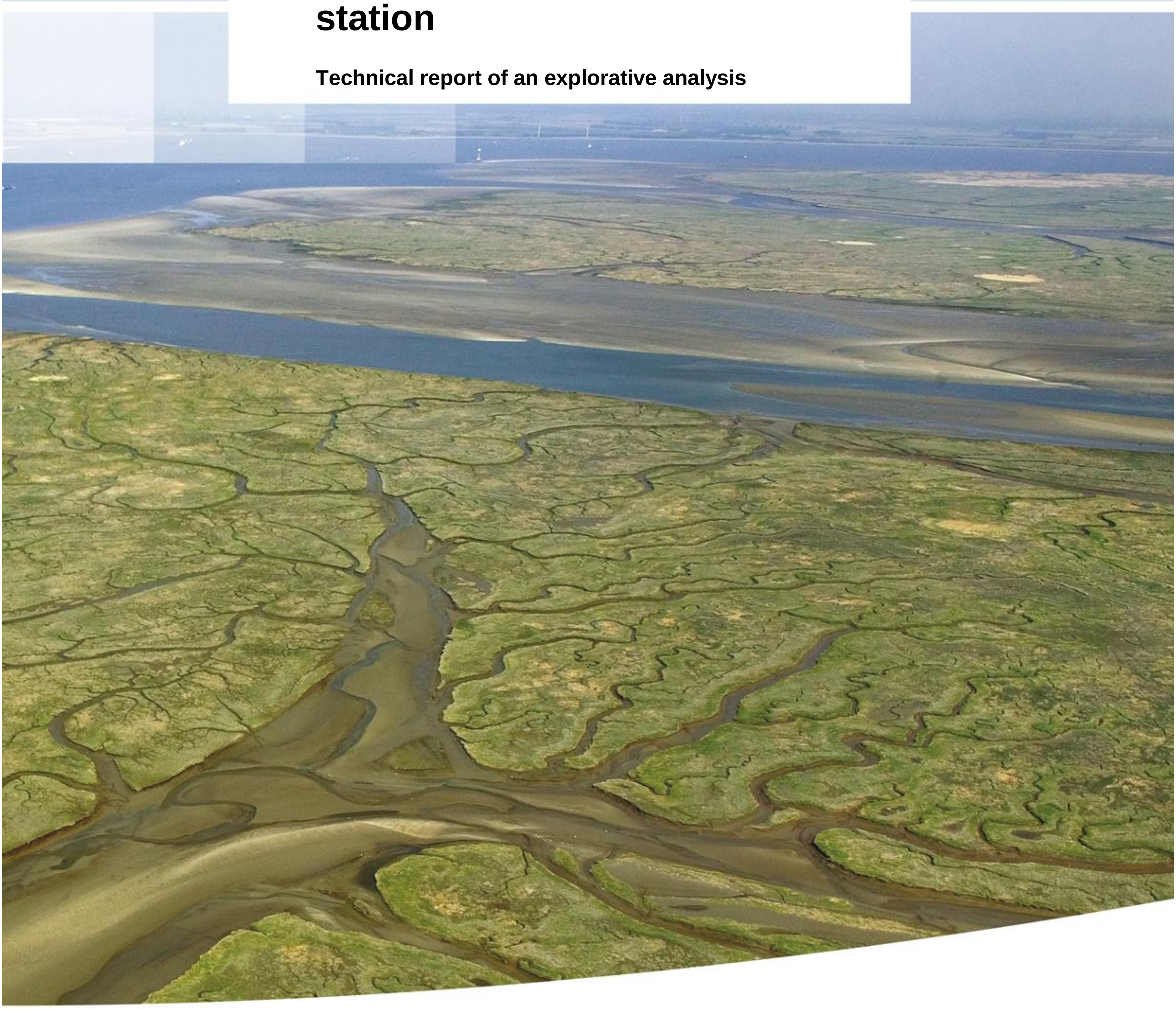
Export potential of the Brouwersdam tidal power station

Technical report of an explorative analysis



Deltares

Export potential of the Brouwersdam tidal power station

Technical report of an explorative analysis

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Deltares

Title
Export potential of the Brouwersdam tidal power station

Client	Project	Attribute	Pages
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Summary
This is the technical documentation of the analysis of export potential of the Brouwersdam tidal power station. The objective of the analysis is to globally assess the potential of exporting a tidal power station combined with pumps, using global datasets and spatial analysis.

First, an exploration for global datasets was necessary to assess the feasibility of the study. Data was found on among others inundation, tides, basin area and delta locations. These datasets are processed in GIS software and with client consultation the found locations are filtered and given a weighed score. The result is a dataset with 451 delta's and 10 lakes with values for flood (inundation), basin area, tidal range, population, category of natural area and GDP.

The method proved to be valuable for global spatial analysis on technical feasibility. Further use of the method could improve and extend the possibilities and level of detail for these kinds of assessments.

References
Part of KPP BOA Zuidwestelijke Delta 2019

Version	Date	Author	Initials	Review	Initials	Approval	Initials
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Status
final

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1 Introduction

The former sea inlet Lake Grevelingen is since 1971 enclosed by the Brouwersdam, see Figure 1.1. Since then, the water quality and ecology have deteriorated because of the lowered dissolved oxygen levels. A possible solution consists of large culverts in the dam combined with energy-generating turbines and pumps.

Figure 1.1 Lake Grevelingen, the Netherlands. Brouwersdam is the western dam.

Tidal power can be used to generate renewable energy. This tidal-pump power station combines turbines and pumps; not only for energy production but for water level management in areas with a high flood risk and/or high energy potential. The projected sea level rise caused by climate change will require more coastal protection and clean energy production is necessary to reduce this climate change. The tidal power station is a method of generating clean energy with the rise of the tides. With low tide, it can pump back the water to the sea even when the sea level is higher than the water level in the lake.

The general idea is that the planned tidal power station in Brouwersdam can serve as an example for other locations facing issues like subsidence, sea level rise, flood hazard and the potential for clean energy production. Until now, the global potential of exporting this knowledge is unknown. This study aims at generating insight into locations where the tidal power station technology could provide a solution by analysing global spatial data.

Reading guide
The process of the analysis in two phases is explained in chapter 2. Thereafter in chapter 3, the results of the analysis are elaborated. Chapter 4 consists of a discussion on the data quality and the indicators, thresholds and weighing that are explained in chapter 2. Finally, in chapter 5, recommendations for further research are given.

2 Process

The export potential of the Brouwersdam type tidal power station is assessed by using global datasets from multiple different sources. The processing of these datasets and analysis is done in an open-source GIS software: QGIS. Because of the explorative nature of the study, it was decided to have a go/no-go moment after an initial search for global datasets and possible methods of analysis. This initial exploration is called the first phase and is explained in section 2.1. The second phase, consisting of more data gathering, data processing and the final analysis, is described in section 2.2.

2.1 First phase

The project kicked off with a meeting on the 16th of May 2019 with the client and Jacob van Berkel. Their valuable input resulted in a list of spatial and technological requirements for the tidal power station, aiding the search for suitable places:

- The focus is on coastal areas with high flood risk, where this technology can offer a possible solution;
- Areas with high river discharges;
- (Subsiding) Deltas;
- Closed basins with defined problems which the turbines can aid, e.g. water quality and biodiversity deterioration, flooding risks;
- Areas that are going to be affected by sea level rise (40 cm threshold);
- Time scale of a 40 cm sea level rise;
- Basins with a minimum of 100 km^2 area;
- Zones with significant tidal variation (higher energy gain potential);
- Freshwater systems are not suitable;
- Areas with high sediment concentration might be problematic.

These requirements were coupled to possible datasets and models which should give the appropriate information for the export potential assessment, see Table 2.1.

Table 2.1 Requirements and possible datasets extracted from the kick-off meeting

Requirement	Possible datasets/models
High flood risk areas	Global or local flood risk maps/models
Deltas	Delta maps, Subsidence scenarios
Closed Basins (~100+ km^2)	Global inland water
Sea level rise affected areas	Climate scenarios
High tidal variation	Tide and surge models
No freshwater systems	Global freshwater maps
High sediment concentration zones	Sedimentation maps

Based on internal and online search of global open databases and scientific studies, most of the data were collected. Flood, tides and sea level data could be derived from models from inside Deltares; a recently published scientific study consisted of the locations of 5.000 deltas and their basin area; and global lakes are found in an open source global database. The sources of all the datasets that are used can be found in Appendix A.

A first quick analysis was performed with the global coastal lakes and delta datasets. The lakes were filtered with a minimum basin area of 50 km² and a maximum range of 10 km from the coastline. The delta dataset was also filtered on a minimum basin area of 50 km². Some examples of the first results were presented at the go/no-go meeting at the end of the first phase.

In the go/no-go meeting, agreements were made on how to present the results and which deliverables were expected. These are: a list and maps of possible locations with their important parameter values and a score for export potential - both of which were determined in the second phase. A go decision followed as sufficient data was found to execute the explorative analysis.

2.2 Second phase

The second phase of the project is focused on achieving the predefined goal (chapter 1), which was proved to be feasible in the initial stage. In the initial stage, the main requirements and the corresponding data were defined, and in this follow-up, the data were gathered, processed and analyzed.

