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The Impact of Sea Level Rise on Roadway Design and Evacuation Routes in Delaware

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Abstract

As the global temperature continues to increase, the sea level continues to rise at a rapid rate that has never been seen before. This becomes an issue for many facets of life but one of the most impacted is the transportation infrastructure. Many people living in low elevation coastal areas can become trapped by flooding with no way in or out. With Delaware being a coastal state, this would affect a large portion of the population and will have detrimental effects over time if nothing is done to combat sea level rise. The issue with sea level rise in transportation is that once the roads become flooded, they become virtually unusable and detour routes would be needed. If all the roads in a coastal area were to be affected by sea level rise, the options for detours would become limited. This article looks at direct solutions to combat sea level rise and indirect solutions that would specifically help transportation infrastructure and evacuation routes in Delaware. There is not one solution that can fix every problem, so many solutions are laid out to see what is applicable to each affected area. Some solutions include defense structures that would be put close to the coast, raising the elevation of vulnerable roads throughout the state and including pumping stations to drain the water on the surface of the road. With an understanding of all these solutions around the world, the ultimate conclusion came in the form of a six-step plan that Delaware should take in order to best design against sea level rise in these coastal areas.

Keywords

Sea Level Rise, Roadway Design, Evacuation Routes

1. Introduction

Sea level rise has been an issue facing our planet since the development of more

industrial practices. While this problem has affected many facets of life, a very important one that everyone must deal with is the effects of sea level rise on transportation. As sea levels rise, roads closer to the sea begin to flood and cause issues for anyone that needs to use them for transportation. Specifically for states such as Delaware, parts of the main evacuation routes are close to the shore which means they are susceptible to flooding. Once the road floods, there are issues with getting in and out of areas on the road for those that live there, paramedics, police, and many more parties that can help with saving lives. This is a pressing matter as the sea level rises will build up over the next few decades and become serious issues for areas around the coast. Combine this with the flooding that occurs after storms, there can be irreversible damage done to the transportation systems across the country and the world.

While sea level rise is a serious issue for transportation, there are solutions that are being developed as this problem progresses. One very direct solution in transportation is raising the elevation of the roads. Being able to raise the elevation of the road is very useful in combating flooded roads as it minimizes the negative effects of a large amount of water covering the roads. Raising the elevation of the roads by a few inches is effective in the short run, however, it will lead to more additions over time once the sea levels continue to rise or a storm hits the area and causes even more issues. When considering the Bowers Beach solution, for instance, double the amount of the porous material will be needed to just become level with the 100-year storm calculations. Add this in with the continuing sea level rise and even more material will be needed. While raising the roads is a direct solution that can work, it can become expensive, and it cannot act by itself to combat flooded roads and sea level rise. This article will explore the effects of raising the road in Delaware through a geometric sense such as the effect of the cross sections.

There are more indirect solutions to help alleviate the issues of sea level rise on transportation systems. A couple of solutions are seawalls, levees, and swales. These solutions do not directly affect the road; however, they can help to lower the effects of sea level rise. Seawalls, levees, jetties, groins, and breakwaters all work to stop water from getting onto the land and causing flooding. Other solutions include swales and increased drainage which works to move the water that hits the road to lower elevations. There are many solutions that can work together; however, this problem has started to be taken more seriously over the past few years. This means that there needs to be creative solutions that work through an engineering sense as well as the eye of the public. For example, an area can tell everyone to move to the highest elevations but there will be restrictions to move from their homes. Not every solution is going to be something that can be built as other solutions will need to be working with the stakeholders involved. This article will look at the effects of all these solutions working together to understand how to best account for all stakeholders involved in Delaware.

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2. Sea Level Rise around the World

Over the past one hundred years, the sea level around the world has risen between six and eight inches but the rate currently is increasing from those past numbers (Blackwood, 2022). The rate is currently at about 0.12 to 0.14 inches a year (Blackwood, 2022), and it will continue to build up over the next few decades and cause serious issues for areas around the coast. This comes from the increased temperatures around the world from global warming due to climate change, carbon pollution and much more stemming from the built environment. While sea level rise is not necessarily a fatal change to humanity, it causes many issues to surrounding areas such as flooding that leads to the loss of beaches, wetlands and infrastructure close to the ocean. This would affect around forty percent of the world population as this is the proportion that lives in coastal communities (United Nations Division of Sustainable Development, 2007). Having this number of people affected by sea level rise shows how much of an issue this can become around the world if action is not taken. While it would be convenient to have one solution that can solve sea level rise around the world, every coastal area has its own specific needs and there is no solution that could benefit them all. This is the reason why this article will focus on understanding the sea level rise in the State of Delaware and solutions for the coastal areas moving forward. The article is of original nature since it applies the existing approaches, combined with expert consultations, to potential solutions that are deemed practical for the State of Delaware. Other states and communities may follow the steps and procedures outlined in this article to determine the unique solution(s) that are practical for their own regions.

