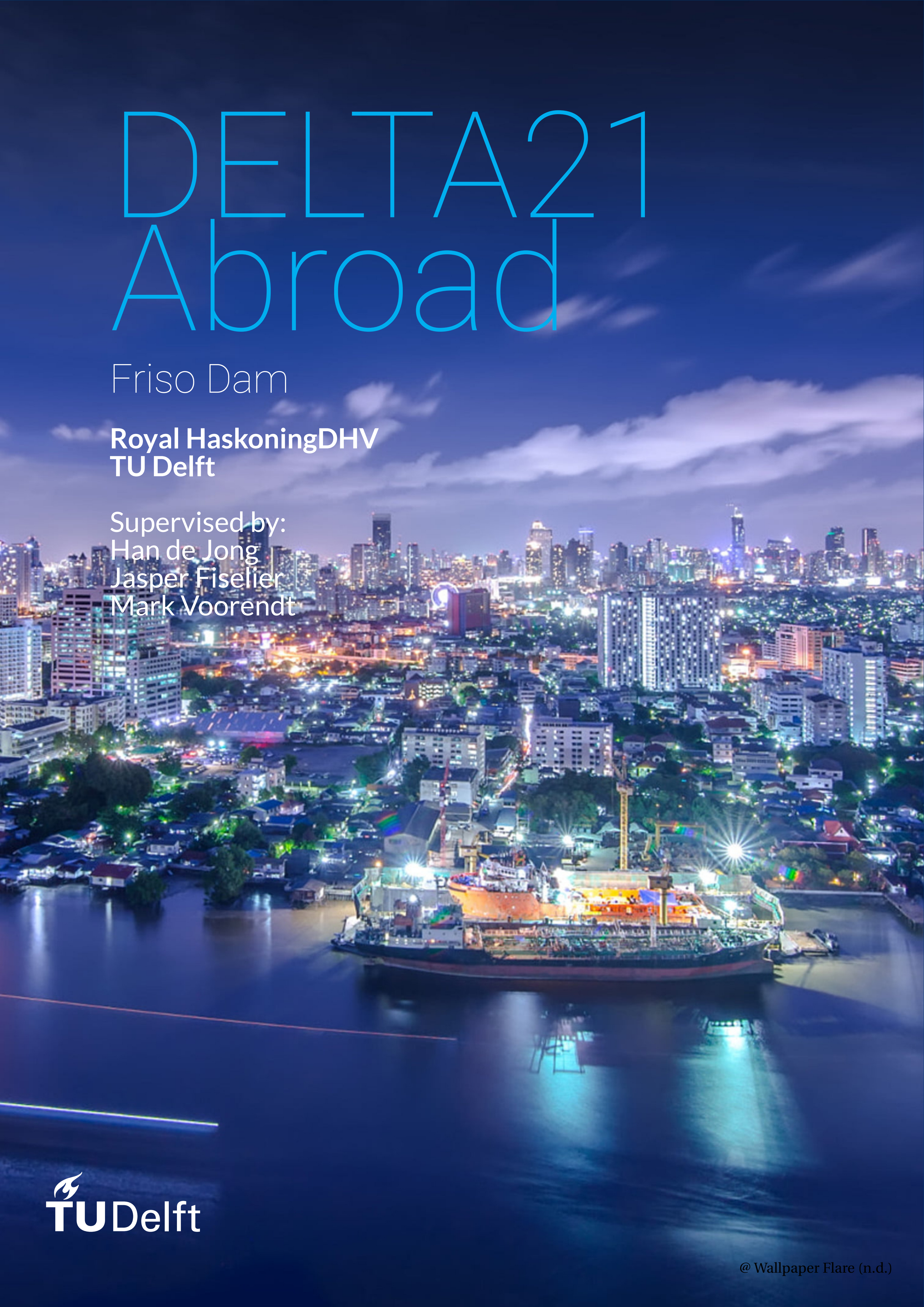

DELTA21 Abroad

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Preface

This report was made for the course CIE4040-09 Internship, which is part of my MSc Hydraulic Engineering at TU Delft. The internship at Royal HaskoningDHV was supervised by Jasper Fiselier and Han de Jong. The university supervisor was Mark Voorendt. I would like to thank my supervisors for all their advice during my internship. Also, I want to thank the Rivers and Coasts team members for the pleasant ambiance in the Rotterdam office.