Since one of the focus points of the technology is tidal energy generation, the tidal model is the main requirement. The Global Tide Surge Model (GTSMv3.0) (Irazoqui, Muis, Verlaan, & Yan, 2018) was developed within Deltares and it was used considering two scenarios. The potential suitability of the technology is investigated for the current conditions of flood risk and tidal capacity, but future applicability is studied as well. Thus, the tidal variation was derived for current coastal conditions and for the future scenario of sea-level rise. The point of interest in time was chosen to be when 40 cm sea-level rise is reached with Representative Concentration Pathway (RCP) 4.5, which corresponds to 2083. In this scenario, greenhouse gas emissions peak around 2040, then decline. Due to the 18.6-year nodal cycle – when tides are most comparable – tide data from 2006 is used for the current coastal conditions (~4 nodal cycles apart). Hence two values for tidal variations along the coastal zones worldwide were derived. However, the comparison between these two datasets yielded an insignificant difference. Therefore, the future scenario tidal amplitude was used. The derived parameters from the model comprise of the annual highest/lowest water levels that can be expected (HAT/LAT) and the average of the higher-high/lower-low water (MHHW/MLLW) level of all tides in 2083. The difference between the latter gives the tidal amplitude (MTR, mean tidal range) at every location in the current situation.

In addition to the tidal variation, flood risk maps were derived in order to identify the areas with high risks. Similarly, the data was obtained in collaboration with an ongoing risk mapping project inside Deltares. The flood risk is derived in this case from inundation maps for the return period of 25 years. This means that every 25 years this kind of flood is estimated to occur. In the analysis, we consider any area with flood risk as relevant.

Finally, two more datasets were included in the calculations, which correspond to secondary conditions such as population and economic development. The presumption for this is that this technology has added value for the protection from flooding. However, such a project would be a major investment, for some locations hardly affordable for the local authorities.

Two datasets, or conditions, that were identified in the first phase were not considered in the final analysis. For sediment concentrations, no global data was found and from discussions in meetings this appeared to be a less important condition. There was also no open data found on global subsidence scenarios. In the inundation dataset (Haer, et al., 2018), future subsidence scenarios are also not considered.

At this stage all required datasets are obtained, therefore the following action is the definition of the methodology for the calculation of the suitability parameters. The implemented methodology, comprises of the following actions, of which the dark blue actions are performed in QGIS and the green actions are performed in Excel:

- Definition of centroid points of water bodies;
- Definition of the area of interest – radius of 50 km around the body or delta point;
- Calculation of raster statistics of the parameters within the area of interest (e.g. mean, sum, max);
- Extraction of tidal amplitude from the closest tidal point;
- Intersection of the 50 km radius with natural zones;
- Calculation of the indicator values for every water body;
- Filtering the dataset based on the predefined thresholds;
- Normalization of the parameter values;
- Calculation of final score based on the indicator weighting.

Firstly, two different global datasets representing lakes are combined. Since the Brouwersdam turbine technology is suitable for coastal areas/lakes, the inland water bodies are filtered out from the dataset by selecting only the areas within 10km of the shoreline. Thus, all possible coastal lakes are derived, and their area is calculated based on the geometry of the data. The geometry is then simplified to the centroids of the polygons for the sake of the further analysis and comparability with the delta dataset. Further, the area of influence of the indicators is defined as 50 km since we are interested in the spatial conditions in the surroundings of the water body not only at its exact location. This radius value is discussed with and accepted by the client. Hence the centroids are buffered with 50 km radius, resulting in the area of interest for the calculation of the suitability indicators. Using these areas, the flood risk, tidal amplitude and population are calculated. Depending on the data type different methods for spatial analysis are implemented. The population, flood risk and elevation values are represented in raster (grid) formats, which allowed the calculation of cell statistics such as sum, mean, min and max values.

For the flood risk, the maximum value in the region was taken since it indicates the highest risk that the area is facing, while all the population in the 50 km zone is aggregated. In addition, the mean elevation in the area of the basin was calculated.

The tidal variation is represented as points every ~20 km along the coast. Therefore, the suitable approach here is to identify the closest point to the water body and to use its value as a representative for the tidal variation. Lastly, the presence of natural/protected areas is calculated by intersecting the areas of interest with the global natural zones and taking the highest IUCN category value (1-7 with 1 as most protected nature reserve). Appendix B elaborates on these categories.

Thus, the desired indicators were calculated for every data point in the dataset. Further, these locations were filtered out by the predefined thresholds: Tidal variation greater or equal to 2 m, flood risk greater than 0, basin area larger than 50 km^2, population greater than 100,000 people and elevation lower or equal to 5 m. Hence the resulting areas are representing all locations possibly suitable for the implementation of the Brouwersdam technology.

The final step of the methodology is the definition of the ranking of all resulting water bodies. For this, the resulting values are normalized with scores between 0 and 1, corresponding accordingly to the lowest and highest values. All those scores are multiplied by their predefined weight and summed all together, see Equation 1. Finally, the results were normalized once more, yielding the final rankings list.

Equation 1 Formula for the calculation of the weighed main score

$$1 \cdot f + 1 \cdot t + 0.8 \cdot p + 0.5 \cdot a + 0.4 \cdot n = \text{final score, where}$$

f = flood risk
t = tidal variation
p = population
a = basin area
n = natural areas

3 Results

The results from the spatial analysis of the potential locations worldwide for the export of the Brouwersdam tidal power station are:

A dataset containing values for all calculated indicators:
- Inundation (flood risk)
- Tidal variation
- Basin area
- Population
- Elevation
- Presence of natural/protected areas
- GDP (not considered for filtering or ranking)

From this dataset, the scores for flood risk, tidal variation, basin area, population and natural area are calculated for each potential location. These scores and indicators are both presented in an interactive Excel spreadsheet (section 3.1) and on maps (section 3.2).

3.1 Adjustable filtering and weighting list

This dataset with original values is provided in an Excel spreadsheet, providing possibilities for changing the threshold values and weight of the indicators. See Figure 3.1 for the overview of the results in the Excel. Here, you can change the different weightings in the light-blue cells and immediately see the results in the top 10 scoring countries.

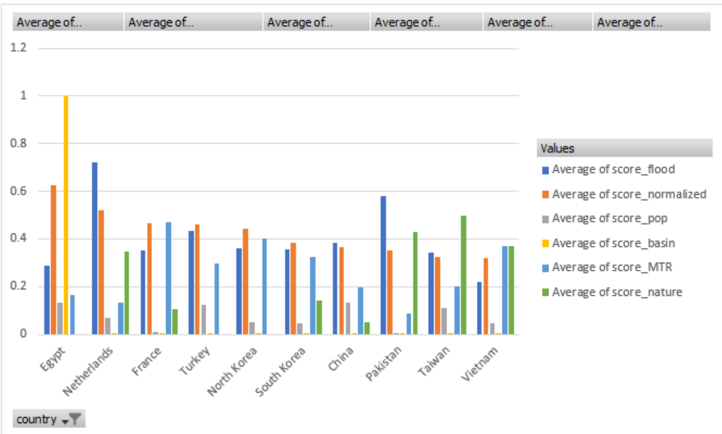
Export potential Brouwersdam

Adjust the tresholds and weighing to your choice to see a change in results

Condition	Spatial/temporal resolution	Threshold	Weighing
Inundation [m]	25 years	>0	1
Tidal variation [m]	year 2083 (40 cm sea level rise)	>=2	1
Basin area [km2]	15 arc-seconds	>50	0.5
Population [estimated count]	year 2020	>100000	0.8
Elevation [m]	90m	<=5	-
Natural areas [IUCN category]	year 2019	-	0.4

input
output

Results - top 10



total locations	461

Figure 3.1 Results excel – overview. The weightings are changeable.

Figure 3.2 shows a part of the Excel where you can filter the dataset. The orange in the orange cells you can define the threshold. In the overview, you must refresh the pivot table chart to see the results of the newly filtered data.

		input		input		
		>0		<=5		
basin_area	score_basin	flood_max	score_flood	elevation	HAT	LAT
139	3.47841E-05	0.088	0.006216878	-17	3.27668	-2.32528
1085	0.000404512	0.13208	0.011567132	3	2.90468	-1.91514
497	0.000174702	0.13208	0.011567132	0	2.90468	-1.91514
355	0.000119204	0.10768	0.008605558	3	2.75789	-1.6302
5086	0.001968234	0.13043	0.011366862	-13	2.86496	-2.66341
8993	0.003495218	0.14235	0.012813664	0	2.75789	-1.6302
12692	0.004940908	0.14235	0.012813664	3	2.75789	-1.6302
1068	0.000397868	0.19715	0.019465068	-1	2.80606	-1.96943
72	8.59832E-06	0.30912	0.033055538	3	2.86001	-2.2093

Figure 3.2 Filtering the total dataset.

3.2 Maps

With the predefined filtering, there are 10 coastal lakes and 451 delta's world-wide that are, according to this study, potentially suitable for a tidal power station like for Brouwersdam. As it can be seen in Figure 3.3, most of the locations are in Asia and Europe. The highest scores – weighed as elaborated in section 2.2 – occur in France (1), China (0.98) and South Korea (0.83). The Netherlands is number six in this list with a maximum score of 0.60.

