Lights Out: Climate Change Risk to Internet Infrastructure

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ABSTRACT

In this paper we consider the risks to Internet infrastructure in the US due to sea level rise. Our study is based on sea level incursion projections from the National Oceanic and Atmospheric Administration (NOAA) [12] and Internet infrastructure deployment data from Internet Atlas [24]. We align the data formats and assess risks in terms of the amount and type of infrastructure that will be under water in different time intervals over the next 100 years. We find that 4,067 miles of fiber conduit will be under water and 1,101 nodes (*e.g.,* points of presence and colocation centers) will be surrounded by water in the next 15 years. We further quantify the risks of sea level rise by defining a metric that considers the combination of geographic scope and Internet infrastructure density. We use this metric to examine different regions and find that the New York, Miami, and Seattle metropolitan areas are at highest risk. We also quantify the risks to individual service provider infrastructures and find that CenturyLink, Inteliquent, and AT&T are at highest risk. While it is difficult to project the impact of countermeasures such as sea walls, our results suggest the urgency of developing mitigation strategies and alternative infrastructure deployments.

CCS CONCEPTS

• **Networks** → *Physical links*; *Network measurement*;

KEYWORDS

Physical Internet infrastructure, climate change, sea level rise, critical infrastructure, risks

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1 INTRODUCTION

Climate change is perhaps the most significant problem facing humanity. The dramatic rise in greenhouse gas concentrations in the atmosphere over the past 100 years is causing changes in weather patterns including increased likelihood of severe storms as well as rapid rise in sea levels due to melting polar ice caps and thermal expansion of seawater [27]. These phenomena have important implications for the planet and the effects are already being felt in many areas [36].

To understand and prepare for the impacts of climate change, a number of models have been developed to project average sea level rise. The models are based on a variety of empirical parameters including sea level rise over the past 100 years and the geographic features of coastal areas. The models predict significant incursions on coastal areas that imply displacement of large human populations. In response, some of the threatened areas are already preparing mitigation plans [37], but holding back the oceans is a formidable undertaking to say the least.

With significant sea level rise predicted, it is important to assess the threat to communication infrastructure. An indication of the potential impacts are the storm surges of major hurricanes such as Katrina and Sandy that devastated communication systems [21, 30]. While the standard buried fiber conduits are designed to be water and weather *resistant*, most of the deployed conduits are not designed to be under water permanently.

In this paper, we make a preliminary analysis of the risks of climate change on Internet infrastructure. The goal of our work is to understand risks and potential impacts over timescales of decades, which is consistent with other work on climate change [11]. Our specific interest in this paper is assessing how the rise in sea levels threatens buried fiber conduits and termination points (*e.g.*, colocation facilities, point of presences (POPs), etc.) in coastal areas in the US. Our analysis is *conservative* since it does not consider the threat of severe storms that would cause temporary sea level incursions beyond the predicted average. Our analysis also does not consider any efforts to harden or fortify communication infrastructure since we argue that this will only be feasible in relatively small geographic areas.

Our study is based on analysis of two data sets. The first is the communication fiber conduit and termination point data in Internet Atlas [24]. The Atlas repository includes geocoded maps of over 1500 networks from around the world. The second is the Sea Level Rise Inundation (SLRI) data from NOAA's Digital Coast project [14]. This diverse dataset includes a collection of geo-based sea level rise projections for the US over the next century. We fuse the Atlas and SLRI datasets by translating them into a consistent shape format, and then analyze how sea levels will overlap communication infrastructure over successive time periods.

The results of our analysis show that climate change-related sea level incursions could have a devastating impact on Internet communication infrastructure even in the relatively short term. In particular, we find that 1,186 miles of long-haul fiber conduit and 2,429 miles of metro fiber conduit will be underwater in the next 15 years. Similarly, we find that 1,101 termination points will be surrounded by sea water in the next 15 years. Given the fact that most fiber conduit is underground, we expect the effects of sea level rise could be felt well before the 15 year horizon. Interestingly, we find that the risks over longer time scales do not increase significantly. Specifically, there is only a modest increase in the amount of additional Internet infrastructure that will be under water at the 6 ft. rise level (the 100 year projection) vs. the 1 ft. rise level (the 15 year prediction).

