PROPOSAL TO MITIGATE THE EFFECTS OF SEA-LEVEL RISE ON THE PROTECTED AREAS OF DARE COUNTY IN EASTERN NORTH CAROLINA

by

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Abstract

Climate change is arguably the most important environmental issue to think about as the 21st century moves into its second decade. This issue is not only important in terms of limiting carbon emissions and its effect on the human race, but also in terms of how it will effect the natural environment. Many coastal areas may be affected by sea-level rise, especially those at or below 1 meter above the current sea-level. Important questions to ask are: If some extent of sea-level rise is inevitable, how quickly will it occur, and will the habitats and the wildlife occupying the lands that will be submerged have time to migrate to new suitable lands?

Dare County is located on eastern coast of North Carolina, and contains a large percentage of protected land, and land that is at or below 1 meter above sea-level. Also, the entire county is dense with drainage ditches and canals. It is this researcher's fear that these features will greatly accelerate the rate and the ultimate extent of sea-level rise for the county. Using ArcGIS, I sought to model how different hydrologic mitigation strategies (i.e. ditch filling, or ditch gating) could alter the rate or the ultimate extent of sea-level rise for Dare County.

My model showed that ditch gating had little to no effect on either the rate or the extent of sea-level rise. Ditch filling, however, might well slow the rate, but was inconclusive regarding its effect on the ultimate extent. Since filling every ditch is not a realistic goal for any potential hydrologic restoration project, I prioritized eleven points in the ditch network based on previous research and expert opinion. After simulating the filling of only the ditch sections between the point, and the next ditch encountered, I was able to show an alteration of the rate of sea-level rise.

Assuming that a large-scale ditch filling project is not feasible, limiting an operation to the points prioritized below would, according to my model, be effective in slowing the rate of sea-level rise in the county, especially in the early and middle stages of the process, or in a less than worst case sea-level rise scenario.

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Introduction

The Albemarle Peninsula on the eastern coast of North Carolina has a large amount of land in protected status. Prominent among these, are the lands of Dare County. Dare County is approximately 245,490 acres large, and, as of 2007, has a small population of about 33,000 people. Using year 2000 population data (this year is used because the acreage data are from 2000) this comes out to only ~78 people per square mile, as opposed to over 165 for North Carolina as a whole (United States Census Bureau, 2009). The population of Dare County has increased since 2000, but it is still quite small even for a state like North Carolina with much of its land remaining in agriculture and forestry. This is because most of the population and development is limited to relatively small areas along the coast, and some along the main highways. Almost the entire county (which is shaped like its own peninsula within the Albemarle) is under government protection including the sizable Alligator River National Wildlife Refuge (ARNWR), managed by and United States Fish and Wildlife Service (USFWS), and a Department of Defense practice bombing range (Figure 1) that features a large amount of natural protected areas, including Red-Cockaded Woodpecker (*Picoides boreali*) habitat.

ARNWR was founded in 1984, and is approximately 152,000 acres large (~62% of the county). It is mostly wetland, with diverse habitats including pocosins, marshes, non-riverine swamp forests, and agricultural fields. Pocosins are peat accreting shrub bogs, whose name comes from the Algonquin for “swamp on a hill.” They are found in the southeastern coastal plain from Virginia to Florida, and are most prevalent in North Carolina. Pocosins have acidic and nutrient poor peat soils and are dominated by Pond

Pine (*Pinus serotina*), (Mitsch, 2007). ARNWAR's pocosin ecosystems are home to many unique animals and plants, including the only wild, free living, population of Red Wolves (*Canis rufus*) in the world (USFWS ARNWR Page, 2008; Phillips, 1995). The Red Wolf is a smaller bodied, skinnier wolf compared to its western, Gray (*Canis lupus*), cousin. They are about 26" tall at the shoulders, about 5' long, and weigh somewhere between 50 and 80 pounds. They have a reddish gray coat, and tend to live about seven years in the wild, but can live much longer in captivity (Defenders of Wildlife: Red Wolf Fact Sheet). Their historic range extended from Southern and Central Texas, to Florida, up to the Ohio River. Some suggest that they were present in Pennsylvania, New England, and even southeastern Canada. Some further suggest that the historic distributions of the smaller Red Wolf and larger Gray Wolf do not overlap further because smaller prey items, such as the white-tailed deer (*Odocoileus virginianus*), are more common in the range of the former, and larger prey items in that of the later (USFWS Southeast Region, 2007). The Red Wolf was first listed as endangered in 1967, shortly after the passing of the original Endangered Species Act, and was officially declared extinct in the wild in 1980 (USFWS Southeast Region). In an attempt to save the wolf, a reintroduction program was initiated beginning in 1986 (the first wolves were not released until 1987) to reintroduce Red Wolves into ARNWR (Phillips, 2003). ARNWR was selected for the restoration program due to its ideal nature in its ability to facilitate the wolf's recovery (USFWS ARNWR Page, 2008; Phillips, 1995). Some of these ideal factors include the fact that it is a peninsula with water on three sides. The fourth side is adjacent to the aforementioned Department of Defense land that is undeveloped. The wild and remote nature of this land means that it has abundant prey items (including white-tailed deer, raccoons and rabbits), and that it is only sparsely populated by humans. Furthermore, upon the founding of the restoration project, there were no coyotes (*Canis latrans*) present in the refuge. Coyotes provide a large problem for Red Wolf populations because they easily interbreed, and can weaken the gene pool (Phillips, 2003; Phillips, 1995).

Today, wolf populations in Dare County are thriving. As of 1999, and up through 2007, the Red Wolf population in ARNWR and the surrounding areas fluctuated between 80-130 wolves. In the earlier part of this continuum, the number was in the 80-100 range, and more recently it has been in the 100-130 range. The USFWS estimates that they have met approximately 26-50% of the recovery objectives set out by their original Species Survival Plan (Flood et al., 2006; USFWS Southern Region).

Due to some of the unique features of the site, mentioned above, the Dare County population is still the only free living, wild population of Red Wolves in the world. It is therefore imperative that this land remain protected, as viable wolf habitat. Unfortunately, despite its protected status, it remains under an even greater anthropogenic threat than land clearing for development purposes: The threat of sea-level rise due to climate change. Much of the land in Dare County (and the surrounding Albemarle) is at very low elevation (less than or equal to 1 meter above sea-level) and it is, therefore, at high risk for submersion due to climate change driven sea-level rise (Figure 2). To further complicate matters, there is a complex network of man-made ditches and canals that infiltrate almost the entire peninsula, and they are especially dense in Dare County. These ditches exist along most roads, and also independent of roads (some dug for logging or agricultural purposes). The effects of salt-water intrusion have become obvious along many of these ditches where Pond Pine dominated pocosin has transformed into grass dominated salt marsh. Also, barriers have been built to temporally halt salt-water intrusion, and it is suspected that this unnatural hydrology may not only exacerbate salt-water intrusion but also the effects of sea-level rise, potentially causing the area to suddenly and catastrophically "fill like a bath tub," as opposed to in a slower, more gradual natural process. This could have disastrous ecological consequences for the pocosin and for the animals that rely on this habitat including the Red Wolf (Poulter 2007, Pearsall). If this wolf population is to be sustained in the long term, a comprehensive hydrologic restoration may be necessary in Dare County or even in the greater Albemarle as well.

The goal of this project is to determine how effective hydrologic mitigation strategies might be in altering the rate and extent of sea-level rise in Dare County and to make a policy recommendation as to how to proceed. Such strategies may include filling ditches, installing one-way flap gates (devices installed into a ditch or canal that allow water out of but not back into the peninsula), or flat board risers (essentially vertical metal slots installed into the side of a ditch or a canal into which several two-by-four boards can be slid depending on the desired height). The later strategy has already been extensively placed throughout Dare County, and has done little to stem the salt-water intrusion that is already evident. While it is possible that flat board risers could be more effective if more intelligently or extensively applied, I have observed that these risers will freely leak water out in between the boards. Consequently, I will focus on a strategy that I hypothesize has a greater probability of success. Therefore, I will focus on the first two methods mentioned above, although, for the purposes of my model a perfectly functioning riser would render the same effect as a flap gate. Another complementary set of methods could consist of soft armoring with constructed oyster reefs, salt marshes, or other natural, adaptable barriers. There is much potential in these methods in combination with a hydrologic restoration, but they are beyond the scope of this analysis at this time, as I choose to focus on the ditching issue here.

The motivation behind attempting to diminish the ultimate extent of sea-level rise is rather clear. If less land is inundated, than there will be more remaining habitat in which the wolves and other pocosin dwellers can survive. The secondary goal mentioned above, however, is to slow the pace of sea-level rise regardless of whether or not the final level of inundation is altered. The benefits of achieving this goal are slightly less obvious, but are just as crucial to this project. In a non-anthropogenically damaged system change comes gradually. Even if change is dramatic, as sea-level rise could be, the water still has to slowly work its way onto the land via overland flow or tidal influences. This slow progression could give animals, and especially plants, which require longer, time to migrate and settle into new sites if they are available (Pearsall). When there is extensive ditching as is the case here, however, the water can quickly flow into the entire peninsula, quickly flooding the land, and killing off the freshwater plant communities. If this inundation rate can be slowed down to, or closer to, a more natural pace, than it could facilitate species and habitat migration. It is with these goals in mind, that I have attempted to model sea-level rise in Dare County, and show to what extent filling and/or gating certain ditches can slow or mitigate inundation.

Materials and Methods

Data

In order to accomplish the aforementioned goals, I sought to model sea-level rise in Dare County using ArcMap 9.3, based on detailed topographic data of the area, and the most up to date Intergovernmental Panel on Climate Change (IPCC) data on estimated sea-level rise predictions. I obtained my digital elevation model (DEM) from The United States Geological Survey (USGS). The data are posted on the internet for the entire United States in what is called the “National Map Seamless Server.” The data are continually updated, providing users with the most detailed data available. The downloaded data had a cell size of 0.00003° by 0.00003° (approximately 3 by 3, or 9 square meter resolution). The data was in ArcGRID format with a Geographic datum of NAD 1983. The boundaries of the data grid downloaded were, according to the WGS 84 Datum, N: 35.97496 W: -76.01393 S: 35.77251 E: -75.9142. The data set was the National Elevation Data Set (NED) 1/9 Arc Second (USGS 2008, Snyder 1987). The data came in six pieces, which I combined using the “Mosaic to New Raster” command. I then reprojected this grid into UTM, NAD 1983 Zone 18N.

Background

In a previous paper Ben Poulter used IPCC data to estimate the amount (in meters) of sea-level rise that would occur in coastal North Carolina (Poulter 2007). He used a low estimate of 0.3 meters and a high estimate of 1.1 meters. I used these numbers as benchmarks for my analysis, with 0.3 meters representing a mild expected scenario, and 1.1 meters representing a worst case scenario. In order to model inundation, I first read Poulter's paper and examined his model that has been described as a "flow-limited bathtub model." A more traditional "bathtub model," would suggest that if the sea-level were modeled to have risen one decimeter, than all cells that are currently less than or equal to 0.1 meter above sea-level would be modeled to have been inundated regardless of whether or not they were adjacent to a water source. This method can cause problems, as it may predict certain areas that are well inland, and that have no connection to a water source, even after a 0.1m sea-level rise, to be inundated (Poulter 2007). While it is possible that some areas along these lines could end up underwater (perhaps due to rising water tables), it is not realistic to assume that they always will. Furthermore, these potentially new wetlands or water bodies could be fresh, and not marine. Therefore, a connectivity element needed to be added to the model. This is where the "flow-limited" portion of the model becomes important. Poulter added a flow-limitation to the bathtub model in which a raster cell would be represented as inundated if it fell at or below a certain elevation threshold and if it was connected to a previously inundated cell. There are two ways to represent this connectivity, what he termed the "4-sided," and the "8-sided" rules. The 4-sided rule means that two grids would only be considered to be connected if they had adjacent sides. The 8-sided rule means that two grids would be considered to be connected if they shared a side or a corner (Poulter 2007). The 4-sided rule provides a more conservative estimate, than the 8-sided rule because it prevents water from spreading out of the corners. Conversely, the 8-sided rule may over estimate inundation because it assumes that water will perfectly flow overland, potentially ignoring small topographic obstacles that might not register as different elevations on the DEM. Furthermore, Poulter found that using the 4-sided technique allowed water control structures to block flow to surrounding cells more effectively, than the 8-sided technique did in this regard. This is most likely because the use of the connectivity of corners in the 8-sided rule would allow the water to bypass the control structure if it was on a small scale (Poulter 2007).