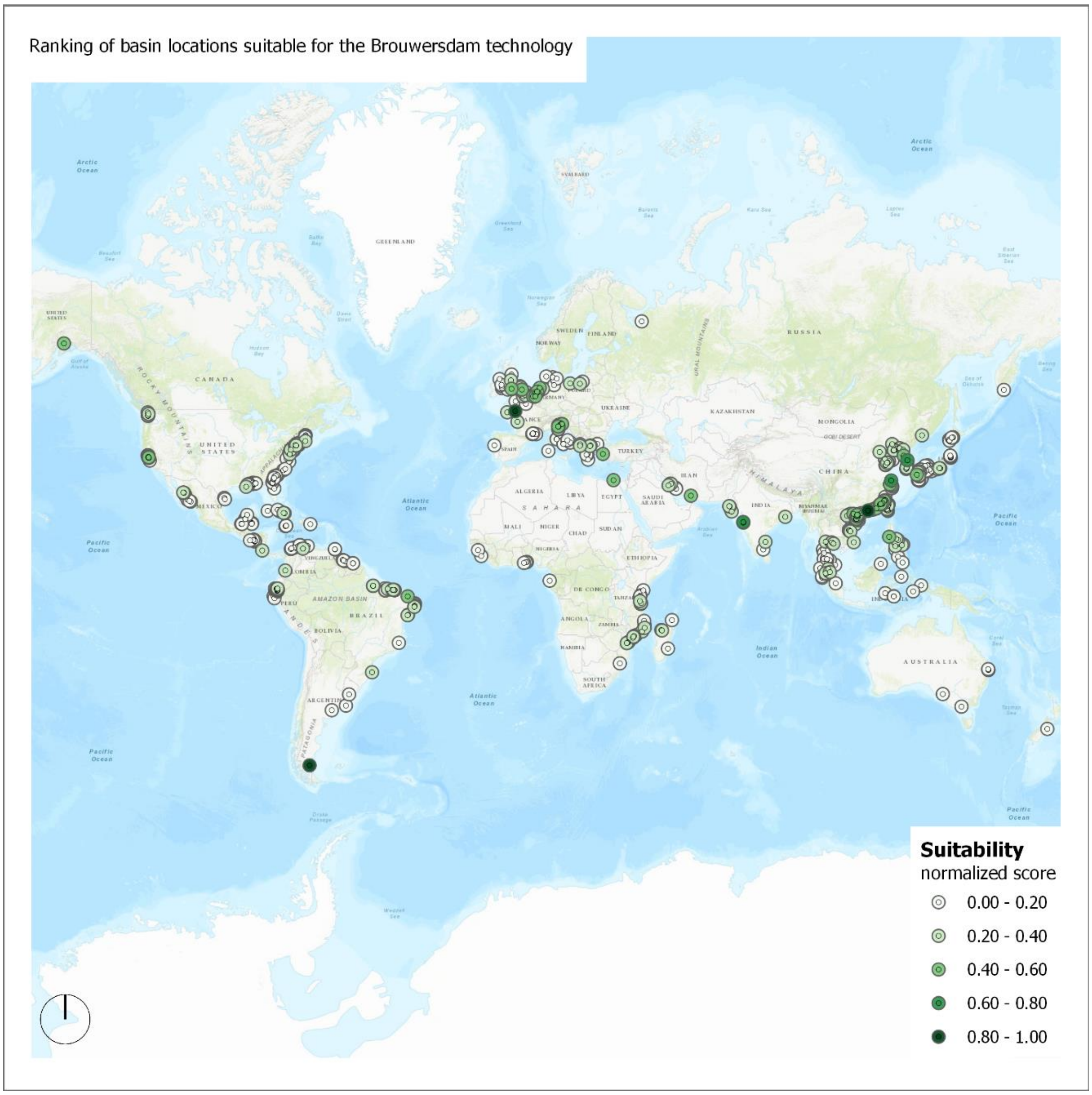


Figure 3.3 World-wide suitability scores at potential export locations – normalized with all main scores

Looking at average scores, Egypt scores best because of the large basin area of their only suitable location. The Netherlands is second on average, while again France, South Korea and China are in the top 10 scoring countries.

These average scores are reflecting mainly the three most weighed indicators and thresholds: flood risk, population and tidal amplitude. The flood hazard threshold filters out 84 locations; the population threshold filters out 238 locations; and the tidal range threshold filters out 297 locations of the total dataset. As you can see in Figure 3.4, most flood prone locations are in Asia and Europe.

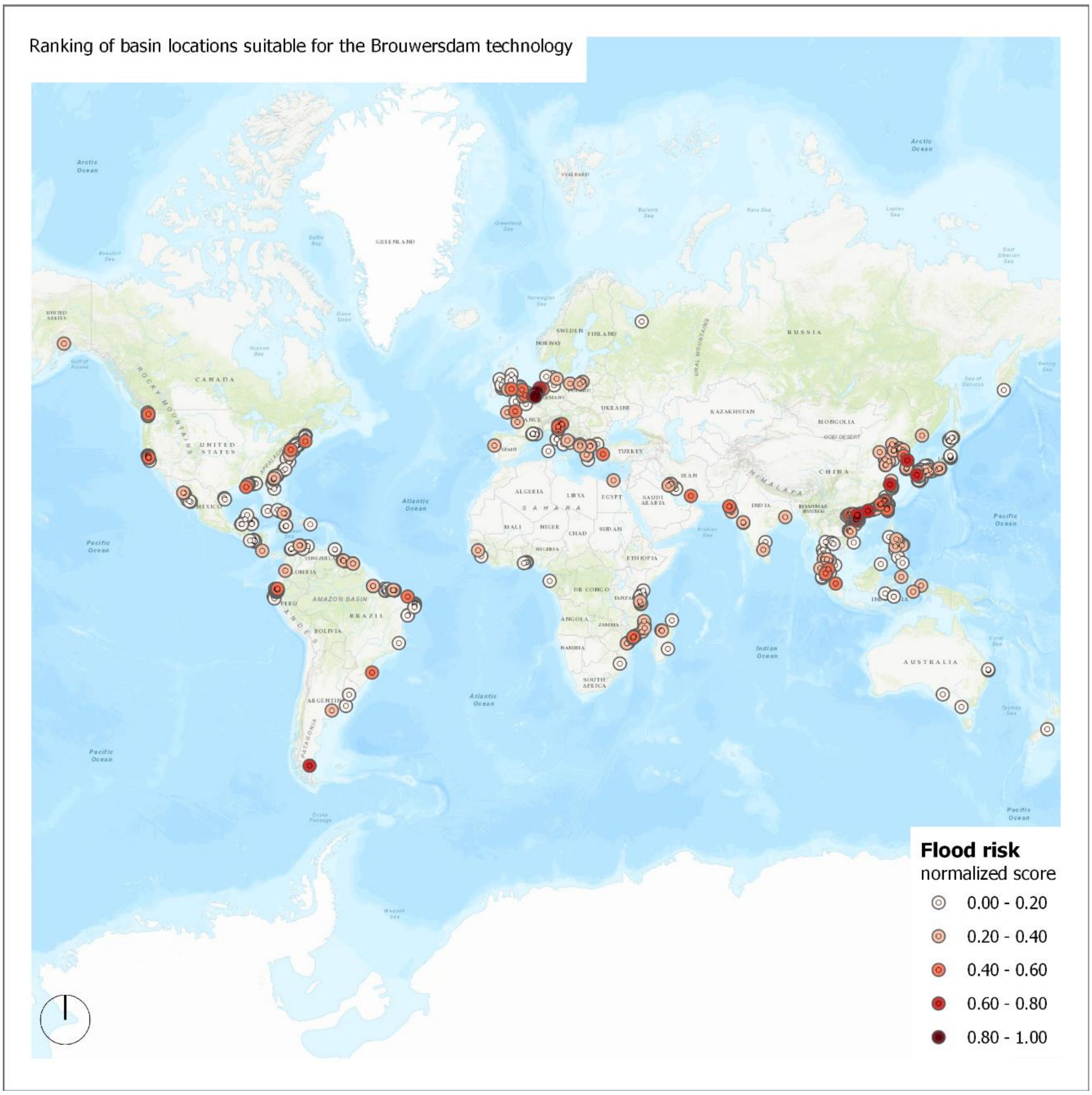


Figure 3.4 World-wide flood risk scores at potential export locations – normalized with all flood risk scores

When comparing the flood risk scores with the population scores in Figure 3.5 you see that China has the largest population with a flood risk. However, the Netherlands scores highest on average flood risk, followed by France and Turkey.