To assess the risk of sea level incursions in specific geographic areas, we define the Coastal Infrastructure Risk (CIR) metric that considers the combination of geographic scope and Internet infrastructure density. We use the CIR metric to examine coastal regions in the US with high population density. Our results show that communication infrastructure in New York, Miami, and Seattle, respectively, are at highest risk. We also quantify the impact to individual service providers and find that CenturyLink, Intelliquent (formerly Tinet), and AT&T are at highest risk. These results highlight where developing mitigation strategies and planning alternative deployments should begin in order to preserve both local and long haul assets.

2 RELATED WORK

Climate change and its effects on the planet have been the focus of many prior research efforts. Such studies include monitoring of atmospheric greenhouse gas concentrations [9, 18], modeling and analysis of the consequences of global warming including rising sea levels [26, 29], impacts on food production [33] and air quality [28], risk of natural disasters [36] and other direct threats to human populations [31], as well as disruption of ecosystems, energy consumption patterns and water resources [35]. Finally, there has been significant focus on policy tools to reduce greenhouse gas emissions in order to mitigate the effects of climate change [4, 13]. These studies serve as a foundation for our work.

Prior work on the impact of natural disasters on communication infrastructure is related to our study. Examples include retrospective analysis on the impact of hurricanes [21, 30], earthquakes [20] and severe storms [34]. Eriksson *et al.* examine infrastructure risks associated with a variety of natural disaster types and describe layer 3 techniques for mitigating these risks in [25]. That study differs from ours in that it does not consider climate change-related sea rise as a risk.

To the best of our knowledge, ours is the first study of the effects of climate change-related sea level rise on Internet infrastructure. However, anecdotal evidence for impact of global warming on communication infrastructure can be found in the popular press. For example, Bogle describes shutdown of communication systems due to air conditioning failures caused by extreme heat in [19]. That article also outlines a variety of climate change-related risks but does not mention sea level rise specifically.

3 ASSESSING CLIMATE CHANGE-RELATED RISKS

3.1 Sea Level Rise and Internet Infrastructure

Optical fiber strands that carry Internet traffic between colocation facilities are typically packaged inside of semi-rigid polyethylene (PE) conduits that range in diameter from 1 to 6 in (larger diameter conduits carry more fiber strands). The PE conduits provide a measure of protection from different levels of mechanical damage (*i.e.,* being crushed or cut). Armored cladded conduits are available for use in hostile environments *e.g.,* undersea deployment. PE conduits containing fiber strands are typically deployed between colocation facilities and POPs in buried trenches (depth varies) or other underground conduits along routes that often follow roads and rail lines [23].[1]

Water, humidity and ice have long been recognized as threats to fiber optic strands and conduit [17]. Water-related threats include *(i)* signal attenuation due to water molecules embedding in fiber micro-cracks, *(ii)* corrosion damage to connectors, *(iii)* signal loss in optical-electrical-optical connections, and *(iv)* fiber breakage due to freezing. Cable construction techniques (*e.g.,* cladding and hydrophobic gels) along with careful deployments enable fiber to function for decades under normal/expected environmental conditions.

The starting point for our work is that while standard Internet infrastructure deployments are designed to be weather and water resistant, they are not designed to be surrounded by or under water. Thus, we posit the following risks due to sea level rise. The first is physical damage at certain nodes (*e.g.*, submarine cable landing stations) and at termination points (*i.e.*, colocation facilities and POPs). A majority of the

[1]Last mile fiber-to-the-home may be deployed above ground, but we do not consider those deployments in this study.

cable landing stations are near a tidally active region and terminate at the nearest colocation facility [8]. Potential effects include physical damage via tidal inundation and corrosion leading to signal loss. Second, buried conduits will become submerged, which will expose them continuously to all of the threats mentioned above, and the possibility of physical damage due to exposure caused by tides and storms. The fact that a great deal of conduit infrastructure was deployed over the past twenty years and is aging means that all seals and cladding are likely to be more vulnerable to damage, especially if they are under water.

