

# Submarine Cable Analysis for US Marine Renewable Energy Development

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## Executive Summary

Marine energy (offshore wind, tidal, wave) promises to diversify the U.S. renewable energy portfolio, which is important to reducing greenhouse gas emissions that contribute to climate change and reducing reliance on foreign non-renewable energy sources for national security. Development of these marine energy resources in the U.S. lags considerably behind Europe and other developed countries. The first (and currently only) U.S. commercial facility in Block Island, Rhode Island went into production December of 2016. As implementation costs for these technologies continue to drop and increasingly ambitious targets for renewable energy are set, planning of new marine renewable energy development needs to effectively evaluate competing ocean uses that may come into conflict. Marine renewable energy is complementary to other large scale renewables by offering consistent energy in high demand times during morning and evening hours when solar is less available and in proximity to coastal areas where populations tend to concentrate.

Operation and maintenance of submarine cables may conflict with marine renewable energy development. The submarine cable industry handles 99% of internet and other forms of telecommunication between land masses for commercial and military purposes, and is thus vital to the larger US economy. Repair and maintenance of cables traditionally involves grappling the cable and floating it to the surface, so allowance for drift of the repairing vessel and laying down of the additional splice of cable is dependent on bottom depth. Although submarine cable locations are publicly accessible through electronic navigation charts, safe setback distances are not yet available for planning new marine renewable energy development.

We applied industry-advised safety buffers that varied with depth to existing submarine cables for new

“facilities” (2\*depth, i.e. “2z”) and new “cables” (3\*depth, i.e. “3z”) horizontal distances, both having a minimum 500 m buffer on either side. Of the original 230,835 km in the “NOAA Charted Submarine cables in the United States as of December 2012” dataset (Figure 1), 97,321 km fell within the 200 nm of the US exclusive economic zone (EEZ), which was analyzed across 12 territories that overlapped with the cables (Figure 1). A custom Equal Area Albers projection based on 1/6th the extent of each territory was individually applied to minimize spatial distortion when buffering distances at 100 m depth increments using the GEBCO 30 arc-second global grid (Weatherall et al. 2015). The cable buffer area ranged from 29.35% (242,031 km<sup>2</sup> [3z] of 824,679 km<sup>2</sup> total) in the West owing to many cables present and the steep continental shelf, to virtually nill 0.39% (6,133 km<sup>2</sup> [2z] of 1,553,288 km<sup>2</sup> total) in the Gulf of Mexico (Table 2).

Overlap of cable buffers with marine renewable energy was assessed for tidal (Haas et al. 2011), wave (P. T. Jacobson et al. 2011) and wind (Schwartz et al. 2010) energy based on energy resource characterizations available through the National Renewable Energy Lab (NREL) Wind Prospector<sup>1</sup> or MHK Atlas<sup>2</sup>.

Assessment of overlap with the advised separation schemes and energy resource was limited to maximum depths (tidal: < 100 m, wave: < 200 m, wind: < 1,000 m) and minimum energy classes (tidal: > 500 W/m<sup>2</sup>, wave: > 10 kW/m, wind: > 7 m/s) viable for energy development. Areas of viable tidal resource are orders of magnitude less than wave or wind owing to requirements for channelized bathymetry (Figure 2) and have up to 4.7% overlap for the lowest energy class (500 - 1,000 W/m<sup>2</sup>) with only 2.3% and 0.9% overlap at higher power classes 1,000 - 1,500 and > 1,500 W/m<sup>2</sup> respectively. Wave energy at either depth bin of 0 - 100 or 100 - 200 m is very low with at most 2% overlap for the lower energy class (10-20 kW/m) at depths 100 - 200 m. The most abundant viable wind in shallow depth (0 - 100 m) and lower energy (7 - 8 and 8 - 9 m/s) overlaps at most 3.1%, but overlaps more at higher speeds (9.6% at 9 - 10 m/s) and in deeper waters (7.8% and 10.5% at 7 - 8 and 8 - 9 m/s respectively in depths 200 - 1,000 m). Small areas at the highest wind speeds > 10 m/s overlap up to 42.1% for the deepest bin (200 - 1,000 m) and highest wind speeds (11 - 12 m/s).

Energy resources are unevenly distributed across territories. Tidal power (Figure 3, Table 3) is most abundant in Alaska (691 km<sup>2</sup> at 500 - 1,000 W/m<sup>2</sup>; Table 3), the East (390 km<sup>2</sup> at 500 - 1,000 W/m<sup>2</sup>) and the West (46 km<sup>2</sup> at 500 - 1,000 W/m<sup>2</sup>), which is where overlap with cable buffers is most significant (23.4 - 31.5%) such as around Port Townsend, WA (Figure 11). Wave energy (Figure 4, Table 4) is most abundant in the Pacific territories having the most exposure to storm activity across the largest ocean. Alaska has the most abundant energy across all viable energy classes. Wind speeds (Figure 5, Table 5) in excess of 9 m/s are not found in the Gulf of Mexico and limited to the offshore New England area of the East (Figure 19), offshore areas of California and Oregon in the West (Figure 19) and dispersed locations in Hawaii (Figure 19).

The proposed avoidance areas should be deemed advisory. Overlap with recommended or even minimum avoidance area does not nullify the possibility of renewable energy development there. Rather, it should alert the developer to contact the cable industry and negotiate reasonable terms. These avoidance zones are advised according to traditional methods of submarine cable repair involving grappling of the submarine cable and buoying to the surface for repair, hence allowance for sway of boat as a function of depth. In future, remotely operated vehicles may narrow safe operating distances.

These avoidance areas are limited to the most recent submarine cable data used to generate them, which is 2012 for this report. In future, more current areas of avoidance could be extracted from electronic navigation charts, which get updated more regularly.

## 1 Background

Demand for abundant and diverse resources in the oceans is growing, necessitating marine spatial planning. To inform development of Marine Hydrokinetic (MHK) and Offshore Wind (OSW) resources, the Department of Energy (DOE) has asked NREL to identify — and mitigate where possible — the competing uses between MHK/OSW technologies and subsea power/telecom cables. The first step in this work is to identify and quantify the overlap between the MHK/OSW resource availability and existing cable routes.

<sup>1</sup>NREL Wind Prospector: <https://maps.nrel.gov/wind-prospector/>

<sup>2</sup>NREL MHK Atlas: <https://maps.nrel.gov/mhk-atlas>

The analysis is done in terms of resource area because the task of quantifying actual impacts on available resource is a non-trivial undertaking that involves subjective decisions of identifying resource opportunities. Quantifying overlap in-terms of resource area—on the other hand—is significantly more straight forward, and useful to marine spatial planners.

Several publicly available data layers are available that identify cable routes (e.g. MarineCadastre.gov currently hosts an offshore cables geographical information system (GIS) data layer) and MHK/OSW resource density (MHK Atlas, Wind Prospector). The cable route linear features, however, do not indicate the setback distance necessary to accommodate submarine cable maintenance requirements. Preliminary work was done within NREL to evaluate the influence of subsea cable setback distance on the overlap with MHK/OSW for the west coast of the U.S (Amante et al. 2016). Industry reports (Communications Security, Reliability and Interoperability Council IV 2014, 2016) from the International Cable Protection Committee (ICPC) of the North American Submarine Cable Association (NASCA)<sup>3</sup> advise on setback distances that inform this analysis.

## 2 Methods

### 2.1 Study Area, Submarine Cables, Depth and Energy Data

The study area consisted of the US waters (Flanders Marine Institute 2016), i.e. the 200 nm extent deemed the exclusive economic zone (EEZ). We used the offshore cable dataset “NOAA Charted Submarine cables in the United States as of December 2012” available through MarineCadastre.gov.<sup>4</sup> The territory of the contiguous US was further divided into regions: Alaska, Hawaii, West coast, East coast and Gulf of Mexico. The Gulf of Mexico description was based on the International Hydrographic Organization (IHO) Sea Areas (VLIZ 2017). To accommodate territories overlapping the international dateline (Hawaii and Alaska), all input and output products were shifted from [-180,180] to [0,360]. For more details on the 12 territories used in this analysis, see Table 1 and Figure 1.

Table 1: Territories having submarine cables within the United States exclusive economic zone (EEZ) of 200 nm. Territory area (km<sup>2</sup>) and summed length of submarine cables (km) are reported with light gray horizontal bars to visually indicate value relative to rest of column. Remaining columns indicate whether energy resources (tidal, wave or wind) are characterized for the territory. Territories having submarine cables but no energy resource characterization are lumped into "Other" territories: Guam, Johnston Atoll, N Mariana Islands, Palmyra Atoll, Wake Island.

Territory	Territory (km <sup>2</sup> )	Cable (km)	Tidal	Wave	Wind
Alaska	3,682,912	15,782	✓	✓	
East	932,351	28,526	✓	✓	✓
Gulf of Mexico	1,553,288	1,909	✓	✓	✓
Hawaii	2,474,715	21,496		✓	✓
Puerto Rico	172,958	3,267	✓	✓	
US Virgin Islands	38,275	974	✓	✓	
West	824,679	20,459	✓	✓	✓
Other	2,174,943	4,908			

Bathymetric depth comes from the GEBCO 30 arc-second grid<sup>5</sup> (Weatherall et al. 2015).

The marine renewable energy datasets are from NREL and accessible online via NREL’s Wind Prospector<sup>6</sup> and MHK Atlas<sup>7</sup>. Tidal data were modeled using the Regional Ocean Modeling System and calibrated with available measurements of tidal current speed and water level surface in terms of watts per square

<sup>3</sup>North American Submarine Cable Association (NASCA): <https://www.n-a-s-c-a.org>

<sup>4</sup>MarineCadastre.gov cable metadata: <https://coast.noaa.gov/dataservices/Metadata/TransformMetadata?u=https://coast.noaa.gov/data/Documents/Metadata/harvest/MarineCadastre/NOAAChartedSubmarineCables.xml&f=html>

<sup>5</sup>GEBCO\_2014 Grid, version 20150318, [www.gebco.net](http://www.gebco.net)

<sup>6</sup>NREL Wind Prospector: <https://maps.nrel.gov/wind-prospector/>

<sup>7</sup>NREL MHK Atlas: <https://maps.nrel.gov/mhk-atlas>

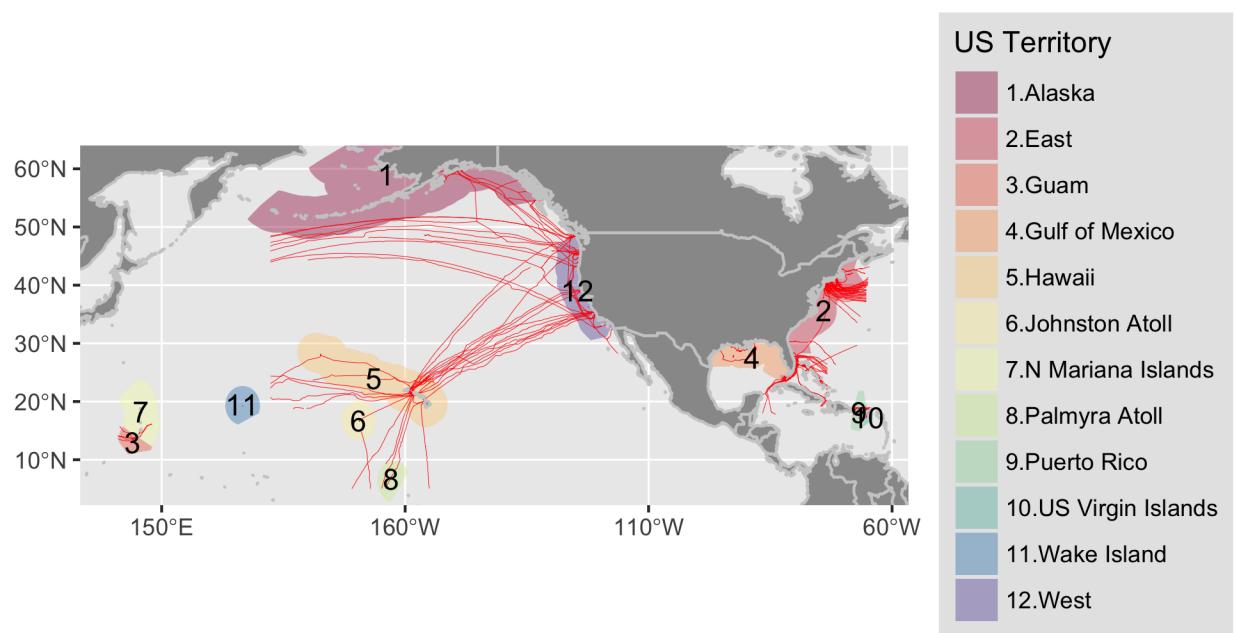


Figure 1: Map of NOAA charted submarine cables (red lines) as of December 2012 within the exclusive economic zone (EEZ; 200 nm) overlapping with United States territories.

meter ( $\text{W/m}^2$ ) (Haas et al. 2011). Wave data is based on a 51-month Wavewatch III hindcast database developed by the National Oceanographic and Atmospheric Administration's (NOAA's) National Centers for Environmental Prediction for estimation of wave power density in terms of kilowatts per meter ( $\text{kW/m}$ ) (P. T. Jacobson et al. 2011). Wind data is for average offshore wind speed in meters per second ( $\text{m/s}$ ) at a 90 m hub height<sup>8</sup> (Schwartz et al. 2010).