3. Sea Level Rise in Delaware

Delaware is a state that borders the Atlantic Ocean which makes it very susceptible to the effects of sea level rise. As of right now, the sea level rise rate in Delaware is one inch every ten years or 0.10 inches per year which is slightly below the worldwide average (Sea Level Rise, 2022). The coastal areas of Delaware, specifically the beaches, make up a large portion of the economy in the state which shows how detrimental issues involving sea level rise can be. These areas would be the first to go without any additional protection as they are closest to the sea. **Figure 1** below shows the effect of sea level rise in Delaware. All the affected areas are along the coast and shore protection would be needed in a large portion of the state.

Now that sea level rise is defined as an issue in Delaware, the conversation can be shifted towards how it affects transportation in order to later understand how to properly design for this pressing issue.

4. How Does the Sea Level Rise Affect Transportation?

Transportation systems are an integral part of everyday life whether it is driving a car, riding a bicycle, taking a train or even just walking. Once this becomes slightly affected, the amount of time it takes to get to a destination increases

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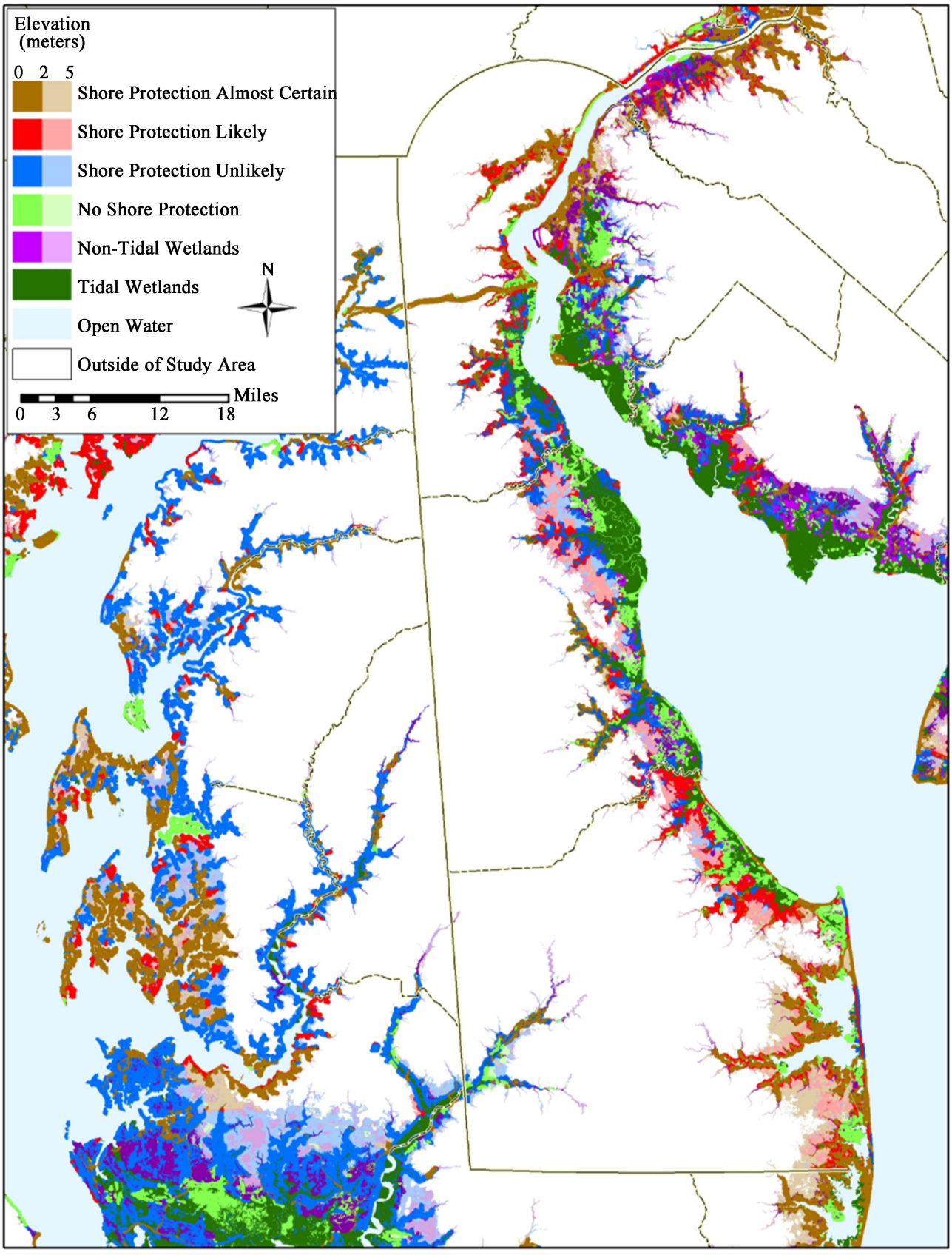