Digital Elevation Models

My sea-level rise model, which I will describe in detail in a sub-section below, differs from Poulter's but does use an 8-sided connectivity rule. Thus, I am forced to address some of the aforementioned issues. One way that I decided to do this was by "burning in" the locations of the ditches into the DEM. Using an accurate shape file of the ditches provided to me by the North Carolina branch of The Nature Conservancy (TNC) I converted it into a raster as the first step of this process. After adjusting this new raster to have negative elevation values, I used a conditional statement to place these elevation values onto the DEM (Con(isnull(ditches)= =0, ditches, DEM). However, since the depths of the ditches were not measured from sea-level, but from the top of the ditch, setting the depths of the ditches as their elevation on the DEM is not accurate. Nevertheless, I ran the models using this DEM because overestimating the depths of the ditches might have been helpful in emphasizing the difference between the hydrologically restored DEMs and status quo DEM containing all of the ditching. In an attempt to achieve greater accuracy, I created another DEM using a different conditional statement (Con(isnull(ditches)= =0, DEM-|ditches|, DEM) that placed the difference between the original DEM and the ditch depth as the new elevation of the ditches. It is important to note, however, that the original DEM from the USGS source showed elevations at the ditches that were often significantly higher than the background elevations. It may be that since many of the ditches were dug in order to create roads, and thus along side of roads, the DEM was picking up the roads that are built up above the landscape. This is possible because despite the extremely fine accuracy of the USGS data, it is still not fine enough to pick up some of the ditches that are quite small in width, and often overgrown. It is also possible that this phenomenon is an artifact, and is inaccurate. It is therefore possible that these adjusted ditch elevations are also inaccurate, although they are most likely more accurate than the first method.

After completing these burns, the DEMs needed to be “filled.” This means that any sinkholes (imagine a hole in the ground) would be filled in. This step is necessary to avoid including what are most likely artifacts of the data from being included in the created DEM. Also, any flow direction commands (I will explain the use of these later) would not result in accurate information. Upon examining the results of both of these methods, and seeing little evidence that the second method underestimated the ditches presence on the landscape, I used the second method for all of my analysis in the Results and the Discussion sections below.

Additionally, as suggested by Poulter, I experimented with the resolution of the data. There is potential for extremely fine resolution in the government data set (as mentioned above approximately 3 by 3 raster grids). There is, however, an inherent trade-off between finer resolution, and therefore seemingly more accurate, data and increasing noise in the data. So, I took the untransformed data (~3 by 3 meter cells but in geographic units), and used the “Raster Project” command to project this raster (using a binomial interpolation) into new raster files with 3, 10 and 15 meter cell sides respectively, and I ran the model on each. I chose to re-project the original data to exactly 3 by 3 meter cells to simplify the analysis, and also because, it is not possible to perform the analysis on the untransformed data if the horizontal units (degrees) were different from the vertical units (meters). Unfortunately, due to processor speed and time constraints, I was unable to run my full analysis on the 3 meter cells, and instead focused on the larger cell sizes. I was, however, able to create viable DEM’s for all three resolutions. After comparing the DEMs for the 10, 15, and 3 meter cell sizes, I decided that the 10 meter cells appeared to be large enough that the aforementioned noise issue would not pose a problem. Also, they were of finer resolution than the 15 meter cells, and therefore more accurate. In light of this, all of the results below are based on the 10 by 10 meter cell sizes. One issue with this choice is that stream widths could not be accounted for when they were burned into the DEMs. This is because in reality none of the ditches are as large as 10 meters wide, and when using a 10 meter cell size, the smallest possible ditch width becomes 10 meters. This is unfortunate, and it may or may not serve to overemphasize the importance of ditches on the landscape. If there is an overemphasis of the ditches in my model, however, it should be slight. This is because no mater how thin or wide a ditch is, once the sea-level rises to the point that the ditch would be breached, the water would begin to flow out onto the landscape, and it is this sort of effect that my model will measure.

Upon determining the proper resolution to use, and the most realistic topography possible given the above constraints, the next step in creating a DEM that will accurately represent the status quo hydrology in Dare County, was to attempt to include the currently functioning water control structures (WCS) into my model. In order to do this, I used another shape file provided to me by TNC. This file contains a point located at each water control structure in the county, as well as some other information (although this extra information was not consistently available for many of the points) including type of structure, condition of the structure, and whether or not it was functional. This file was created by in 2005 using a hand held GPS device. Five of these points had to be removed because they were listed as not functioning, missing, etc. Figure 3 shows the locations of the WCS that I used in my model. I should stress here that having spent time at the site; I know that many of the remaining water control structures are not perfect. As mentioned above, any flat board riser style WCS tends to leak through the boards when it is holding back a significant amount of water. Also, many WCS are not always functioning depending on the desires of the manager, or other factors (for example in my experience, not all risers contain boards at any one time). Keeping all of the above caveats in mind, I still assumed a best-case scenario, and perfect functionality for all WCS listed in Figure 3. In order to do this, I examined each WCS in the shape file to ensure that it was still located within the burned in ditch. This process is necessary because using a 10 meter cell size means that when I transformed the shape file into raster cells the computer was constrained to use a 10 by 10 cell to represent each small segment of the ditch network (imagine a series of pixels used to represent a curvy line). Therefore, there were some places within the ditch network in which the burned in raster version did not exactly match the shape file version. Along these lines, there were also a few cases in which the WCS no longer fell within the burned in ditch (this error was never greater than one cell). For each of these errors, I used the Editor function in ArcMap to move the WCS from the bank to the middle of the burned in ditch in the proper location. Next, I converted these WCS points to raster cells, and assigned each of their elevations to be 4 meters. I chose 4 meters because I wanted to assure that the WCS would effectively block all incoming water until it overflowed the ditch. At this point, I burned the WCS into the ditched DEM using a similar conditional statement to the first one used above, except I burned the WCS raster, not the ditch raster. At this point, I had a DEM with the ditches burned in, as well as the current WCS assuming perfect functionality. With these status quo elements in place, I was ready to begin exploring how hydrologic modifications could be used to alter the rate and/or extent of sea-level rise for Dare County.

Herein, as previously stated, in the objectives of this study, I explore different hydrologic restoration strategies that might be effective in achieving my goals. I will have to alter my status quo DEM to reflect these changes. This is because, in order to determine what hydrologic mitigation techniques may be effective in altering the severity of the effects of sea-level rise in Dare County, I will have to model them and compare the results to those obtained from the status quo model. I made several alterations to the DEMs that represent ditch filling as well as strategic flapper gate placement. The first and most straight forward scenario modeled here was the filling of all ditches. This is a best case scenario, and is useful for comparison with the more realistic scenarios below. I used the transformed 10 meter UTM version of the original DEM from the USGS source for this scenario. As mentioned above, the ditches were not present in the USGS product. For the strategic flap gate scenario (the next subsection will discuss how these gates were placed), I added the gates to the status quo DEM in the same way, and with the same process that I used to add the water control structures.[1] For the strategic partial ditch filling scenario, I used the Editor function in ArcMap. This time, instead of moving points, I erased portions of the ditch network from the original TNC ditch shape file. Several portions of the ditch network were erased from a selected point (explained below) until the next intersecting ditch inland (Figure 4 shows one area of the county before and after one piece of the ditch network was erased from the shape file). Using this altered shape file, I burned it into the transformed 10 meter UTM version of the original USGS DEM, as I did above for the status quo DEM.

Prioritization

If this project were nothing more than an academic exercise, than the easiest, and most obvious thing to do would be to fill all of the ditches, and to study how this altered the rate and extent of sea-level rise. Fortunately, this is not an academic exercise, and it has very real world applications. Therefore, I cannot recommend here as a course of action that all ditches in the county be filled, even if this is the ideal solution. Instead, I had to prioritize where to conduct hydrologic mitigation strategies in order to maximize the efficacy and efficiency of each gate placed or ditch filled. Here, I must again acknowledge The Nature Conservancy and Ben Poulter, because it is through work that he did with their funding that provided me with a means to solve this problem. Via TNC Poulter recently published a study examining the ditch network in Dare County. From

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[1] I simplified this model by only concerning myself with how the gates affected the flow of water into the county. A flap gate's ability to allow water out of the county could have many important effects in the short term, including mitigating saltwater intrusion. My sea-level rise model, however, predicts how hydrologic mitigations might alter the flow path of water as it floods over time, and a flap gates ability to allow water out of the peninsula should have little baring on this process. For a further explanation of this model see the "Sea-Level Rise Model" subsection below.

TNC, I was able to obtain the data that Poulter worked with for his report. Also, I have read a copy of Poulter's study. In this study, Poulter uses graph theory to elucidate the flow paths and patterns in the waters of the Dare County ditch network. He breaks the entire network into a series of edges and nodes. He concludes by ranking the various shoreline nodes in terms of their tendency to bring water inland and their relative "importance" to the hydrology of the network. He notes that there are six nodes that are most important in this regard (Poulter, 2008). Based on the maps from his report, some other node ranking information found in the TNC data, and expert knowledge from USFWS and USFS employees, I prioritized eleven nodes (Figure 5). These eleven consist of what I thought to be Poulter's six nodes based on his study, four more highly ranked nodes in terms of their importance for salt water intrusion that did not over lap with those that I had already selected, and one expert picked location that did not overlap with any the previous ten (Scott Smith, personal communication). It was at these nodes that I placed my strategic gates, and that I began my strategic ditch filling (as stated above, I began filling at each node, and ended at the next intersecting ditch, see Figure 4). Now that I have laid out exactly how I prioritized my mitigation strategies and how I altered my DEMs to simulate these actions, I must explain how I modeled sea-level rise.

Sea-Level Rise Model

Upon completing the status quo DEM, as well as DEMs for the different hydrologic mitigation scenarios, I compared their predictions to assess their differing impacts on sea-level rise. Since I am interested not only in the final inundation results, but also in how rapidly/gradually these results occur, I must employ a method that will estimate the inundation effects over time. Time is an elusive dimension to model spatially. Therefore, I propose to impose a substitution of space for time. As such, I ran my model in an iterative manor on each DEM.

The first step in my model is to simply conduct a straightforward "bathtub" scenario on each DEM. This means that I reclassified each map to be equal to a value of one if it was below a sea-level rise threshold (e.g. the 0.3 meter scenario mentioned above), and equal to "NoData" otherwise[2] (see Figure 6 for an example). Obviously, in this case cells with a value of one are represented as submerged, and those with a value of NoData are represented as dry. Now the goal is to begin to represent this bathtub model temporally. As I alluded to above, the strategy for doing this is by running the model incrementally. In this case, I ran the model for each decimeter of sea-level rise (beginning with 0.1 meters), thus providing a "snapshot" of the inundation of the area at each of these moments in time. I do not, however, attempt to predict exactly when each decimeter of sea-level rise will occur. I continued to run these iterations on each DEM until the worst-case scenario of 1.1 meters was reached. This was the first step in allowing me to estimate the potential impact of the hydrologic mitigation strategies both on the final extent of inundation, and on the rate of inundation over time (gradual or extreme). This iterative bathtub technique alone, however, is not enough. In the "Background" subsection above, I explain all of the problems with the bathtub model, and why a connectivity aspect must be included in the model. This is doubly important for this project because without a connectivity element in the model, the ditched DEM

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[2] "NoData" is a value in ArcMap that means that no data are present in a particular cell or cells of a raster file, but the computer is still aware that they are present. As such, a modeler can represent these cells with a color on a map, or use them in simple mathematical equations (like zero, NoData multiplied by any other value, is equal to NoData).

will not differ greatly from the filled one (other than within the ditches themselves, see Figure 6 for an example of how the ditches appear in a conventional bathtub model).

In order to add this connectivity element to my model, the first step was to run "Flow Direction" commands on each DEM. This command determines (using the "8-sided rule") to what direction water would flow if it were in each cell in the DEM, and creates a new raster grid representing this information. In other words, starting from the first cells inland from the coast around the peninsula, the computer looks at all of the surrounding cells and, based on elevation, decides which direction a drop of water would flow and gives that cell a new value of 1-8 (each number represents one of the eight possible directions that the water could flow in such as up, upper-left, right, etc.). This Flow Direction raster is important; because if one knows which direction water would flow in from any given cell than they are one step closer to discovering how water will flow inland due to sea-level rise. Indeed, a Flow Direction raster is an important input for several of the built in hydrologic functions in ArcMap. One of these is the "Flow Length" function, which was run on each of the DEMs. This function, determines how far, in meters, a drop of water would have to travel in order to get from the coast to each cell of the DEM. It is important to remember that this is based not on Euclidean distances, but on hydrologic flow distances as determined by elevation. Essentially, this function tells you how circuitous a path the water must take to get from point A (the coast) to point B (some inland location). Throughout the rest of this paper, I will refer to these values as circuity values (again the distance in meters that it takes water to travel from the coast to any given point). These circuity values are the method that I chose to represent connectivity in my model, as opposed to something more similar to Poulter's flow-limited bathtub model, because, as I stressed above, I am interested in the rate of sea-level rise. This circuity value is another way that I was able to model time using a spatial scale. In other words, the higher the circuity value at any one point the longer it would take for that point to become inundated. Thus, if a particular hydrologic mitigation method can increase the circuity values in the county, than it essentially slows the rate of sea-level rise as well.