## 2.2 Submarine Cable Avoidance Zones

The International Cable Protection Committee (ICPC) of the North American Submarine Cable Association (NASCA) outlined recommendations for siting new offshore renewable wind energy facilities and routing new cables. For new facilities they recommend a minimum of 500 m and further offshore twice the depth to the seafloor, per ICPC Recommendation 13 No. 2 (Communications Security, Reliability and Interoperability Council IV 2014). So for depths  $\leq 250$  m, a 500 m buffer from the cables applies and for depths  $> 250$  m,  $2 * \text{depth}$  is to be used. For placing new submarine cables, separation distances are specified for minimum ( $2 * \text{depth}$ ) and recommended ( $3 * \text{depth}$ ), per related to ICPC Recommendation 2 No. 10 (Communications Security, Reliability and Interoperability Council IV 2014). We combined these two criteria into 2 sets of buffer distances for siting new facilities (“2z”:  $2 * \text{depth}$ ) and cables (“3z”:  $3 * \text{depth}$ ) avoidance zones, both with a minimum 500 m width.

## 2.3 Depth-Varying Cable Buffer

A depth-varying buffer from existing submarine cables for new facilities (2z) and cables (3z) was calculated by intersecting depth with cables and buffering the cable by depth. Depth from the GEBCO grid was reclassified into 100 m increments starting with 250 m to apply a 500 m minimum for the 2z and 3z products, and converted to polygons for intersecting with the cable linear features. A custom Albers Equal Area Conic projection based on 1/6th the extent<sup>9</sup> of each territory was individually applied to minimize spatial distortion when buffering.

## 2.4 Reproducible Code

All analytical code to generate outputs, including this data driven report, are available in a publicly accessible online repository: <http://github.com/ecoquants/nrel-cables>. Here are particularly noteworthy files:

- `data/`
  - `lns_d1x.geojson`: lines of submarine cables segmented at 100 m increments with depth value for buffering, ie minimum 500 m and depth ( $z$ ) for multiplying by 2 (2z) or 3 (3z).
  - `buf_2xdepth_incr100m.geojson`: polygons for siting new facilities buffered from existing submarine cables at twice the depth (2z), minimum 500 m.
  - `buf_3xdepth_incr100m.geojson`: polygons for siting new cables buffered from existing submarine cables at three times the depth (3z), minimum 500 m.
- `docs/`
  - `packages_vars.R`: R code with variables and packages used across analysis (`create_cable-buffer.R`, `extract_cable-energy.R`) and reporting (`report.Rmd`)
  - `create_cable-buffer.R`: R code to generate cable buffers at 100 m depth increments.
  - `extract_cable-energy.R`: R code to extract renewable energy for cabled territories.
  - `report.Rmd`: R markdown document for reproducible, data-driven generation of various report output file formats (`report.pdf`, `report.docx`, `report.html`)

<sup>8</sup>Wind data for 90-meter offshore: [http://www.nrel.gov/gis/data\\_wind.html](http://www.nrel.gov/gis/data_wind.html)

<sup>9</sup>The “one-sixth rule” for Albers Equal Area Conic projection: <http://desktop.arcgis.com/en/arcmap/latest/map/projections/albers-equal-area-conic.htm#GUID-2158C4F9-F197-458E-94F0-84933C1BE6B7>

### 3 Results

#### 3.1 Cable Buffer

Of the original 230,835 km in the “NOAA Charted Submarine cables in the United States as of December 2012” dataset (Figure 1), 97,321 km fell within the 200 nm of the US exclusive economic zone (EEZ), which was analyzed across 12 territories that overlapped with the cables (Figure 1). The cable buffer area ranged from 29.35% (242,031 km<sup>2</sup> [3z] of 824,679 km<sup>2</sup> total) in the West owing to many cables present and the steep continental shelf, to virtually nill 0.39% (6,133 km<sup>2</sup> [2z] of 1,553,288 km<sup>2</sup> total) in Gulf of Mexico (Table 2).

Table 2: Area of separation schemes from submarine cables for new facilities (2 \* depth) and new cables (3 \* depth) as absolute area (km<sup>2</sup>) or as a percentage (%) of territory total area. Horizontal bars indicate value relative to rest of column. Territories having submarine cables but no energy resource characterization (tidal, wind or wave) are lumped into "Other" territories: Guam, Johnston Atoll, N Mariana Islands, Palmyra Atoll, Wake Island.

Territory	Facilities (2z)			Cables (3z)		
	Name	Area (km <sup>2</sup> )	Area (km <sup>2</sup> )	(%)	Area (km <sup>2</sup> )	(%)
Alaska		3,682,912	167,361	4.5%	237,610	6.5%
East		932,351	133,108	14.3%	165,004	17.7%
Gulf of Mexico		1,553,288	6,133	0.4%	9,211	0.6%
Hawaii		2,474,715	302,348	12.2%	419,341	16.9%
Puerto Rico		172,958	23,659	13.7%	32,350	18.7%
US Virgin Islands		38,275	7,444	19.4%	10,693	27.9%
West		824,679	183,110	22.2%	242,031	29.3%
Other		2,174,943	104,139	4.8%	151,849	7.0%

#### 3.2 Overlap of Cable Buffer with Renewable Energy

Overlap of cable buffers with marine renewable energy was assessed for tidal (Haas et al. 2011), wave (P. T. Jacobson et al. 2011) and wind (Schwartz et al. 2010) energy based on energy resource characterizations available through the National Renewable Energy Lab (NREL) Wind Prospector<sup>10</sup> or MHK Atlas<sup>11</sup>. Assessment of overlap with the advised separation schemes energy resource was limited to maximum depths based on current assessment of technology limitations: < 100 m for tidal (Haas et al. 2011), < 200 m for wave (P. T. Jacobson et al. 2011), and < 1,000 m for wind (Musial et al. 2016). The lowest energy classes were also dropped from the assessment (tidal: > 500 W/m<sup>2</sup>, wave: > 10 kW/m, wind: > 7 m/s) to consider viable energy development.

Areas of viable tidal resource are orders of magnitude less than wave or wind owing to requirements for channelized bathymetry (Figure 2) and have up to 4.7% overlap for the lowest energy class (500 - 1,000 W/m<sup>2</sup>) with only 2.3% and 0.9% overlap at higher power classes 1,000 - 1,500 and > 1,500 W/m<sup>2</sup> respectively. Wave energy at either depth bin of 0 - 100 or 100 - 200 m is very low with at most 2% overlap for the lower energy class (10-20 kW/m) at depths 100 - 200 m. The most abundant viable wind in shallow depth (0 - 100 m) and lower energy (7 - 8 and 8 - 9 m/s) overlaps at most 3.1%, but overlaps more at higher speeds (9.6% at 9 - 10 m/s) and in deeper waters (7.8% and 10.5% at 7 - 8 and 8 - 9 m/s respectively in depths 200 - 1,000 m). Small areas at the highest wind speeds > 10 m/s overlap up to 42.1% for the deepest bin (200 - 1,000 m) and highest wind speeds (11 - 12 m/s).

Energy resources are unevenly distributed across territories. Tidal power (Figure 3, Table 3) is most abundant in Alaska (691 km<sup>2</sup> at 500 - 1,000 W/m<sup>2</sup>; Table 3), the East (390 km<sup>2</sup> at 500 - 1,000 W/m<sup>2</sup>) and the West (46 km<sup>2</sup> at 500 - 1,000 W/m<sup>2</sup>), which is where overlap with cable buffers is most significant (23.4 - 31.5%)

<sup>10</sup>NREL Wind Prospector: <https://maps.nrel.gov/wind-prospector/>

<sup>11</sup>NREL MHK Atlas: <https://maps.nrel.gov/mhk-atlas>

such as around Port Townsend, WA (Figure 11). Wave energy (Figure 4, Table 4) is most abundant in the Pacific territories having the most exposure to storm activity across the largest ocean. Alaska has the most abundant energy across all viable energy classes. Wind speeds (Figure 5, Table 5) in excess of  $9 \text{ m/s}$  are not found in the Gulf of Mexico and limited to the offshore New England area of the East (Figure 19), offshore areas of California and Oregon in the West (Figure 19) and dispersed locations in Hawaii (Figure 19).

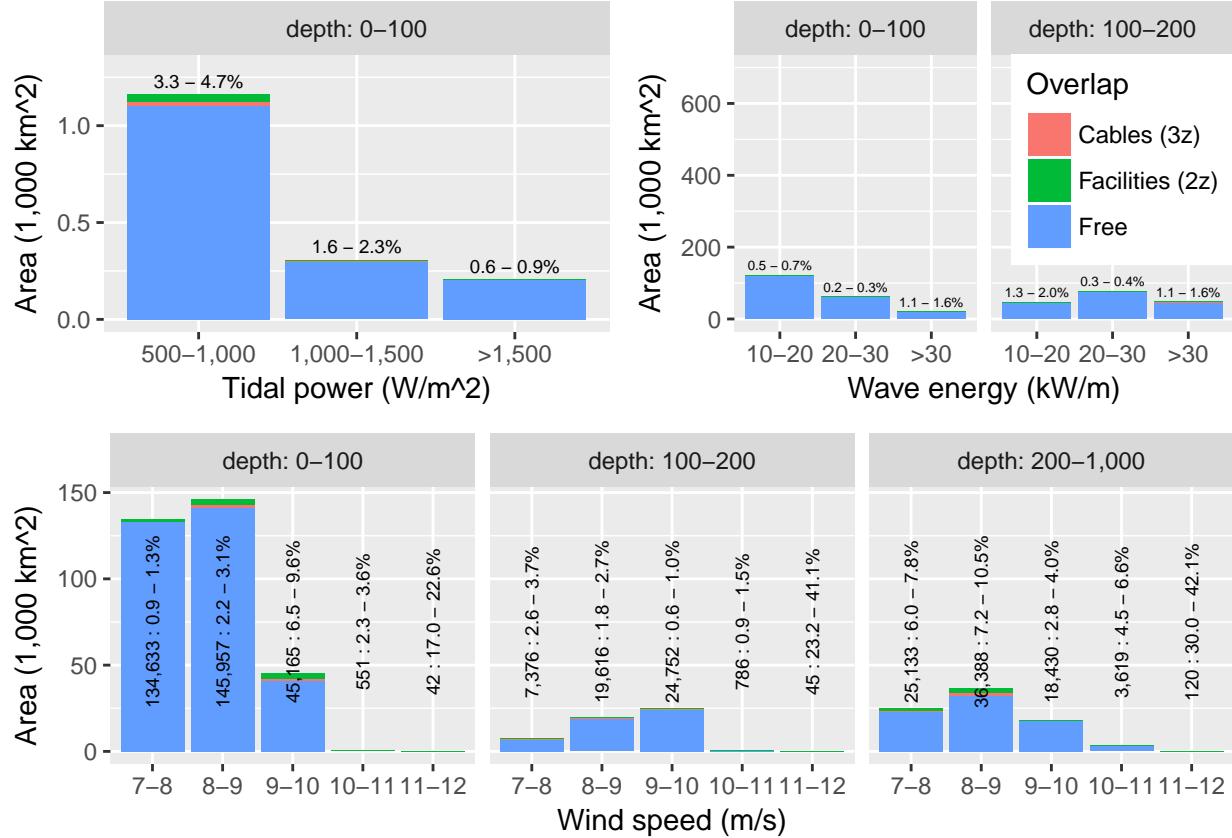


Figure 2: Area of energy classes per depth bin across forms of energy resource characterization (tidal, wave and wind) with percent overlap of horizontal safety separation scheme from existing submarine cables for new facilities ( $2 * \text{depth}$ ) and new cables ( $3 * \text{depth}$ ). Overlap of new cables buffer ( $3z$ ) is inclusive of the new facilities buffer ( $2z$ ) so the height of the bar represents total area for the energy class. Assessed area of overlap with energy resource characterization is limited to a maximum depth (tidal:  $< 100 \text{ m}$ ; wave:  $< 200 \text{ m}$ ; wind:  $< 1000 \text{ m}$ ) and minimum energy classes (tidal:  $> 500 \text{ W/m}^2$ ; wave:  $> 10 \text{ kW/m}$ ; wind  $> 7 \text{ m/s}$ ) for viable renewable energy development.