3.2 Datasets

Internet Infrastructure. In this study, we use the physical topology data from the Internet Atlas project [24]. Internet Atlas is a visualization and analysis portal built on top of a Geographic Information System (GIS). The Atlas repository contains geocoded physical infrastructure data of over 1500 Internet service providers (ISPs) around the world. The data for each ISP includes *(i)* node locations (*e.g.*, colocation facilities, POPs and data centers), *(ii)* conduits/link locations (*e.g.*, long-haul, metro and submarine conduits) that connect these nodes, and *(iii)* relevant meta data (*e.g.*, source provenance). To facilitate our analyses, we used the following information from Internet Atlas: *(a)* Nodes located in the US including Internet exchange points (IXPs), data centers, colocation facilities and submarine cable landing stations (or simply, landing stations); *(b)* Links in the US including long-haul and metro fiber conduits and submarine cables.

Sea Level Rise Projections. We obtain the *Sea Level Rise Inundation* (SLRI) data [14] from the Digital Coast project, which is managed by NOAA's Office for Coastal Management [2]. This dataset is a collection of projected sea level rise scenarios, flood exposures, and affected coastal counties, and is amassed from a number of partner organizations [3]. Specifically, we use the GIS-based projected sea level rise scenarios, with scenarios covering the whole range of predictions from 1 to 6 feet in this study, which span the next century.

Table 1: Timeline of projected Global Mean Sea Level Rise. Data is based off of "Highest" (*i.e.*, most extreme) projections.

Year	2030	2045	2060	2075	2090	2100
Projected rise (ft)	1	2	3	4	5	6

To fuse the datasets, we had to reconcile the different geographic projections used in these GIS-based repositories. To tackle this issue, we align the two geographic projections using the *projection and transformation* tool from ESRI ArcGIS data management toolbox [5]. This step is complicated by the size and varying shape formats of the two GIS datasets. Once resolved, we were able to visualize and analyze the overlap of projected average sea level with current internet infrastructure. Figure 1 depicts the overlap of Internet infrastructure with seawater in four major areas in the US as a result of a 1 ft. rise in sea level, which is projected over the next 15 years. The figure highlights the potential for dramatic impact on Internet infrastructure due to climate change-related sea level rise. We quantify these effects using several different metrics in §3.3.

3.3 Infrastructure Inundation Analysis

We use *overlap models* to capture and analyze the risks of climate change-related sea level rise on the Internet infrastructure (§3.1). Specifically, we develop metrics based on the datasets described in §3.2 to understand where and the extend to which Internet infrastructure will be surrounded by water or submerged. We augment these risk models with a temporal component (Table 1) based on the projected *Highest Mean Sea Level Rise* scenario described in NOAA's climate assessment report [32, Figure 10]. This scenario is recommended by the NOAA report as the most appropriate for situations with low risk-tolerance, such as deployment of new infrastructure with a long anticipated life.

We project geographic areas from SLRI data on top of node and link locations to reveal infrastructure inundation risks. To localize overlap we develop a Coastal Infrastructure Risk (CIR) metric that highlights the concentration of Internet infrastructure per geographic location (*e.g.*, city). The CIR metric will be used to elucidate the impact of sea level rise on Internet assets temporally. Using CIR, we identify the top 10 major geographic locations most at risk, and thus in need of action by municipalities and service providers to secure existing deployments and plan for new deployments.

Implementation. We use the *overlap* capability in ArcGIS [6] to implement the three infrastructure analysis models. In particular, after layering the two GIS-based datasets, we first issue *spatial query* on the combined layers to calculate the number of nodes and length of fiber cables (in miles) that will be under seawater for every sea level rise scenario for every city in SLRI data. Next, to calculate the CIR metric, we use the *kernel density* tool [7] in ArcGIS and obtain the *output raster*, which is a floating point value that highlights the top affected areas. We sort the floating point values in descending order and identify cities with highest risk.