The last necessary step in modeling sea-level rise is to combine the circuity values with the iterated bathtub model. In order to do this, I multiplied each bathtub raster (0.1-1.1 for each scenario) by the corresponding Flow Length raster. Since the Bathtub raster files equal 1 when they are flooded and NoData when they are not, the raster layers created from the above multiplication will equal the circuity values when the raster cell is low enough to be flooded and NoData otherwise. In this way, I am able to examine inundation rates on two scales: First, in one decimeter "snapshots," and second, within these snapshots I have a metric that indicates how long individual areas of the county will take to flood.

Results

For my resultant maps and figures I used the DEMs with 10 by 10 cell sizes. As mentioned above, I used the method of subtracting the ditch depth from the DEM value to burn in the ditches. Figure 7 (a-k) shows the final sea-level rise models for the status quo DEM, the status quo with out water control structures, the strategic flap gate map, the strategic fill map, and the map with all of the ditches filled. The map with the unencumbered ditches was included to help evaluate the effectiveness of the current water control structures as predicted by my model. The map with all of the ditches filled was included for comparison as a best case scenario. Comparing the strategic gate and fill maps with a best case scenario and a status quo scenario helped to elucidate how effective they can be. Figure 7a compares these maps for 0.1 meters of sea-level rise, and Figures 7 (b-k) shows 0.2-1.1 meters respectively. The yellow and pale tones represent areas with relatively short circuity values. These cells would be flooded relatively quickly at the given sea-level rise scenario. The orange and red cells (the darker the red the longer the value) represent cells with longer circuity values. The inland black cells represent areas that will not be flooded and the black cells around the inundated cells represent cells that are outside of the study area. For each decimeter sea-level rise scenario, I used the filled DEM and divided the circuity values into ten categories. I then imposed the symbology of these ten categories on all of the other maps at this same scenario. I chose the filled DEM because it always has the highest maximum circuity value of all of the maps in the scenario (see Table 1 a-k). In this way all of the maps for each scenario use the same scale and are directly comparable to each other, while maps at different sea-level rise scenarios are not. In other words, a dark red square for the worst case 1.1 meter sea-level rise maps represents a far larger range of circuity values (Figure 7 k, approximately 11,000-14,000 meters), than does a dark red square for the three decimeter maps (Figure 7 c, approximately 3,000-4,000 meters).

Table 1 (a-k) shows the maximum, mean, and standard deviation circuity values for each sea-level rise iteration (0.1-1.1 meters respectively). The maximum circuity value essentially represents the longest “time” that it takes for the furthest point hyrdologically that is still below the sea-level rise threshold to become inundated. The mean circuity value represents the average “time.” The standard deviation represents a measure of spread. Using these data, I will explain what my model predicts for the potential future of the peninsula below.

Discussion

The resultant maps and statistics from my analysis show some interesting trends. When looking at the maps, for the first time one quickly notices (Figures 7 a-k) the greater or lesser amount of red/orange on the map depending on the hydrologic treatment or the sea-level. This varies from map to map even within sea-level thresholds. The amount of black space (or definitely unsubmerged space), however, looks much the same from map to map within each sea-level rise threshold. The exceptions here are the completely filled maps, but they only tend to differ along the ditch network. This is because, as explained earlier, the bathtub portion of the model is what determines if the land is low-lying enough to be inundated. Therefore, one would expect the black space to differ only where the DEMs differ (e.g. along the ditch network). It is the Flow Path portion of the model that provides it with connectivity. It is for this reason that this model is, by design, more effective at predicting sea-level rise rates than it is at predicting inundation extents.

The output raster from the Flow Path function creates a value for each cell in the study area. As stated above, my model only shows the circuity values for those cells that are below the desired sea-level rise threshold. Since, however, every cell of the Flow Path raster has a circuity value, every cell shown to be inundated by the bathtub model has a circuity value. What this means it that the resultant maps show the areas that are, and are not at the appropriate elevation to be inundated. Within the areas that are at the appropriate elevation, they also show how far water would have to travel to get there (which, as previously stated, is a substitution for time). More than this, the circuity values also provide the connectivity for a model that would otherwise be a simple bathtub model. Therefore, it is not unreasonable to assume that as these values get particularly high there is a chance that the path to get to a point from the coast could become so circuitous that said point ostensibly becomes disconnected, and will never be flooded at that sea-level. The problem with this assumption is that using this model, there is no way to know what this cutoff value might be, or if a specific cutoff even exists. This provides an interesting opportunity for future research, in which one could run a Poulter-esque flow-limited bathtub model for each decimeter iteration, and examine how these predicted extents compare with my circuity value maps. For the purposes of this report, however, I must say that any differences in circuity values from map to map suggest a change in sea-level rise rates, but not necessarily a change in sea-level rise extent. With this important step clarified, it is possible to draw some conclusions from my results.

First, looking at Table 1 (a-k), for each decimeter snapshot of sea-level rise, it appears that neither the current water control structures, nor the strategic flap gates have much if any effect on the rate of sea-level rise. This is illustrated by the maximum and the mean circuity values, as well as the standard deviations for the maps with intact ditches, intact ditches with the current WCS, and the strategic flap gates. While they do change over time, for each threshold of sea-level rise all three scenarios have identical mean and maximum values. This suggests that within each decimeter sea-level rise, Dare County would be inundated at approximately the same rate for all three scenarios. Furthermore, the standard deviations are the same for each. This is further evidence that there is not a statistical difference in circuity values for each of the three scenarios. The maps (Figures 7 a-k) corroborate this conclusion. For the three aforementioned scenarios, the maps for each decimeter threshold show no noticeable large-scale differences between the three. There are some minute, small scale differences, but nothing that one would expect to have a large impact on the county as a whole. These small scale differences could possibly represent the more subtle, short term, small scale effects of the WCS, but there is more to this issue than this simple explanation.

One thing to keep in mind is that, as discussed at length in the "Methods and Materials" chapter, the sea-level rise model uses the 8-sided rule for connectivity. By allowing the water to "leak" out of the corners of cells, it could possibly tend to bypass water control structures. This could be a partial explanation as to why my model represents the WCS as being mostly ineffective. After giving the issue more thought, however, one must remember that even using an 8-sided connectivity rule, a drop of water that is in a ditch and runs up against a WCS cannot leak around the WCS, unless the sea-level rise extent is high enough that one of the surrounding cells is below the threshold. Once it does leak out on to the landscape, it is likely to quickly find the ditch again, on the other side of the WCS, and continue to travel along the ditch. Realistically, this is probably similar to the way that water would actually behave in this scenario. Thinking about the problem in this way, one realizes that it is likely that my model is realistically portraying the fact that ditch gates will not appreciably slow the rate or extent of sea-level rise for the county. This is not to say that flap gates are useless however. One thing that my model does not account for is their beneficial effect in the short term, especially on salt water intrusion. In his 2008 paper, Poulter suggests that gates can have an appreciable effect on salt water intrusion, especially if placed intelligently. I would argue, however, that this is only while the sea-level is at or near its current extent. Once sea-levels rise to the point that they facilitate water flowing over the banks of the ditches, ditch gating becomes ineffective, and this is what is evident in my model. Unlike ditch gating, my model shows that ditch filling (full or strategic) can increase the circuity values within a sea-level rise threshold.

Table 1 a-k shows some interesting differences in both mean and maximum circuity values between the status quo, the strategically filled, and the completely filled maps. It will be useful to go through these results. Table 1 a depicts the results of a one decimeter sea-level rise. As you can see there is little difference between the mean or the maximum values for each. The means of the status quo and the partially filled ditches are both under ten, and they differ from each other by less than one. The filled ditches mean is slightly higher, but still a very small 18. The maximum values increase by about fifty between each scenario and even the completely filled ditches don't even reach a maximum of 250. A look at the corresponding map (Figure 1 a) shows why this might be: excepting the ditch network, only the very outermost cells are shallow enough to be inundated at this level. Since they have nearly identical means, maximums and standard deviations, the status quo and the partial filling look almost identical. The completely filled map has some distinct concentrations of dark red and this is reflected in its relatively higher mean, and spread. Also it has a maximum in the darkest red category unlike the other two. Essentially, for this scenario it appears that the sea-level rise is not high enough for the partial filling to have an effect, or for there to be any severe effects of any kind on the county.

The next sea-level rise benchmark is two decimeters. Here (Table 1 b) we begin to see a larger separation between the three scenarios. The maximum for each is 779, 1191 and 2566 respectively, and the means are 44, 65 and 556. Here we see that the filled ditches have begun to completely separate themselves from the status quo. Whereas they were relatively close together for the 0.1 threshold, the filled ditches increased ~10 times in maximum and ~30 times in mean, and the status quo only increased ~5 and ~9 times respectively. Even more interestingly the strategically filled version has also begun to separate itself. While it is still closer to the status quo than the filled ditches, the mean and max values are clearly higher that the status quo (increasing by ~6 and ~12 times respectively). This is the first sign of the partial filling beginning to take effect in terms of its ability to force the water out onto the landscape, thus slowing its progression, and increasing the circuitousness of its route. A look at the corresponding map (Figure 7 b) shows a distinct red and orange patch in the Northwestern quadrant of the all filled map that is conspicuously missing from the other maps. This time, unlike at 0.1 meters, at 0.2 meters, the partially filled map shows a distinct light orange spot (about halfway down the western cost of the study area) that is absent from the status quo map. It is not as distinct as the filled map, but it is the first evidence of the partial filling having a visible effect on the rate of sea-level rise.

Upon examination of the three decimeter threshold (Table 1 c) one will find that the completely filled map is continuing to increase, though not nearly to the same extent that it did from 0.1 to 0.2. The maximum values increased from 2556 to 4012 (only ~1.5 times), and the means increased from 556 to 746 (only ~1.3 times). The status quo also increased, and at very similar rates to the filled maps: The maximums and the means increased from 779 to 1162 (~1.5 times) and from 44 to 93 (~2 times), respectively. At this threshold, the partially filled map has clearly separated itself from the status quo map, in that its maximum moved much closer to that of the filled map. This could happen because it increased at about twice the rate of the filled map. The maximums and means increased from 1191 to 3354 (~2.8 times) and from 65 to 195 (~3 times), respectively. A look at the corresponding maps (Figure 7 c) is revealing. Here, the red and orange shape on the filled map is in a similar location as in Fig. 7 b, except it is expanded in size but less intense in hue (as last time, none of the other maps have similar markings). The partially filled map contains the same subtle orange spot as above but this time it also contains a much more color intensive splotch on the eastern coast that is also absent from the Status quo map. This is a clear visual example of a coastal area of the county that this model predicts will have its sea-level rise rate reduced. Recall that this threshold of 0.3 meters was chosen as an optimistic scenario for a final sea-level. If this prediction comes to pass, than this partial filling provides an encouraging result, because it has a high maximum circuity value (nearly as high as the all filled scenario), and a mean ~2 times higher than the status quo (though it admittedly falls short of the best case all filled mean).

As the project sea-level rises above the optimistic 0.3 to 0.4 meters, Table 1 d reveals that the slow increase of circuity values has continued. Here the all filled map increased its maximum and mean values from 4012 to 5324 (only ~1.3 times, even less than last time) and from 746 to 1040 (~1.4 times, slightly higher than last time), respectively. The status quo map's maximum and mean values increased from 1162 to 1415 (only ~1.2 times, even less than the filled map) and from 93 to 142 (~1.5 times, more than the filled map, but less than it increases at the 0.3 threshold), respectively. Finally, the partially filled map's maximum and mean values increased from 3354 to 3379 (1.007 times, essentially not at all) and from 195 to 306 (~2 times, more than either of the other two), respectively. Here, since none of the maps increased their maximums by much, the partially filled scenario was able to maintain a large advantage over the status quo scenario, while remaining about equidistant between the ideal scenario's maximum and the status quo's maximum. Also it increased more than the other two in mean and established a mean more than twice that of the status quo. This can be visualized in Figure 7 d. Here the Eastern "spot" has grown substantially. At this scenario it once again appears that the partial filling solution would be quite successful in slowing the rate of sea-level rise, at least for a portion of the peninsula, especially when compared to the status quo map that still shows few visual signs of any pockets of relatively high circuity values.