Figure 1. Delaware sea level rise planning map.

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which is a huge issue in emergencies. Sea level rise affects transportation in the same way that flooding would. Roads become inaccessible due to the water or become hard to maneuver due to lower speeds out of caution for water on the surface. Wet pavement causes nearly 5700 deaths and 544,700 injuries annually in the United States showing how much of a problem flooded roads can become even if it is a small amount of water touching the surface (US Department of Transportation Federal Highway Administration, 2022). Specifically in Delaware, roads close to the coast will become unusable over time which is a huge issue for Route 1. This is the main evacuation route for the state and when areas become affected by sea level rise, the route is unusable for most of Sussex County which holds around a quarter of a million people. Making sure that this route is above sea level is very important in Delaware and a proper solution is needed.

When looking more into how sea level rise affects transportation, detour routes become a large part in making sure people can get to the locations they need to go to. Once a road floods, the road is shut down and then a detour route is needed to continue the flow of traffic. Sea level rise can increase the density of traffic which can ultimately lower the flow and negatively impact the level of service for a road. No one enjoys traffic but if there is an emergency where an ambulance needs to get to a location, but the roads are taken out by flooding, it becomes a huge issue.

Once flooding occurs, the asphalt that makes up the road begins to deteriorate over time which weakens its performance. This can cause cracks and potholes once water enters the asphalt which would cause issues for the road even if all the water is drained. Maintenance of very low-level roads could become costly if they are not raised and constant repair is needed to get rid of the potholes and cracks. Now that the correlation between transportation and sea level rise is defined, an exploration of current direct and indirect solutions for sea level rise can be explored.

5. What Is Currently Being Done to Combat Sea Level Rise?

There are many direct solutions to deal with sea level rise that have been implemented around the world and in Delaware. To begin, a seawall is a coastal defense that stops the impact of the ocean directly. There are three different types of walls that can be implemented depending on the environment: vertical, curved and mound (Thaler Contracting, 2022). Vertical seawalls are easy to construct and deflect wave energy away from the coast. However, they need a strong material due to the large amount of impact taken in a short amount of time. Curved seawalls prevent overtopping and reduce turbulence from the waves. However, these walls cost more due to the more complex design needed compared to the vertical wall. Mound seawalls are the cheapest option as they use concrete and rock. Due to the lower material costs, the performance is poor and has the shortest life expectancy. Later in the article, there will be a discussion on what seawalls could work best for Delaware that would help the transportation

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systems combat sea level rise.

Another direct solution for sea level rise is the addition of a levee. These are built parallel to a waterway to reduce the risk of flooding towards the land (Federal Emergency Management Agency, 2020). This is commonly seen near rivers, but these can be built in the form of dunes which are common along the beaches. The Delaware beaches implement dunes to stop flooding from high waves. For the areas further north in Delaware, adding a proper levee could be useful and serve the same purpose of protecting the land from flooding.

A final direct solution to sea level rise is implementing jetties and groins. Jetties are rock or concrete structures that are built as inlets to control the water moving near channels (North Carolina Coastal Federation, 2021). Groins are similar but they are built perpendicular to a coast and serve the same purpose (North Carolina Coastal Federation, 2021). These structures are seen throughout the coastal areas of Delaware to help control the sediment transport from the ocean. Now that the direct solutions for sea level rise are defined, there can be a discussion on the indirect solutions to the issues that are related to transportation.

