGIS's Spatial Analyst Neighborhood toolset (Esri, 2014c). The polygons of the original data layer were extended into the study area by creating new polygons overlapping the study area. These new polygons were populated with values equaling the mean value of a surrounding three by three neighborhood of polygons. Figure 4.3.4 shows an example of how this extrapolation technique was applied for the Significant Wave Height data layer. As seen in Figure 4.3.4, the hatch pattern polygons are the polygons for extrapolation, using the surrounding neighborhood of grid polygons (highlighted in yellow), where the mean value of the neighborhood polygons was used to populate the unknown polygon. Other criteria data layers that required some level of extrapolation to provide continuous data coverage in the study area included the substrate and wind criteria data layers. Figure 4.3.5 shows an example of how the substrate and wind data layers did not completely cover the entire study area. The polygon edges of these two data layers were translated laterally to the western boundary of the study area to fill in the gaps in data, using ArcGIS's Topology Edit and Reshape Edge tools (Esri, 2013b). Because these two criteria (e.g., substrate and wind) represent continuous phenomena in the real world, their respective data were extrapolated to provide continuous data coverage throughout the study area. Once all digitizing tasks were complete, each data layer was clipped by the study area boundary layer using ArcGIS's Clip tool (Esri, 2014d) for the vector-based data layers, and the Extract by Mask tool (Esri, 2014e) for the raster-based depth criterion data layer.

Before the conversion to raster data format and raster resampling task, the data layer for the slope criterion needed to be created. This data layer was derived using ArcGIS's Slope tool (Esri, 2014f). Utilizing the depth criterion data layer as the input, the Slope tool was used to create a raster layer, containing the gradient values of the study area's seafloor, in units of degrees.

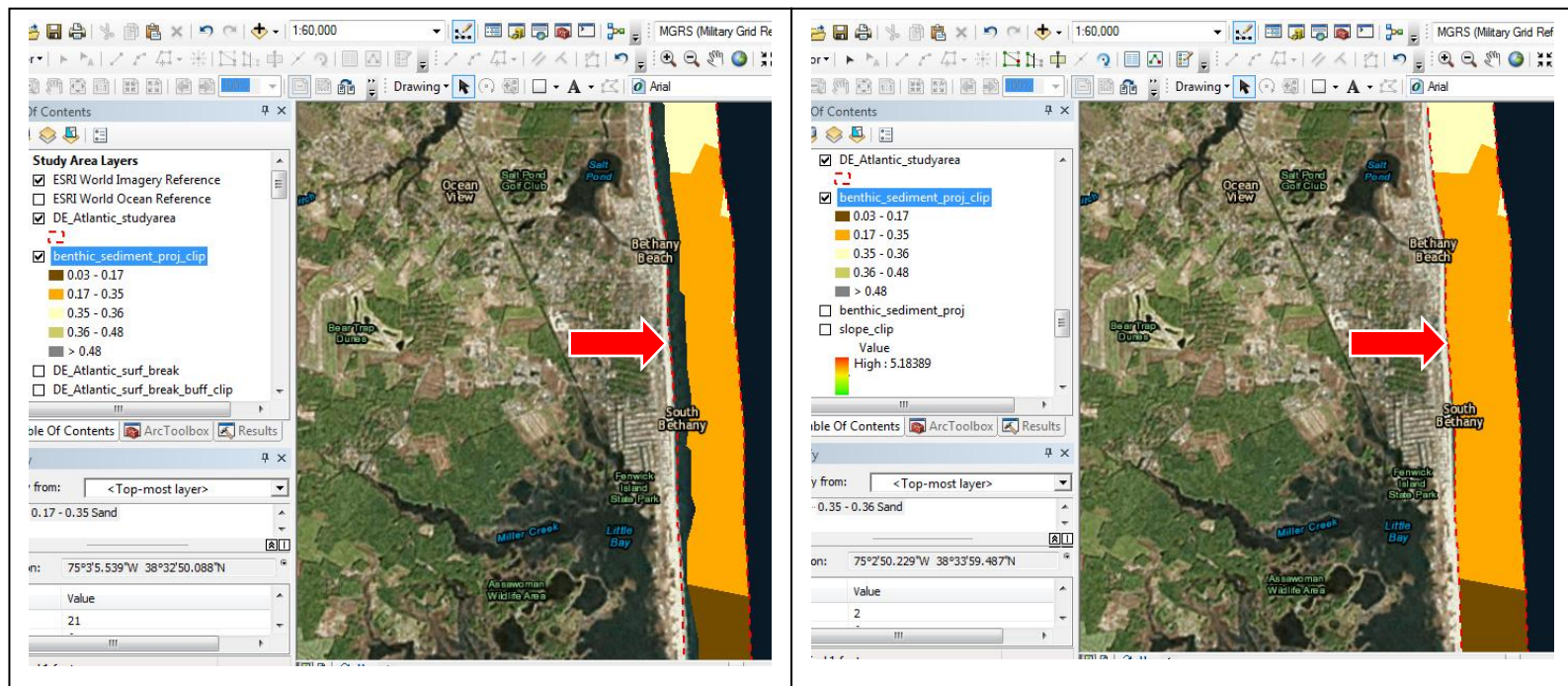
The last of the initial GIS processing encompassed the task of converting each data layer to raster data format and resampling the raster representations of each data layer to a common analysis grid resolution. Resampling raster data in a GIS involves estimating the data values of cells (also



**Figure 4.3.4 – Wave Climate Criterion Data Layer Extrapolation.** This map shows the extrapolation technique used for the Significant Wave Height data layer (wave climate criterion). The unknown polygon was populated with the mean value of the surrounding neighborhood (3x3) of polygons. Created with Esri ArcGIS/ArcInfo Desktop 10.2.1. ©2014 Esri. All rights reserved. Produced here for educational purposes only.

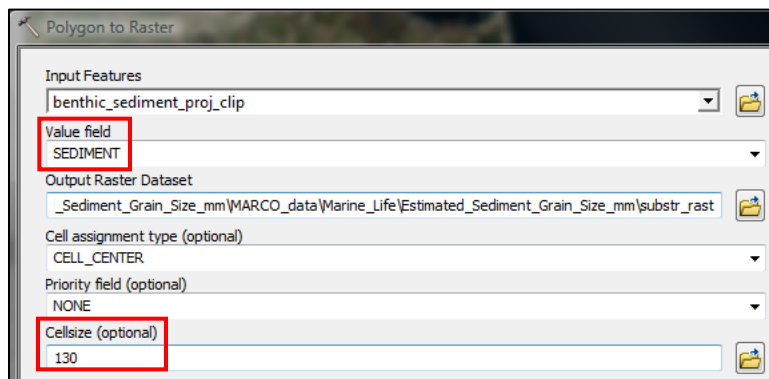
called pixels) in a raster data layer with a differing grid resolution (i.e., cell size) than the original, input raster data layer (Esri, 2014g). Resampling each raster surface into a common grid resolution ensured that the same locations were evaluated across all data layers when calculating suitability. The analysis grid resolution was a cell size equal to the average length or width of existing and proposed ASRs from around the world, calculated from the dimensions seen in Table 2.3, with the smaller of the two average values being the raster cell size used in analysis. After calculating these two average values, it was found that the average length of these ASRs was ~130 meters, while the average width was ~135 meters. This means that a cell size of 130 meters was used to produce the final suitability layer. Each vector-based data layer was then converted to raster data format using ArcGIS’s Polygon to Raster tool (Esri, 2014h). When using the Polygon to Raster tool, the “Value field” tool parameter was specified as the field in the respective data layer that contained the values used to determine suitability for an ASR, and these values would be assigned to the output raster’s cells (Esri, 2014h). For example, in the

## GIS-Based Site Suitability Analysis for an Artificial Surf Reef on Delaware's Atlantic Coast



**Figure 4.3.5 – Substrate Criterion Data Layer Extrapolation.** These screenshots show the extrapolation technique used for the Benthic Sediment data layer (substrate criterion). The original data polygons (left) were simply translated laterally to the western boundary of the study area (right) in order to provide continuous data coverage for this criterion across the study area. The Atlantic Coast 90m Windspeed Offshore Wind data layer (wind criterion) underwent the same extrapolation process. Created with Esri ArcGIS/ArcInfo Desktop 10.2.1. ©2014 Esri. All rights reserved. Produced here for educational purposes only.