The next sea-level rise threshold is five decimeters. Table 1 e shows some interesting trends that are beginning to emerge. The all filled scenario increased its maximum and mean values from 5324 to 5571 (only 1.05 times,) and from 1040 to 1300 (1.25 times), respectively. The status quo map increased its maximum and mean values from 1415 to 2428 (~1.7 times) and from 142 to 183 (~1.3 times), respectively. Lastly, the partially filled ditches map increased its maximum and mean values from 3379 to 3384 (~1 times, essentially not at all) and from 306 to 361 (~1.2 times), respectively. Here we can see that the partially filled maximum has essentially not increased. At the same time, the status quo maximum has steadily increased. This may be a sign that by this sea-level rise threshold, the partial fills are beginning to lose their effectiveness compared to the status quo. Nevertheless, the wholly filled ditches' maximum has also remained relatively stagnant, so the partial paving map did not fall as far behind as it could have. In total, the partially filled maximum remained well above that of the status quo (although it is now closer to the status quo than it is to the ideal values). Also, the partially filled mean remained solidly above that of the status quo as well. A look at the maps (Figure 7 e) shows once again the large eastern "spot" as well as some other lesser dark spots that are not present on the status quo image. The status quo image is, however, beginning to show some slight coloration in some areas. All of this evidence combines to suggest that the partial filling solution is still proving to be effective in slowing sea-level rise at this threshold compared to the status quo in mean and maximum circuity values, as well as visually on the map. There does, however, appear to be a trend emerging that perhaps will prove to limit the partial filling's efficacy as the sea-level rises further.

For the 0.6 meter threshold, Table 1 f shows that both the partially filled and the status quo maps have essentially stagnated in both maximum value, and mean value. The partial fill's maximum remained identical and its mean increased by only 1.05 times. The status quo's maximum increased by only 1.08 times, and its mean by only ~1.1 times. At the same time the fully filled map made steady increases of ~1.6 times and ~1.3 times for the maximum and the mean respectively. Here, the ideal values are beginning to completely out-compete the other two scenarios. The partial fill is no longer operating anywhere near the level of the full fill. The maps (Figure 7 f) corroborate this. The easterly spot that has been present on the last few partial fill maps is still present and of similar size, but it is much paler. This is because the maximum values for the ideal solution are beginning to get quite a bit larger than those of the strategic solution. When comparing the status quo to the strategic solution, however, the maximum and mean circuity values of the partial fill are still higher (although the status quo values appear to be catching up). Both this and the map confirm that it should still prove comparatively effective at slowing the sea-level rise rate.

For the 0.7 meter threshold, Table 1 g shows us that the completely filled map has continued to well exceed the maximum and mean values for the other two scenarios. In fact, looking forward (Table 1 h-k), this trend only continues. For this reason I will stop comparing it to the others except to stress that moving forward the partial fill is not at all approximating the efficacy of a full fill. The value of a partial fill at this point is to what extent it can be effective compared to the status quo. In this case the partial fill has an even smaller advantage over the status quo in maximum and mean values. Nevertheless, these advantages are still present, even if they are not as large as they were at the less severe sea-level rise scenarios. Once again, the map (Figure 1 g) shows a similar pale red spot on the partial fill map but not on the status quo maps. There is still evidence to suggest that at this sea-level rise severity the partial fill is likely slowing the extent of sea-level rise, but it is clearly less effective at doing so than at less dire scenarios.

Starting with the 0.8 meter threshold, and continuing with the 0.9, 1 and 1.1 meter thresholds (Table 1 h-k), the maximum circuity values are within two meters of each other. This means that they are essentially equal, and that the partial fill no longer has any advantage over the status quo in this regard for these thresholds. The mean circuity values, however, remain securely in favor of the partial fill over the status quo in each case. In addition, the maps (Figures 7 h-k) still show the same spot from the above thresholds on each partial fill map up to and including the worst case scenario. This spot is still not present on any of the status quo maps. It is important to note, however, that both maps begin to share increasingly more red/orange spots as the sea-level threshold increases. The fact that the partial fill maps do have higher mean circuity values, and that they have more visual evidence of relatively high circuity values suggests that even at these extreme scenarios the partial fill is still showing signs that it may be to some extent effective in slowing the rate of sea-level rise for the county.

To summarize, my model predicts that the rate of sea-level rise can be slowed down by implementing a strategic partial ditch fills (but not flap gates) based on the eleven prioritized nodes (Figure 5). Furthermore, there is evidence, that this solution will be far more effective for less severe sea-level rise predictions (0.3-0.7 meters) then for the more dire predictions (0.8-1.1 meters). Also, it is possible to speculate that some of this slow down may also yield to actual reductions in extent, however, without further research I will not make such a bold claim, and will simply conclude that this model is inconclusive as to changes to the ultimate extent of sea-level rise.

Considering some of the caveats with this study listed above, I cannot in good conscience suggest that an organization looking to address this issue immediately begin digging up the county based on my exact specifications. I will say, however, that I believe that there is enough evidence here to suggest that: 1) strategically filled ditches can potentially slow the rate of sea-level rise 2) If one’s main goal is slowing the rate of sea-level rise then gating within ditches will not be the most effective solution to this problem. I will recommend several steps moving forward: First decide if your goal is long term mitigation of sea-level rise rate, or if it is salt water intrusion management, because these problems will likely have similar but different solutions. Second, if you wish to combat sea-level rise conduct a budgetary meeting to discuss exactly how many feet of ditch fill are conceivable. Third with this information in hand conduct a more in depth prioritization study tailored specifically to your ability and budget. Fourth, conduct some even more rigorous modeling studies to assure that the ditches that you prioritized will net similar benefits to the ones shown in this study. Armed with the results of this study, we can move forward with confidence knowing that a hydrologic restoration project in Dare County does have the potential to mitigate the rate of land submergence due to sea-level rise.

Figures and Tables

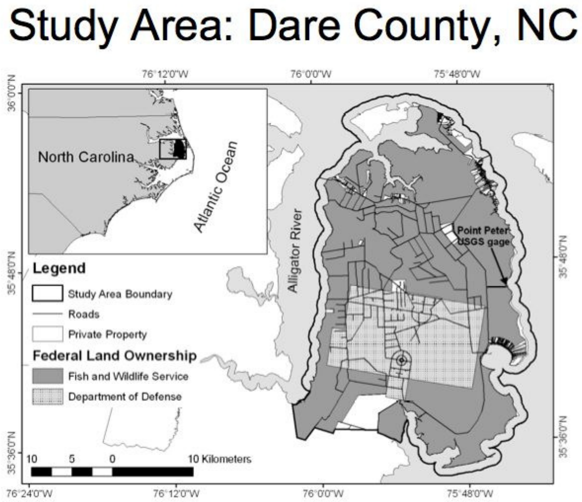

Figure 1: Depicting the study area. Figure courtesy of B. Poulter et al., 2008.

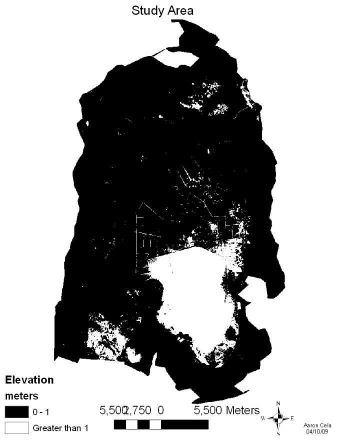

Figure 2: The area at or below one meter above the current sea-level for the study area.

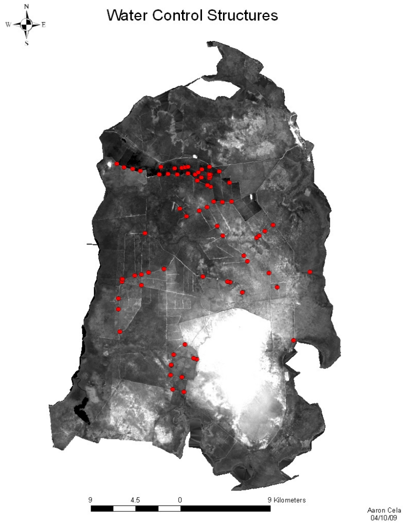

Figure 3: Locations of the water control structures used in the analysis.

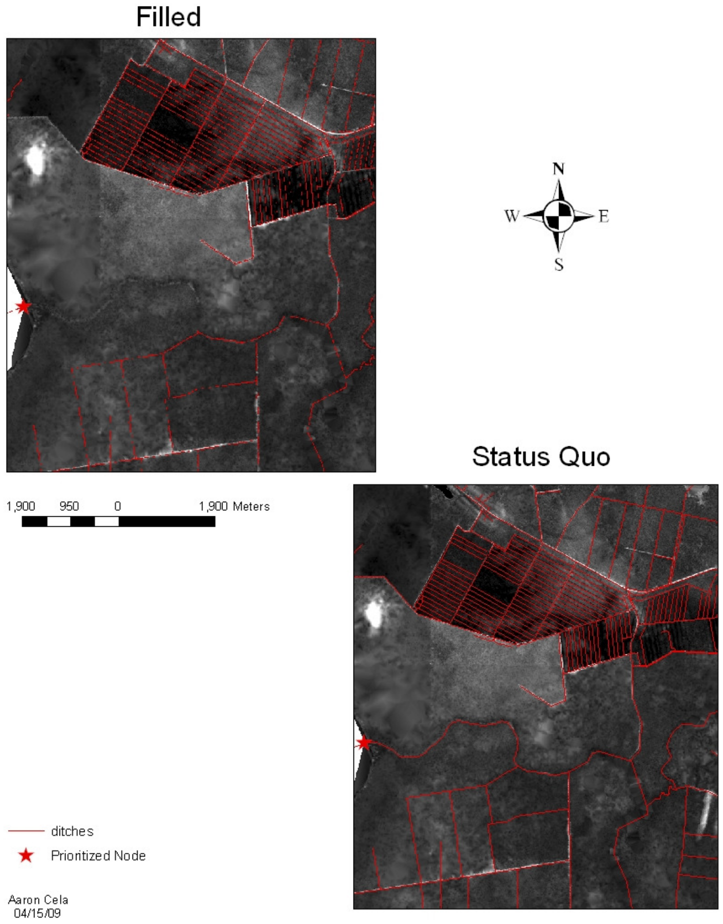

Figure 4: A visual example of how each ditch was filled at each prioritized node.

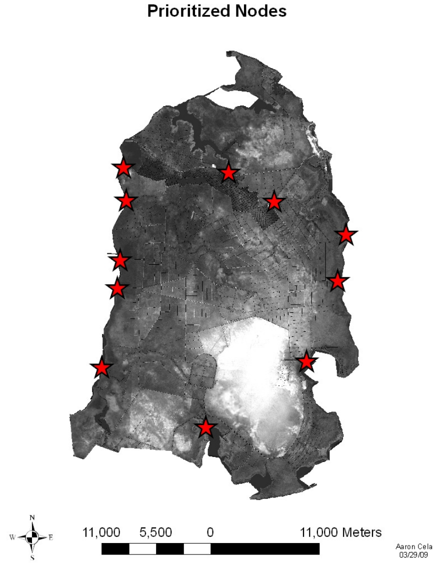

Figure 5: Prioritized ditch network nodes based on importance for hydrologic flow, saltwater intrusion, and on expert opinion.