6. Current Solutions to Sea Level Rise in Transportation

The most prominent solution for sea level rise in transportation is raising the roads. Delaware is beginning to investigate raising the elevation of the roads in the coastal areas, specifically in Bowers Beach. The Delaware Department of Transportation (DELDOT) is creating higher roads through a lighter porous material which helps with funneling the water (Kirkpatrick, 2022). This solution will take between four to six weeks and cost just less than seven hundred thousand dollars, which is a quick solution to this issue. Typically, raising a block of road by two feet costs around two million dollars which shows that this solution is very cost effective (Jacobs & Daniel, 2017). Being able to raise the elevation of the road is very useful in combating sea level rise as it minimizes the negative effects of a large amount of water covering the roads.

A more common way of raising the roads is using the same materials that made the road (soil, sand, gravel and asphalt) and building on top of the existing surface through a backfill. **Figure 2** shows this solution with a three-foot sand backfill increasing the elevation of the road.

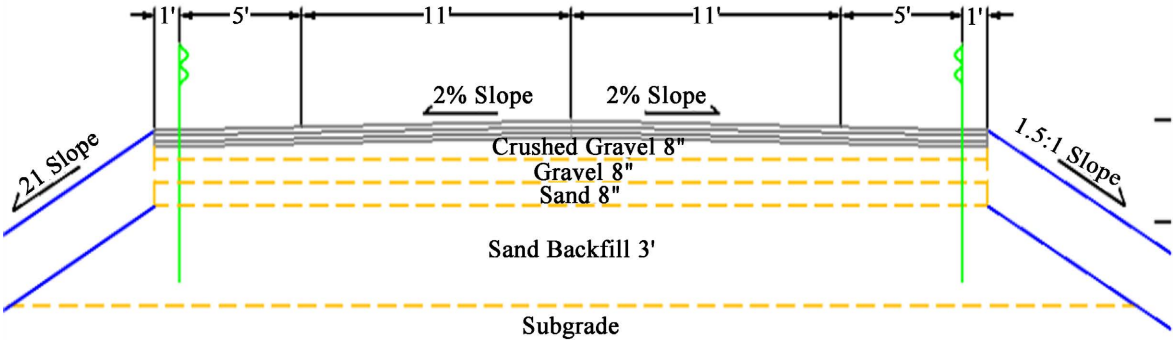

Figure 2. Cross section of raised and widened road.

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The benefits of this method over the Bowers Beach solution are that it is easy to build with easily obtainable materials and cost effective. The downside to this method is that it creates more environmental impacts, it is not adaptable and can violate existing permits which would take a large amount of time to implement. This method can be improved even more with the addition of gabion walls to raise and reinforce the road rather than raise and widen. **Figure 3** shows what this would look like if implemented.

A raised and reinforced road is beneficial as not widening the road will lead to less permits violated, and it is cost effective. However, there are limited designs available to reinforce the structure and the gabion walls will not last forever leading to them needing to be replaced over time. Raising the elevation of the roads by a few inches is very effective in the short run, however, it will lead to more additions over time once the sea levels continue to rise or a 100-year storm hits the area and causes even more issues. While 100-year storms only have a one percent chance of occurring, they can be detrimental to the affected areas and serve a key role in determining how much the road should be raised. This can be accounted for in the design of roads by implementing base flood elevation.

Base flood elevation is the height in which roadways and bridges should be raised above to avoid issues with flooding (Risk Factor, 2022). This specific height is found using the FEMA flood insurance rating map. Using the FEMA map from Delaware, **Figure 4** shows the results of the southern part of the state being affected by flooding.

The figure shows how multiple areas of Route 1 are affected and many areas near the coast would have issues using the evacuation route. While 100-year storms only have a one percent chance of occurring, they can be detrimental to the affected areas. To put this into perspective, Austin, Texas considers a 100-year storm as ten inches of rainfall over a twenty-four-hour period (Austin Texas Government, 2022). Implementing a tool like this into the design standards for roads in Delaware would help combat flooding from storms and account for sea level rise in the future.