Significant Wave Height data layer (e.g., wave climate criterion), the attribute field chosen for Value field parameter was the “Annual SSH” field containing the wave height values, while the field chosen from the Sediment Grain Size data layer (e.g., substrate criterion) was the “Sediment” field containing the average sediment grain size values (Figure 4.3.6). Additionally, the “Cellsize” parameter was set to 130 meters, as determined previously (Figure 4.3.6).



**Figure 4.3.6 – Data Layer Raster Conversion.** This diagram shows a screenshot of the Polygon to Raster tool in ArcGIS used to create raster data format representations of each vector data layer. The “Value field” parameter was the data layer field used to assign values to each output raster cell. The “Cellsize” parameter was set to 130 meters. Created with Esri ArcGIS/ArcInfo Desktop 10.2.1. ©2014 Esri. All rights reserved. Produced here for educational purposes only.

For the two raster data layers, the depth and slope criteria data layers, ArcGIS’s Resample tool was used to change the raster cell sizes to the 130 meter target cell size (Esri, 2015e). For this tool’s parameters, the cell size parameter was set to 130 meters, and the “Resampling Technique” parameter was set to “BILINEAR.” The bilinear interpolation resampling technique involves calculating the value of an output raster cell using a “weighted distance average” value of the four nearest input raster cell centers, and is best for continuous data, such as depth and slope data (Esri, 2015e).

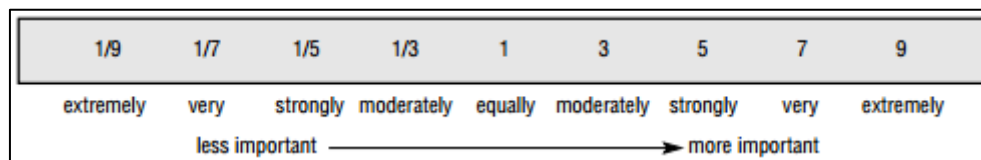
Each criterion’s raster-based data layer values were then reclassified to a common suitability ranking scale. This reclassification task ensured meaningful comparisons were made between each data layer in terms of how suitable a particular location was for ASR deployment, as reclassifying to a relative scale is necessary to compare criteria to one another (Esri, 2014i). The suitability ranking scale employed was a five point scale of integers, ranging from 1 to 5, where higher values (i.e., 4, 5) represented locations of higher suitability for ASR deployment and lower values (i.e., 1, 2) represented less suitability. A value of zero (0) was used in cases where the deployment of an ASR was not feasible, such as places where access to and ownership of the beach is private, or where the slope of the seafloor is too steep, following Barber *et al.* (2009). Table 4.3.1 lists the reclassification values for each data layer, showing how the original data

**Table 4.3.1 – Criteria Data Layer Reclassification Assignments.** Table lists the reclassified values (e.g., 1 – 5) assigned to each criterion data layer’s original values. These reclassified values were multiplied by weight values to produce the final ASR suitability values.

Criterion	Original Values	Reclassified Values	Criterion	Original Values	Reclassified Values
<i>General</i>			<i>General</i>		
Depth (Bathymetry - m)	0 - 3	4	Existing Surfing	0 - 500	5
	3 - 6	5	Breaks	500 - 1,500	4
	6 - 9	3	(Proximity to Surf Break - m)	1,500 - 2,500	3
	9 - 12	2		2,500 - 3,500	2
	> 12	1		3,500 - 4,500	1
Slope (Seabed Gradient)	0 - 1 °	5	Surfer Numbers (Jul - Dec. '13 Total)	0 - 1	1
	1 - 2 °	4		2 - 4	2
	2 - 3 °	3		5 - 14	3
	3 - 4 °	2		15 - 30	4
	4 - 5 °	1	31 - 51	5	
> 5 °	0	Parking Amenity (Proximity to Parking - m)	0 - 500	5	
Substrate (Sediment Grain Size - mm)	0.03 - 0.17		1	500 - 1,000	4
	0.17 - 0.35		2	1,000 - 2,000	3
	0.35 - 0.36		3	2,000 - 3,000	2
	0.36 - 0.48	4	3,000 - 4,000	1	
0.48+	5	Beach Accessibility (Proximity to Dune Crossing - m)	0 - 500	5	
Wave Climate (Annual Significant Wave Height - m)	0 - 0.42		1	500 - 1,000	4
	0.42 - 0.50		2	1,000 - 1,500	3
	0.50 - 0.55		3	1,500 - 2,000	2
	0.55 - 0.60	4	2,000 - 3,000	1	
0.60 - 0.65	5	<i>Study Area Specific</i>			
Wind (Speed at 90 m Elevation - m/s)	7.125 - 7.275	1	Restricted Areas on Surfing	Yes	0
	7.275 - 7.425	2	(Restricted? - Y / N)	No	100
	7.425 - 7.575	3	Recreational Conflicts (# of Conflicts)	1	5
	7.575 - 7.725	4		2	4
	7.725 - 7.875	5		3	3
		4		2	
			5	1	

layer values were assigned new, reclassified values. To convert each layer’s original values to the respective reclassified values seen in Table 4.3.1, ArcGIS’s Reclassify tool was employed (Esri, 2014j).

Weight values, signifying each criterion’s importance to the analysis goal of determining ASR suitability, were determined using the Analytic Hierarchy Process (AHP). This technique involves making pairwise comparisons between the various criteria related to their importance to the overall goal of the study. In the case of this study, the goal is suitability for ASR deployment, so comparisons made between each pair of criteria are essentially stating how criterion A is to some degree more or less important than criterion B for determining suitability for ASR deployment. Given AHP’s successful use in calculating weights for GIS-based multi-criteria evaluation (MCE) studies (Eastman, 2005), including AR site suitability studies (Tseng *et al.*, 2001), this technique was employed for this study. Figure 4.3.7 shows the importance rating scale used in a typical AHP. A square matrix is used to hold these comparison values for each criterion to criterion comparison, where a value of “1” is placed in the cells that correspond to comparing a criterion to itself.



**Figure 4.3.7 – AHP Pairwise Comparison Importance Rating Scale.** This scale shows the range of importance scores used in an AHP decision matrix, including intermediate values (i.e., 1/8, 1/6, 1/4, 1/2, 2, 4, 6, 8), when making pairwise comparisons between each criterion. These were used to express importance in determining ASR suitability when comparing this study’s criteria (Eastman, 2005). ©2005 John Wiley & Sons, Inc. All rights reserved. Reproduced here for educational purposes only.

Figure 4.3.8’s matrices show how these pairwise comparison importance values were applied for this study’s criteria and how the weight values (principal eigenvectors) were calculated. To calculate the principal eigenvector values (i.e., weights) seen in Figure 4.3.8’s matrix “b.,” each importance value in matrix “a.” was normalized by dividing by its column total (“∑” row), and then the mean value of each matrix “b.” row was found (Estoque, 2011). These pairwise comparisons and weight value calculations were conducted using Microsoft’s Excel spreadsheet software (2016), allowing for the efficient updating of weight values in matrix “b.” when importance values in matrix “a.” were altered.

The AHP Consistency Ratio (CR) was then used to evaluate how consistently the importance ratings were applied in comparing each criterion’s importance over other criteria (Triantaphyllou & Mann, 1995). The pairwise comparisons are deemed consistent if the CR is less than 10%, (Triantaphyllou & Mann, 1995). The CR is calculated as follows: Consistency Index (CI) / Random Consistency Index (RCI). The CI is found by the following equation:  $CI = (\lambda_{max} - n) / (n - 1)$ ;  $\lambda_{max} = \sum$  of products between principal eigenvectors and column totals ( $\sum$ ), and  $n$  = number of criterion being compared (Estoque, 2011). The RCI for varying  $n$  is taken from Table 4.3.2.