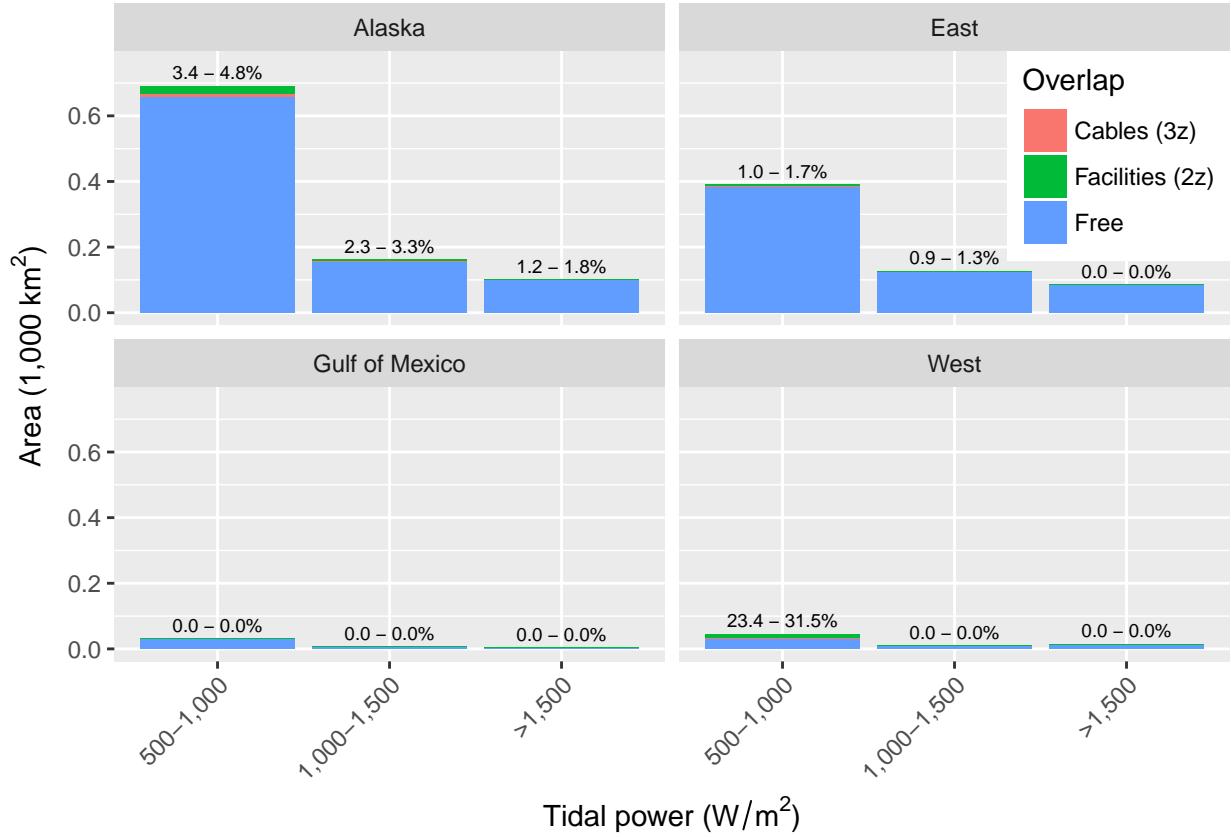


Figure 3: Area of tidal power classes ( $W/m^2$ ) per US territory with percent overlap of horizontal safety separation scheme from existing submarine cables for new facilities ( $2 * \text{depth}$ ) and new cables ( $3 * \text{depth}$ ). Overlap of new cables buffer ( $3z$ ) is inclusive of the new facilities buffer ( $2z$ ) so the height of the bar represents total area for the energy class. Assessed area of overlap with tidal energy resource characterization is limited to a maximum depth (< 100 m) and minimum energy classes ( $> 500 W/m^2$ ) for viable tidal energy development.

### 3.2.1 Tidal

Table 3: Area of tidal power classes ( $\text{W/m}^2$ ) per US territory with percent overlap of safety separation scheme from existing submarine cables for new facilities (2 \* depth) and new cables (3 \* depth). Width of colored bars indicate value relative to rest of column. Assessed area is limited to a maximum depth (< 100 m) and minimum energy classes (> 500  $\text{W/m}^2$ ) for viable tidal energy development.

Territory	Tidal power ( $\text{W/m}^2$ )	Area ( $\text{km}^2$ )	Facilities (2z)		Cable (3z)	
			Area ( $\text{km}^2$ )	(%)	Area ( $\text{km}^2$ )	(%)
Alaska	500-1,000	691	23	3.4%	33	4.8%
	1,000-1,500	162	4	2.3%	5	3.3%
	1,500<	101	1	1.2%	2	1.8%
East	500-1,000	390	4	1.0%	6	1.7%
	1,000-1,500	127	1	0.9%	2	1.3%
	1,500<	87	0	0.0%	0	0.0%
Gulf of Mexico	500-1,000	32	0	0.0%	0	0.0%
	1,000-1,500	8	0	0.0%	0	0.0%
	1,500<	3	0	0.0%	0	0.0%
West	500-1,000	46	11	23.4%	14	31.5%
	1,000-1,500	9	0	0.0%	0	0.0%
	1,500<	14	0	0.0%	0	0.0%

### 3.2.2 Wave

Table 4: Area of wave energy classes ( $\text{kW/m}$ ) per US territory with percent overlap of horizontal safety separation scheme from existing submarine cables for new facilities (2 \* depth) and new cables (3 \* depth). Width of colored bars indicate value relative to rest of column. Assessed area is limited to a maximum depth (< 200 m) and minimum energy classes (> 10  $\text{kW/m}$ ) for viable wave energy development.

Territory	Wave Energy ( $\text{kW/m}$ )	Area ( $\text{km}^2$ )	Facilities (2z)		Cable (3z)	
			Area ( $\text{km}^2$ )	(%)	Area ( $\text{km}^2$ )	(%)
Alaska	10-20	146,572	707	0.5%	1,032	0.7%
	20-30	129,680	154	0.1%	246	0.2%
	>30	36,122	12	0.0%	20	0.1%
East	10-20	16,463	359	2.2%	536	3.3%
Hawaii	10-20	1,604	11	0.7%	21	1.3%
	20-30	311	0	0.0%	0	0.0%
West	10-20	4,637	121	2.6%	168	3.6%
	20-30	10,608	187	1.8%	251	2.4%
	>30	32,910	737	2.2%	1,079	3.3%

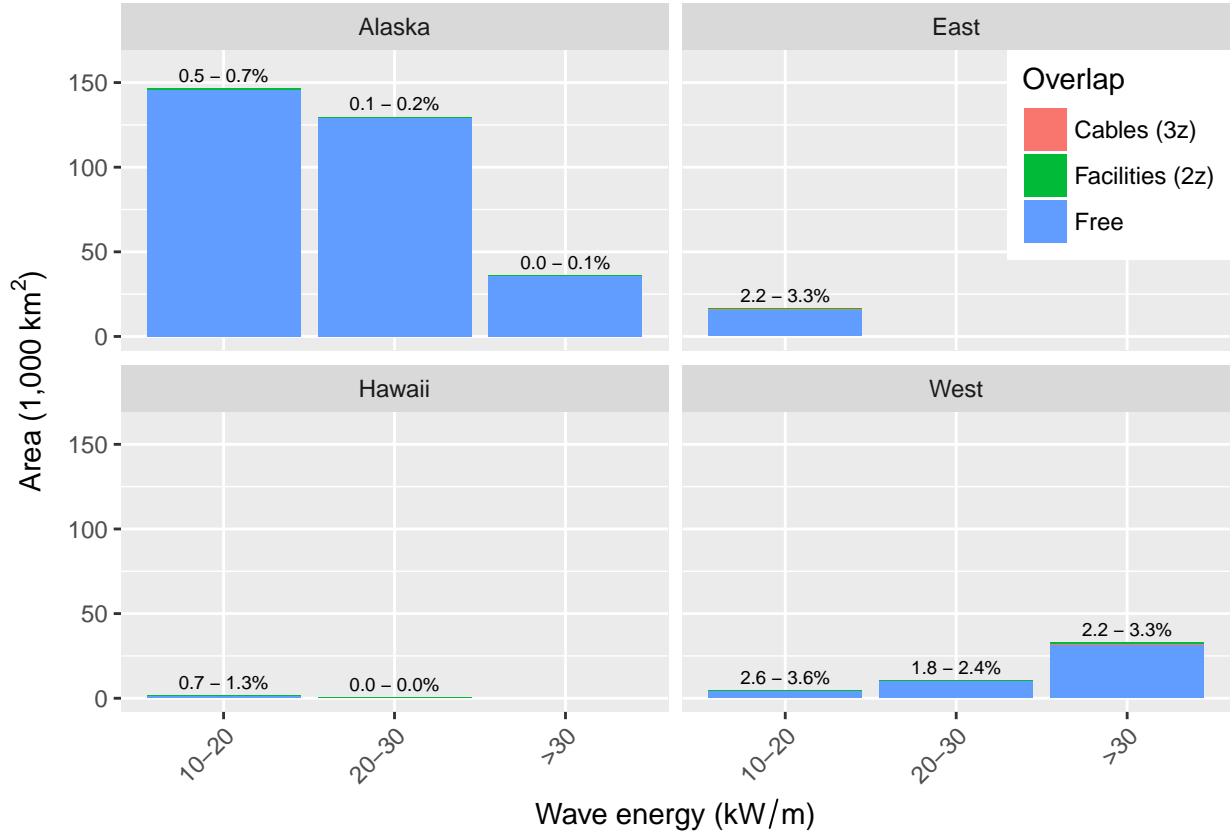


Figure 4: Area of wave energy classes ( $kW/m$ ) per US territory with percent overlap of horizontal safety separation scheme from existing submarine cables for new facilities ( $2 * \text{depth}$ ) and new cables ( $3 * \text{depth}$ ). Overlap of new cables buffer ( $3z$ ) is inclusive of the new facilities buffer ( $2z$ ) so the height of the bar represents total area for the energy class. Assessed area is limited to a maximum depth ( $> 200 \text{ m}$ ) and minimum energy classes ( $> 10 \text{ kW/m}$ ) for viable wave energy development.

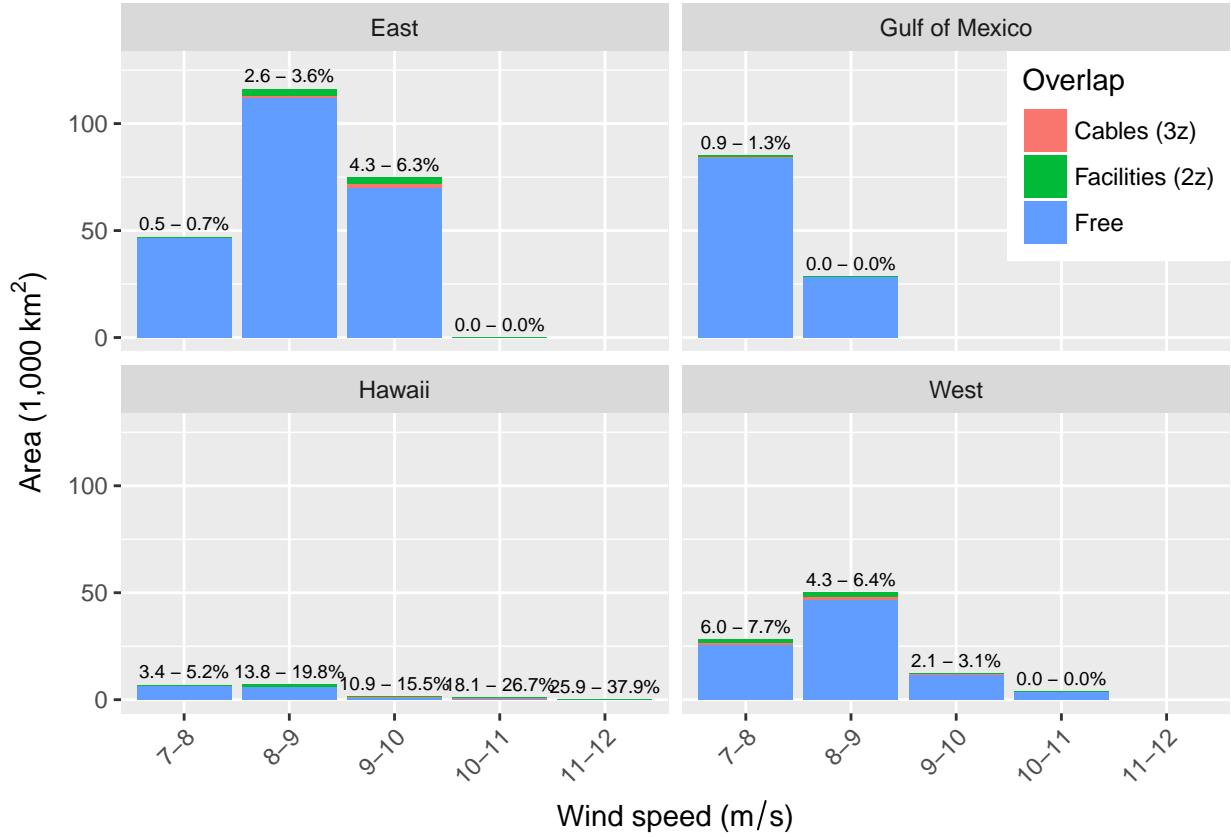


Figure 5: Area of wind speed classes ( $m/s$ ) per US territory with percent overlap of horizontal safety separation scheme from existing submarine cables for new facilities ( $2 * \text{depth}$ ) and new cables ( $3 * \text{depth}$ ). Overlap of new cables buffer ( $3z$ ) is inclusive of the new facilities buffer ( $2z$ ) so the height of the bar represents total area for the energy class. Assessed area is limited to a maximum depth ( $< 1,000 \text{ m}$ ) and minimum energy classes ( $> 7 \text{ m/s}$ ) for viable wind energy development.

### 3.2.3 Wind

Table 5: Area of wind speed classes (m/s) per US territory with percent overlap of horizontal safety separation scheme from existing submarine cables for new facilities (2 \* depth) and new cables (3 \* depth). Width of colored bars indicate value relative to rest of column. Assessed area is limited to a maximum depth (< 1,000 m) and minimum energy classes (> 7 m/s) for viable wind energy development.

Territory	Wind Speed (m/s)	Area (km <sup>2</sup> )	Facilities (2z)		Cable (3z)	
			Area (km <sup>2</sup> )	(%)	Area (km <sup>2</sup> )	(%)
East	7-8	47,001	232	0.5%	343	0.7%
	8-9	116,082	3,016	2.6%	4,198	3.6%
	9-10	74,826	3,214	4.3%	4,749	6.3%
	10-11	1	0	0.0%	0	0.0%
Gulf of Mexico	7-8	85,032	740	0.9%	1,102	1.3%
	8-9	28,530	0	0.0%	0	0.0%
Hawaii	7-8	6,931	237	3.4%	362	5.2%
	8-9	7,178	991	13.8%	1,421	19.8%
	9-10	1,329	145	10.9%	206	15.5%
	10-11	1,009	183	18.1%	269	26.7%
	11-12	207	54	25.9%	78	37.9%
West	7-8	28,178	1,685	6.0%	2,175	7.7%
	8-9	50,171	2,160	4.3%	3,197	6.4%
	9-10	12,192	261	2.1%	380	3.1%
	10-11	3,946	0	0.0%	0	0.0%

## 4 Conclusions

Given climate change impacts of fossil fuel energy production (Pachauri et al. 2015), development of clean renewable energy alternatives are imperative for the sustainable future of the United States and rest of the planet. These energy sources however vary widely in geographic and temporal availability and may compete with other uses. The submarine cable industry provides critical power and telecommunication services, such that safe operation and maintenance must be heeded as marine renewable energy sources are developed (Communications Security, Reliability and Interoperability Council IV 2014, 2016). The submarine cable safety avoidance zones created and evaluated through this report are products intended to minimize conflict at the planning stage between these competing uses.