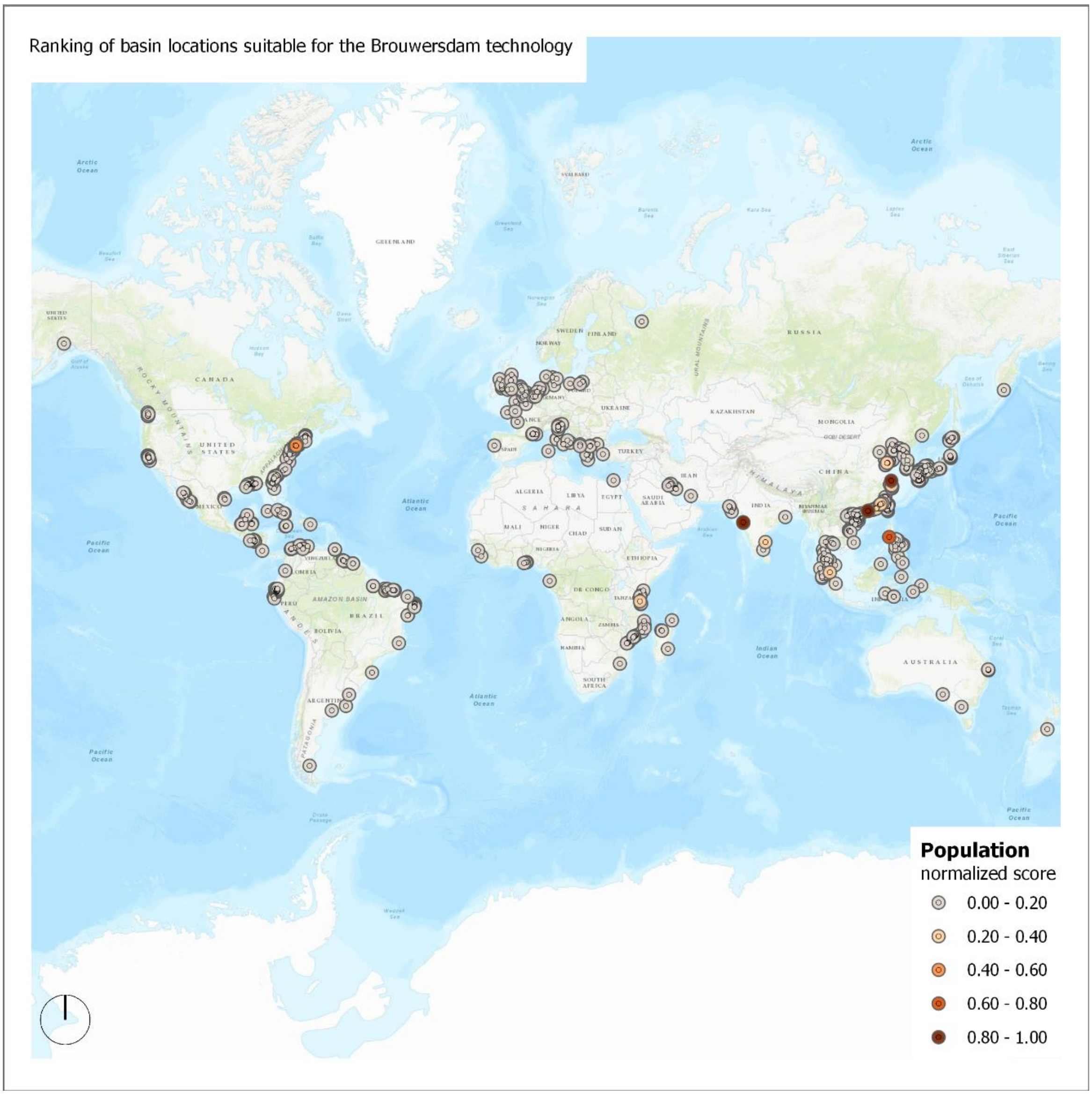


Figure 3.5 World-wide population scores at potential export locations – normalized with all population scores

The largest populations in a 50 km radius from the selected locations are found in China, the Philippines, India and the USA.

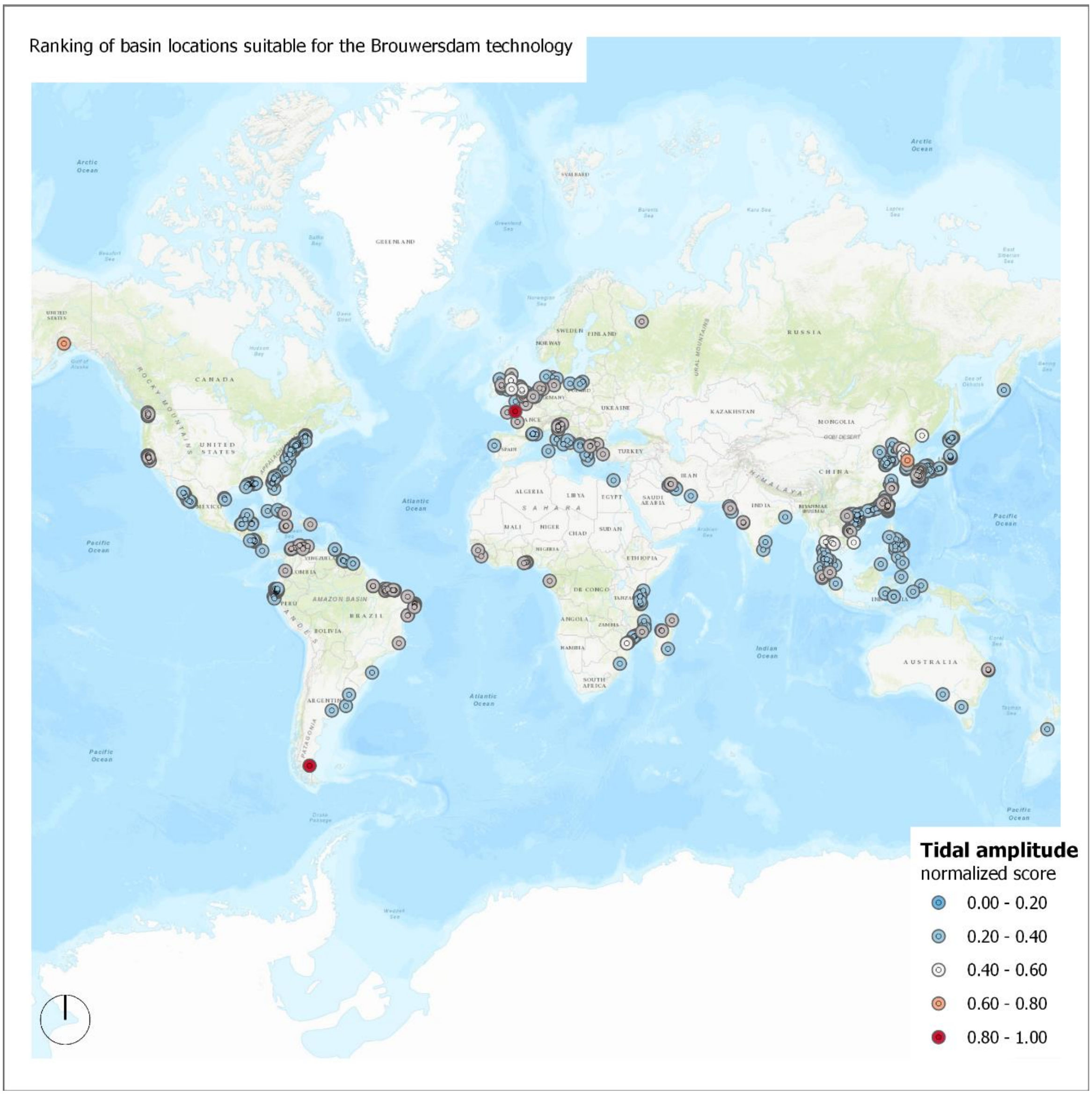


Figure 3.6 World-wide tidal amplitude scores at potential export locations – normalized with all tidal amplitude scores

The highest mean tidal ranges are found in France, Alaska (USA), South Korea and the United Kingdom.

The world-wide basin area score map is displayed in Appendix C, together with maps of the main suitability score zoomed in on North- and South-America, Europe and Africa. Because Asia scores high in all the scores, the main score of those locations is depicted in Figure 3.7. Of the filtered dataset, 11% of the locations are in China.