**a.**

Criterion	Depth	Slope	Substrate	Wave Climate	Wind	Surf Breaks	Surf Numbers	Parking	Beach Access	Rec. Conflict
Depth	1	2	3	1/2	5	1/4	1/5	8	5	7
Slope	1/2	1	2	1/3	3	1/5	1/6	7	4	6
Substrate	1/3	1/2	1	1/4	2	1/6	1/7	6	3	5
Wave Climate	2	3	4	1	4	1/2	1	9	6	8
Wind	1/5	1/3	1/2	1/4	1	1/5	1/6	3	1/2	2
Surf Breaks	4	5	6	2	5	1	1	8	5	7
Surf Numbers	5	6	7	1	6	1	1	9	6	8
Parking	1/8	1/7	1/6	1/9	1/3	1/8	1/9	1	1/4	1/2
Beach Access	1/5	1/4	1/3	1/6	2	1/5	1/6	4	1	2
Rec. Conflict	1/7	1/6	1/5	1/8	1/2	1/7	1/8	2	1/2	1
$\Sigma$	13.5012	18.3929	24.2000	5.7361	28.8333	3.7845	4.0790	57.0000	31.2500	46.5000

**b.**

Criterion	Depth	Slope	Substrate	Wave Climate	Wind	Surf Breaks	Surf Numbers	Parking	Beach Access	Rec. Conflict	Principal Eigenvector (Weight)
Depth	0.0741	0.1087	0.1240	0.0872	0.1734	0.0661	0.0490	0.1404	0.1600	0.1505	0.1133
Slope	0.0370	0.0544	0.0826	0.0581	0.1040	0.0528	0.0409	0.1228	0.1280	0.1290	0.0810
Substrate	0.0247	0.0272	0.0413	0.0436	0.0694	0.0440	0.0350	0.1053	0.0960	0.1075	0.0594
Wave Climate	0.1481	0.1631	0.1653	0.1743	0.1387	0.1321	0.2452	0.1579	0.1920	0.1720	0.1689
Wind	0.0148	0.0181	0.0207	0.0436	0.0347	0.0528	0.0409	0.0526	0.0160	0.0430	0.0337
Surf Breaks	0.2963	0.2718	0.2479	0.3487	0.1734	0.2642	0.2452	0.1404	0.1600	0.1505	0.2298
Surf Numbers	0.3703	0.3262	0.2893	0.1743	0.2081	0.2642	0.2452	0.1579	0.1920	0.1720	0.2400
Parking	0.0093	0.0078	0.0069	0.0194	0.0116	0.0330	0.0272	0.0175	0.0080	0.0108	0.0151
Beach Access	0.0148	0.0136	0.0138	0.0291	0.0694	0.0528	0.0409	0.0702	0.0320	0.0430	0.0379
Rec. Conflict	0.0106	0.0091	0.0083	0.0218	0.0173	0.0377	0.0306	0.0351	0.0160	0.0215	0.0208

**Figure 4.3.8 – AHP Pairwise Comparison Decision Matrix and Weights Calculation.** These matrices show how an AHP decision matrix was applied using this study’s criteria to calculate weights for suitability analysis. Matrix “a.” lists the importance ratings (Fig. 4.3.7) assigned to the pairwise comparisons of the criteria, while matrix “b.” shows how the weights or principal eigenvectors were calculated using these importance ratings.

**Table 4.3.2 – AHP RCI Table.** Table lists the RCI values for varying *n*, or the number of criteria being compared in AHP. The RCI value is used to calculate the AHP’s CR value that evaluates how consistently importance ratings were applied in the pairwise comparison decision matrix. If the CR is less than 10%, importance ratings were applied consistently, and weights (i.e., principle eigenvectors) calculated in the decision matrix are acceptable to use in suitability analysis (Saaty & Vargas, 2012). ©2012 Springer Science & Business Media. All rights reserved. Reproduced here for educational purposes only.

Average random consistency index (R.I.)										
N	1	2	3	4	5	6	7	8	9	10
Random consistency index (R.I.)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

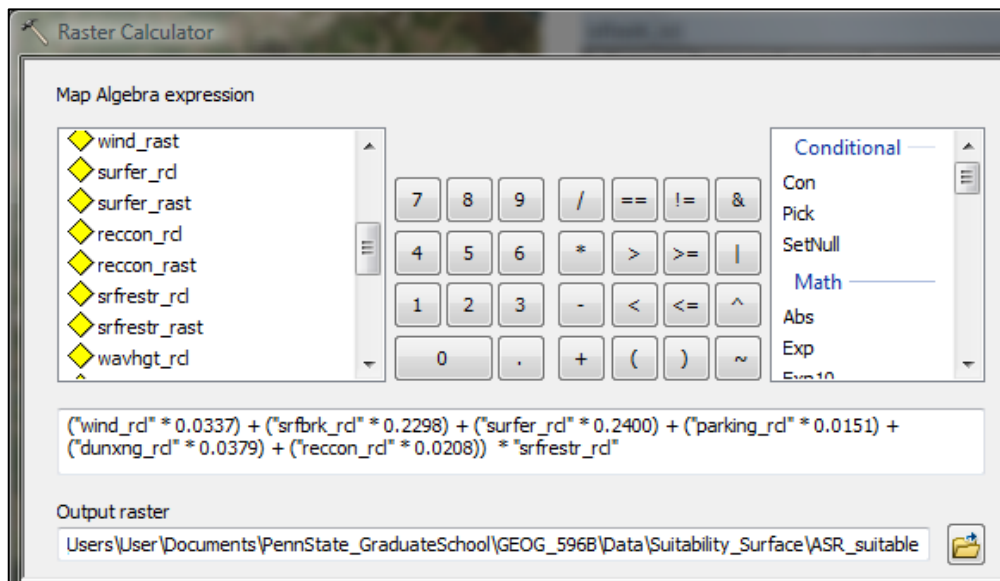
For this study, the following is how the CR was determined:

- $\lambda_{\max} = (13.5012 * 0.1133) + (18.3929 * 0.0810) + (24.2000 * 0.0594) + (5.7361 * 0.1689) + (28.8333 * 0.0337) + (3.7845 * 0.2298) + (4.0790 * 0.2400) + (57.0000 * 0.0151) + (31.2500 * 0.0379) + (46.5000 * 0.0208) = \sim 11.2627$
- **CI** =  $(11.2627 - 10) / 10 - 1 = \mathbf{0.1403}$ ; **RCI** = **1.49** ( $n = 10$ ; Table 4.3.2)
- **CR** =  $0.1403 / 1.49 = \mathbf{0.09}$ ;  $\mathbf{0.09 < 0.10 = Consistent}$

With the CR below 10%, the importance ratings used in comparing criterion in the decision matrix were applied consistently, meaning the weights (i.e., principal eigenvectors in Figure 4.3.8) calculated from the AHP were acceptable for use in suitability analysis.

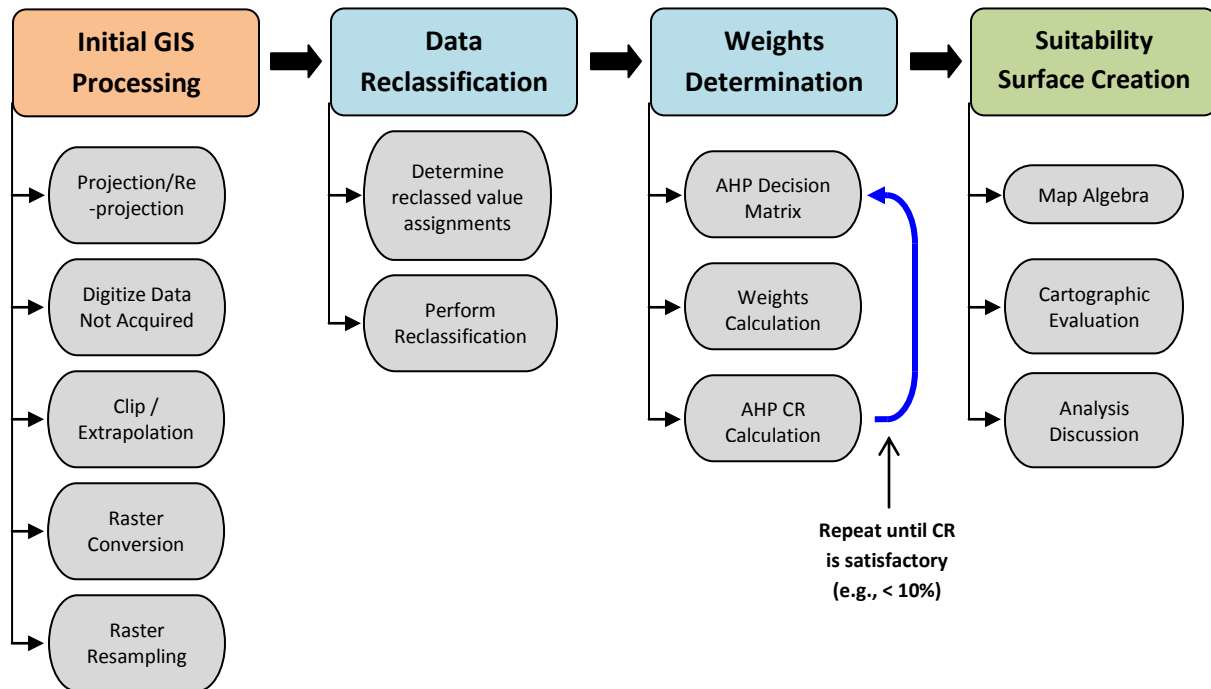
The analysis’ suitability layer was then produced through map algebra by multiplying each reclassified data layer’s values by the weight value associated with the criterion, as determined in the AHP, then finding the sum of these individual products, and multiplying by the restricted areas on surfing criterion layer (Figure 4.3.9). This map algebra task was conducted using ArcGIS’s Raster Calculator tool (Esri, 2014k). The following is the equation that was entered in the Raster Calculator tool to produce the suitability layer:

$$((\text{"oc\_md\_rcl"} * 0.1133) + (\text{"slope\_rcl"} * 0.0810) + (\text{"substr\_rcl"} * 0.0594) + (\text{"wavhgt\_rcl"} * 0.1689) + (\text{"wind\_rcl"} * 0.0337) + (\text{"srfrbk\_rcl"} * 0.2298) + (\text{"surfer\_rcl"} * 0.2400) + (\text{"parking\_rcl"} * 0.0151) + (\text{"dunxng\_rcl"} * 0.0379) + (\text{"recon\_rcl"} * 0.0208)) * \text{"srfrestr\_rcl"}$$