Although the US currently only has one marine renewable energy facility in full production at Block Island NJ, many more are in pilot and proposal phases with much future potential (Beiter et al. 2017; Lehmann et al. 2017; Uihlein and Magagna 2016). These spatial avoidance zones are advisory. Should there be overlapping interest, negotiations between renewable energy developers and cable operators should be sought.

## A Maps by US Territory of Cable Buffer and Renewable Energy

### A.1 Tide

A.1.1 Alaska

A.1.2 East

A.1.3 Gulf of Mexico

A.1.4 Puerto Rico

A.1.5 US Virgin Islands

A.1.6 West

### A.2 Wave

A.2.1 Alaska

A.2.2 East

A.2.3 Gulf of Mexico

A.2.4 Hawaii

A.2.5 Puerto Rico

A.2.6 US Virgin Islands

A.2.7 West

### A.3 Wind

A.3.1 East

A.3.2 Gulf of Mexico

A.3.3 Hawaii

A.3.4 West

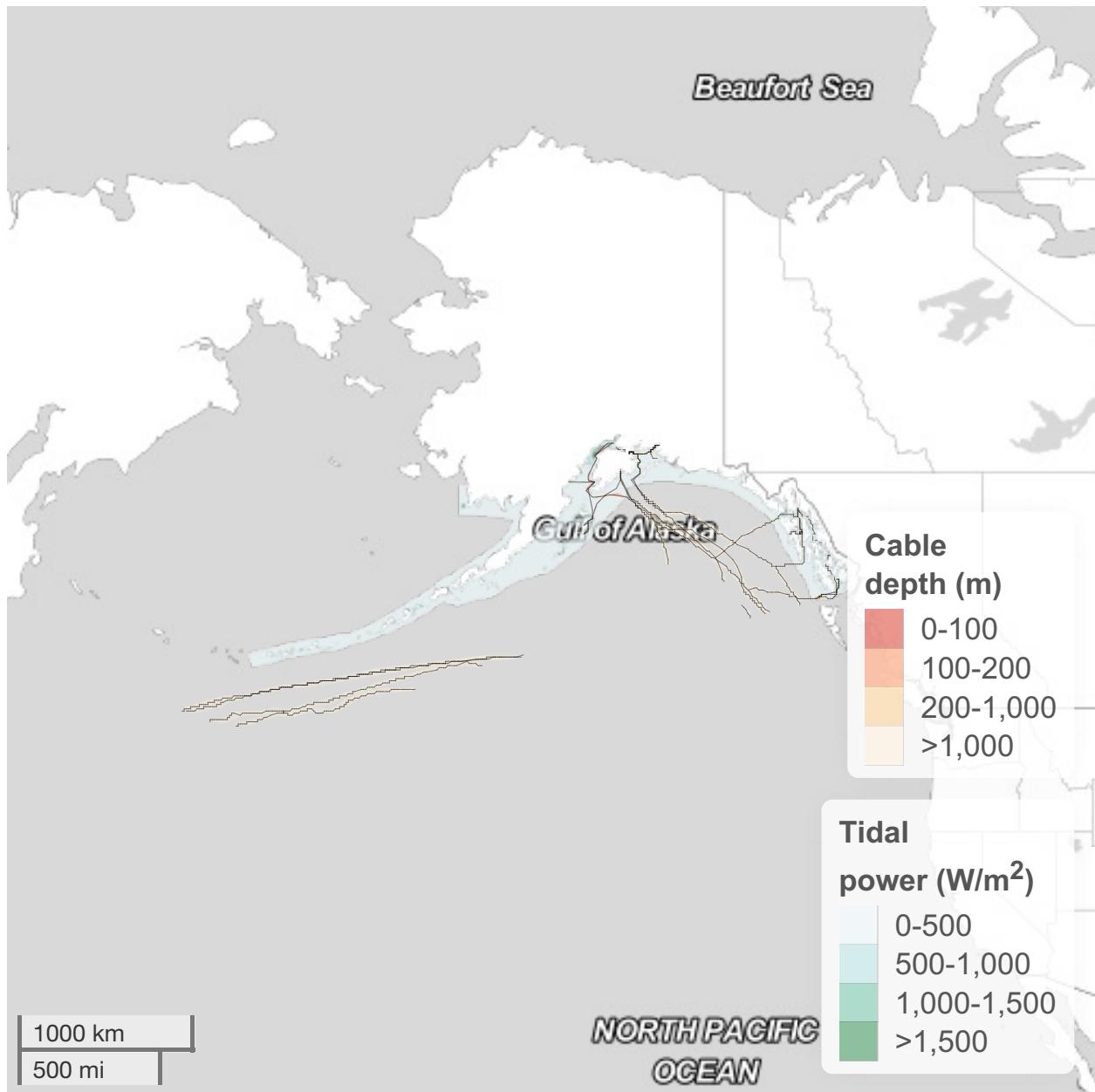


Figure 6: Map of tidal power ( $W/m^2$ ) in Alaska with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

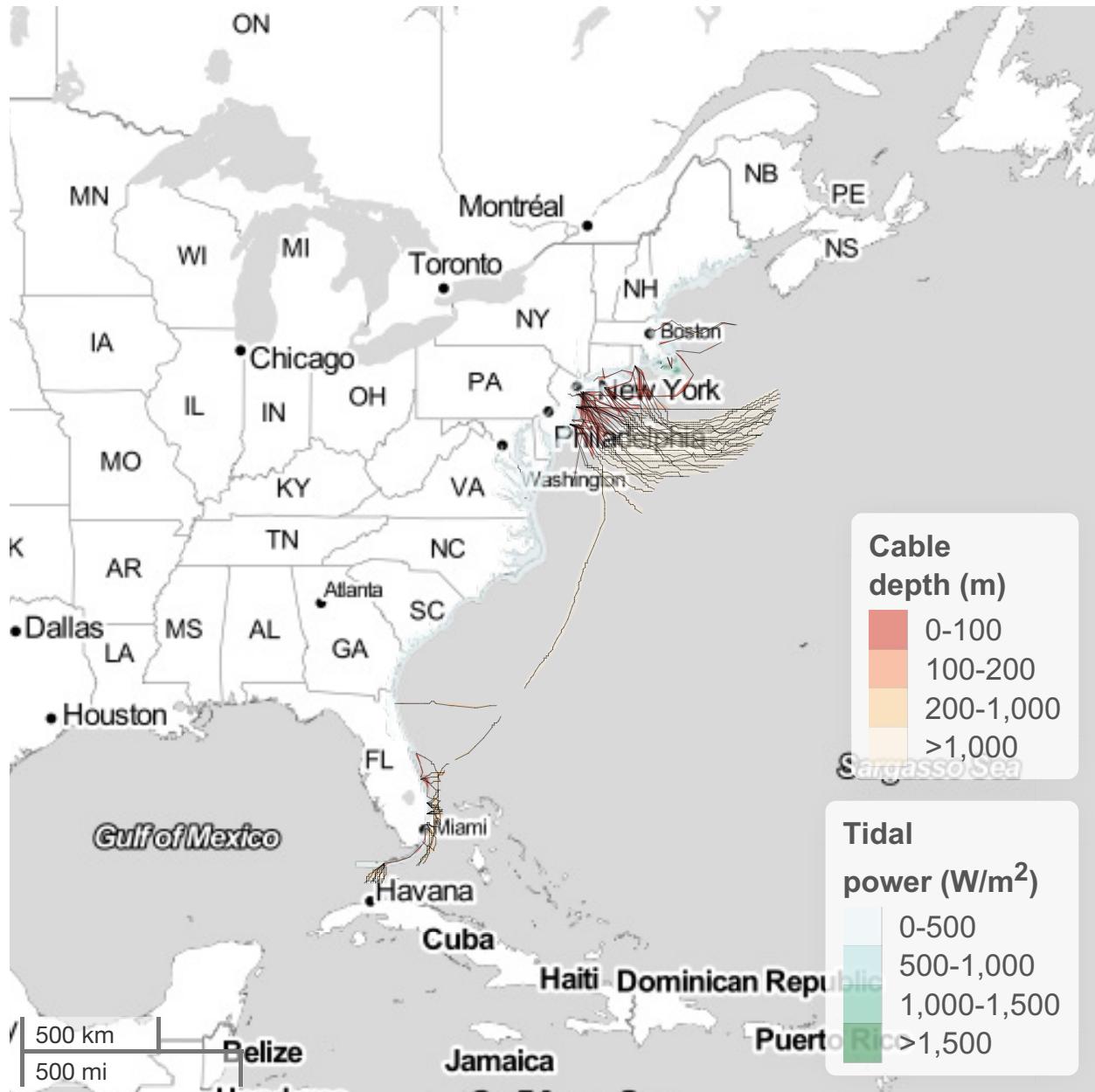


Figure 7: Map of tidal power ( $\text{W/m}^2$ ) in the East with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

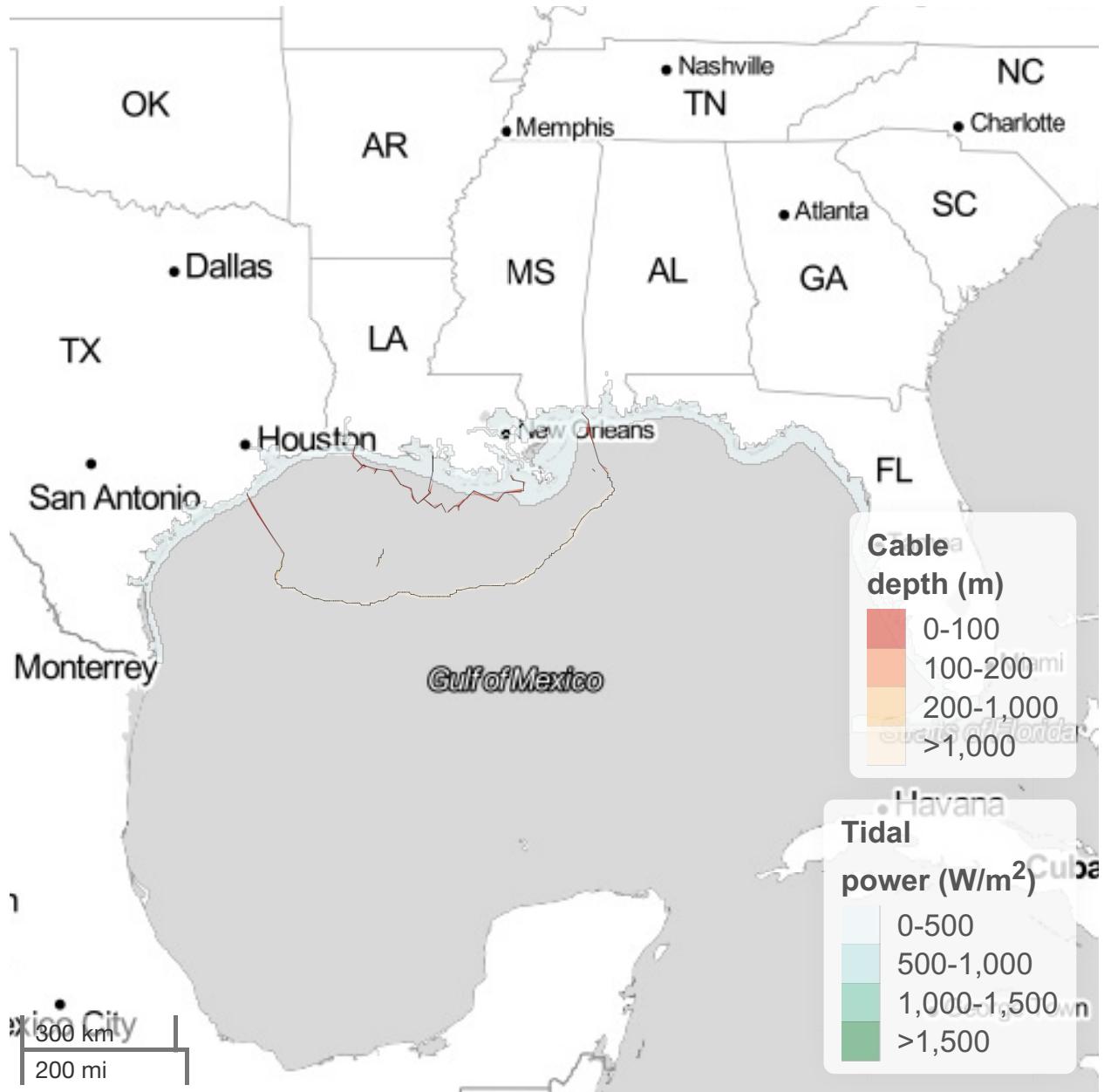


Figure 8: Map of tidal power ( $W/m^2$ ) in the Gulf of Mexico with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