Another solution to sea level rise in transportation comes from removing the

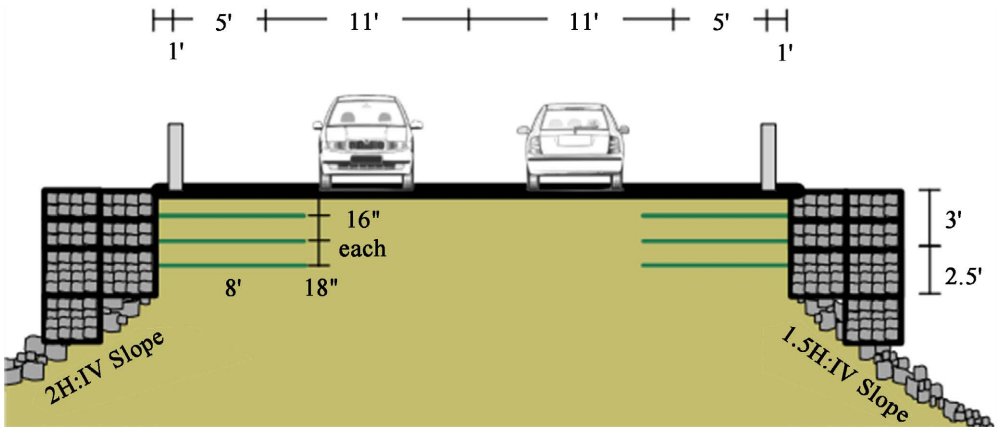

Figure 3. Cross section of raised and reinforced road.

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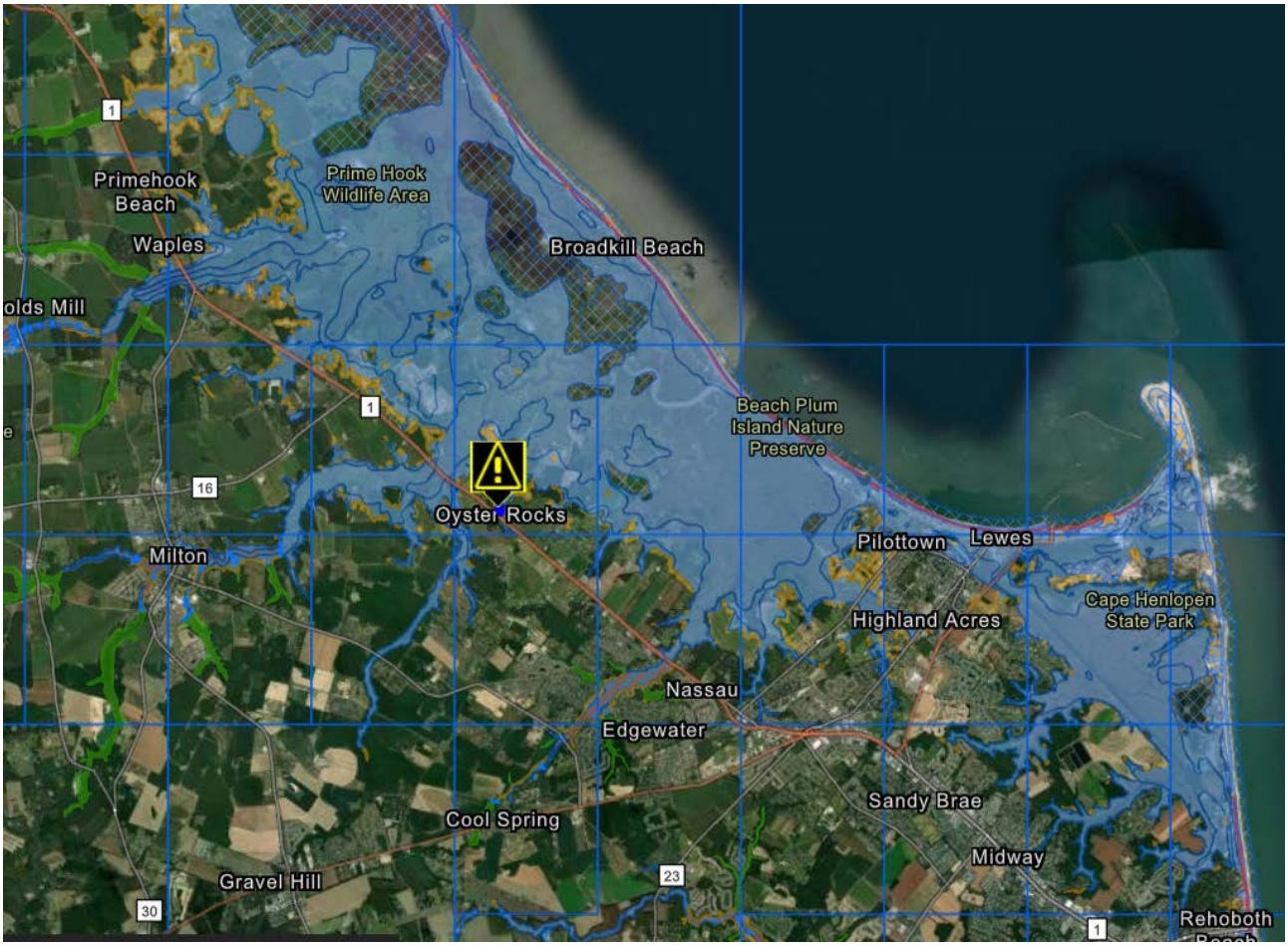