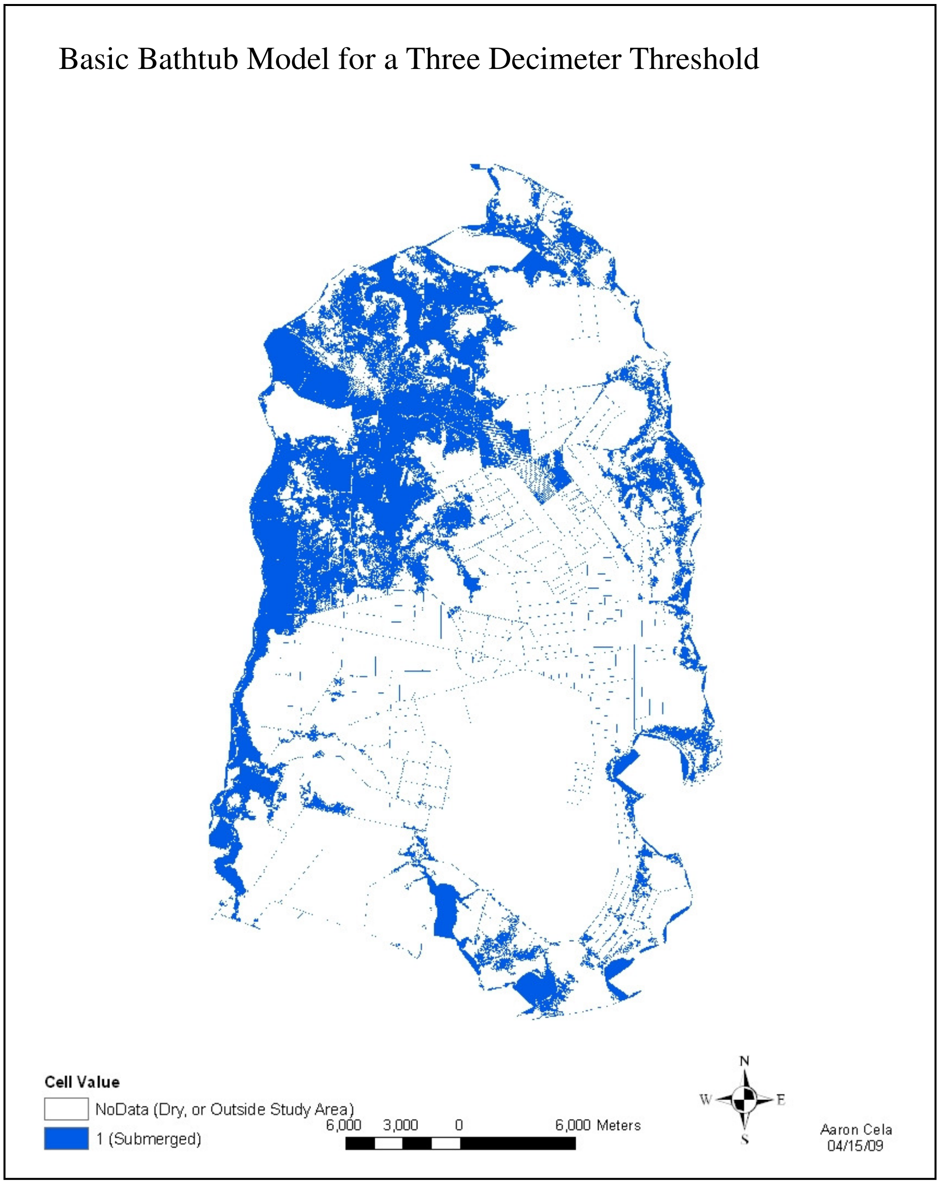

Figure 6: An example of a simple of a simple bathtub sea-level rise model for the three decimeter sea-level rise threshold. The cells with a value of one are below this threshold, and are modeled as submerged. All other cells are "NoData," and represent either dry cells, or those outside of my study area. Note the blue cells values at one in the interior of the county surrounded by otherwise dry cells. These cells are inside of the ditch network and are in this simple model represented as submerged, whereas if they were filled they would be represented as dry.