**Figure 4.3.9 – Suitability Layer Map Algebra.** This diagram shows a screenshot of the Raster Calculator tool in ArcGIS used to create the final ASR suitability raster layer. Each reclassified data layer was multiplied by its respective weight value (determined in AHP), and then each layer was added together (cell by cell) and multiplied by the “Restricted Areas on Surfing” layer to create the suitability layer. Created with Esri ArcGIS/ArcInfo Desktop 10.2.1. ©2014 Esri. All rights reserved. Produced here for educational purposes only.

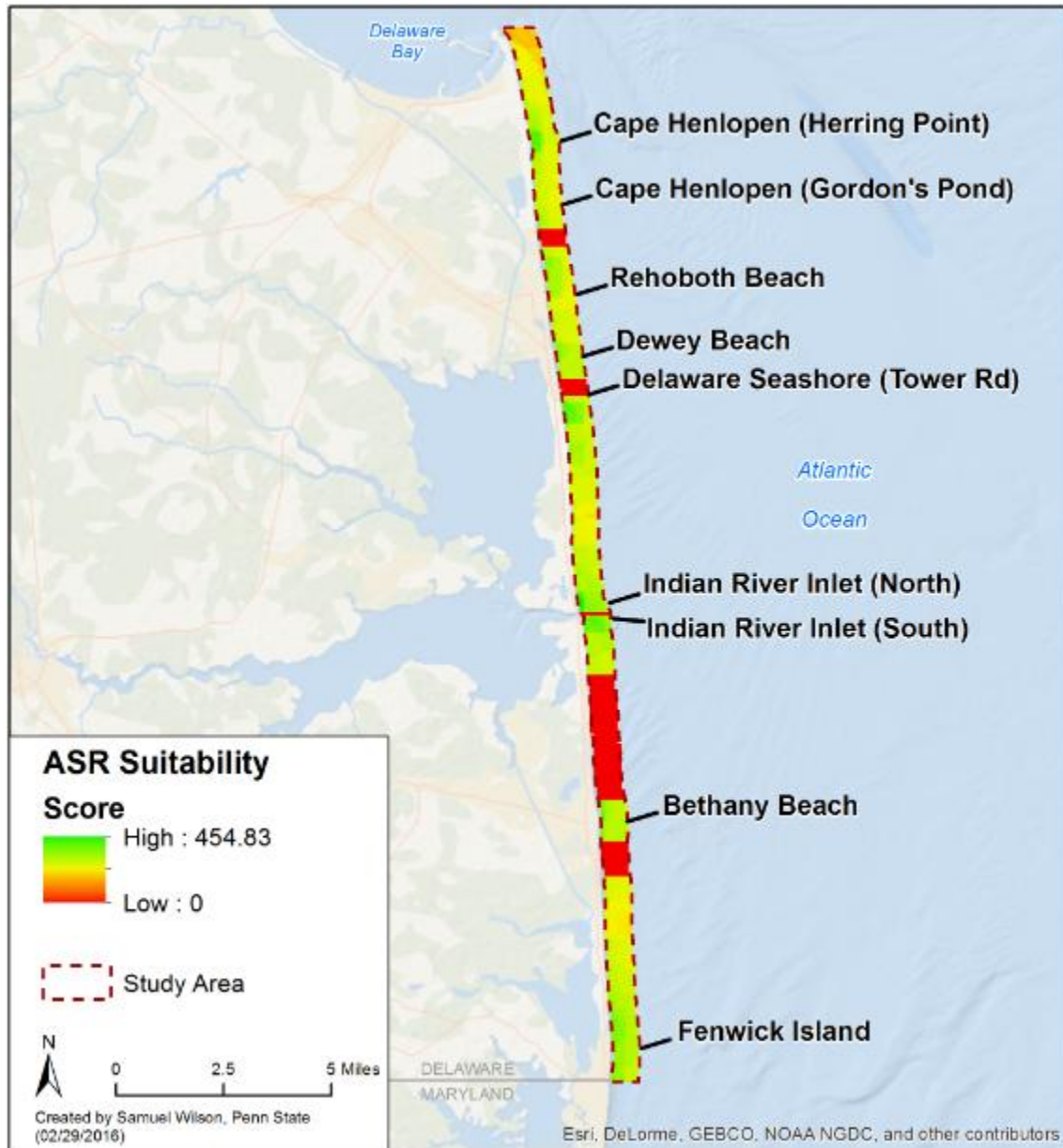
Figure 4.3.10 shows the workflow followed for this study, starting with initial GIS processing through to suitability surface discussion, with sub-tasks listed for each major task.



**Figure 4.3.10 – Analysis Workflow.** This diagram shows this study’s workflow for conducting GIS-based site suitability analysis. Starting with initial GIS processing tasks to prepare each data layer for further suitability analysis tasks, each data layer’s original values were then reclassified to a common 5-point scale, then weights of criteria were determined through the AHP (iterative until CR was satisfactory), followed by a map algebra operation that combined each data layer’s reclassified values with the associated weight value to produce a raster suitability surface. The suitability output surface was then evaluated through maps and discussion.