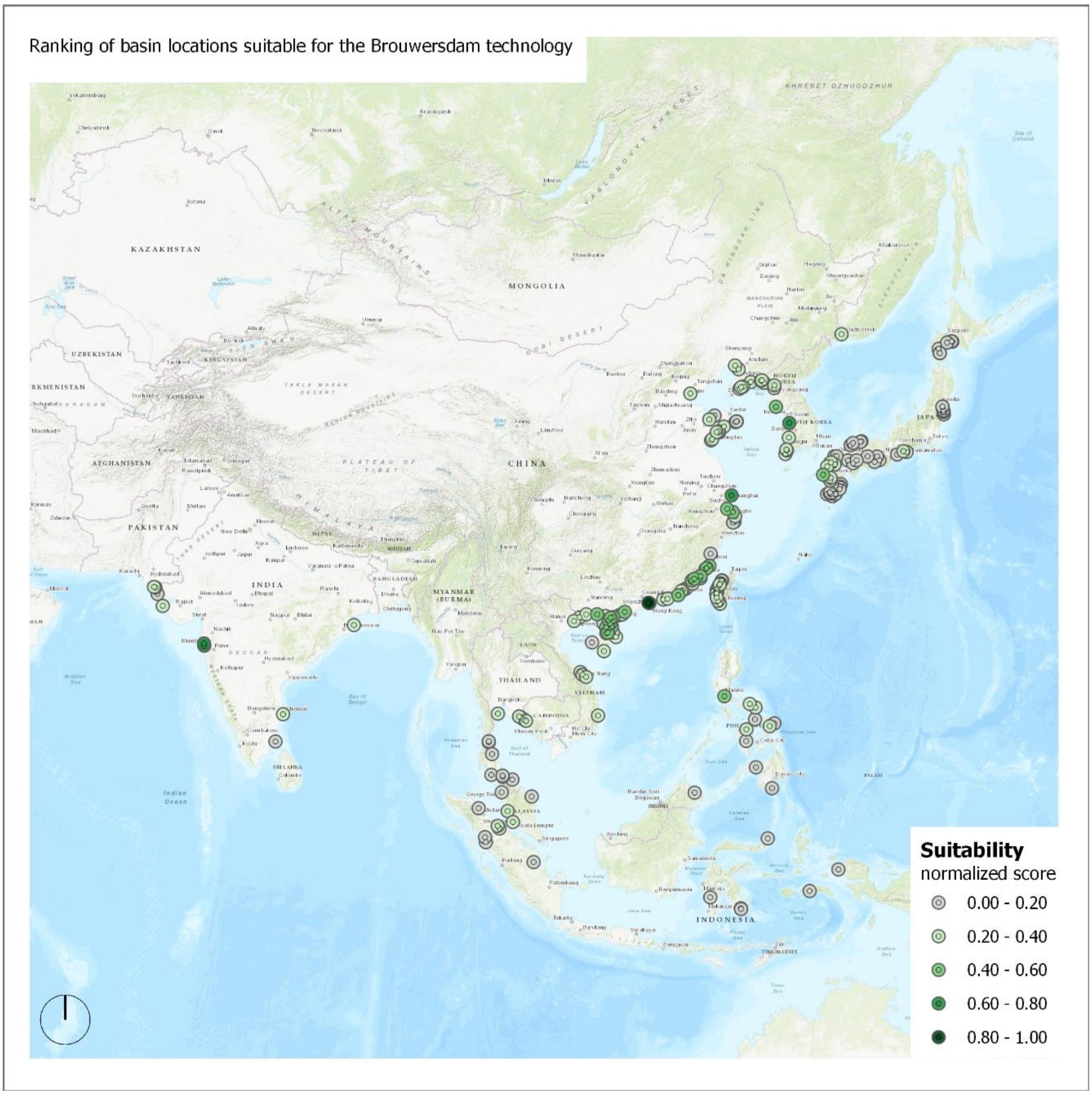


Figure 3.7 Suitability scores of locations in Asia

More detailed maps are in Appendix D. These could be used for further analysis.

The number and suitability scores of the locations suggest there are many places where the Brouwersdam tidal power station could be a solution to the challenge of climate change of the coming years.

4 Discussion

The result from this research project comprises of a global dataset with identified possible locations for the export of the Brouwersdam technology. These locations were selected based on a set of indicators such as the population count in the region, tidal amplitude, presence of flood risk and others.

However, the quality of the results is strongly dependent on the spatial and temporal resolution of the data used for the calculation of the indicators. The main goal was to use as recent as possible data with high spatial resolution and global coverage. In order to achieve this, a certain balance between the quality of the data and its applicability had to be preserved.

The resolution of the used datasets is varying between the different data types – rasters have different cell sizes and the vector layers have a different level of simplification. For example, the derived areas of the water bodies are based on the geometry of the polygons that were used. The geometry is represented with a certain level of simplification, which could result in a difference between the calculated area and the actual size of the basin. The Global Lakes and Wetlands Database, which was used in this project is generated based on global maps with varying quality (1:1 to 1:3 million resolution). Hence, the calculated basin areas might not be accurate in some places, where for example old maps with low resolution have been used.

The quality of the data is most important for the indicators which are used for the filtering of the data and namely the basin area, the flood risk, the elevation, the tidal variation and the population. Some of those limitations are minimized in the spatial analysis by, for example, considering a bigger area of influence, thus smoothing the data inputs. For other indicators like the elevation, the quality of the output could be greatly improved by incorporating for example hydrologically correct models with high resolution. These could be used to correctly consider the height of the basin. However, in every situation, the balance between the processing time and the data quality needs to be kept.

Regarding to the relation between the delta points and the country boundaries, there is a gap, i.e. some deltas are located near the coast. This results in no data values for some delta locations, considering the country they belong to. Therefore, these attributes need to be manually verified.

Further, the thresholds that were used in this analysis are generated in an expert discussion. The motivation for the chosen values is based on the example of the lake Grevelingen, where this technology is initially planned. These values can be further refined by a technology expert, where the chosen limits can be driven by physical or economical properties. During the analysis of the results the influence of these thresholds was spotted, where some presumably “good-looking” locations were filtered out, while others were preserved in the dataset.

However, a big part of these limitations can be overcome by the implemented methodology. The flexible nature of the chosen approach leaves space for improvements of any of the predefined thresholds or weights. Any user of the resulting Excel sheets can tweak the thresholds and weights to their own wish. Thus, iteratively the output of this analysis can be improved.

Finally, the method used in this study can be categorized as a form of unsupervised classification driven by the purely spatial aspects of the data. Thus, all outputs are plausibly suitable locations for the implementation of this technology. As further research, suitability of every location should be investigated in terms of the technology itself. This means that for example the potential energy generation can be calculated based on the parameters of the basin. Additionally, different cost-benefit analyses can be applied in any further decision-making process.

The results are promising for the potential of exporting the Brouwersdam technology and we think they can confidently be used for further assessment and promotion of the export

5 Further research

To conclude the technical report of the analysis of the Brouwersdam technology export potential, some advice is given on how to proceed with further research.

First, also mentioned in the last paragraph of chapter 4, is the calculation of the energy potential. This can be done when the tidal period is known for every location. To do this precisely and to get the information needed for calculating the correct energy potential, the time between highest high tide (HHW) and lowest low tide (LLW) should be computed in the Global Tide Surge Model or a similar model. From this, the different types of tide cycles (diurnal, semidiurnal, mixed semidiurnal) can be derived. However, this is not yet the tidal period. For example, with a mixed semidiurnal type, the time between HHW and LLW is 6 hours from high to low, and 18 hours from low to high. To quantify the tidal period types, decisions on how to approach the calculation must be made.

Second, to quantify more the benefits for export, the possible construction of a dam in which the turbines are placed should be considered. The cost of this dam can be estimated with parameters such as estuary mouth width and depth at the coast. Adding these parameters would help estimating the order of scale such an export product would be in.

Third, a more in-depth analysis should be done to select promising locations. This can be done by visually scanning the coasts of the highest scoring locations. After selection, the export potential at the locations and their contribution to the Dutch economy can be assessed qualitatively.

6 References

Haer, T., Botzen, W. J., Van Roomen, V., Connor, H., Zavala-Hidalgo, J., Eilander, D., & Ward, P. J. (2018). Coastal and river flood risk analyses for guiding economically optimal flood adaptation policies: A country-scale study for Mexico. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2121), 20170329.

Irazoqui, M., Muis, S., Verlaan, M., & Yan, K. (2018). *Global modelling of future extreme sea-levels using a high-resolution.* Retrieved from Copernicus: https://meetingorganizer.copernicus.org/EGU2019/EGU2019-2199.pdf.

A Dataset sources

Dataset	Source
Global flood hazard map	http://data.jrc.ec.europa.eu/dataset/jrc-floods-floodmapgl_rp20y-tif
flood occurences historical	http://waterriskfilter.panda.org/en/Explore/DataAndMethod
projected flood occurences	http://waterriskfilter.panda.org/en/Explore/DataAndMethod
global delta dataset - wave height high water (m)	https://www.earth-surf-dynam-discuss.net/esurf-2019-12/esurf-2019-12.pdf
global delta dataset - tidal range high tide (m)	https://www.earth-surf-dynam-discuss.net/esurf-2019-12/esurf-2019-12.pdf
Today's tides	Global Tide Surge 18 Model v3.0 (GTSMv3.0)
RCP85-SLR from CMIP5 ensemble mean (2040-2070) - sea level rise & tides	Global Tide Surge 18 Model v3.0 (GTSMv3.0)
global delta dataset - sea level change (mm/year)	https://www.earth-surf-dynam-discuss.net/esurf-2019-12/esurf-2019-12.pdf

global delta dataset - delta's: ~5000	https://www.earth-surf-dynam-discuss.net/esurf-2019-12/esurf-2019-12.pdf
global river delta's: ~10.000	https://ui.adsabs.harvard.edu/abs/2018AGUFMEP23B..01N/abstract
rivers = fresh, sea/oceans = salt	
Sediment Thickness	https://www.ngdc.noaa.gov/mgg/sedthick/index.html
Global lakes	https://www.worldwildlife.org/publications/global-lakes-and-wetlands-database-small-lake-polygons-level-2
shoreline changes 1984-2016	http://aqua-monitor.appspot.com/?datasets=shoreline
World water bodies	https://www.arcgis.com/home/item.html?id=e750071279bf450cbd510454a80f2e63
stage of future hydropower dams	http://atlas.freshwaterbiodiversity.eu/atlasApp/full/index.html?map=3.4.3-global-hydropower-dams
water strategy	http://waterriskfilter.panda.org/en/Explore/DataAndMethod
population	https://sedac.ciesin.columbia.edu/data/set/gpw-v4-admin-unit-center-points-population-estimates-rev11/data-download
population	https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-rev11/data-download
protected areas	https://www.protectedplanet.net/
GDP, gridded	http://www.cger.nies.go.jp/gcp/population-and-gdp.html
country borders	https://www.naturalearthdata.com/downloads/50m-cultural-vectors/50m-admin-0-countries-2/
elevation	https://data.noaa.gov//metaview/page?xml=NOAA/NESDIS/NGDC/MGG/DEM/iso/xml/316.xml&view=getDataView&header=none