3.4 Results

Infrastructure Overlap with Seawater. We quantify the raw number of nodes and fiber conduit miles at risk using the overlap models described in §3.3. Figure 2 depicts the raw of number of POPs, data centers, IXPs and landing stations overlapping with the projected sea level rise scenarios (Table 1). In 2030, about 771 POPs, 235 data centers, 53 landing stations, 42 IXPs will be affected by a 1 ft. rise in sea level. Interestingly, the number of vulnerable landing stations and IXPs are constant throughout the graph, despite the rise from

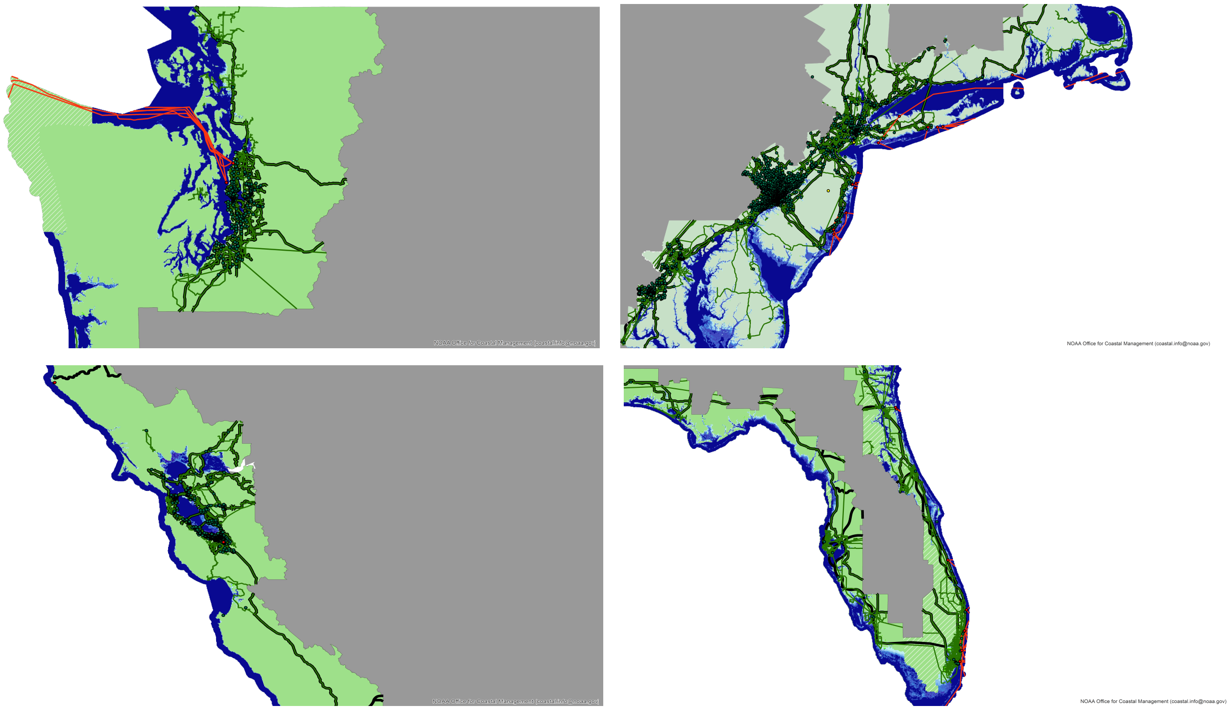

Figure 1: Overlap of Internet infrastructure based on 1 ft average sea level rise in North-Western US (top-left), North-Eastern US (top-right), Los Angeles (bottom-left) and Florida (bottom-right). SLRI is shown in blue (in green background). Submarine landing stations, POPs, Data centers and IXPs are depicted in red, green, black and yellow dots respectively. Submarine, metro and long-haul fiber-optic cables/conduits are shown in red, green and black lines respectively. Infrastructure in the SLRI-unaffected areas is greyed out.