Figure 4. Delaware 100-year storm map.

water from the roads. This has been done recently in Miami as part of their four hundred-million-dollar project tackling the issue of sea level rise. The roads have new storm sewers and eighty pumping stations being added to help with the water on the surface (Allen, 2016). Having these solutions remove the water off the road is effective, however, it has to be implemented quickly as discussed earlier with asphalt failing in performance when water seeps into the surface. Now that the current solutions to sea level rise in transportation are defined, the conversation will move towards understanding what needs to be done in Delaware to get these solutions implemented.

7. What Needs to Be Explored in Delaware?

As of now, there are not many standards in Delaware that are set in place for designing to combat sea level rise. The Delaware Department of Transportation (DELDOT) has a Transportation Resiliency and Sustainability program that aims to provide the citizens of Delaware with the most resilient and sustainable infrastructure through all stages of design life. Their specific goal for sea level rise is to understand its impact on transportation infrastructure and implement methods of resiliency and sustainability in the project planning, design, con-

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struction and maintenance (Pappas, 2022). This program also recognizes that the main issue that sea level rise causes in transportation is the flooding of lower elevation roads and that there is not just one solution that can fix every problem. They are in the process of developing policies that maximize resources within a budget to protect and maintain these vulnerable areas. Currently, DELDOT is looking to improve the drainage of the existing roads and knowing which roads are affected through a flood matrix. This is very similar to using the FEMA map that was discussed before to identify these areas. As mentioned before, DELDOT is also exploring raising the roads through a more sustainable material that can deal with water filtration better than asphalt. With all the current methods of designing for sea level rise defined in Delaware, there can be more exploration into what needs for research and then the authors' recommendations for the state.

In terms of what needs to be explored more, the main aspect in design needs to be creating the standards for how much the road needs to be raised, what materials to use and how to raise the road. These will be discussed further in the discussion section where there can be more of an understanding as to how these ideas can be tied into the existing Delaware design standards to help all stakeholders involved.

8. Discussion

This article has looked at how transportation in Delaware has been affected by sea level rise and what is currently being done to combat the issue, however, there needs to be recommendations on how to standardize the design process. This will be presented in a six-step plan to show how to best design for sea level rise.

To begin, Delaware needs to identify areas of risk using the FEMA flood insurance map as well as the sea level rise planning map seen in **Figure 1**. Combining the 100-year storm and sea level rise heights will help show where roads need to be raised. Delaware already uses a flood matrix but combining this with sea level rise data will allow for a better understanding of how much the roads can be impacted over time.

Next, Delaware must equally account for all areas affected by sea level rise flooding in order to avoid any social injustice. This is a key aspect in helping all stakeholders involved because there have been similar projects in the past that have neglected specific communities that were also affected by sea level rise. For example, the Miami project that was mentioned earlier mainly accounted for the wealthier communities (Ariza, 2020). With a quarter of the city population living in affected areas, only designing for the higher wealth communities is detrimental to such a large portion of population. Delaware needs to account for all areas impacted and make sure the roads are safe and usable for everyone. It may cost more in the future, but it is hard to put a price on lives lost.

Once the roads are identified, the next step is to raise the elevation of the road

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in vulnerable areas by two inches over the height presented in the FEMA map and sea level rise data. The two-inch value allows for an extra twenty years of service if the current sea level rise rate in Delaware is upheld. It is a very conservative value and could cost a large sum of money, however, it will make sure a large portion of the state and economy is functioning well. If this area becomes less susceptible to sea level rise, they can continue to promote tourism and boost the economy to eventually pay off the extra money needed to pay for projects such as this.