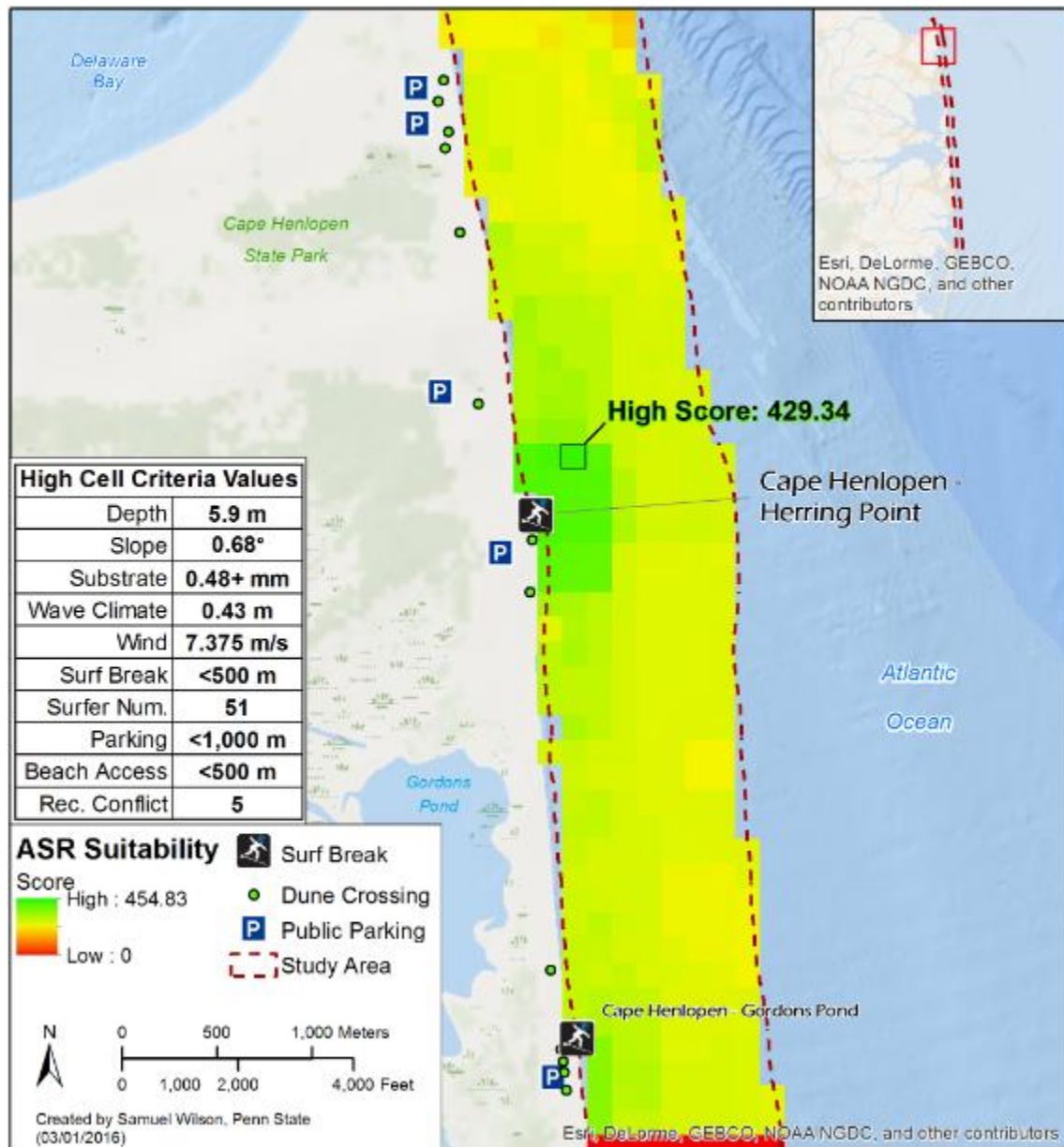
## V. RESULTS

Figure 5.1 shows the final ASR suitability raster layer produced from the map algebra equation seen in Figure 4.3.9. As seen in Figure 5.1's map of ASR suitability along Delaware's Atlantic coast, there was a wide range of suitability scores along the 25 miles of coastline. At the one end of the spectrum, those stretches of coastline where restrictions to the activity of surfing exist, such as beaches where ownership is private and access to the beach is restricted to the public,



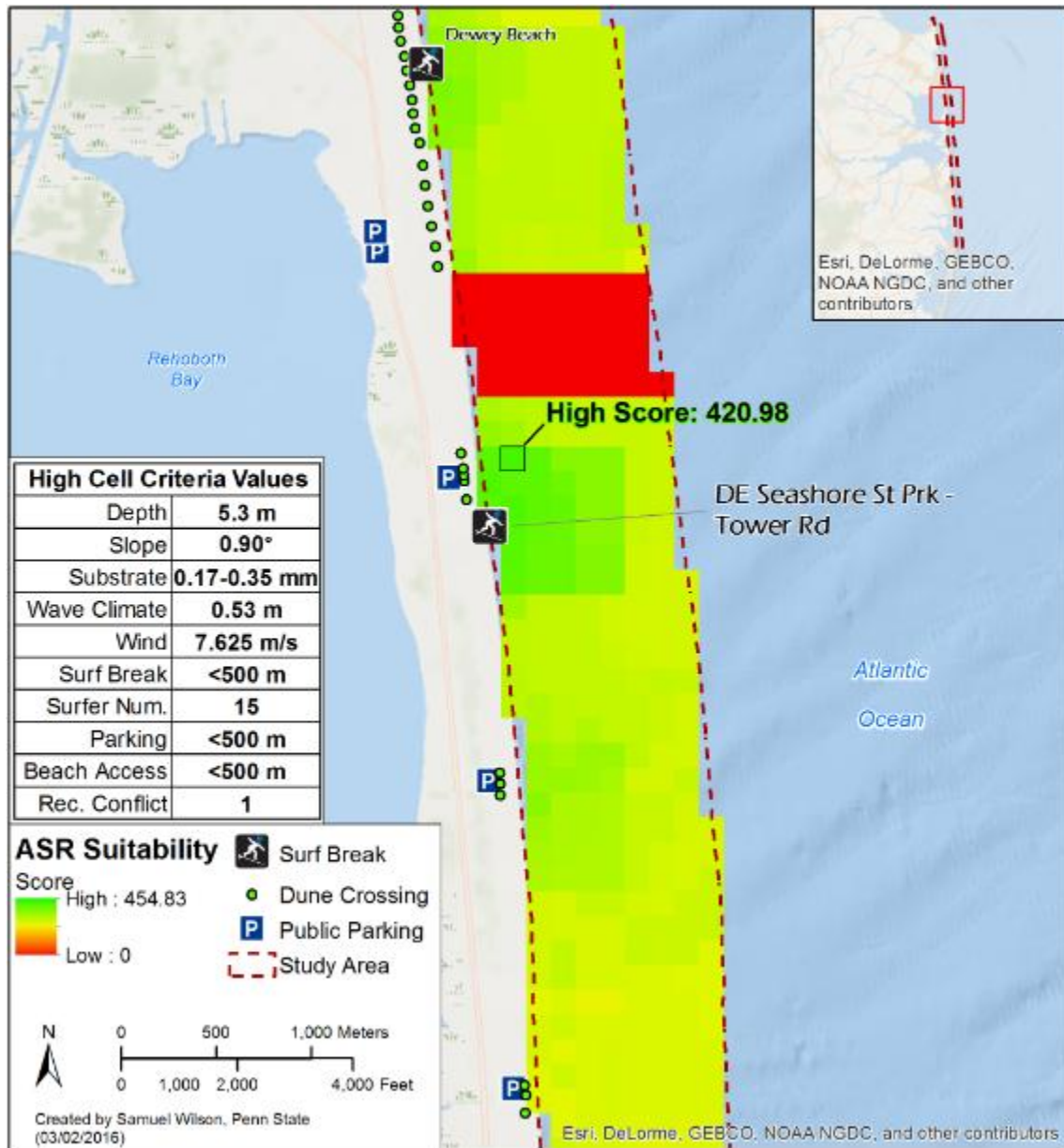
**Figure 5.1 – ASR Suitability on Delaware's Atlantic Coast.** This map shows the final ASR suitability layer, as produced by the map algebra equation that multiplied each individual criterion layer by its respective weight value, and then added each layer together (Fig. 4.3.9). Final suitability values ranged from 0 – ~455, where those raster cells with values of 0 (bright red) corresponded to areas of the coastline that restrict the activity of surfing. Created with Esri ArcGIS/ArcInfo Desktop 10.2.1. ©2014 Esri. All rights reserved. Produced here for educational purposes only.

correspond to suitability scores of 0 (bright red areas in Figure 5.1). On the other end of the range in suitability, the highest suitability scores existed only in a few locations. The top four locations included the Cape Henlopen – Herring Point surf break area (Figure 5.2), Delaware Seashore State Park’s Tower Road surf break area (Figure 5.3), and the Indian River Inlet’s North and South Side surf break areas (Figure 5.4). Figure 5.2’s map shows the suitability layer at the Cape Henlopen – Herring Point surf break area, indicating the highest scoring raster cell in that location and the surrounding area (e.g., 429.34). Also displayed in the map is a table listing each criterion data layer’s original data values at the highest scoring cell. Figure 5.3 presents a