Table 2: Top 5 cities with high climate change risk index for node assets along with the count of nodes.

City (POPs)	City (Data centers)	City (IXPs)	City (Landing Stations)
New York, NY (46)	New York, NY (43)	New York, NY (8)	Manasquan, NJ (2)
Miami, FL (31)	Newark, NJ (21)	Miami, FL (4)	Miami, FL (2)
Seattle, WA (28)	Seattle, WA (16)	San Francisco, CA (4)	Pacific City, OR (2)
Houston, TX (26)	Miami, FL (15)	Seattle, WA (4)	Tuckerton, NJ (2)
Washington, D.C. (23)	Palo Alto, CA (8)	Houston, TX (3)	Bandon, OR (1)

1 to 6 ft. over the next century. This is due to the limited number of entry/exit landing stations to/from different continents and their corresponding colocation facilities where the landing stations terminate. In contrast, the risk to the POPs and data centers near the coastal regions is increasing as evident from the trend in the number of node overlaps with seawater. For example, as many as 780 POPs and 242 data centers will be surrounded by 4 ft. of seawater in 2075; 6 ft. of seawater will affect 788 POPs and 249 data centers by the end of this century.

Figure 3 shows the amount of long-haul and metro conduit and submarine cable that will be under water based on the projected sea level rise scenarios. We make the following observations based on this link overlap graph. First, metro fiber links are at highest risk, especially the northeastern and northwestern regions of the US and the gulf coast area from western Florida to Texas. Specifically, in the next 15 years, as much as 2,429 miles of metro fiber conduit will be submerged after a 1 ft of sea level rise, whereas as 2,637 miles of metro fiber conduit will be affected in the next century. Next, the long-haul fiber conduits that connect IXPs and colocation facilities along coastal areas are also vulnerable to effects of sea level rise. This include gulf coast area from Florida to Texas and the northeastern and northwestern regions of the US, ranging from 1,186 miles of fiber conduit in 2030 (1 ft) to as high as 1,239 miles of fiber in 2100. Similar to the constant trend in the number of landing stations, the affected lengths of submarine cables are not highly variable: we observe an increase of one mile in 2060 (3 ft) and it remains constant there after. Given the large number of nodes and miles of fiber conduit that are at risk, the key takeaway is that *developing mitigation strategies should begin soon.*

Table 3: Top 5 cities with high climate change risk index for link assets. The corresponding fiber miles and percentage under water are given in parenthesis.

City (Long-haul)	City (Metro)
Los Angeles, CA (89, 14.54%)	New York, NY (337, 19.8%)
New York, NY (79, 32%)	Seattle, WA (236, 23.6%)
Miami, FL (62, 5.3%)	San Francisco, CA (158, 9.43%)
New Orleans, LA (43, 22.51%)	Miami, FL (149, 13.27%)
San Francisco, CA (31, 7.4%)	Los Angeles, CA (138, 20.14%)

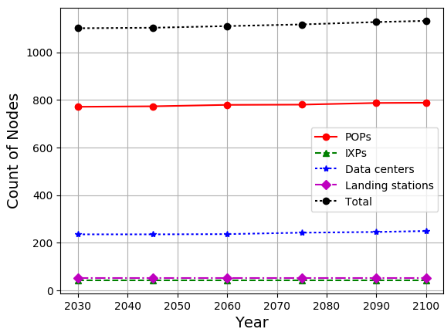

Figure 2: Number of POPs, data centers, IXPs and landing stations affected by SLRI.