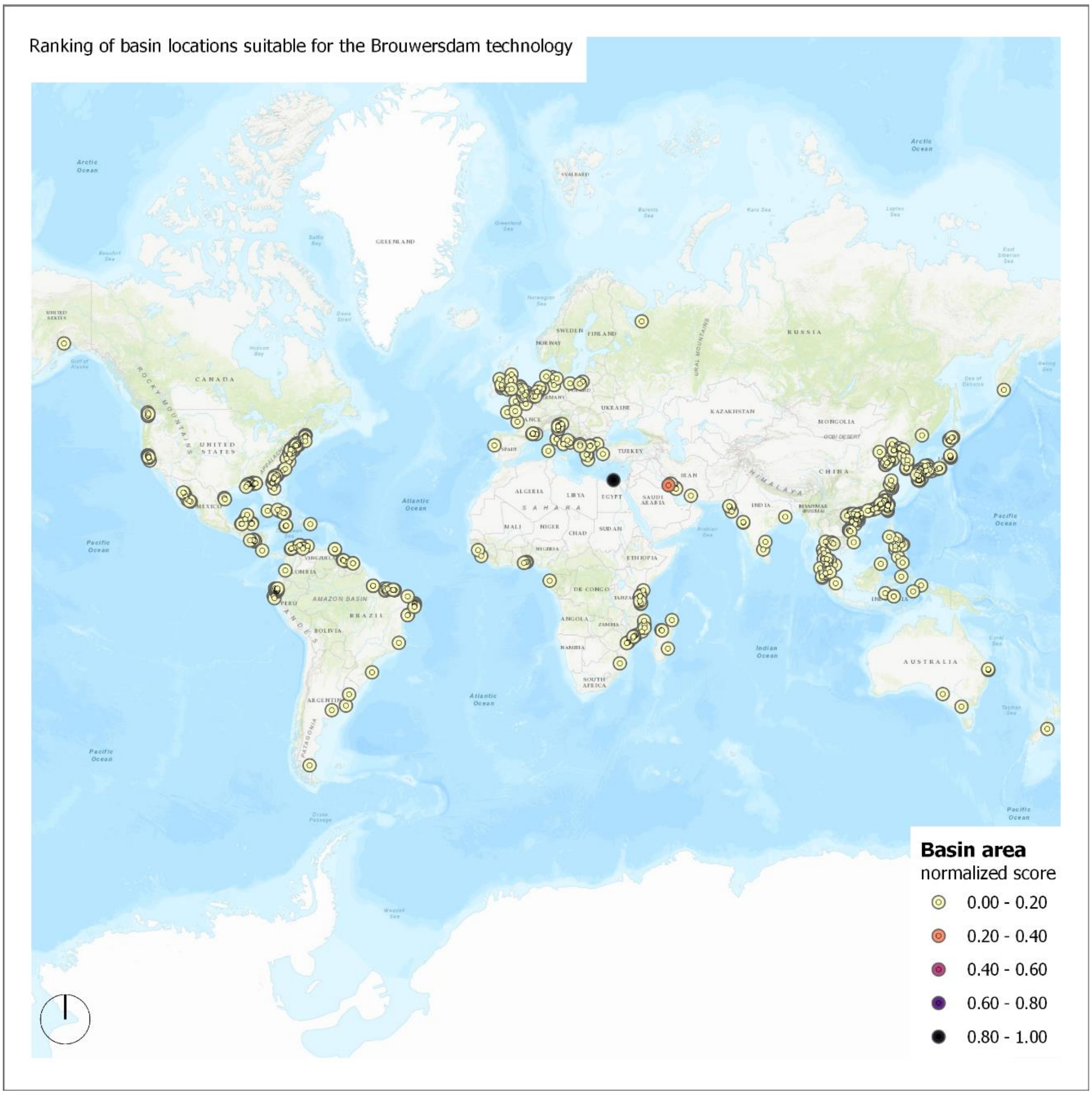
ocean bathemetry/coast polygon	https://opendem.info/download_bathymetry.html

B Nature classifications

International Union for Conservation of Nature		
https://portals.iucn.org/library/sites/library/files/documents/PAG-021.pdf		
IUCN category	***number in raster***	**areas managed mainly for:**
Ia	1	Strict nature reserve
Ib	2	Wilderness area
II	3	Ecosystem conservation and protection (i.e., National park)
III	4	Conservation of natural features (i.e., Natural monument)
IV	5	Conservation through active management (i.e., Habitat/species management area)
V	6	Landscape/seascape conservation and recreation (i.e., Protected landscape/seascape)
VI	7	Sustainable use of natural resources (i.e., Managed resource protected area)
	null value = not recorded, not applicable	