Next, Delaware should implement the raise and reinforce method discussed earlier but instead of paving with asphalt, they should continue to use the porous material used down at the Bowers Beach project. The raise and reinforce method seen in **Figure 3** would allow for the road to keep the same cross section as opposed to the raise and widen method seen in **Figure 2**. This is important for tying into the existing standards in Delaware and would not impact the environment as much as widening the right-of-way limits. Being able to tie into the existing roadway design standards is crucial because it will help to make the transition for designing for the future more seamless.

After the raise and reinforce method is implemented, Delaware should begin to add more direct solutions to combat sea level rise along the coast. **Figure 1** shows areas where protection is needed and being able to add specific seawalls, levees, jetties and groins will help minimize the impact of the continuously rising sea level elevation rate. Having direct solutions for sea level rise will help make sure the impact of flooding will be delayed. With the roads already raised in vulnerable areas, this improves the design life of the roads.

Finally, Delaware needs to implement pumping stations in the most vulnerable areas to make sure the flooding does not become detrimental. Having pumping stations can be expensive but it will make sure the lowest elevation areas will not be hit hard by flooding. Being able to implement this six-step plan would be expensive but it is an important way to benefit all stakeholders and keep the transportation infrastructure safe in Delaware for years to come. This plan can be explored in a case study of the evacuation routes that are present in Sussex County Delaware.

9. Delaware Evacuation Routes

Delaware is made up of many evacuation routes but for the purposes of this article, the evacuation routes in Sussex County will be the focus as this is where sea level rise is most prominent and it is the lowest elevation and closest to the coast. Evacuation routes can either be primary or secondary. A primary route is a road that has the most traffic capacity for the weather threat that is presented. A secondary route is used to mitigate the amount of traffic on the primary routes and move people inland. For Sussex County, there are three primary evacuation routes of interest: SR 1, US 13 and US 113 (Pappas, 2022). The secondary routes of interest include SR 14, SR 15, SR 20, SR 24, SR 40, SR 54 and US 9. All these

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routes can be seen in Figure 5 below.

These routes are of most interest because they experience flooding regularly and are already prone to water issues. If these routes are prone to flooding, the impact of sea level rise will truly damage these roads. They will need solutions to keep these routes active and limit the damage from flooding whether the road is completely shutting down or damaged faster than originally designed for. Now that the main evacuation routes of interest are identified, it is important to look at current projects in order to find more specific solutions that can be applied in how to combat sea level rise for these routes in Sussex County.

Delaware is currently working on many projects that deal with sea level rise and combating it in Sussex County. This section will look at four current projects and highlights the main takeaways from each in the next section at what was learned.

To begin, DELDOT is working on a SR 1 resilience study which ties in perfectly with one of the primary evacuation routes of interest. This study looks at SR 1 right on the coast of Sussex County near Fenwick Island and conducts ocean and bay modeling (Pappas, 2022). The modeling is used to understand the effect of sea level rise in the area and how it will look over the next couple of decades. This is done by breaking down the corridor into sections and studying the effect of sea level rise in each of these areas to assess the risk involved. There has been a decent amount of public outreach so far through talking to local businesses, officials in surrounding towns and the public to discuss the findings so everyone has an idea of the potential threat that sea level rise has on the coastal community.

Moving on, the next project is being conducted in Lewes on Pilottown Road by Delaware's Department of Natural Resources and Environmental Control

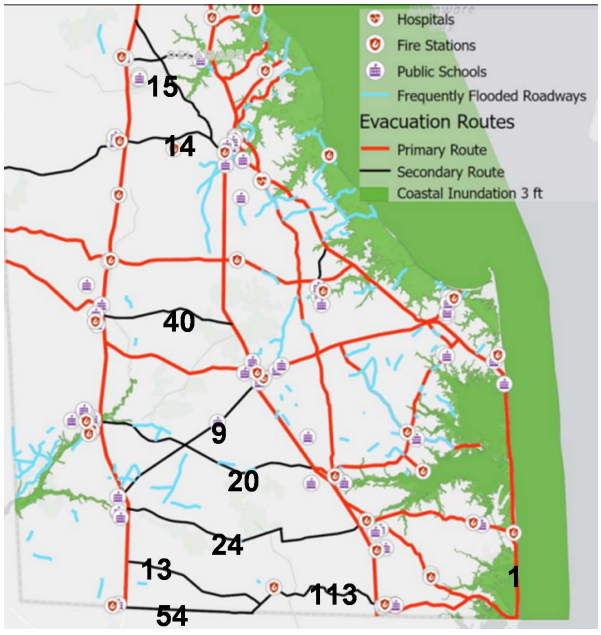

Figure 5. Delaware evacuation routes of interest for sea level rise.