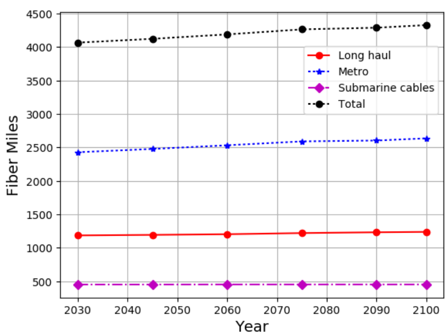

Figure 3: Miles of fiber of long-haul, metro and submarine cable paths affected by SLRI.

Coastal Infrastructure Risk Analysis (CIR). Next, we identify cities with Internet infrastructure that are at risk based on the concentration of nodes and links in those cities using our CIR metric. Table 2 shows the five cities most at risk based on node type are listed. From Table 2 we observe that infrastructures in the coastal cities are *the* most vulnerable assets in the Internet. In particular, the cities in the northeastern region and the southern part of the US are at highest risk. For example, as many as as 46 POPs, 43 data centers and 8 IXPs in New York will have seawater incursion. Such effects are observable in other coastal areas including Miami and Seattle. These results expand and are consistent with many recent articles [10, 15, 16] about the threats to populations and businesses [1, 31].

In Table 3, we list the five cities in the US that will be most affected by sea level rise based on link infrastructure concentration. The number of affected fiber conduit miles are also shown. We observe not unexpectedly that the number of metro fiber conduit miles that are at risk is far greater than the number of long haul conduit miles. However, outages in the long haul infrastructure will likely have much more far-reaching effects in the US and the Internet writ large. Considering those effects is a topic for future work. We also stress that while it may be feasible to harden and secure nodes for some period of time in the next century, securing links will be much more challenging since they are buried and therefore much more difficult to access.

To complement the results in Table 2 and Table 3, Figure 4 shows how a 6 ft. rise in sea level will overlap with Internet assets in New York (left) and Miami (right). Considering only the node assets, we find that New York has a total of 97 modes and has the highest risk. Similarly, New York is the city at highest risk in the US with 337 and 79 miles of metro and long-haul fiber conduit respectively, when considering only the fiber assets. Combining the results from Tables 2 and 3, New York, Miami and Seattle[2] have the highest risk/overlap with node and fiber conduit in the US.

Table 4: Top 10 providers with the most infrastructure at risk due to climate change.

Cities
CenturyLink
Intelliquent
AT&T
BroadSky
TW Telecom
Verizon
Beyond The Network
Cogent
Zayo
Sprint

Provider Analysis. We conclude by identifying the service providers with the *most* infrastructure that is at risk in the next 15 years in Table 4. We construct the list by counting the number of nodes and fiber conduit miles associated with each provider in each of the top-10 cities with high CIR metrics. Providers including CenturyLink, Intelliquent and AT&T have most infrastructure—hence, the most risk—in the coastal areas.

4 NEXT STEPS

4.1 Expanding Vulnerability Assessment

While our assessment described in §3 highlights the extent to which the Internet infrastructure overlaps with projected seawater ingress, it is static and is limited in terms of *(i)* the scope of climate change related threats (*e.g.*, storms, which

[2] Affected long-haul conduit miles for Seattle, which ranked 6th, is 23 miles.