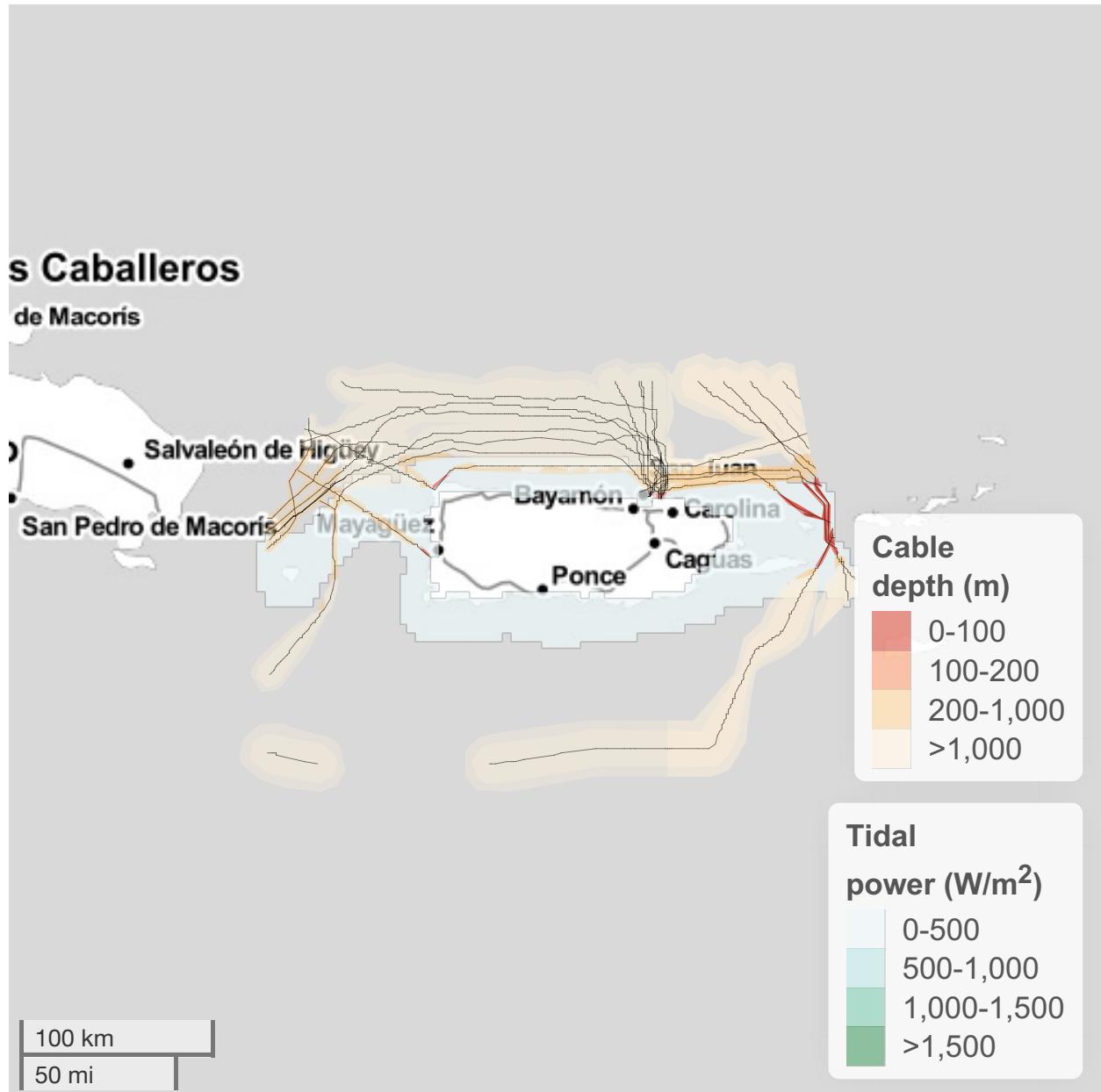


Figure 9: Map of tidal power ( $W/m^2$ ) in Puerto Rico with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

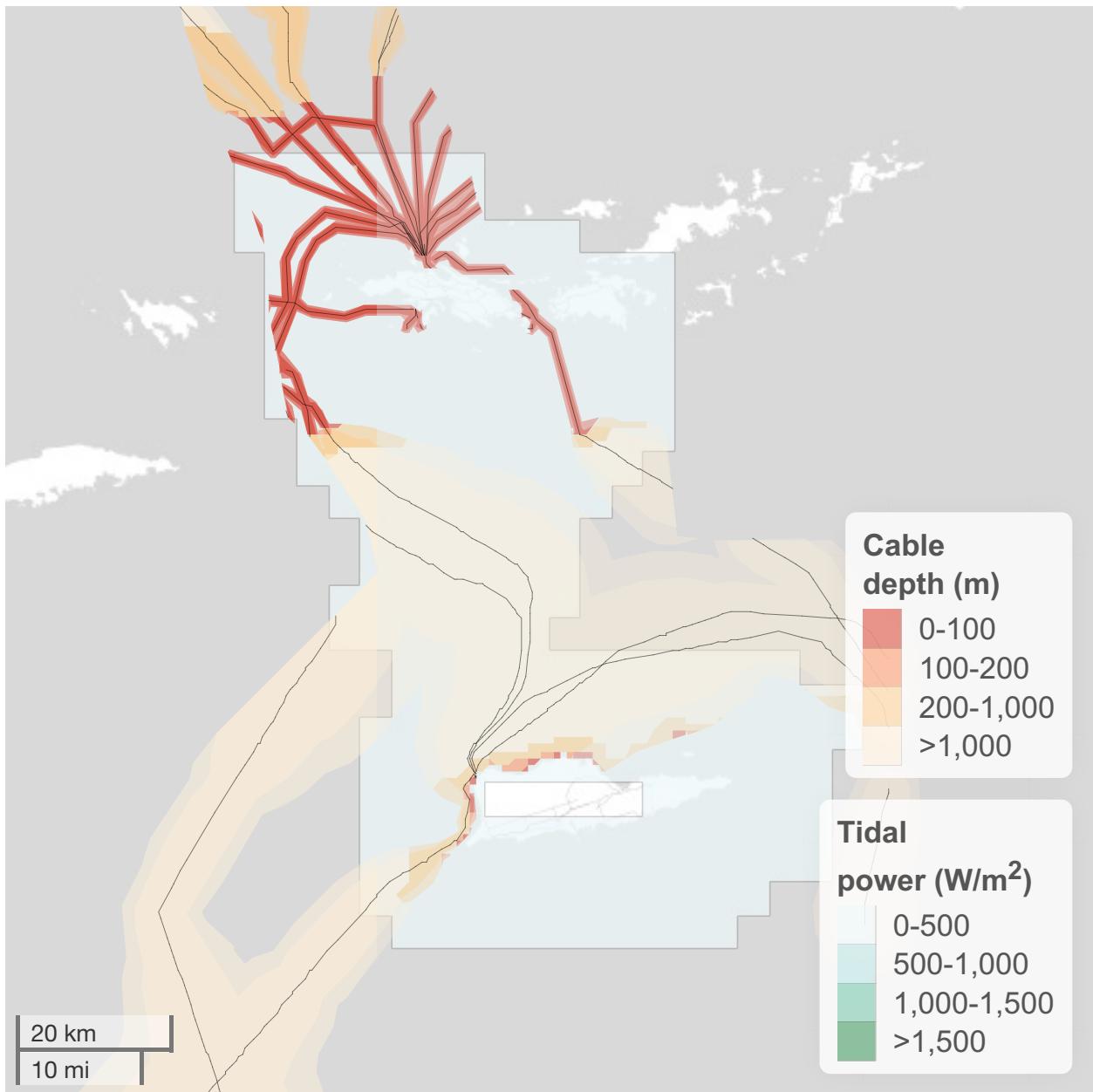


Figure 10: Map of tidal power ( $W/m^2$ ) in the US Virgin Islands with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

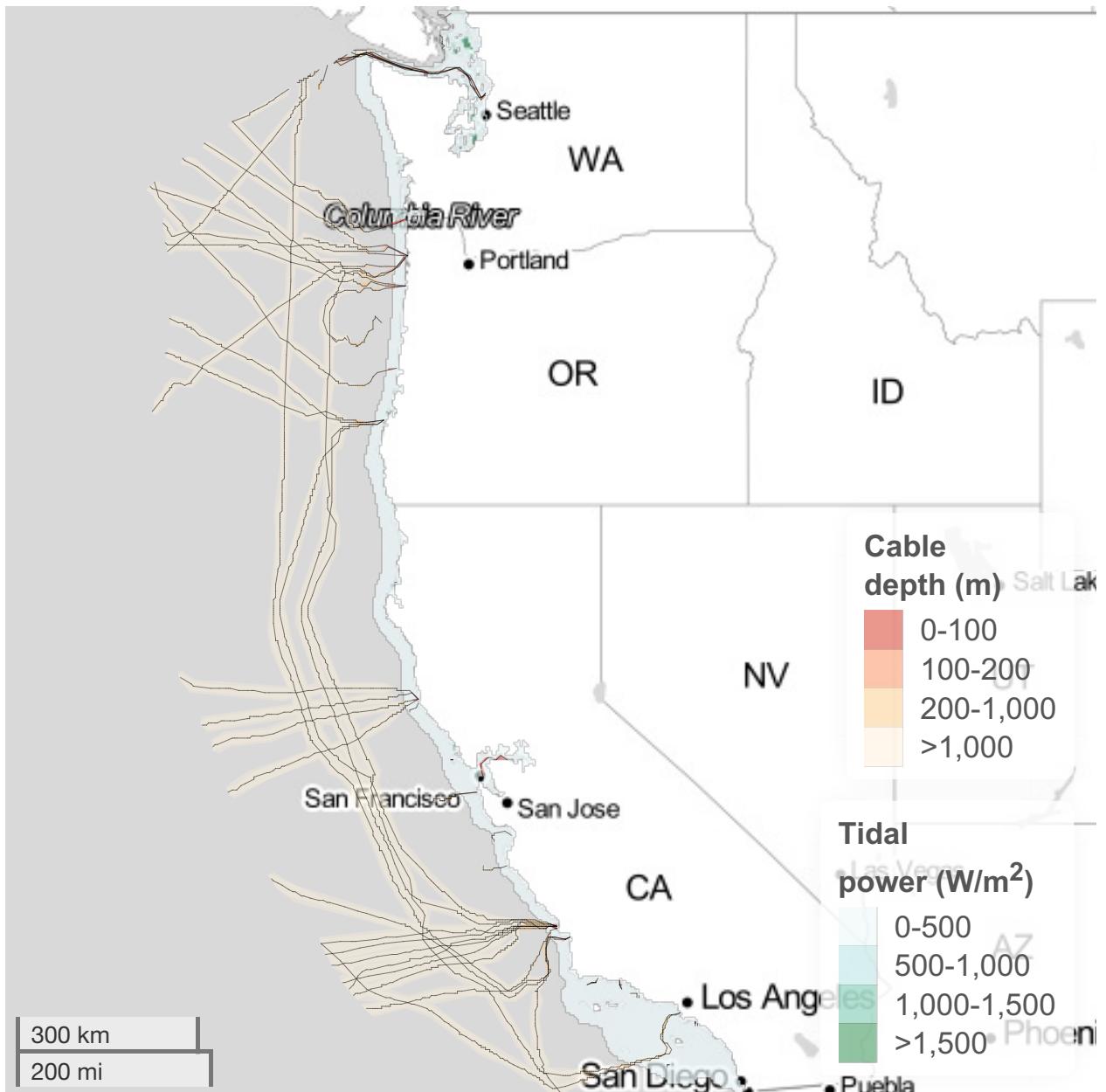


Figure 11: Map of tidal power ( $W/m^2$ ) in the West with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

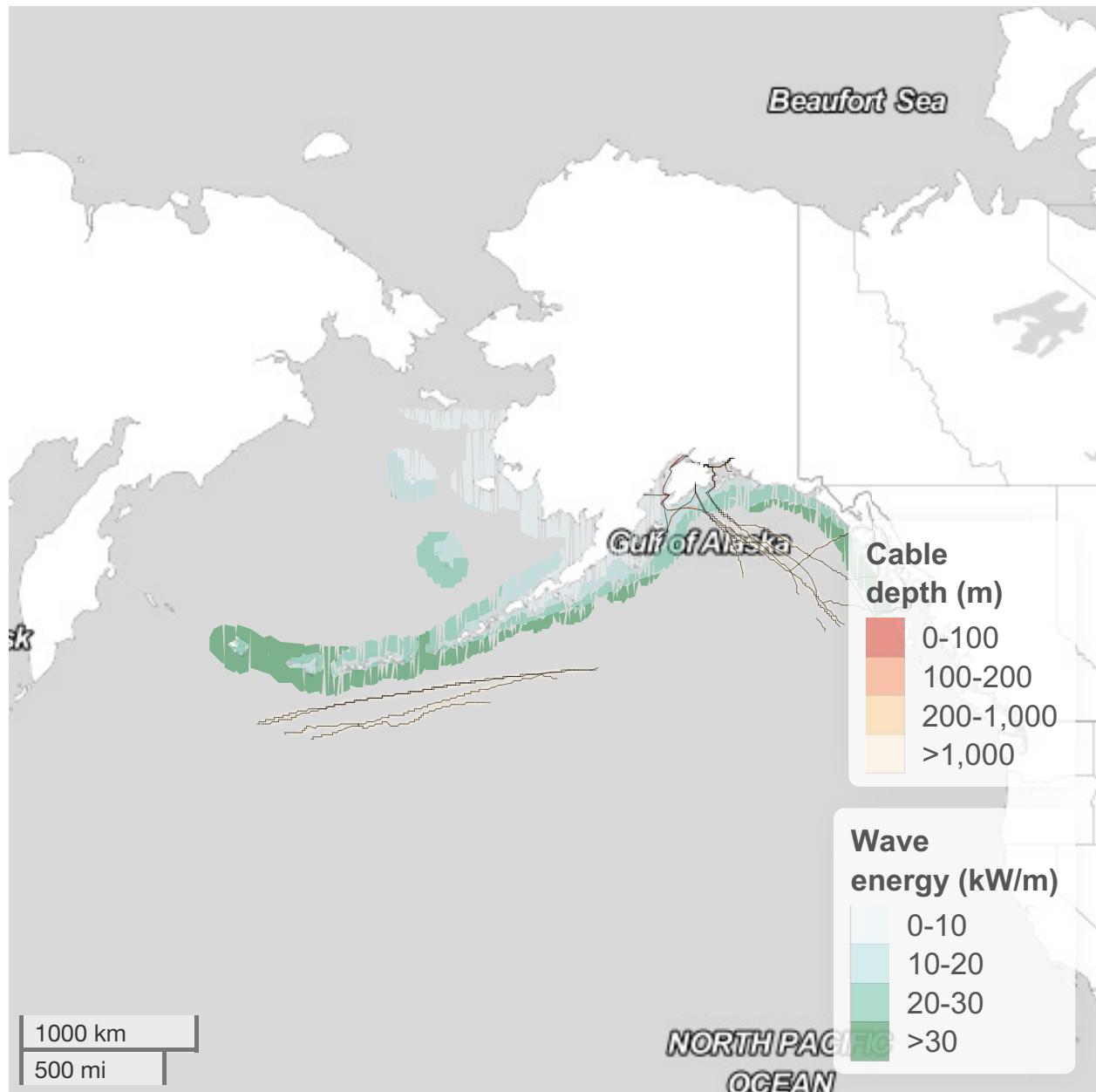


Figure 12: Map of wave energy ( $kW/m$ ) in Alaska with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