One Decimeter Sea-Level Rise

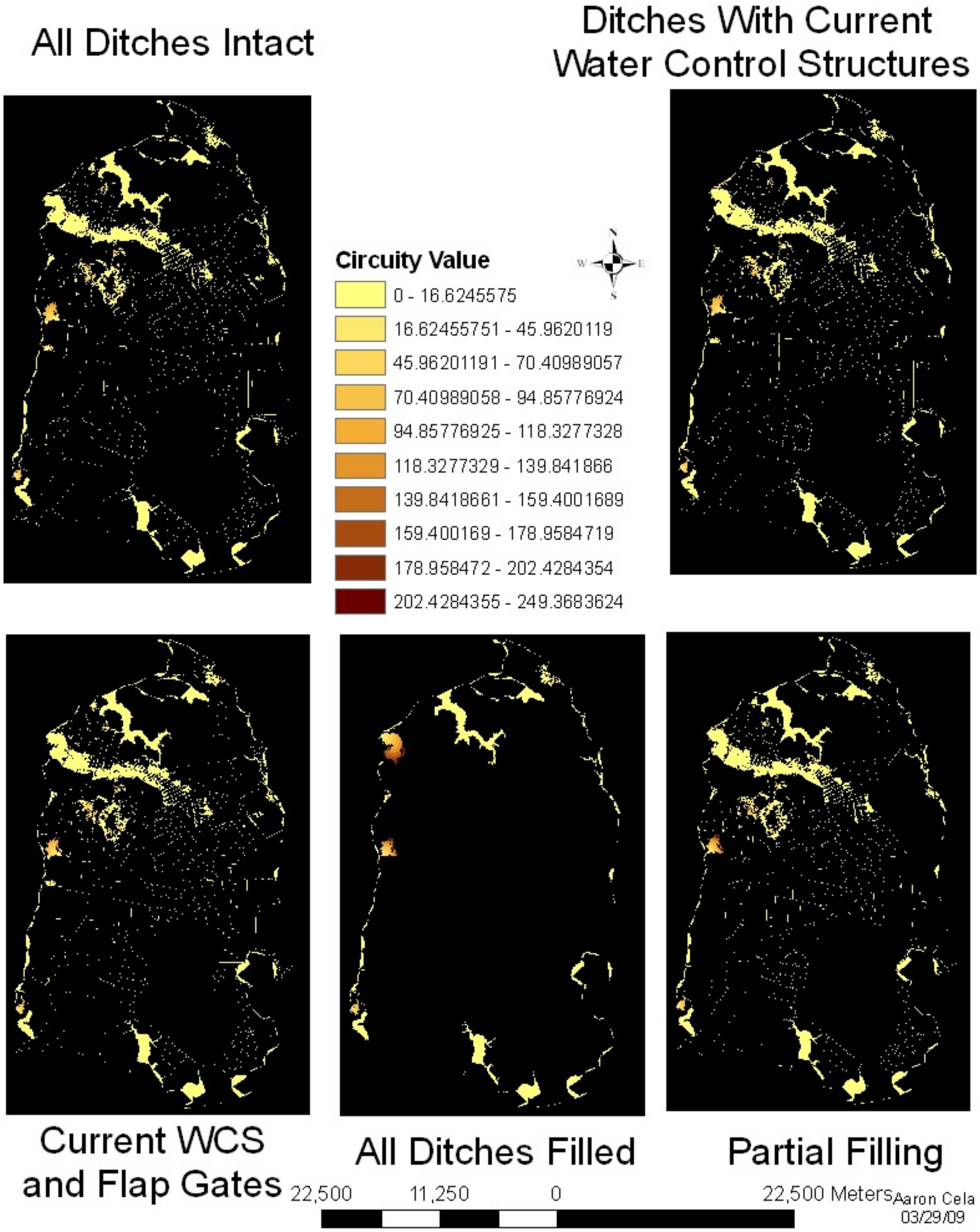

Figure 7 a

Two Decimeter Sea-Level Rise

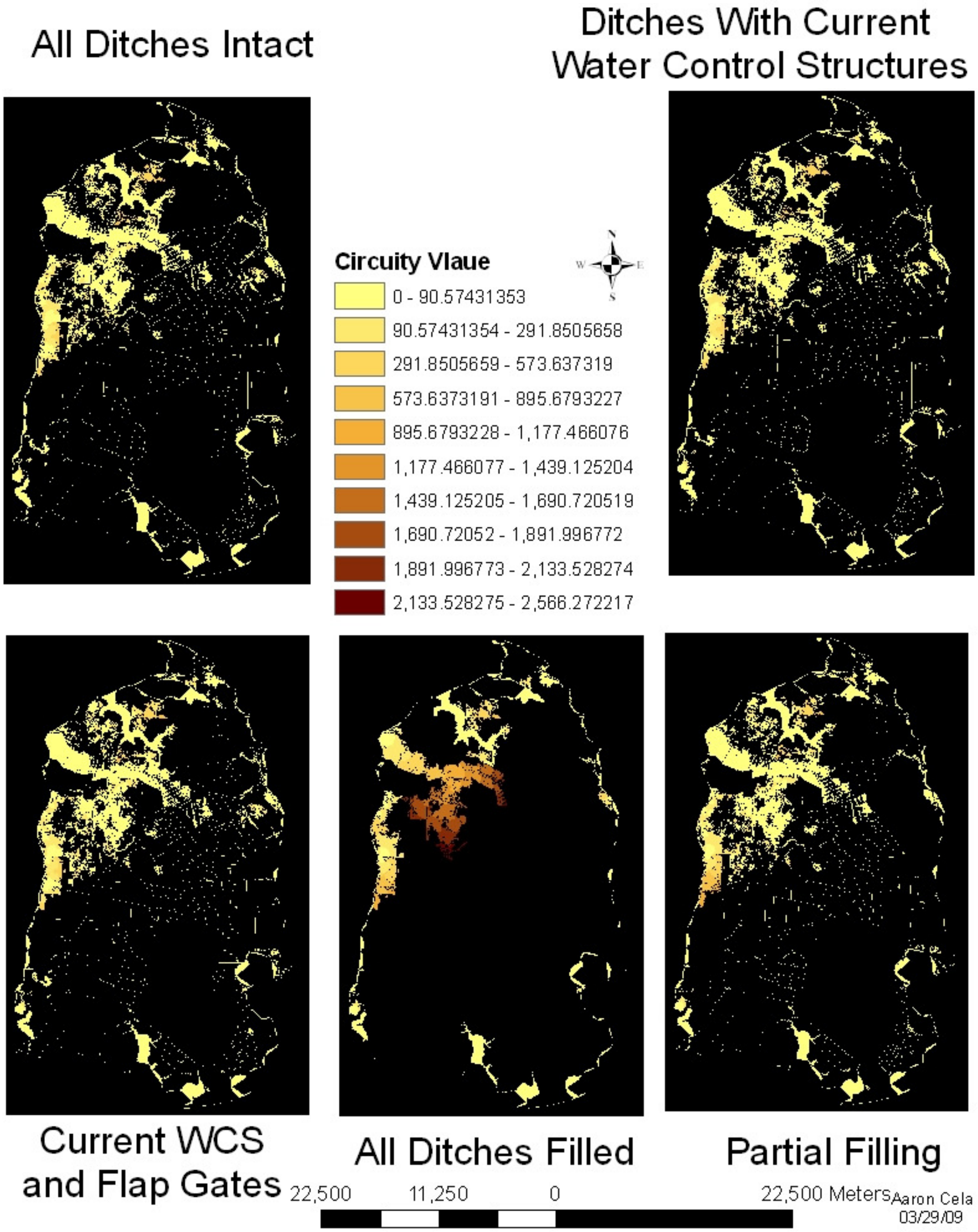

Figure 7 b

Three Decimeter Sea-Level Rise

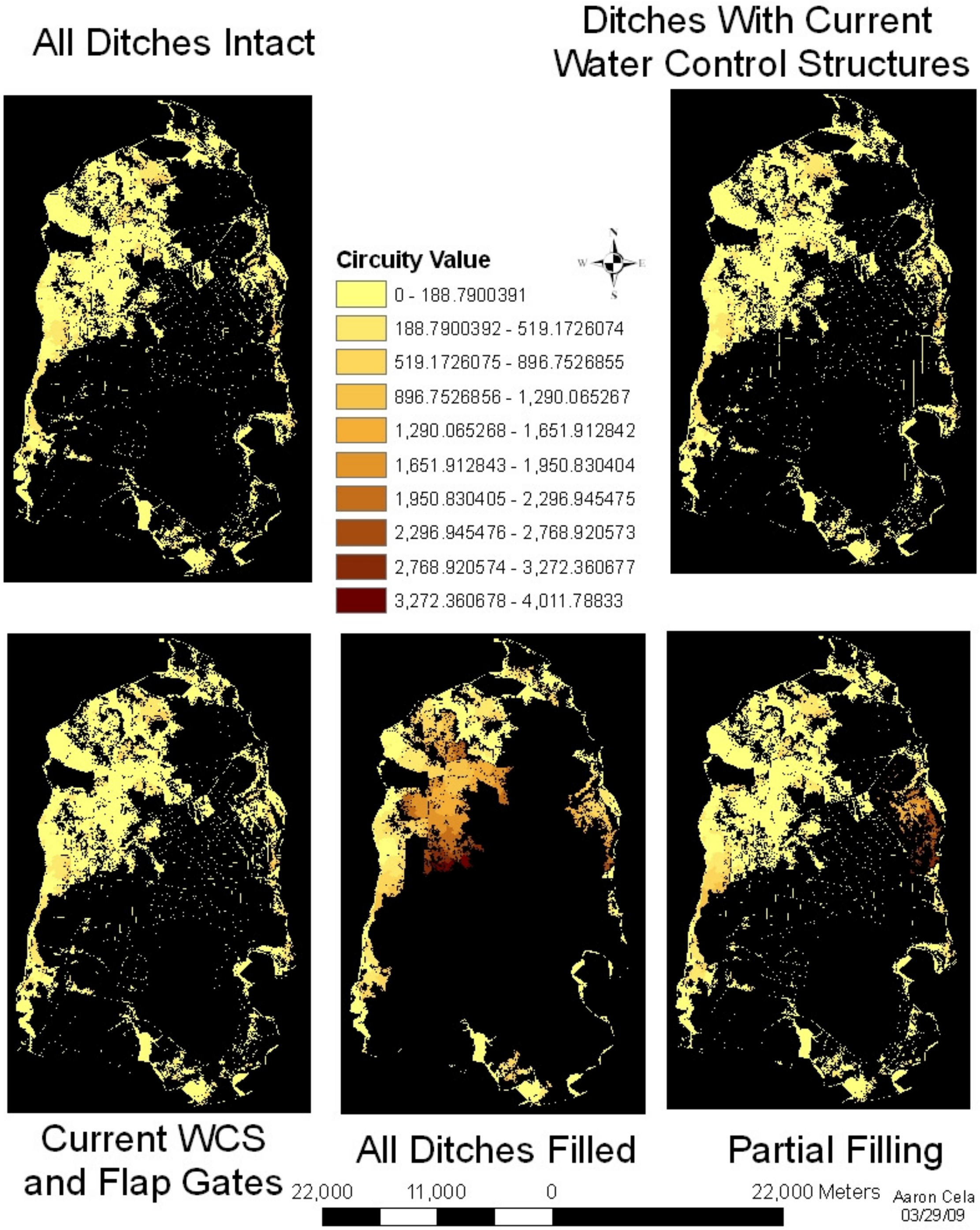

Figure 7 c

Four Decimeter Sea-Level Rise

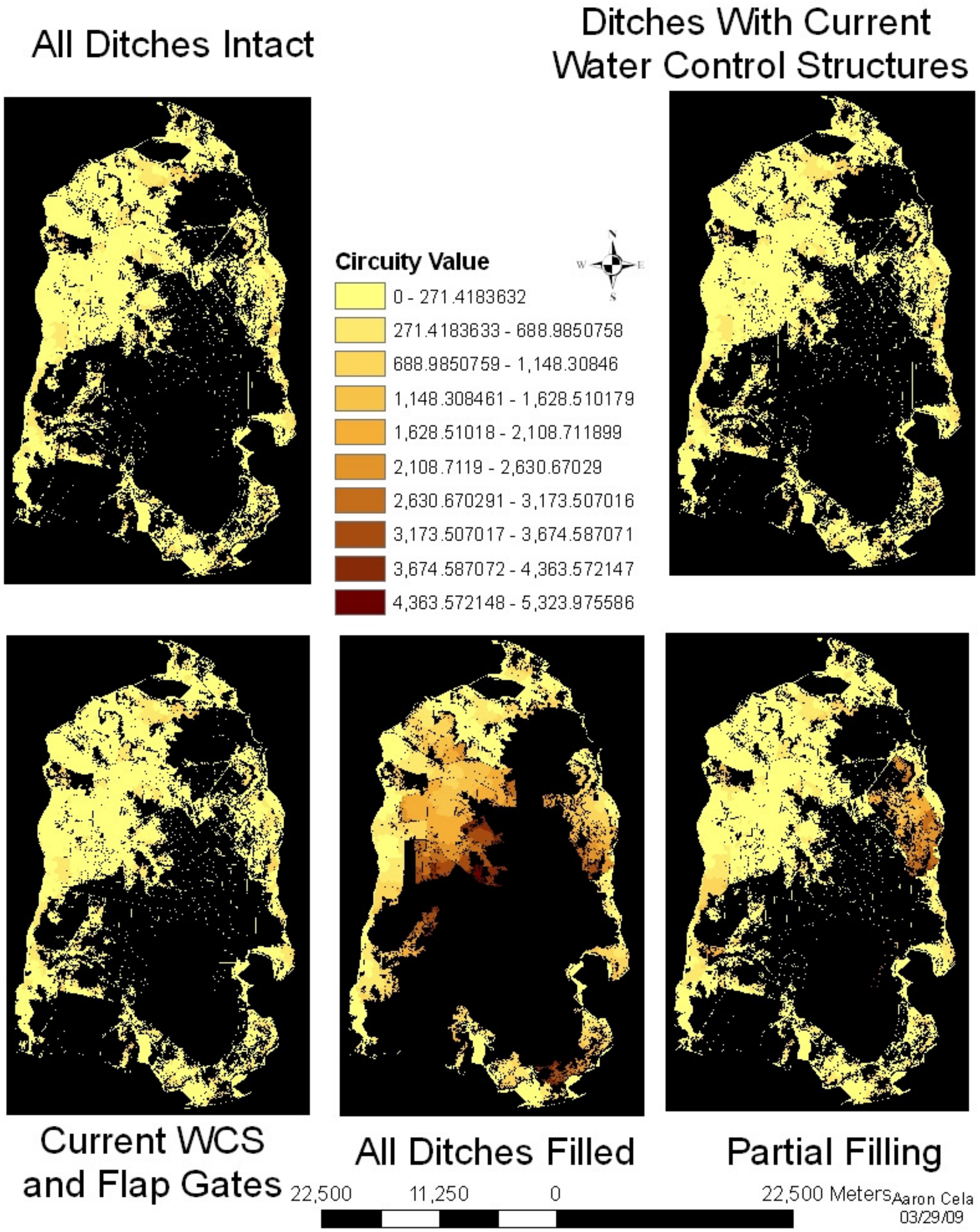

Figure 7 d

Five Decimeter Sea-Level Rise

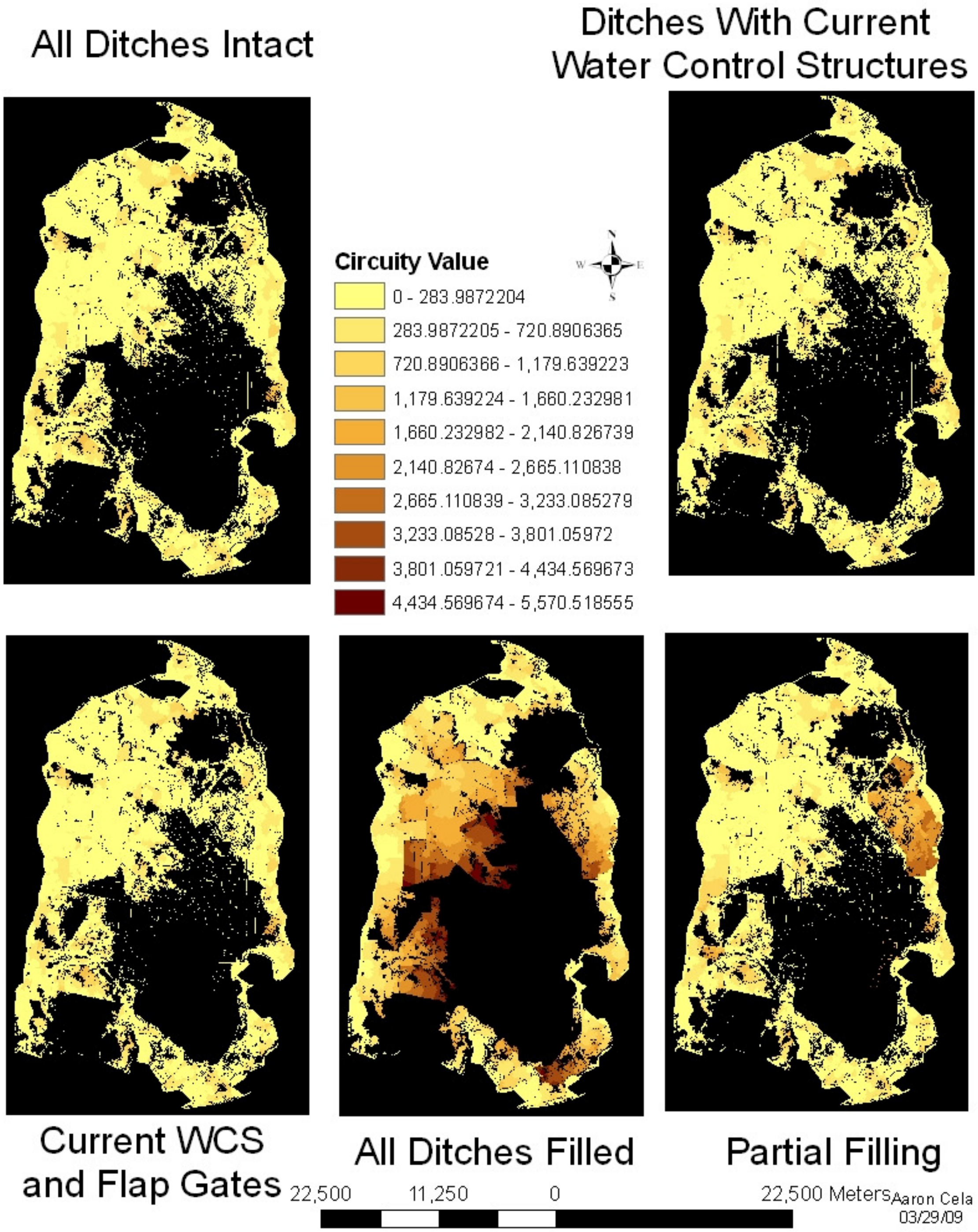

Figure 7 e

Six Decimeter Sea-Level Rise

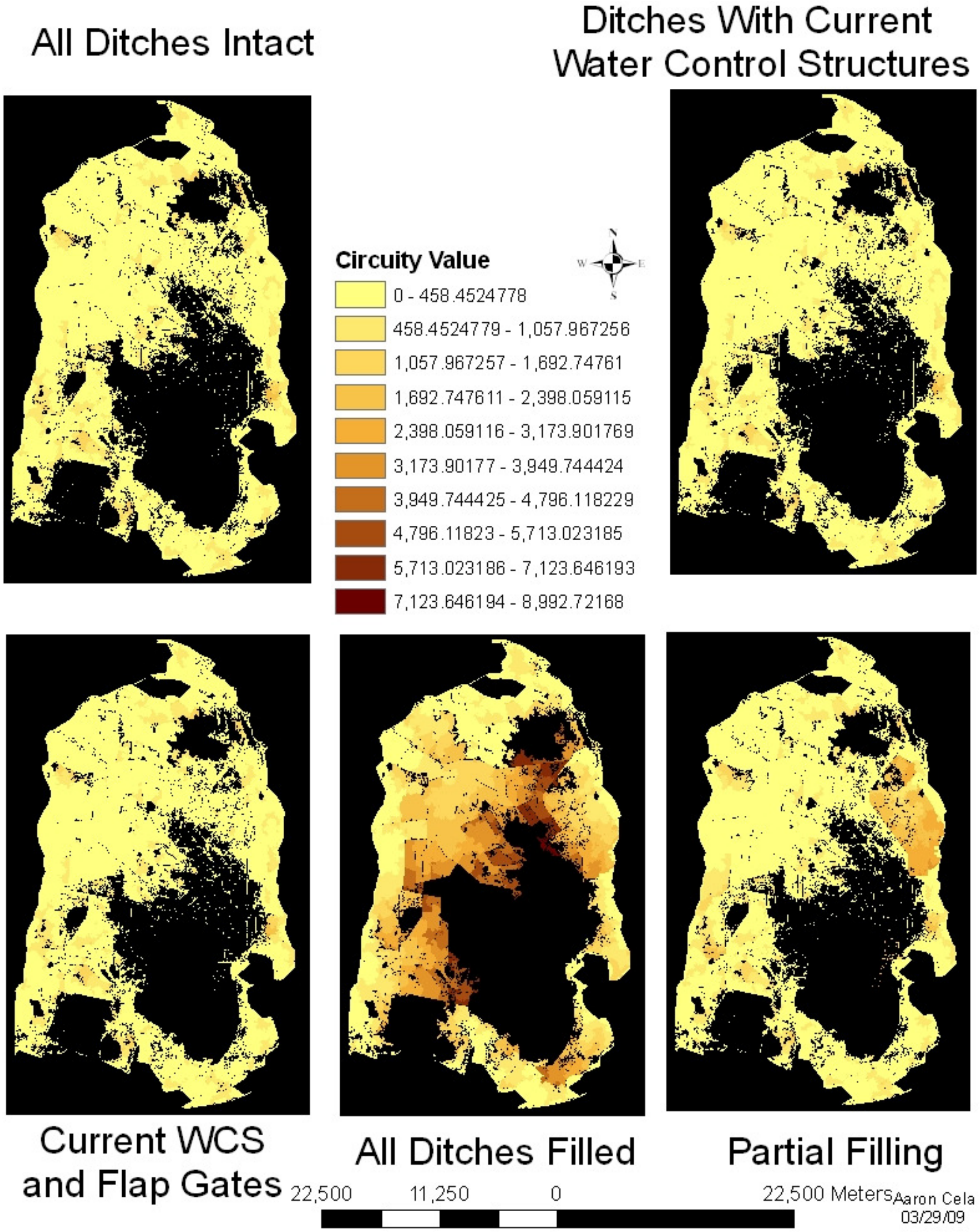

Figure 7 f

Seven Decimeter Sea-Level Rise

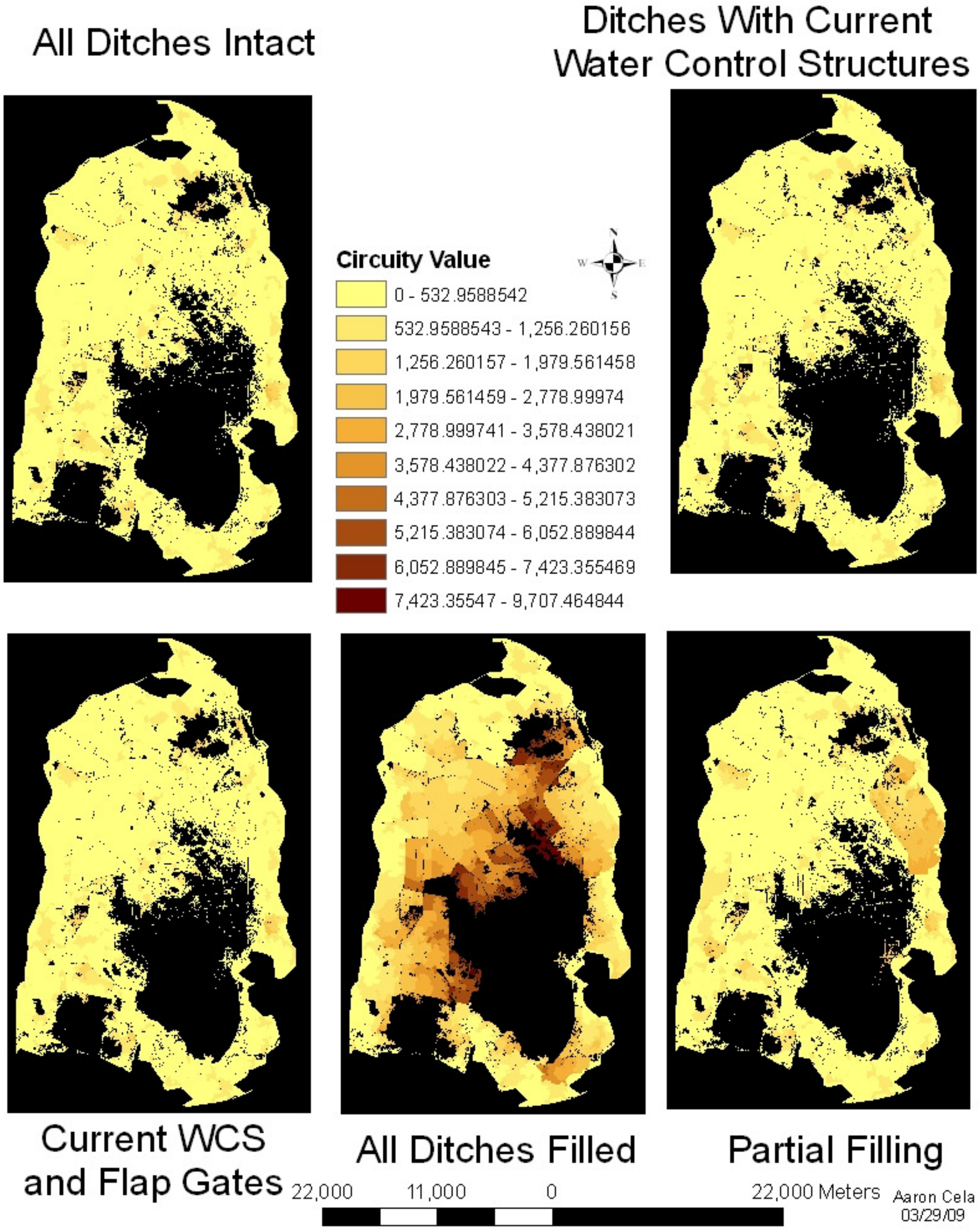

Figure 7 g

Eight Decimeter Sea-Level Rise

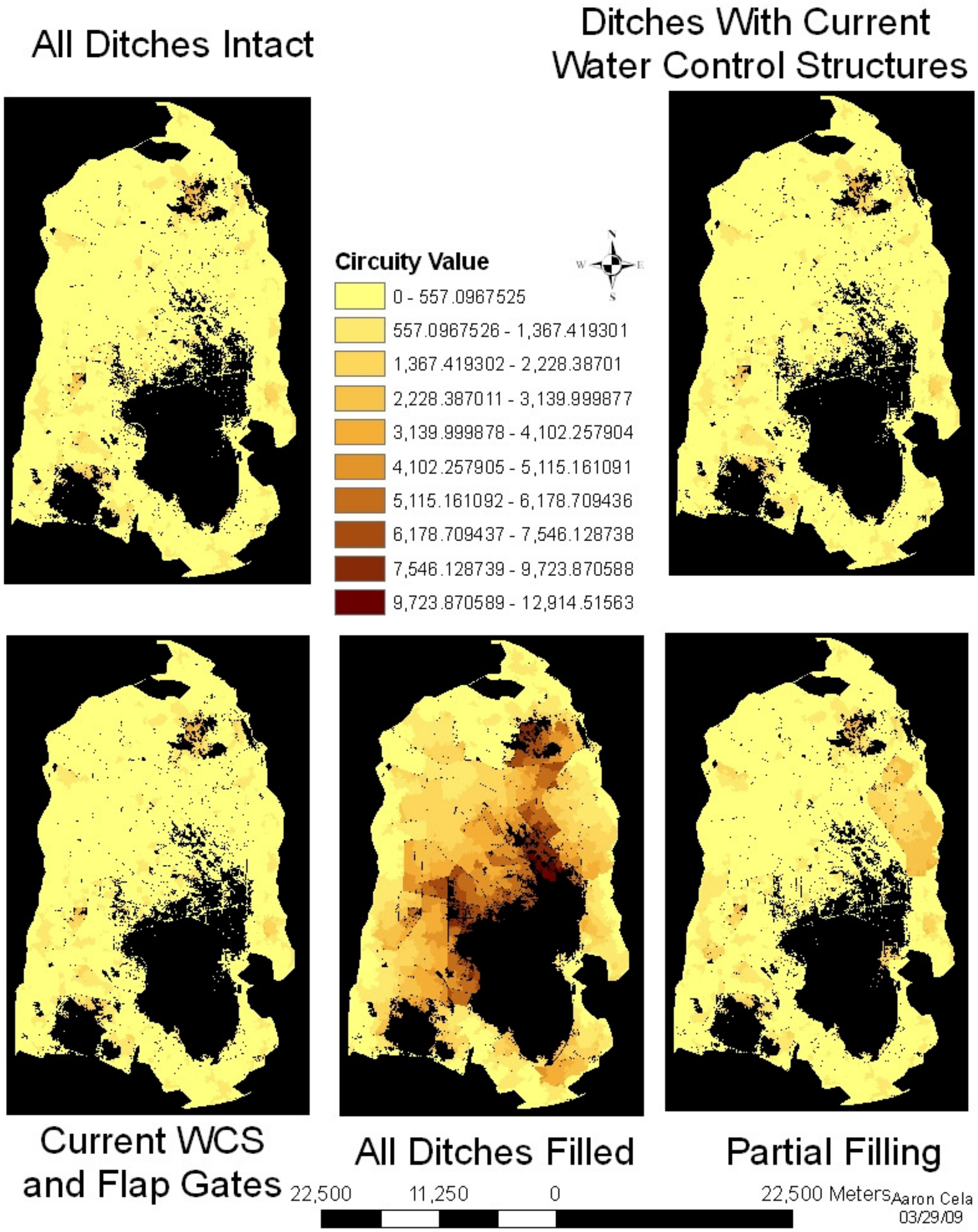

Figure 7 h

Nine Decimeter Sea-Level Rise

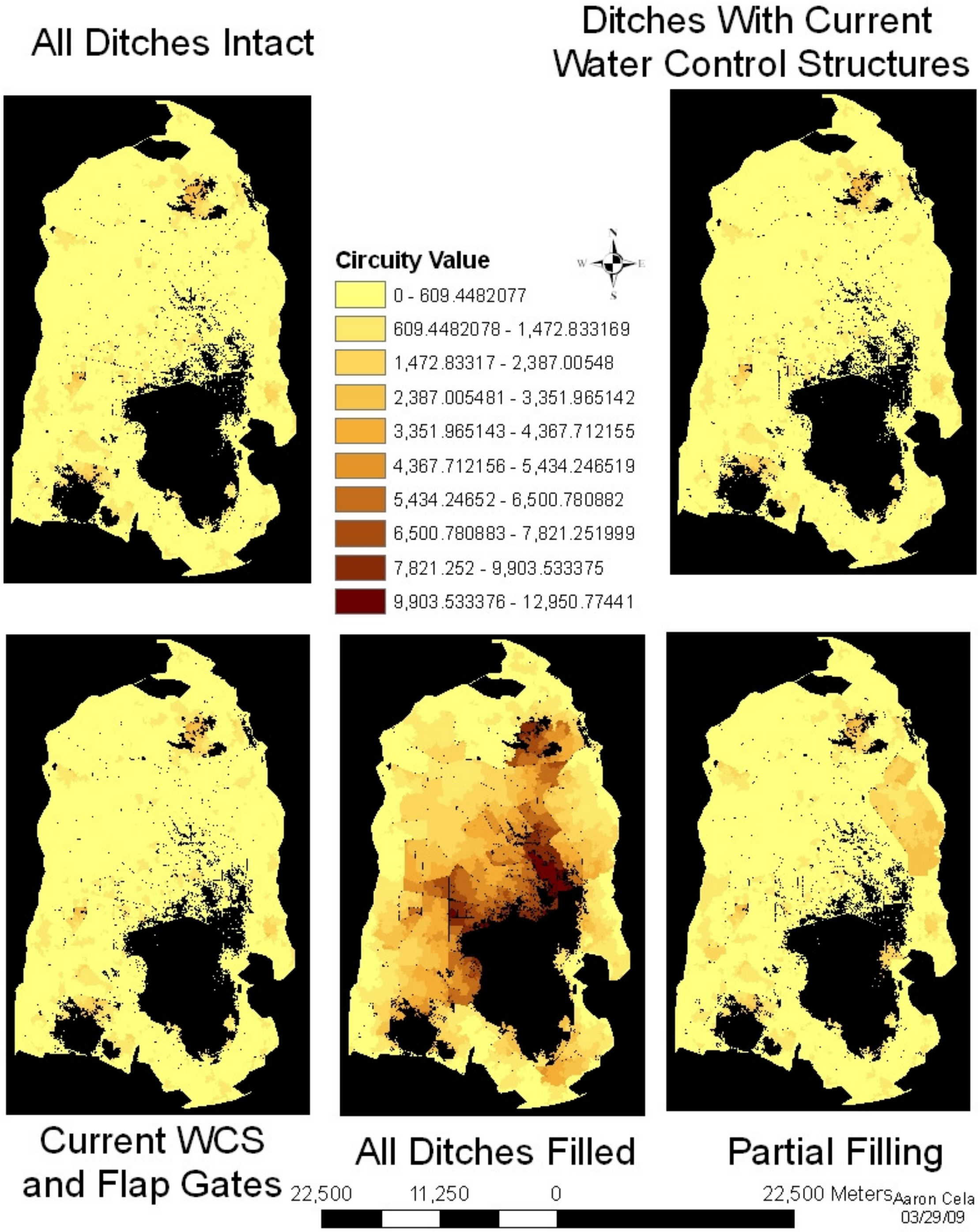

Figure 7 i

One Meter Sea-Level Rise

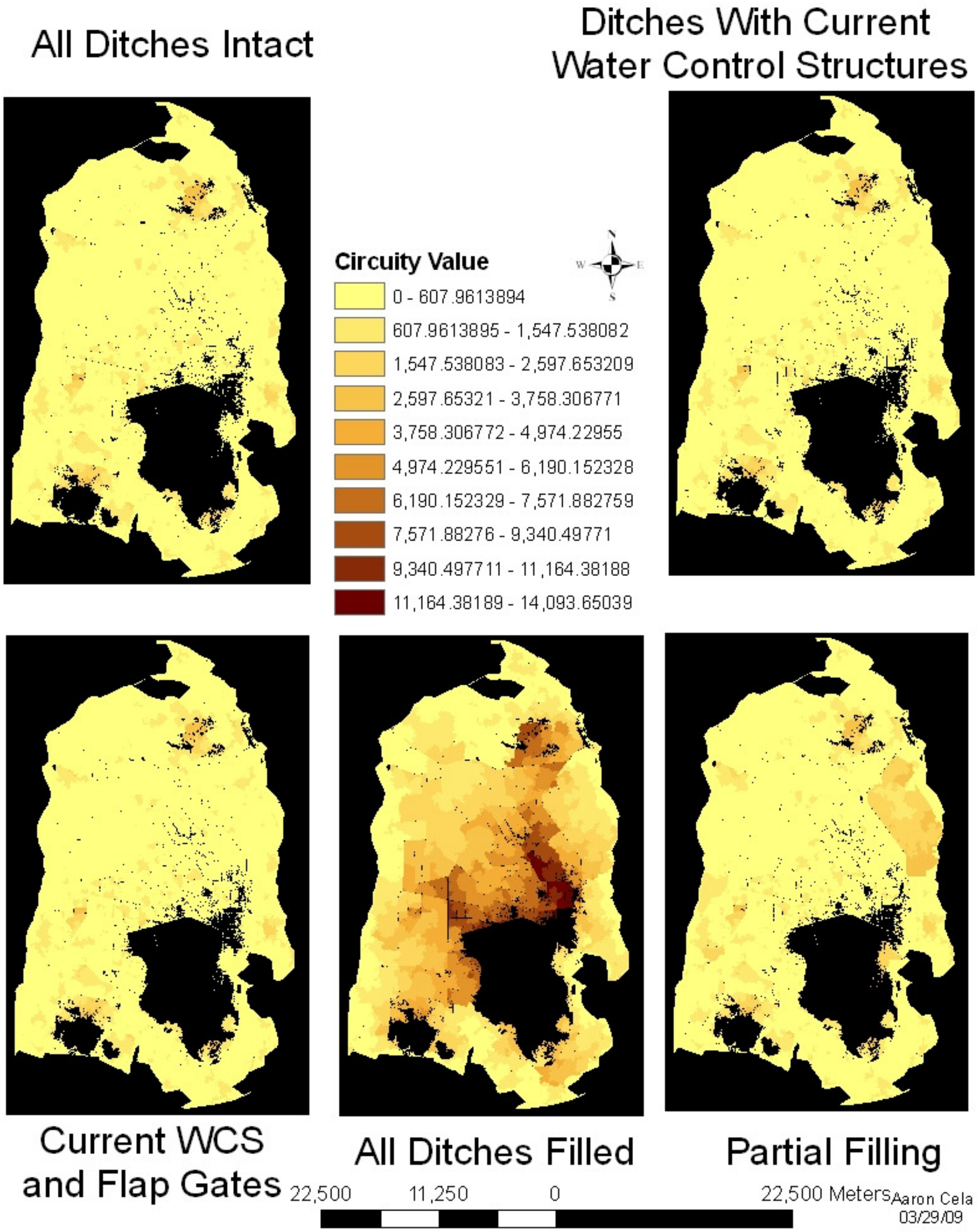

Figure 7 j

Worst Case Scenario 1.1 Meter Sea-Level Rise

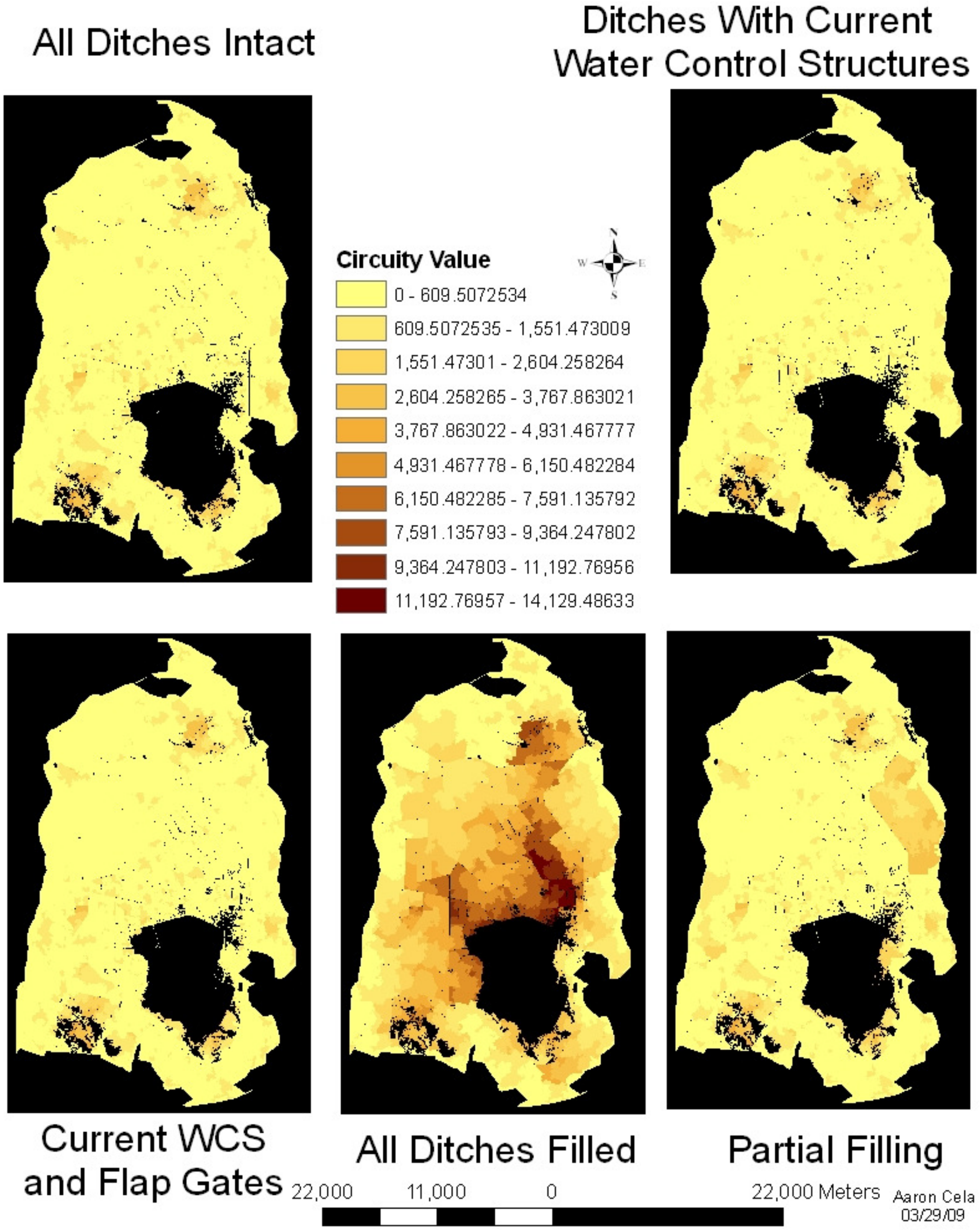

Figure 7 k

Figures 7 a-k: Circuity values (meters) for each hydrologic scenario, at each sea-level rise extent. The yellow to red scale represents low to high circuity values, and the interior black represents land that remains unsubmerged at each decimeter sea-level rise. The exterior black is outside of the study area.

Table 1 (a-k): Maximum, mean and standard deviation for circuity values (meters) for each hydrologic scenario, at each sea-level rise extent. All values rounded to the nearest meter, unless they were less than 10 meters, in which case they were rounded to the nearest decimeter.

Table 1 a(left), b(right): 0.1, 0.2 meter sea-level rise, respectively