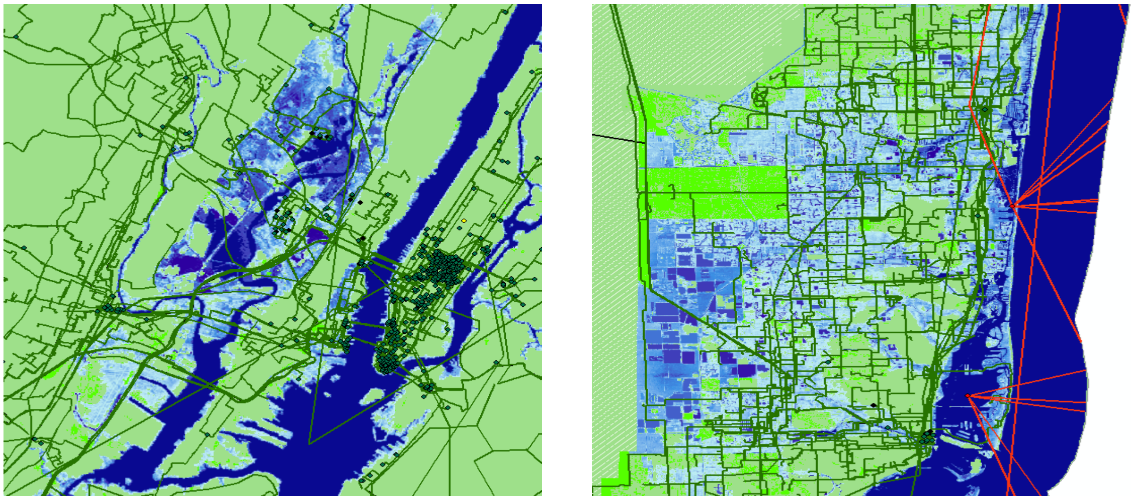

Figure 4: Overlap of Internet infrastructure and seawater in New York (left) and Miami (right) with average sea level rise of 6 feet.

are dynamic), *(ii)* understanding how coastal infrastructure outages can lead to cascading failures on inland assets, *(iii)* quantifying the risks to users and businesses that might be affected by the failed infrastructure, and *(iv)* the fact that it only considers the US. This calls for expanded analysis of infrastructure risk improve our understanding of the potential impact of climate change on the Internet and thereby enable more accurate and comprehensive mitigation planning.

4.2 Mitigation Planning

An important next step after a risk assessment such as ours is developing mitigation strategies. The strategies should be designed to minimize the impact of failures in coastal areas on inland infrastructure. One approach would be to consider how CIR metrics can be integrated into existing inter- and intra-domain routing substrate to create backup and alternative routes that reduce the impact of coastal infrastructure failures (*e.g.*, related approach can be found in [25]).

Another important strategy for mitigating climate change-related risks is to harden critical infrastructure in vulnerable areas. To this end, we believe that our analysis and expanded vulnerability analyses will provide a foundation for *(i)* frameworks to assess the impact of physical countermeasures such as seawalls and hardened enclosures for submarine cable landing points, *(ii)* mechanisms, protocols and systems to enable new methods for risk-aware and reliable routing, and *(iii)* policies for spectrum re-allocation so that first responders can communicate with minimum or no interruption.

4.3 Risk-aware Future Deployments

Future deployments of Internet infrastructure (including colocation and data centers, conduits, cell towers, etc.) will need to consider the impact of of climate change. Flexible decision support capabilities that include risk-/failure-awareness along with other ISP objectives (*e.g.,* revenue growth, operational cost control, etc.) will be important in the planning process. These plans must include consideration of issues including new rights of way, costs and projections of how populations will move. One approach is to formulate deployment as a multi-objective optimization problem where the objective is to maximize the revenue of ISPs for deployments in low-risk locations that cost-effective [22]. Other aspects of risk-aware deployment include developing new methods for hardening fiber cables, conduits and other infrastructure to be more resistant to severe weather that will be a consequence of climate change.

5 SUMMARY

In this paper, we describe an investigation of the threat of climate change-related sea level rise to Internet infrastructure in the US. Our study is based on fusing two spatial datasets: the Internet Atlas repository of Internet infrastructure and NOAA's Sea Level Rise Inundation, which projects sea level rise in the US over the next century. Our analysis recognizes the vulnerability of buried fiber conduit and colocation centers in coastal areas. The results of our overlap analysis show that ~4.1k miles of fiber conduit will be under water and over 1.1k colocation centers will be surrounded by water in the next 15 years. We develop a geo-based metric to assess Internet infrastructure risks in local areas and find New York, Miami and Seattle to be the most vulnerable areas, and that large service providers including CenturyLink, Intelliquent and AT&T have the most infrastructure risk. We believe that these results highlight a real and present threat to the management and operations of communications systems and that steps should be taken soon to develop plans to address this threat.

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