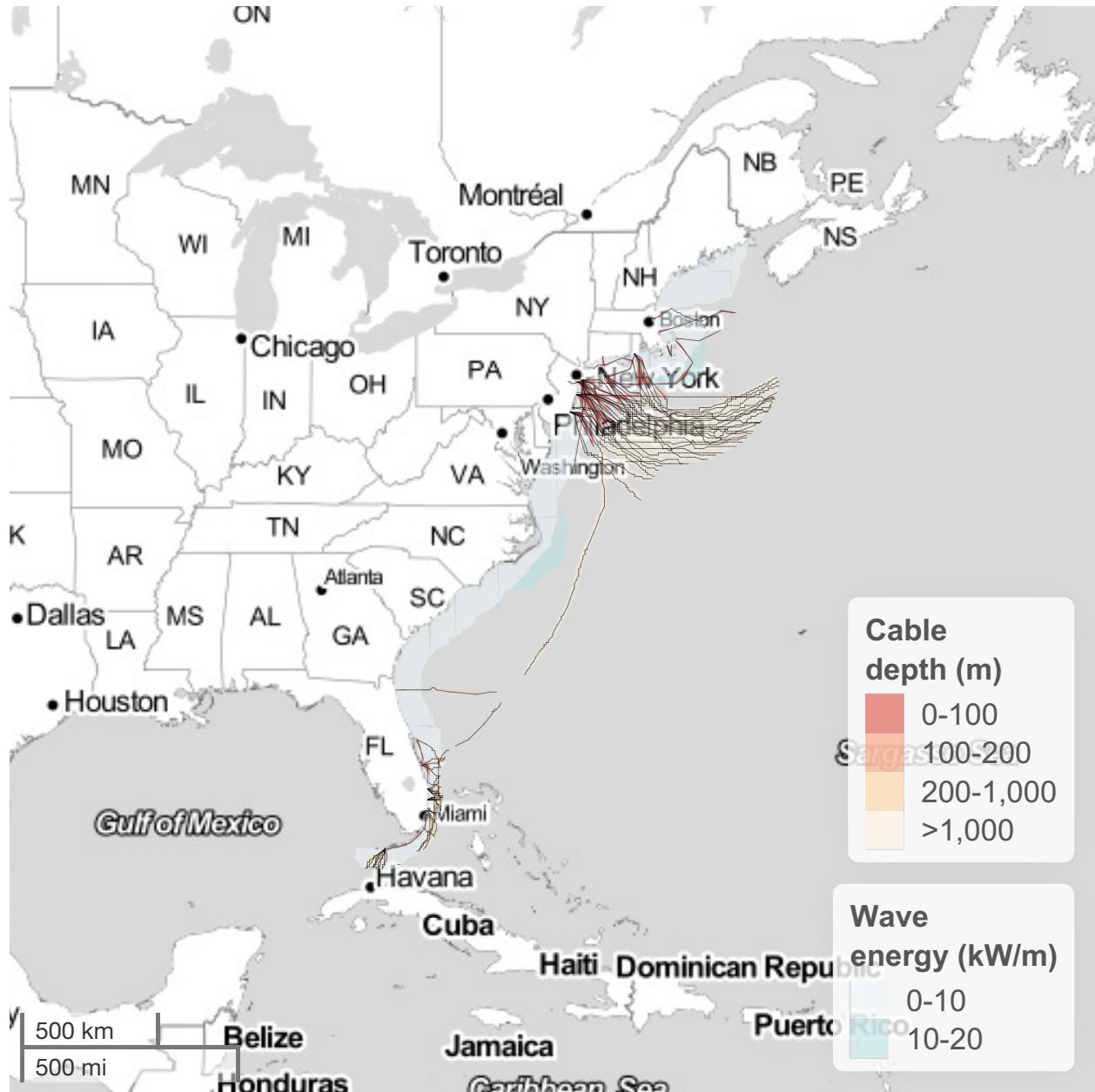


Figure 13: Map of wave energy ( $kW/m$ ) in the East with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

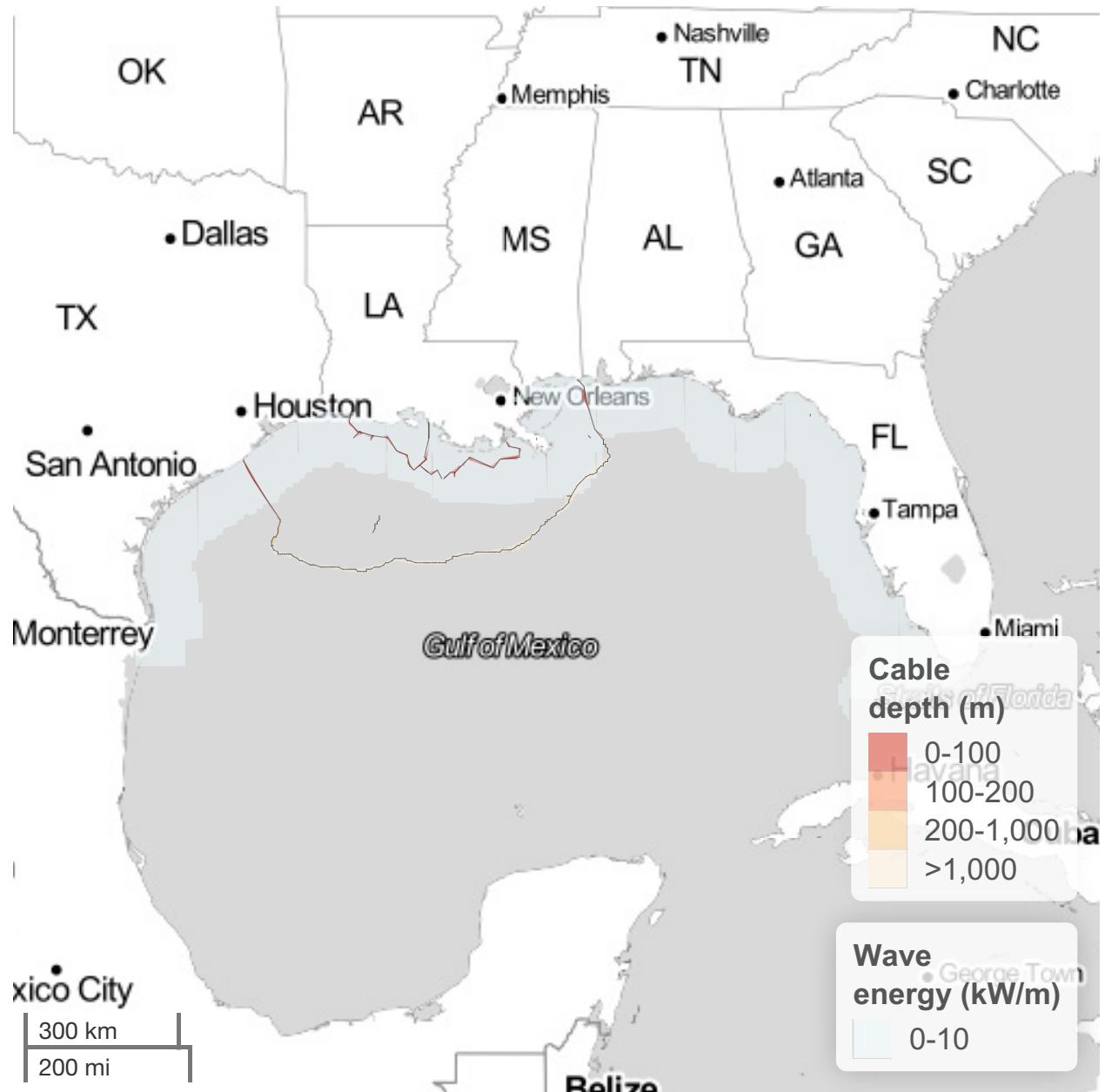


Figure 14: Map of wave energy ( $kW/m$ ) in the Gulf of Mexico with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

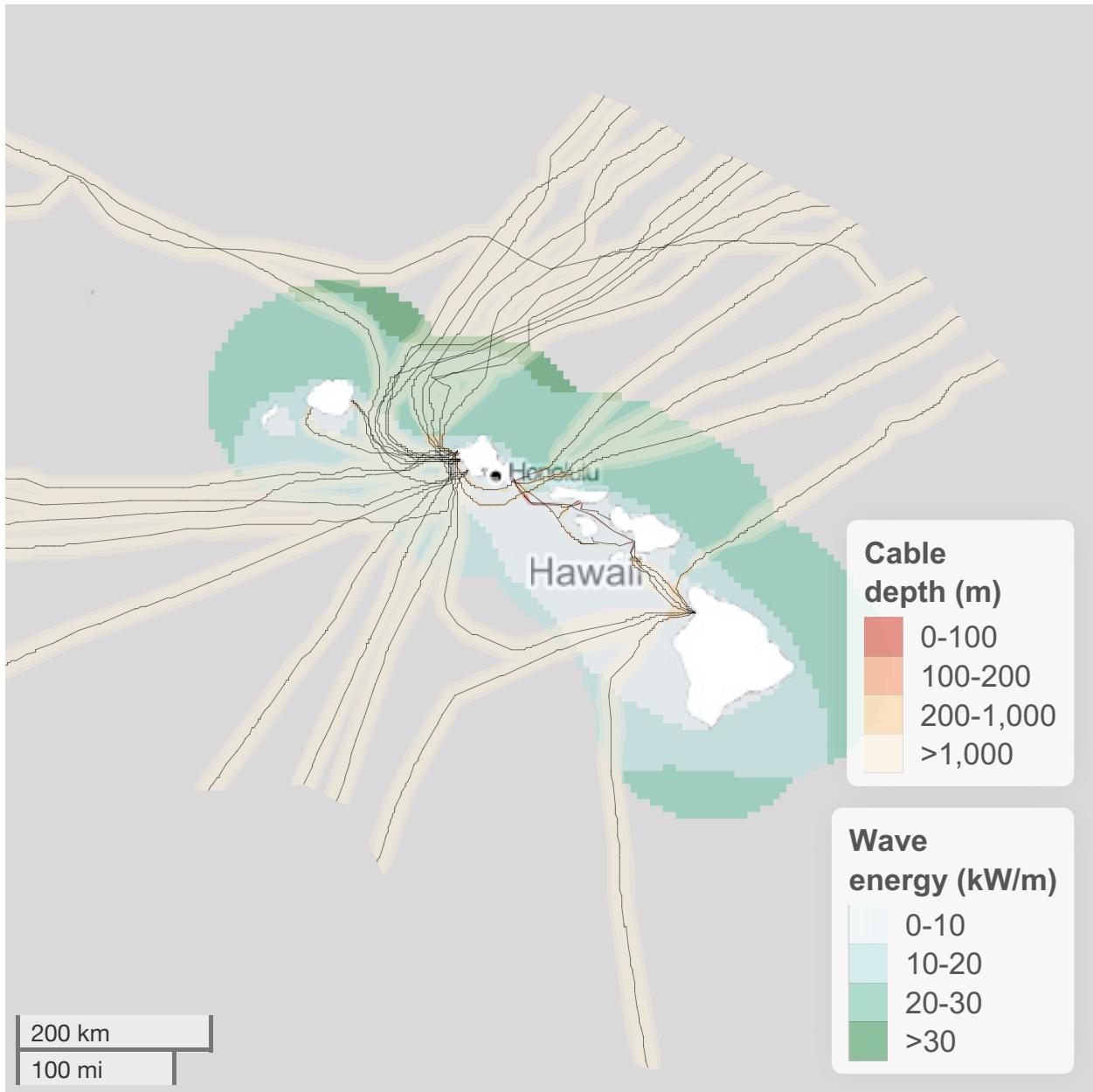


Figure 15: Map of wave energy ( $kW/m$ ) in Hawaii with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