DEM Type	Maximum Circuity Value (meters)	Mean Circuity Value (meters)	Standard Deviation
Intact Ditches	148	4.7	17
Ditches With WCS	148	4.7	17
Ditches With WCS and Flap Gates	148	4.7	17
Ditches Partially Filled	201	5.4	20
All Ditches Filled	249	18	44

DEM Type	Maximum Circuity Value (meters)	Mean Circuity Value (meters)	Standard Deviation
Intact Ditches	779	44	88
Ditches With WCS	779	44	88
Ditches With WCS and Flap Gates	779	44	88
Ditches Partially Filled	1191	65	157
All Ditches Filled	2566	556	703

Table 1 c(left), d(right): 0.3, 0.4 meter sea-level rise, respectively

DEM Type	Maximum Circuity Value (meters)	Mean Circuity Value (meters)	Standard Deviation
Intact Ditches	1162	93	139
Ditches With WCS	1162	93	139
Ditches With WCS and Flap Gates	1162	93	139
Ditches Partially Filled	3354	195	440
All Ditches Filled	4012	746	807

DEM Type	Maximum Circuity Value (meters)	Mean Circuity Value (meters)	Standard Deviation
Intact Ditches	1415	142	187
Ditches With WCS	1415	142	187
Ditches With WCS and Flap Gates	1415	142	187
Ditches Partially Filled	3379	306	580
All Ditches Filled	5324	1040	1048

Table 1 e(left), f(right): 0.5, 0.6 meter sea-level rise, respectively

DEM Type	Maximum Circuity Value (meters)	Mean Circuity Value (meters)	Standard Deviation
Intact Ditches	2428	183	235
Ditches With WCS	2428	183	235
Ditches With WCS and Flap Gates	2428	183	235
Ditches Partially Filled	3384	361	614
All Ditches Filled	5571	1300	1218

DEM Type	Maximum Circuity Value (meters)	Mean Circuity Value (meters)	Standard Deviation
Intact Ditches	2631	208	262
Ditches With WCS	2631	208	262
Ditches With WCS and Flap Gates	2631	208	262