C Global and continental maps

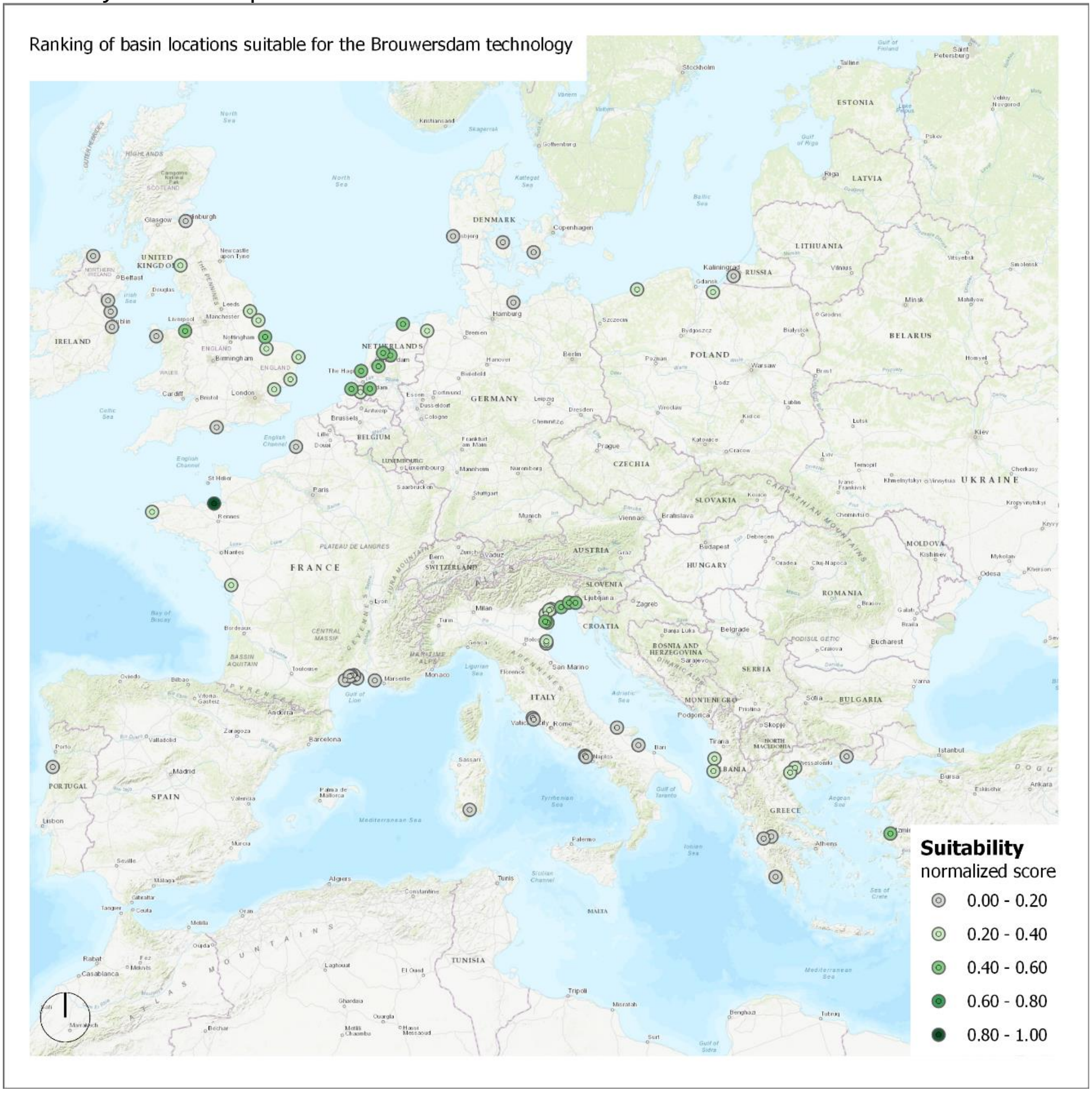
Basin area score worldwide



Suitability score South America

Suitability score North America

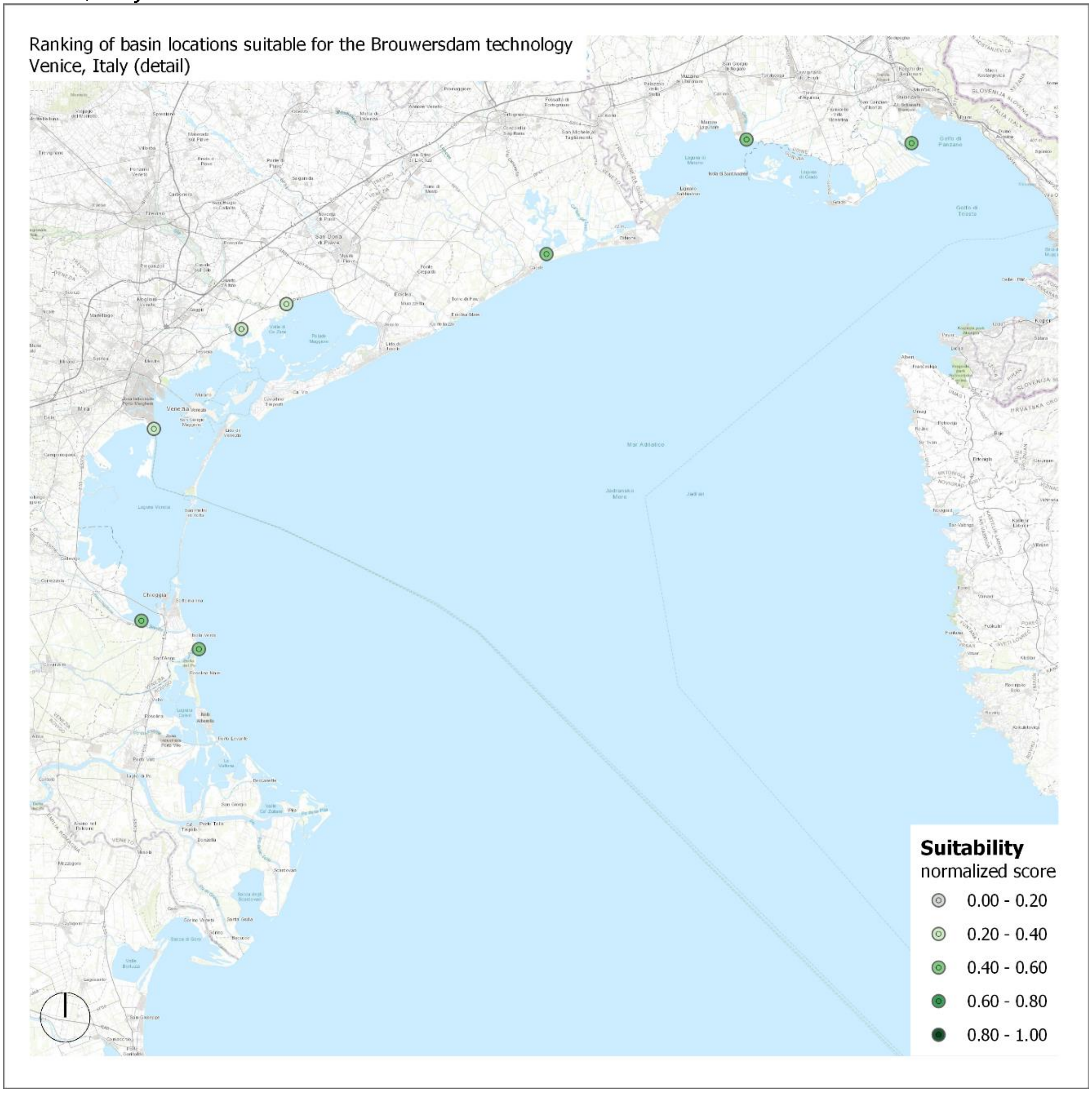
Suitability score Europe



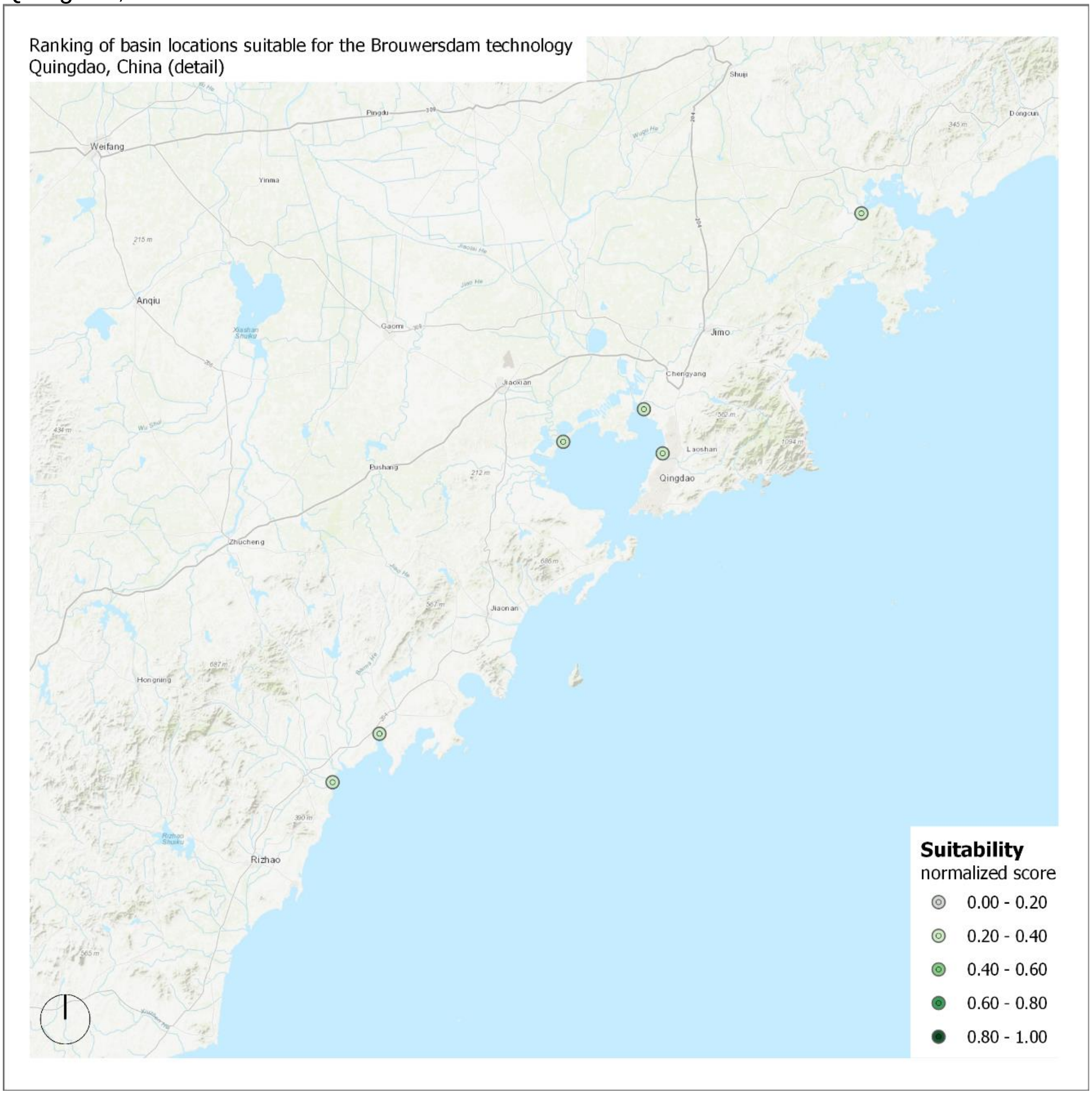