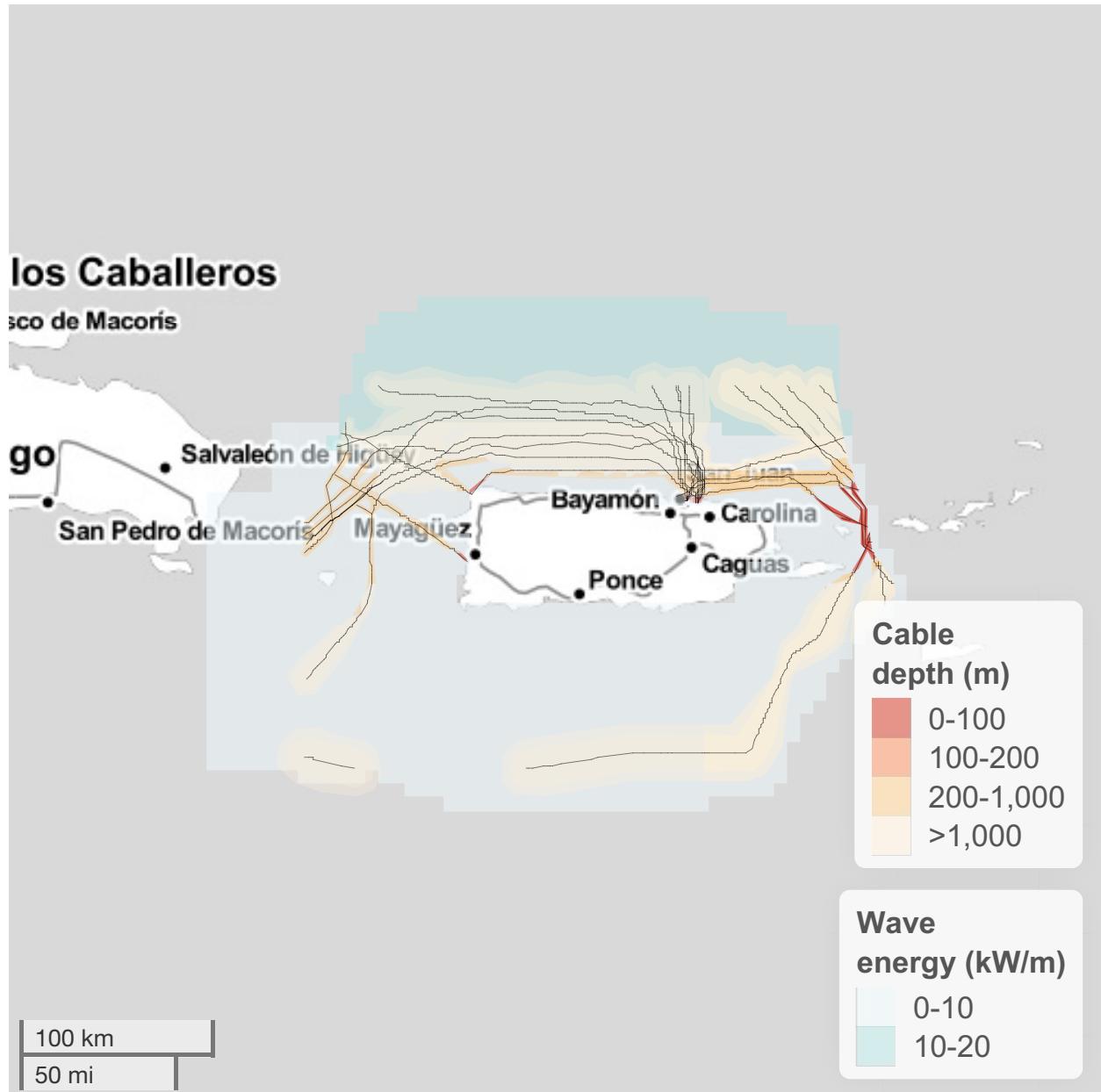


Figure 16: Map of wave energy ( $kW/m$ ) in Puerto Rico with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

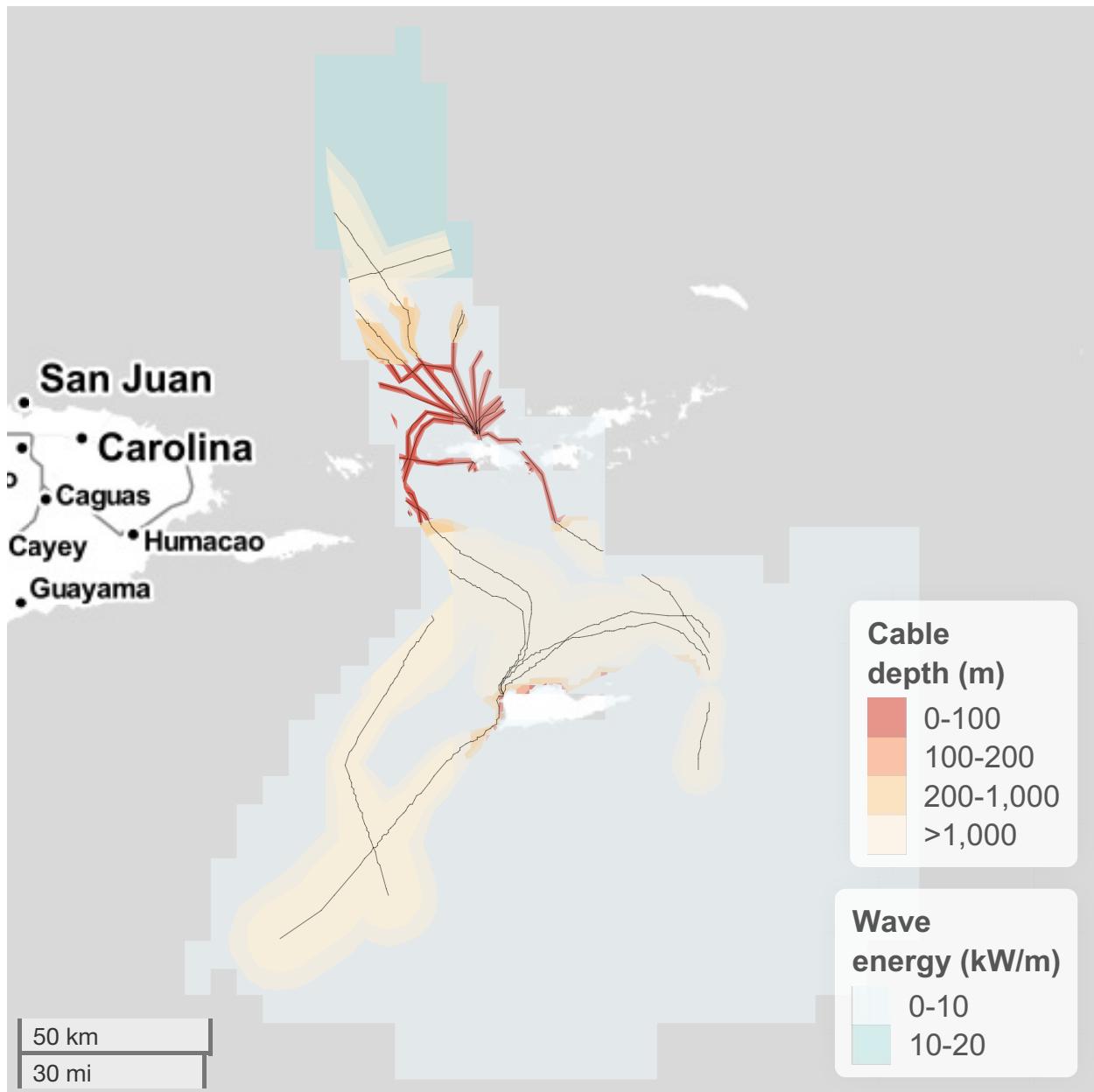


Figure 17: Map of wave energy ( $kW/m$ ) in the US Virgin Islands with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

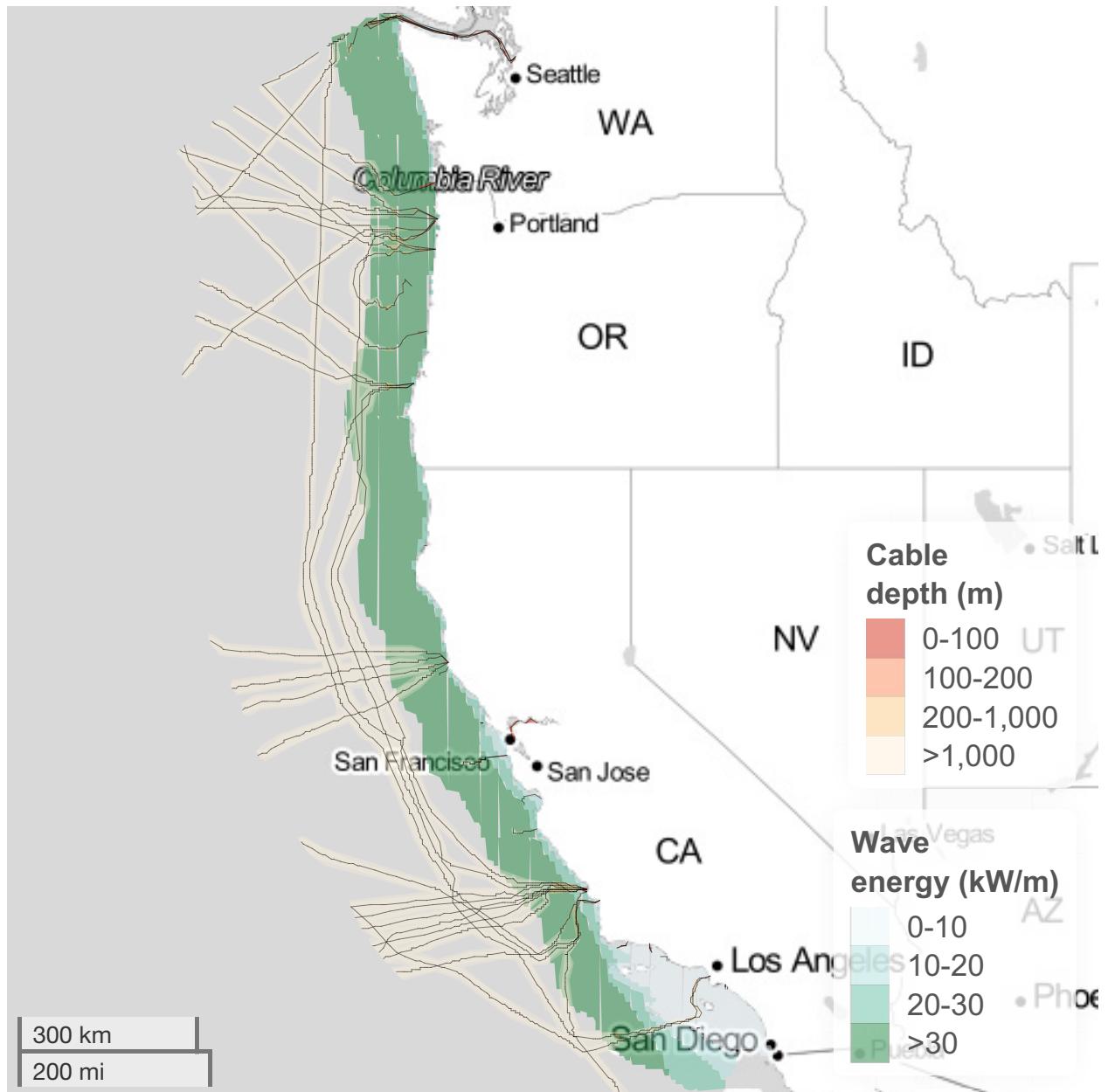


Figure 18: Map of wave energy ( $kW/m$ ) in the West with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

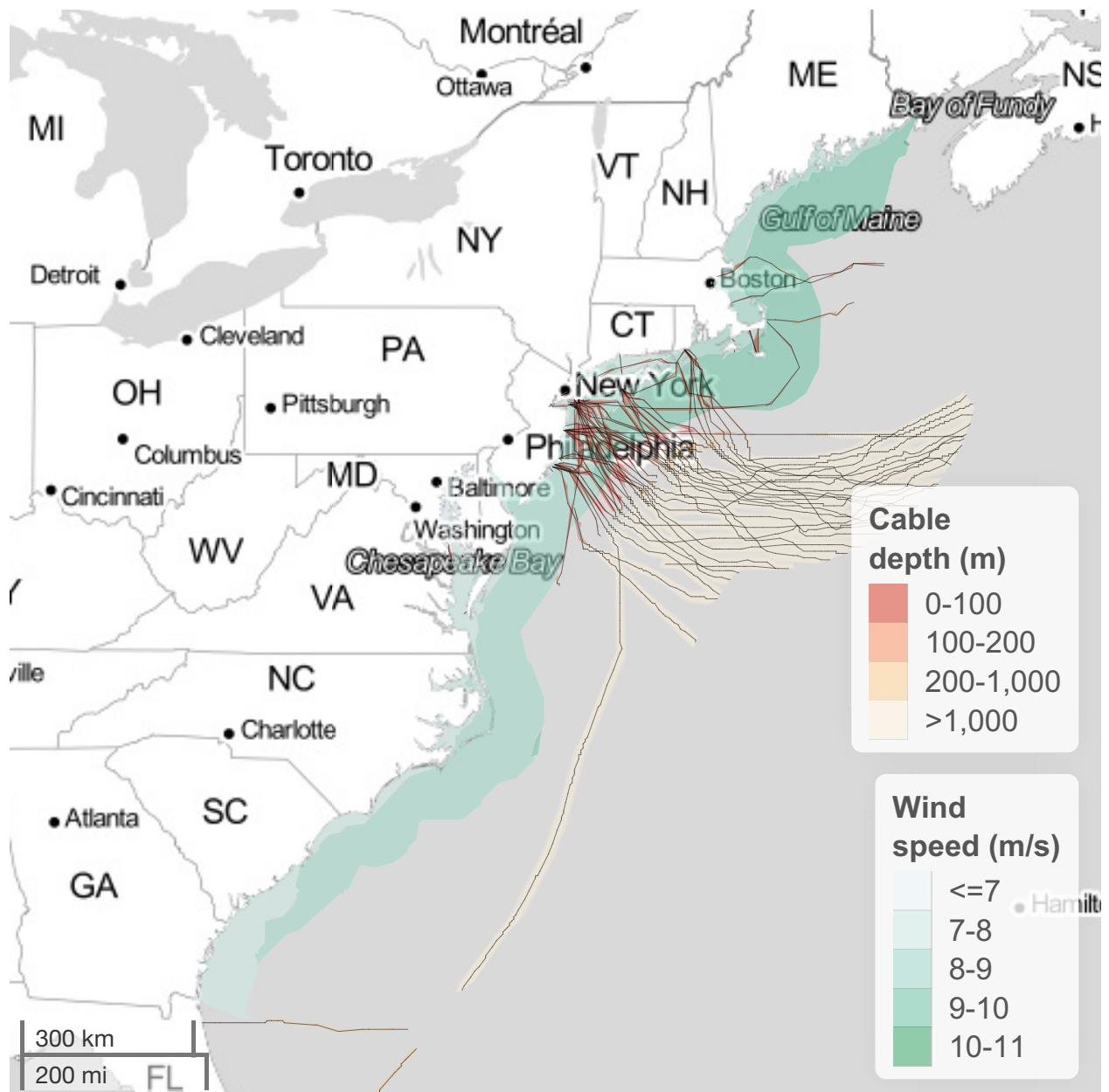


Figure 19: Map of wind speed ( $m/s$ ) in the East with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