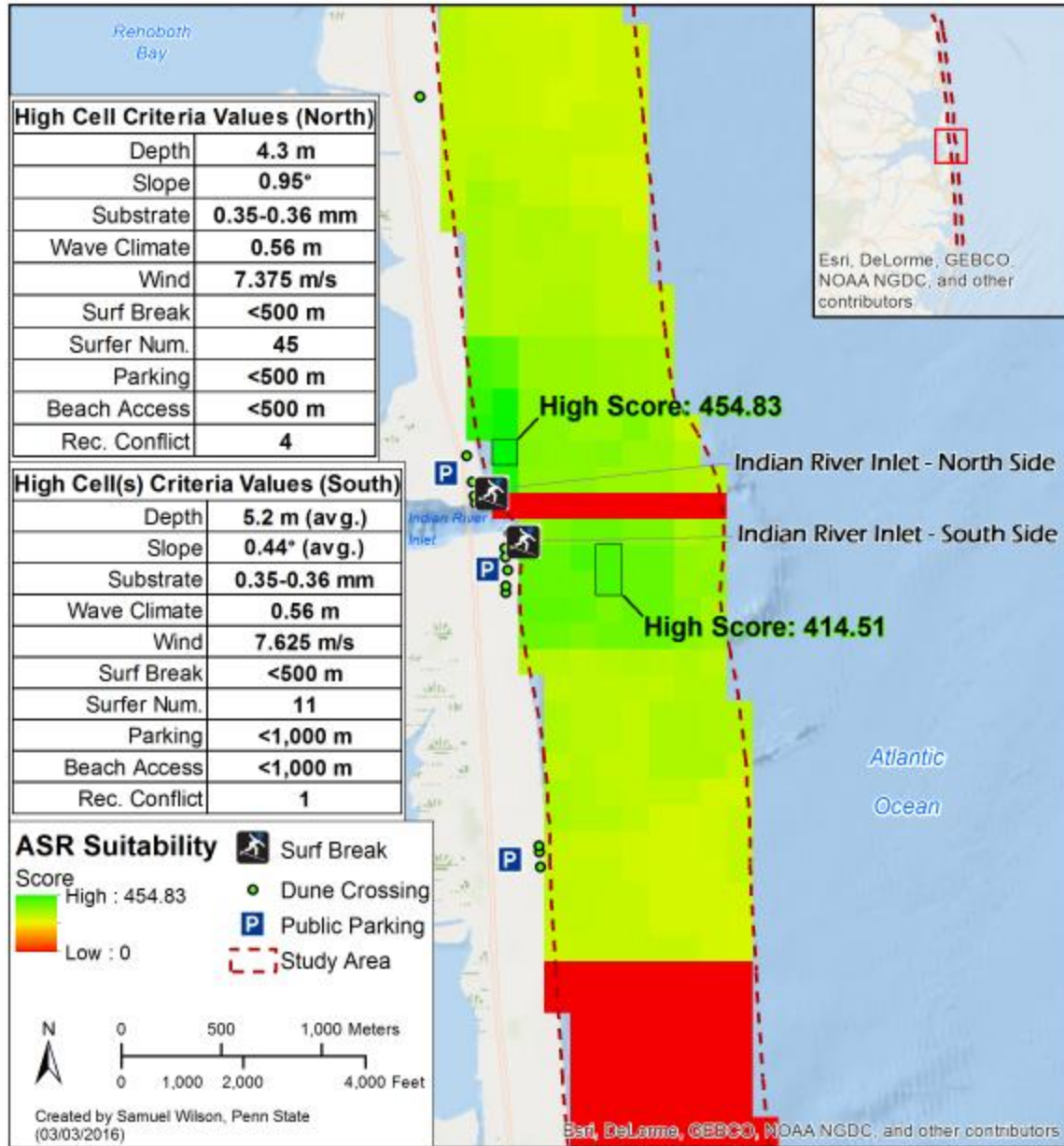


**Figure 5.2 – Cape Henlopen-Herring Point ASR Suitability.** This map shows the ASR suitability layer at the Cape Henlopen – Herring Point surf break area, one of the highest scoring locations in the study area. The highest scoring cell at this location is labeled (e.g., “High Score: 429.34”), with a table listing each criterion’s original data values at the cell also displayed. Created with Esri ArcGIS/ArcInfo Desktop 10.2.1. ©2014 Esri. All rights reserved. Produced here for educational purposes only.

similar map for Delaware Seashore State Park’s Tower Road surf break area, where the highest scoring cell in that location was 420.98. The highest scoring cells at the Indian River Inlet’s North and South Side surf break areas were 454.83 and 414.51, respectively, with the North Side’s score being the highest of any location in the study area (Figure 5.4).



**Figure 5.3 – Delaware Seashore State Park-Tower Road ASR Suitability.** This map shows the ASR suitability layer at the Delaware Seashore State Park – Tower Road surf break area, one of the highest scoring locations in the study area. The highest scoring cell at this location is labeled (e.g., “High Score: 420.98”), with a table listing each criterion’s original data values at the cell also displayed. Created with Esri ArcGIS/ArcInfo Desktop 10.2.1. ©2014 Esri. All rights reserved. Produced here for educational purposes only.



**Figure 5.4 – Indian River Inlet North and South Side ASR Suitability.** This map shows the ASR suitability layer at Indian River Inlet’s North and South Side surf break areas, two of the highest scoring locations in the study area. The highest scoring cell at the North Side location was 454.83 (highest in study area), while the highest score at the South Side location was 414.51 (2 cells with this score). Tables listing each criterion’s original data values at the cells are also displayed. Created with Esri ArcGIS/ArcInfo Desktop 10.2.1. ©2014 Esri. All rights reserved. Produced here for educational purposes only.

Other places where there was ASR suitability in the higher range of scores included Bethany Beach, Fenwick Island State Park’s southern-most area, and Dewey Beach, though the highest scoring cells at these locations were lower than the top scoring locations, at 389.42, 385.98 and 368.51, respectively. Areas of intermediate suitability (yellowish areas) were located at or adjacent to the mid-way point between existing surf break locations. This is evident between the

surf breaks of Fenwick Island and Bethany Beach, as well as between the Tower Road and Indian River Inlet North Side surf breaks (Figure 5.1). Other notable results included study area locations receiving suitability scores on the lower side of the scale, but above 0 (i.e., not restricted). These scores were concentrated in the northern-most part of the study area, off of Cape Henlopen's point (orange area in Figure 5.1).



## VI. DISCUSSION

The final ASR suitability surface (Figure 5.1) reveals some interesting trends regarding the location of varying levels of ASR suitability. The suitability scores ranged from 0 to approximately 455, and some patterns can be observed that explain where these scores are located in the suitability layer. For the purposes of interpreting the suitability layer, a single raster cell corresponded to the size of a single ASR.

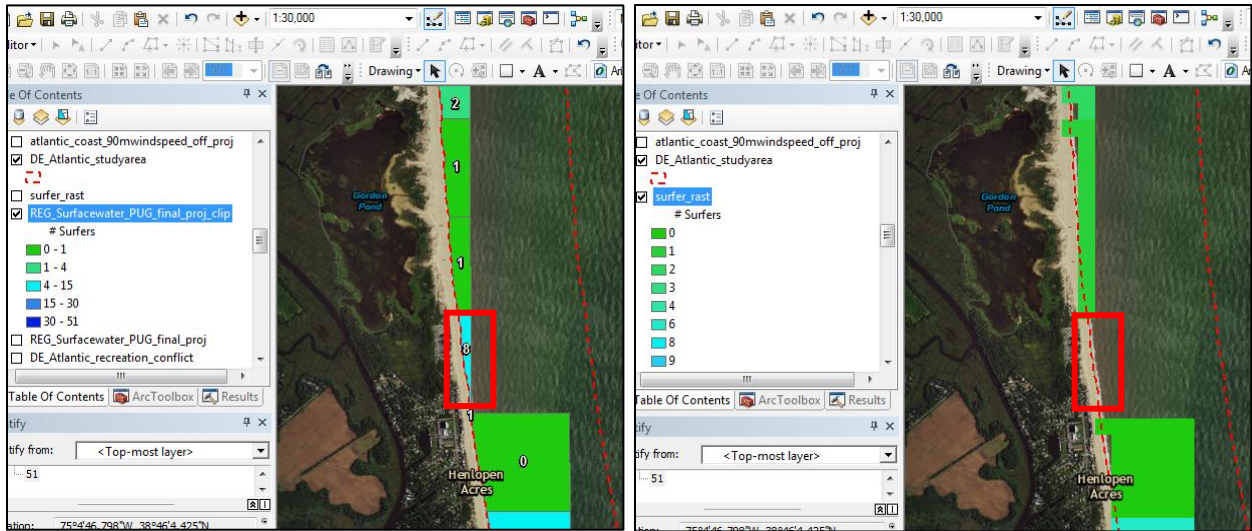
As was expected and intended, the locations in the study area that received suitability scores of 0 corresponded to beaches that are privately owned and access is restricted to the public. There are many private communities along Delaware's coast that only allow access to their beaches for their residents, such as those on the north and south sides of Bethany Beach, and those adjacent to Dewey Beach and Rehoboth Beach (Magill, 2002). While there may be locations along these privately owned stretches of coastline that are suitable for an ASR, for the purposes of this study, these areas were treated as "no-go" locations due to limited access. Since these areas are not feasible for ASRs and given that the restricted areas criterion is binary in nature (e.g., yes or no), these areas were assigned a reclass value of 0. In the map algebra expression, this had the effect of making data values for each of the criterion data layers convert to a value of 0 when multiplied by a restricted area cell (Figure 4.3.9). All other locations in the study area were assigned a value above 0 so that the corresponding raster cells would have positive values in the suitability layer to signify that they are feasible for ASR deployment. Although any positive integer could have been used, a value of 100 was assigned to the non-restricted cells in the reclassification task. This had the effect of producing suitability scores with three whole numbers on the left side of the decimal point.