Suitability score Africa

D Details maps

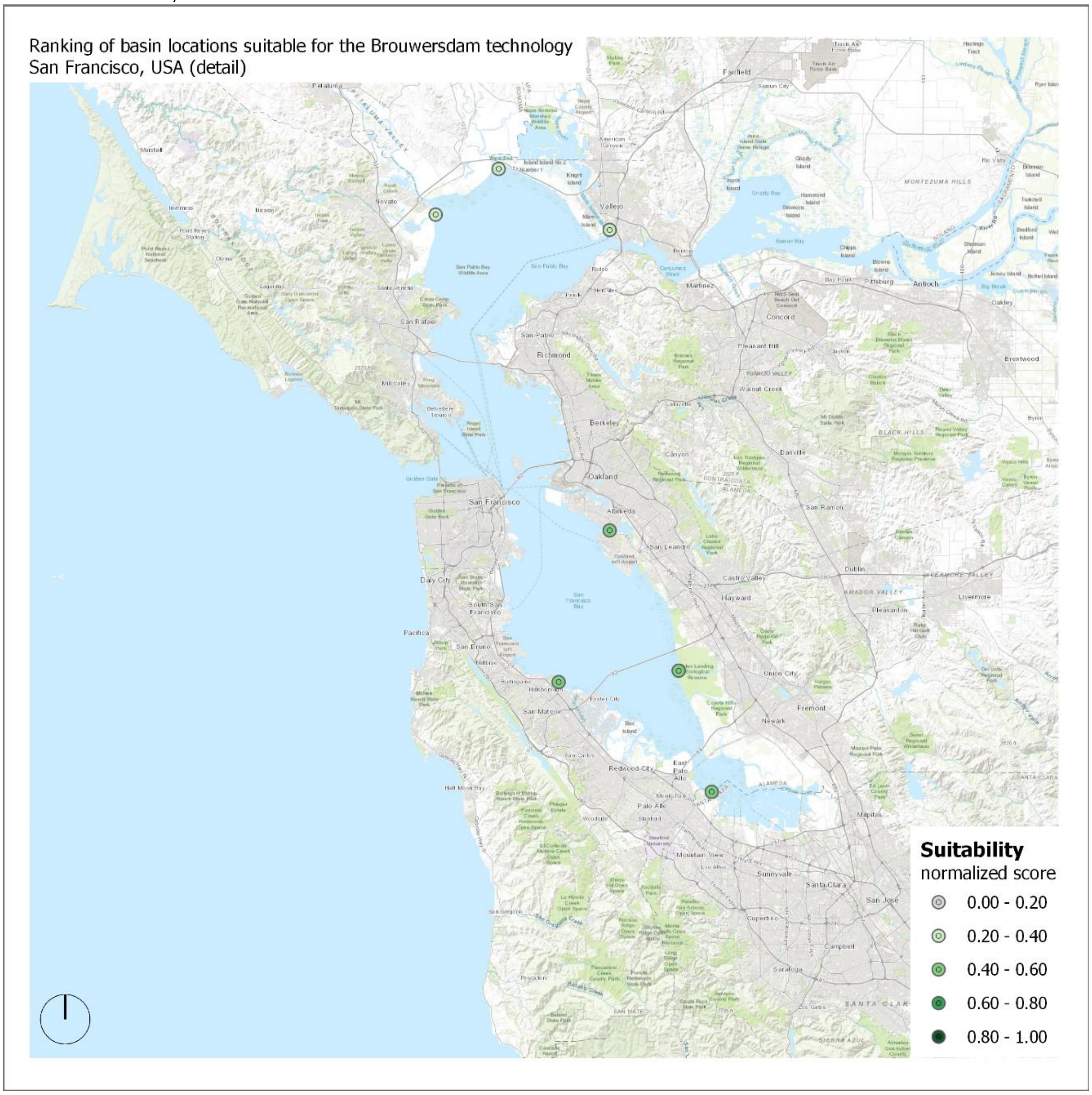
Venice, Italy



Quingdao, China

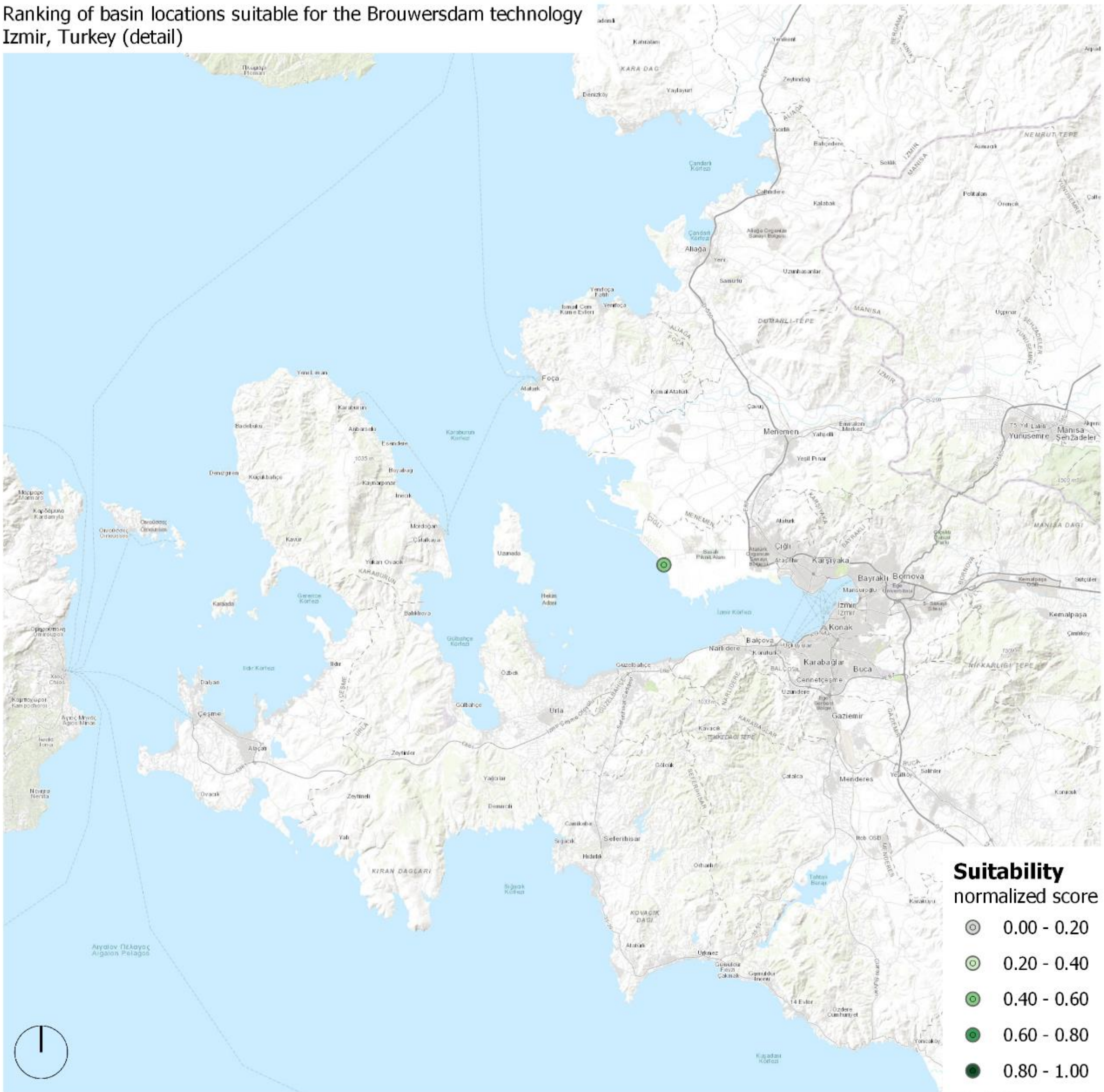


San Francisco, USA

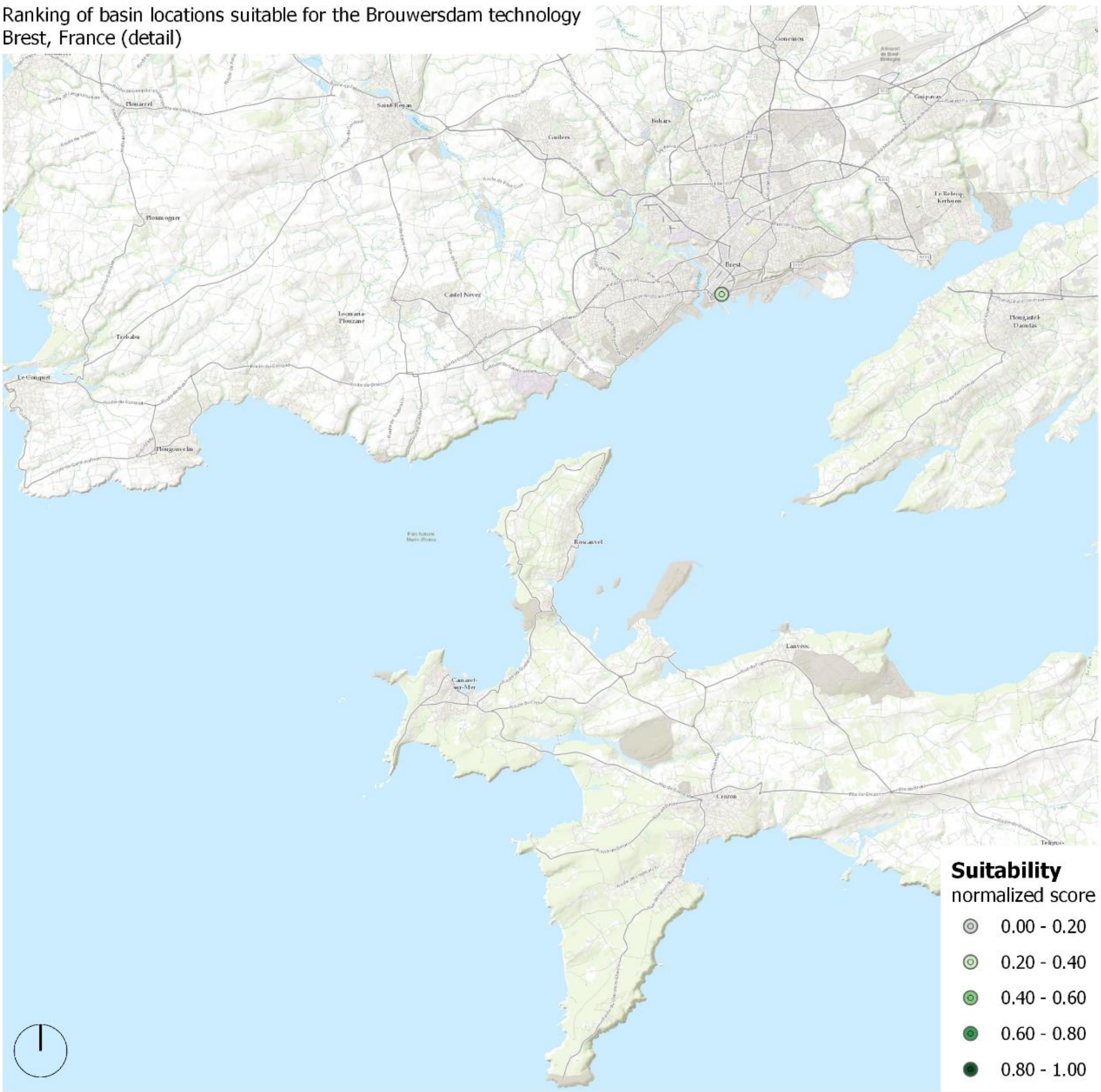


Songak, South Korea

Izmir, Turkey



Brest, France



Mumbai, India