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(DNREC). This project looks at trying to raise the elevation on this road to limit the flooding (Pappas, 2022). Pilottown Road is right near SR 1 and is near a frequently flooded area which will be interesting to see how this project pans out to see how effective raising the elevation will be in these areas. In terms of public outreach, DNREC has met with the mayor of Lewes, the city manager and the public to show a solution that will affect all parties involved.

Finally, DELDOT is working on Woodland Beach Road that is very prone to flooding. This road is considered a "one way in one way out" road which means there is only one road used to enter and exit the community (Pappas, 2022). There are 44 houses here which means if this road goes down many people will be affected, and emergency vehicles may not be able to enter the community. So far, they have looked at "water on road" signs as well as sensors to understand when the road is becoming undriveable with water on top of it. Additional solutions that they are looking at include roadway slabs, raising the road elevation and overall soil stabilization. With all the current projects defined, there can now be a discussion of what can be used for the evacuation routes of interest.

10. The Solution for Evacuation Routes

After looking at the current projects that Delaware is working on, the authors discovered a few common themes and solutions that popped out as applicable for the evacuation routes of interest. To begin, raising the elevation of evacuation routes is very common in combating sea level rise. Raising the elevation has its problems with cost and sustainability but there are proven ways around that and it directly saves the roads from flooding. Next, using the "water on road" signs are a cost-effective way of helping drivers know the conditions of the road and should continue to be a standard for these evacuation routes even in non-emergency situations. Moving on, flood maps are such an important piece in designing roads which is not always heavily considered in the design process. Finally, public outreach is a critical component in design as the evacuation routes are for the people and sea level rise is an issue that affects the entire community, and everyone has the right to know how it will impact their homes.

The authors believe that the evacuation routes of interest should be raised using 100-year maps and sea level rise data. This can be done by taking the base flood elevation and the sea level rise data that is available and checking these routes to make sure the elevation of the road exceeds it. Base flood elevation is the height at which roadways and bridges should be raised above to avoid issues with flooding. This specific height is found using the FEMA flood insurance rating map. Using the FEMA map from Delaware, **Figure 4** shows the results of the southern part of the state being affected by flooding.

The figure shows how multiple areas of Route 1 are affected and many areas near the coast would have issues using the evacuation route. While 100-year storms only have a one percent chance of occurring, they can be detrimental to the affected areas. Implementing a tool like this into the design standards for

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roads in Delaware would help combat flooding from storms and account for sea level rise in the future.

Additionally, public outreach is the other most important aspect of planning for sea level rise as the public needs to be involved with the design process. The routes are for them, and they are going to use them, so it is important to make sure they are fine with any changes made.

Finally, "water on road" signs as well as sensor deployment should be implemented on sections of these roads. These are very important and cost-effective short-term solutions to help drivers know the conditions of the roads in non-emergency situations. It will also help DELDOT know when there is a large amount of water on the road which can help point out susceptible sections of the evacuation routes that need to be repaired.

11. Conclusions and Future Explorations

It is evident how important designing against sea level rise is for coastal areas such as Delaware. Being able to understand the area will help save many lives and continue to boost the economy into the future. Implementing the six-step plan highlighted in this article will allow for all stakeholders to be satisfied and roads to be safe. It will help tie into the existing standards placed in Delaware and work with the Transportation Resiliency and Sustainability program to uphold their goals of creating the best transportation infrastructure possible in the presence of sea level rise. The plan would be quite expensive, but it is a worthy investment for the state to make sure that lives are saved, and the tourism economy is thriving.

Future exploration can investigate working with surrounding coastal states to standardize the sea level rise design practices so their economies can work together towards funding projects to combat the issues. Working with New Jersey, Maryland and Virginia to implement standards on how to combat sea level rise would be beneficial for all states. While they may stray away in the specific road design cross sections, standardizing how the roads are raised, the use of direct sea level defense structures and pumping stations would help everyone involved. This discussion can be furthered by looking at the number of jobs created needed to work on these projects. All in all, sea level rise is a fact that engineers and planners have to deal with, so being able to prepare for the worst will help save many facets of life even at a higher cost.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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