The study area locations receiving low suitability scores, but above a score of 0, seemed to be concentrated in the northern-most part of the study area, off of Cape Henlopen's point (orange area in Figure 5.1). This was most likely due to the fact that this area had some of the highest slope values in the study area. The water depth in that area seemed to change rapidly, leading to high gradients on the seafloor. Also, this area was fairly distant from surf break locations and high surfer numbers, and the wave climate in this area was poor compared to the rest of the study area (e.g., 0.43 m annual significant wave height). As stated in the results section, areas of intermediate suitability (yellowish areas) tended to be located at or adjacent to the mid-way point between existing surf break locations. This trend was most likely due in part to the existing surf breaks criterion being based on distance, and distances closer to surf break locations were assigned higher (i.e., more suitable) reclassified values (e.g., 4, 5), while distances farther away were assigned lower values. Additionally, this criterion was one of the most highly weighted criteria (e.g., weight value = 0.2298), affecting the suitability scores to a higher degree than other criteria in the map algebra expression. Therefore, the suitability scores at locations (i.e., raster cells) farthest from the surf break locations were ultimately lower than those closer to surf break locations.

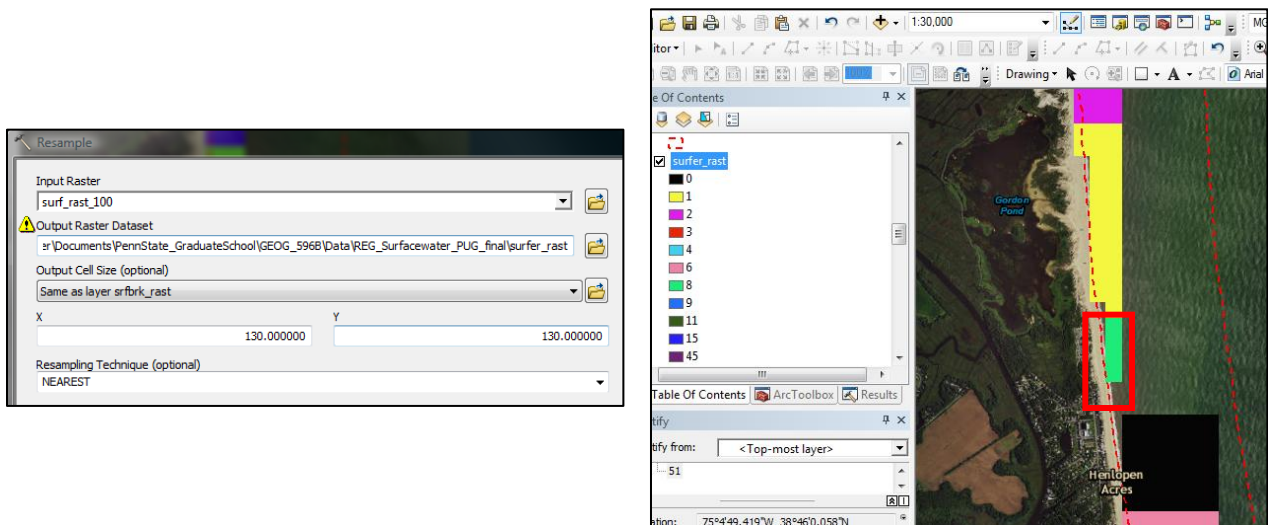
Study area locations with the highest suitability scores tended to be located at or adjacent to existing surf break locations. For similar reasons to the intermediate scoring locations described previously, the high scoring locations received these high scores most likely because of the high reclass values and weights assigned to the raster cells at these locations. Furthermore, at the existing surf break locations, there tended to be higher numbers of surfers (i.e., surfer numbers

criterion), and this criterion was assigned the highest weight value (e.g., 0.2400) in the map algebra expression. Therefore, the raster cells in close proximity to existing surf breaks were affected by the two most highly weighted criteria in this study, leading to the highest suitability scores of any study area location. As was focused on in the Results section, in descending order of suitability scores, the most suitable location for an ASR was the Indian River Inlet North Side surf break site (e.g., score: 454.83) (Figure 5.4), followed by the Cape Henlopen – Herring Point surf break site (e.g., score: 429.34) (Figure 5.2), then the Delaware Seashore State Park – Tower Road surf break site (e.g., score: 420.98) (Figure 5.3), and finally the Indian River Inlet South Side surf break site (e.g., score: 414.51) (Figure 5.4). The reason the Indian River Inlet North Side surf break raster cell received a higher suitability score than the Cape Henlopen – Herring Point surf break raster cell is due to a few differences in the original criteria values for these two locations. Both of these surf break sites had the highest number of original criteria values reclassified to the highest reclass value of any study area location (e.g., 6 criteria receiving reclassified value of 5). The difference most likely came down to the fact that the Indian River Inlet North Side site had a better wave climate criterion value (e.g., 0.56 m annual significant wave height, reclassified to value of 4) than the Herring Point site (e.g., 0.43 m, reclassified to value of 2). Given that the wave climate criterion was assigned the third highest weight value in the suitability map algebra expression (e.g., 0.1689), the map algebra expression resulted in the raster cell at the North Side site being assigned a higher suitability score than the Herring Point site.

This study was concerned with locating the best site for an ASR in the study area, and not determining the best design of a proposed ASR, so an approximate design (e.g., length and width) for a typical ASR was used as a basis for measuring a location's suitability for an ASR. The 130 meter cell size used for the suitability raster layer's cell size was deemed appropriate for the purposes of this study as it reflected an average ASR's dimensions based on known constructed and proposed ASRs. With this cell size, interpretation of the suitability layer was more straightforward as each raster cell represented suitability for a single ASR. Furthermore, given that many of the original data layers used had resolutions much lower than 130 x 130 meters, such as the wave climate data layer with its original data aggregated to polygons approximately 7,400 meters in size (e.g., length and width) and the surfer numbers data layer aggregated to 1 x 1 kilometer polygons, 130 meters was selected as a sufficient compromise for analysis resolution. Though, there was a loss of resolution in other layers when resampled to the 130 meter cell size, such as the depth and slope criterion's DEM layer that was originally a 10 x 10 meter resolution raster layer. This generalization of data may have affected the scores in the final suitability layer, as original depth values may have been masked and distorted for certain locations. Additionally, an issue with the 130 meter cell size used did present itself with surfer numbers data when the original data was converted to raster format. Figures 6.1 and 6.2 show this conversion issue in more detail. When the surfer numbers data layer was first converted to raster data format using a cell size of 130 meters, a portion of the data was lost at the Gordons Pond surf break site (e.g., "8," cyan color polygon) (Figure 6.1). To resolve this issue, the original surfer numbers layer was converted to raster format using a 100 x 100 meter cell size, and the 100 meter raster layer was then resampled to a raster layer with a 130 x 130 meter cell size to capture the original data at the Gordons Pond surf break (Figure 6.2). The alignment of the new 130 meter raster layer with the original 130 meter raster layer was slightly off, as seen when comparing the right screenshot in Figure 6.1 with the right screenshot in Figure 6.2. There were also raster cells that existed in the original raster layer did not exist in the new layer. These



**Figure 6.1 – Surfer Numbers Data Layer Raster Conversion Issue.** These screenshots show the conversion issue that arose when the surfer numbers polygon layer was originally converted to raster format with a cell size of 130 x 130 meters. The small, cyan polygon labeled “8” (left) was not captured in the raster layer (right). The incorporation of this data was deemed necessary in order for the final suitability layer to truly represent all input data. Created with Esri ArcGIS/ArcInfo Desktop 10.2.1. ©2014 Esri. All rights reserved. Produced here for educational purposes only.



**Figure 6.2 – Surfer Numbers Data Layer Raster Conversion Solution.** These screenshots show ArcGIS’s Resample tool (left) used to convert the 100 x 100 meter cell size raster layer to a raster layer of a 130 x 130 meter cell size, and the resulting 130 x 130 meter cell size raster layer capturing the original surfer numbers data at the Gordons Pond surf break site (right). Created with Esri ArcGIS/ArcInfo Desktop 10.2.1. ©2014 Esri. All rights reserved. Produced here for educational purposes only.

differences in the raster cells from their original positions may have affected final suitability scores across the study area when considering the surfer numbers criterion.