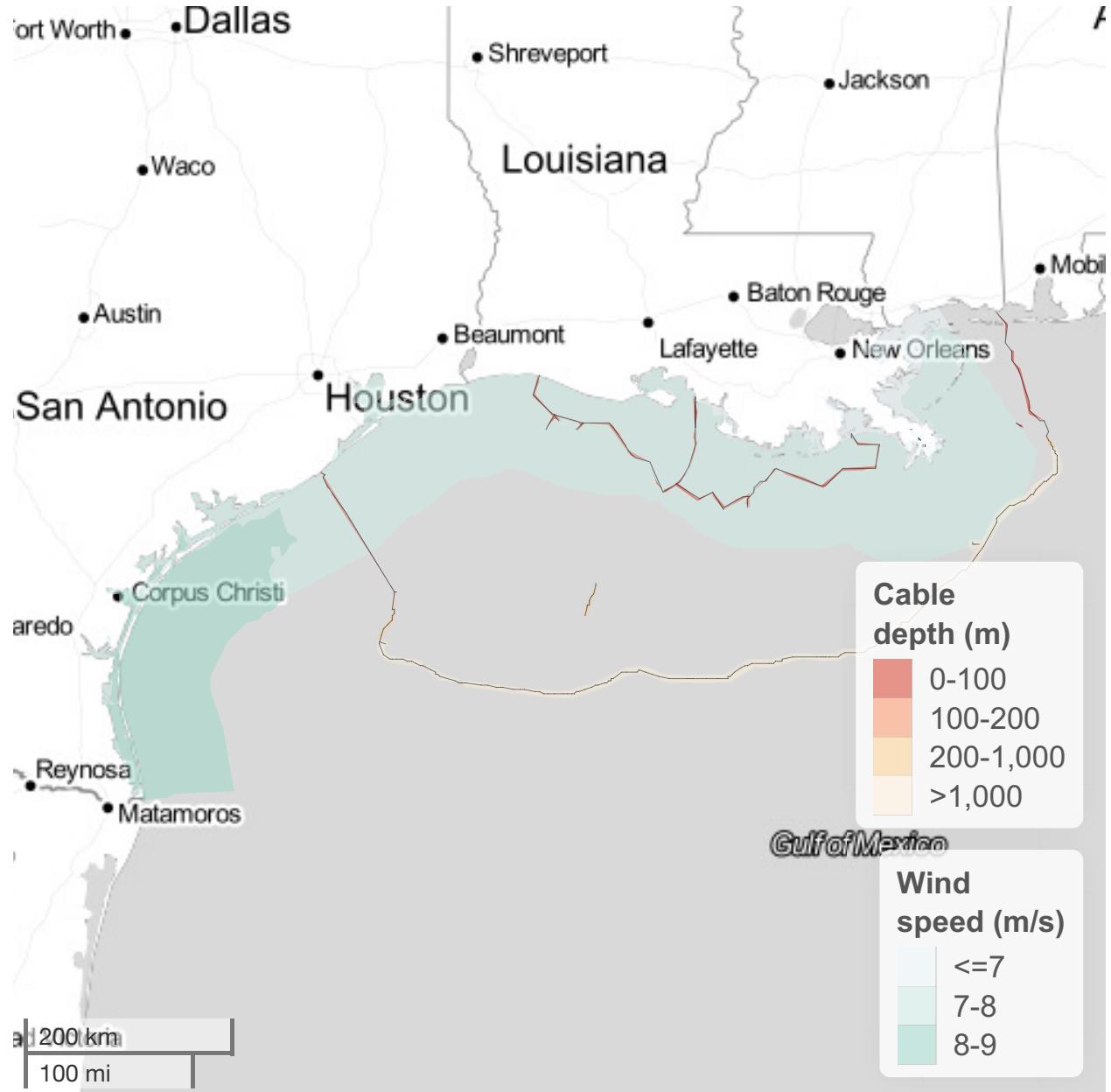


Figure 20: Map of wind speed ( $m/s$ ) in the Gulf of Mexico with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

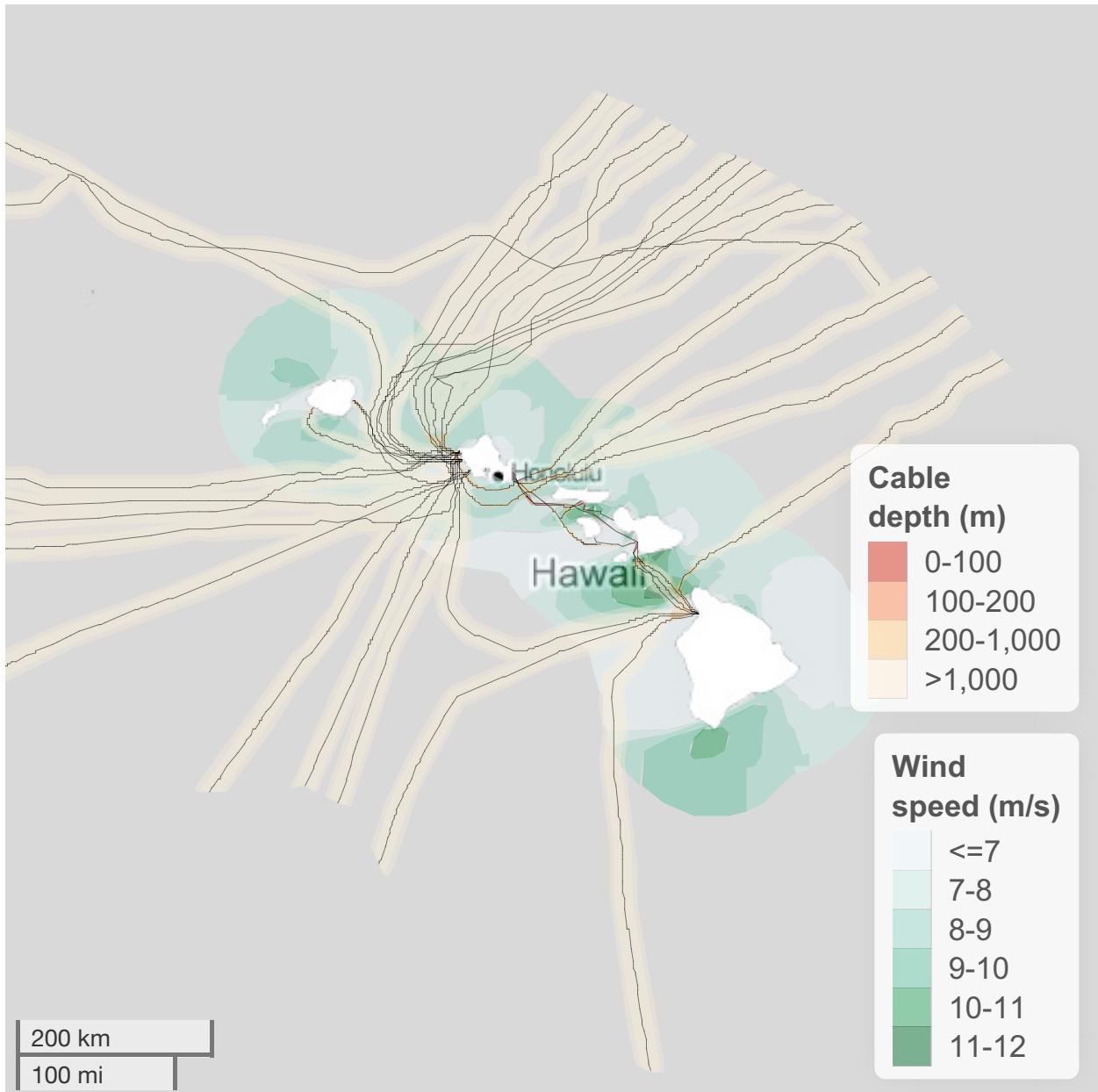


Figure 21: Map of wind speed ( $m/s$ ) in Hawaii with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

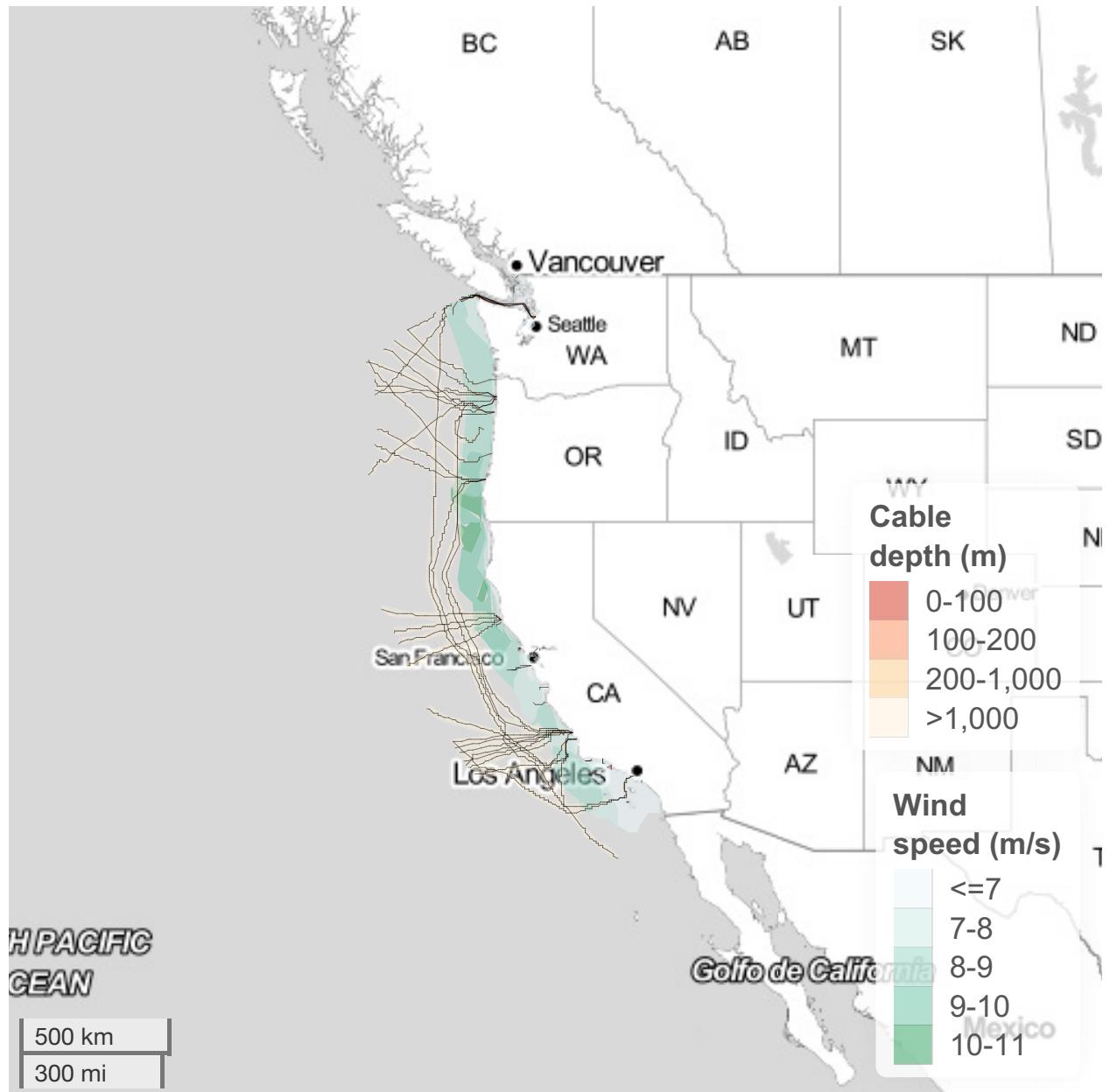


Figure 22: Map of wind speed ( $m/s$ ) in the West with submarine cables (black lines) and advisory buffers colored by bottom depth. The buffers are plotted with transparency so the inner more opaque band represents the advised horizontal separation scheme for new facilities ( $2 * \text{depth}$ ) and outer less opaque band the scheme for new cables ( $3 * \text{depth}$ ). At large scales this detail is not visible. Alternatively, you can zoom and pan interactively on these layers at <http://ecoquants.github.io/nrel-cables/maps.html>.

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