Ditches Partially Filled	3384	378	607
All Ditches Filled	8993	1672	1601

Table 1 g(left), h(right): 0.7, 0.8 meter sea-level rise, respectively

DEM Type	Maximum Circuity Value (meters)	Mean Circuity Value (meters)	Standard Deviation
Intact Ditches	2973	227	291
Ditches With WCS	2973	227	291
Ditches With WCS and Flap Gates	2973	227	291
Ditches Partially Filled	3572	390	607
All Ditches Filled	9707	1903	1810

DEM Type	Maximum Circuity Value (meters)	Mean Circuity Value (meters)	Standard Deviation
Intact Ditches	3943	256	362
Ditches With WCS	3943	256	362
Ditches With WCS and Flap Gates	3943	256	362
Ditches Partially Filled	3945	411	627
All Ditches Filled	12915	2170	2114

Table 1 i(left), j(right): 0.9, 1.0 meter sea-level rise, respectively

DEM Type	Maximum Circuity Value (meters)	Mean Circuity Value (meters)	Standard Deviation
Intact Ditches	3982	275	393
Ditches With WCS	3982	275	393
Ditches With WCS and Flap Gates	3982	275	393
Ditches Partially Filled	3984	424	634
All Ditches Filled	12951	2371	2343

DEM Type	Maximum Circuity Value (meters)	Mean Circuity Value (meters)	Standard Deviation
Intact Ditches	4102	290	419
Ditches With WCS	4102	290	419
Ditches With WCS and Flap Gates	4102	290	419
Ditches Partially Filled	4104	437	643
All Ditches Filled	14094	2518	2515

Table 1 k: 1.1 meter sea-level rise

DEM Type	Maximum Circuity Value (meters)	Mean Circuity Value (meters)	Standard Deviation
Intact Ditches	4717	321	495
Ditches With WCS	4717	321	495
Ditches With WCS and Flap Gates	4717	321	495
Ditches Partially Filled	4717	466	685
All Ditches Filled	14129	2596	2562

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