In terms of the criteria used in this analysis, these criteria are certainly some of the more

important aspects to consider when determining ASR suitability, though the incorporation of additional marine related data, such as tides and currents (both tidal-induced and along-shore currents), would have produced a more accurate suitability layer. Environmental properties such as tides and currents can affect the surfability at a given location by changing the depth and affecting the ability of surfers to stay within take-off zones (Phillips *et al.*, 2003; Scarfe *et al.*, 2009). There was some difficulty in locating data for these criteria mainly because there was a lack of data coverage and high resolution data for the study and surrounding areas. In light of this, criteria for tides and currents were not included in this analysis. Other factors that may affect surfing conditions and the environmental properties of ASR sites, especially in this analysis' study area, include the frequency and intensity of storms (e.g., hurricanes in the Eastern United States), permanence of sandbars, and locations where other coastal management efforts are planned (e.g., replenishment/dredging). Though, Saaty (1987) argues that the number of criteria compared in the AHP should be limited (e.g., 10 or fewer) to ensure that the relative priorities (i.e., eigenvectors, weights) assigned to the criteria are not too small, where smaller values could be affected more by any error in the AHP. However, the inclusion of these other criteria in future analyses and the collection of datasets representing these factors would be important in determining the most precise measure of ASR suitability for this study area, as well as other domestic and international locations. Other study areas, both domestic and international, will also need to identify study area specific considerations that affect surfing conditions and how suitable a location may be for an ASR. Study area specific criteria may include stretches of the coast that have restrictions in place that prohibit the activity of surfing or where there may be conflicts between surfers and other recreational users of coastal waters, as was the case in this study. Additional considerations for other domestic and international study areas include current submerged structures (e.g., utility pipelines, breakwaters), marine wildlife conservation zones, and any marine transit in the study area, including shipping lanes or fishing zones.

On a similar note, while the data layers selected for the analysis criteria represented some of the most current, publicly available data at this time, there were still some drawbacks associated with the data that may have affected analysis results. The differences in data resolution across the data layers were considerable. For example, the depth and slope criteria DEM data layer had a horizontal resolution of approximately 10 meters, while the wave climate criterion data layer used polygons approximately 7,400 meters in size (length and width) (Table 4.2.2). The extremely low resolution in some of the data layers had the effect of generalizing data values across the study area to a high degree, leading to less variability in the suitability layer. Using higher resolution data layers in the analysis could provide a more detailed view of ASR suitability, revealing subtleties such as rapid changes in seabed slopes or substrate types. Another issue with the data layers used concerns the currentness of the data. A few of the data layers were current as of 2009 or earlier (e.g., substrate data layer from 2005) (Table 4.2.2), and may have not been as accurate in their representation for this study. Since their creation, conditions may have changed, such as a particular substrate type changing grain size due to the longshore transport of sediment over the last several years. To produce the most accurate depiction of ASR suitability, data collection should be more iterative to provide current representations of the associated geographic feature. Furthermore, a few of the data layers used were lacking in their completeness within the study area and required an extrapolation task to extend the data values across the entire study area. These data layers included the wave climate criterion data layer (Figure 4.3.4), the substrate criterion data layer (4.3.5), and the wind criterion data layer. Since each of these data layers represent continuous values, it was deemed necessary to provide

continuous data coverage in the study area for each of the layers. Though, extrapolation does introduce a level of error into the data because unknown data values are determined based on known values without any field verification to confirm the accuracy of extrapolated values (Morais, 2013). The uncertainty of data values in these layers most likely introduced some inaccuracies in the final suitability layer. The availability of current, detailed and accurate marine-related data will determine the effectiveness of site suitability analyses for any coastal structure that depends on environmental conditions for the structure to be successful. Each of these data concerns need to be addressed in future analyses.

Another matter concerning the methods used in this analysis was the AHP. The pairwise comparisons made when comparing each criterion to the other criteria were fairly subjective (Figure 4.3.8), based on how one person interprets each criterion's importance to the goal of ASR suitability. Any one criterion could have been assigned higher importance over the other criteria simply based on the AHP user's experiences and notions towards the goal of the analysis. In an ideal setting, this step of the AHP would have been more objective and included input from all stakeholders of the proposed ASR, such as coastal planners and the surfing community. The collective judgements of all stakeholders would allow for more objective assignment of criterion importance. Although, gathering input from all stakeholders may encompass a great deal of data collection time, but the AHP is very adaptable and could be updated with stakeholder input almost immediately (Tseng *et al.*, 2001). Employing the AHP in a spreadsheet environment (e.g., Microsoft Excel) would allow the input from each stakeholder to be quickly incorporated into the criteria decision matrix, and the weight values signifying criteria importance would be automatically updated. Methods for gathering stakeholder input could include "town hall" type meetings or other group brainstorming sessions where open discussion could be conducted. To more effectively plan for coastal management structures such as ASRs, future analyses should include stakeholder input when defining how to measure and prioritize ASR suitability, as this will ensure the goals for the structure and the needs of all stakeholders are met.

Through weighted overlay methods using a GIS, the most suitable locations for an ASR were successfully identified in the study area. Although there were some drawbacks associated with some aspects of the methods and data layers used in the analysis, the suitability layer produced offered insight into the study area's varying environmental and surfing-related conditions. Improvements in data accuracy and coverage, as well as input from the necessary stakeholders in future analyses will lead to more accurate identification of suitable ASR sites. Though the exact GIS software tools used and techniques may vary among site suitability analyses, this analysis can provide an applied framework for determining a study area's varying levels of suitability for an ASR through the use of weighted overlay GIS methods. If site suitability for surfing enhancement becomes a common application of GIS-based weighted overlay techniques, this analysis can serve as the framework for developing a standardized GIS model for determining suitability of proposed surf-enhancing structures. Having a standardized GIS allows users to perform the site suitability analysis in a timely manner, more efficiently providing coastal planners with cartographic materials and other reports detailing analysis results, leading to an overall more effective coastal planning effort. The GIS model could then be shared with coastal planners across the globe to create an environment of consistent coastal planning.

## VII. CONCLUSIONS

While surfing has maintained its status as a popular recreational activity along Delaware's Atlantic Ocean coast since it first began, the degradation of the shoreline due to major storm events and the resulting coastal management responses have changed accessibility to surfable conditions. Given the importance of tourism and its associated recreation component for Delaware's economy, the involvement of these recreational user groups in coastal planning is imperative. Current coastal management practices, mainly beach replenishment, have the effect of reducing the traditionally good surfing conditions that have existed in Delaware. Future coastal management efforts in Delaware should take into account the benefits of including other coastal user groups in the mitigation process, such as surfers, to implement structures that have multiple benefits. Artificial surfing reefs (ASRs) are structures that have the potential to accomplish the goal of enhanced surfing conditions and improved coastal protection.

Based on the data used and methods employed in this site suitability analysis, the most suitable site for an ASR on Delaware's Atlantic Ocean coast is the Indian River Inlet North Side surf break site (Figure 5.4). Given that this is one of Delaware's legally designated and recognized surfing beaches, it seems appropriate that ASR suitability would be highest at this location (DE SRF, 2014). Although a suitable site was identified using a GIS-based method, more extensive site specific data collection and analysis should be conducted to design the most effective ASR structure for the specific location, to meet the needs of relevant stakeholders (e.g., surfing community, coastal protection engineers, coastal planners, and other recreation groups). Additional data that would be pertinent to designing and constructing an ASR for a specific site include swell directions and periods, predominant wave peel angles, level of wave refraction, wind directions, tidal and current patterns, average surfer skill levels (Scarfe *et al.*, 2009). Having these datasets in hand, the design and construction of the ASR could be tailored to the exact specifications that may create ideal surfing conditions at the specific location.

If an ASR is constructed on Delaware's coast and produces successful results (e.g., enhanced surfing, improved coastal protection), this could potentially draw higher numbers of local and visiting surfers to Delaware beaches wanting to experience the enhanced surfing conditions. An increase in surfer numbers could mean potentially more money being spent in the local area, leading to a more thriving coastal community, whose economy is highly dependent on tourism and an influx of visitors to the area especially in the summer season. Additionally, successful ASR results and an influx of more surfers could set the stage for an expansion in the local surfing industry, including more surf-related businesses, surfing competitions, and other industry sectors. Furthermore, a successful outcome for the proposed ASR could mean increased awareness of the importance of coastal management and planning that takes into account multiple user groups. The management and conservation of coastal resources that can benefit the local community both economically and socially, such as surfing areas and associated features at these areas that can produce surfable conditions, will be important to the future of coastal communities.

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