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Rotterdam, December 2019

Summary

With the idea of DELTA21, a multi functional project is constructed south of the Tweede Maasvlakte in the Netherlands. However, there is a lot of locations worldwide where this concept can be successful. The goal of this report is finding such a location.

The starting point of this report is the hundred participant cities of 100 Resilient Cities. This choice is made because more available information is expected about those cities. Not all of the participant cities were relevant, because not every city lies close to the coast and a river mouth. Therefore, the city list was filtered by location. After this, there were still 36 possible cities left that have a suitable location.

The 100 Resilient Cities website also gives information about the threats/challenges in the participant cities. This information was used to reduce the list of 36 cities further. Threats regarding flooding, energy, secondary functions of DELTA21, future scenarios were selected. Also disadvantageous threats were selected to make the involved cities less attractive. That resulted in a list of just fifteen cities.

The next aim was to find three appropriate cities to make a first design for. More information was found about the fifteen remaining cities. This information contained the city populations and the river discharges through the cities. The selection of three cities was based on the coast type, the peak river discharge and the population. In this phase it was also preferred to find three very different cities. The designs were namely a learning method for the final city selection. The three chosen cities were Bangkok (Thailand), Lagos (Nigeria) and New Orleans (USA).

After the designs were made, the expected distributions of benefits of DELTA21 were made for the three locations. This resulted in the conclusion that the savings on dike reinforcements or new flood protections are crucial for DELTA21. The other conclusion here was that project space is important as well in the attractiveness of a location.

In the final part of the report, a multi criteria analysis is performed. The four criteria are, in ascending order of importance:

- Space for the project
- Coast type
- Threats/opportunities
- Profits/benefits

The analysis was done for the list of 36 cities obtained after the first filter. The city with the best score was Bangkok (Thailand), followed by Can Tho (Vietnam), New Orleans (USA) and Surat (India).

Therefore, the recommended location for DELTA21 abroad is Bangkok. It is important that the regulations allow the construction of such a project and that the Thai government is willing to cooperate. Also, a more specific cost estimation is necessary for determining whether DELTA21 in Bangkok can be successful. In case of a negative result in either of these steps, Can Tho, New Orleans and Surat are the recommended alternative locations.

Contents

1

Introduction

DELTA21 is a concept project started by Leen Berke and Huub Lavooij (2018b). This project is supposed to be constructed south of the Maasvlakte near Rotterdam, the Netherlands. The main functions of the area are flood protection, energy storage and nature restoring in the Haringvliet.

The main part of DELTA21 is a storage lake with a relatively low but variable water level. When high river discharges and storm surge from the sea occur simultaneously, water in the storage lake can be pumped to the sea. This allows river water to flow over the spillway into the storage lake. The storage of the river water limits the maximum water level at more upstream locations. These locations are below the mean sea level and are therefore at risk for flooding. This is also the case for high sea water levels and a failure of the Maeslant barrier. Then, sea water can flow through the Nieuwe Waterweg into the Haringvliet. When the water reaches the Haringvliet, it can flow into the storage lake.

The storage lake will also function as a battery, for the storage of energy (Berke & Lavooij, 2017). Because of the increased part of solar and wind energy, the amount of generated energy depends more and more on the weather. This leads to fluctuations in the energy surplus and shortage. The solution to this problem is energy storage, but the current batteries are not efficient enough, too expensive and limited in storage capacity. However, 'Pumped Hydrostorage' is growing worldwide and is a very promising solution for energy storage.

Before human interventions, the Haringvliet was the main mouth of the Rhine and Meuse rivers. The water here was brackish and the tide dominated the water levels. Because of the Haringvliet sluices, the Haringvliet water became more fresh and the ecology here changed. Recently, it was decided to open the Haringvliet sluices in case of high river discharges and low sea water levels. This means that salt water can flow in the Haringvliet and that there is some exchange between the sea and the Haringvliet. However, this decision does not lead to the situation before the Deltawerken. With the idea of DELTA21, the Haringvliet sluices will only be closed in case of extreme events. The constructed dikes will function as a primary flood defense. This allows more interaction in the Haringvliet and can lead to fish migration through the Haringvliet (Berke & Lavooij, 2018a).

In the Energie report (Berke & Lavooij, 2017) the benefits of DELTA21 are expressed in euros. Figure 1.1 shows the distribution of the expected profits per function of the Dutch DELTA21 design. The chart shows that most benefits come from the savings on dike reinforcements. In case of the worst climate scenario, two third of the benefits are expected to be from dike reinforcements.

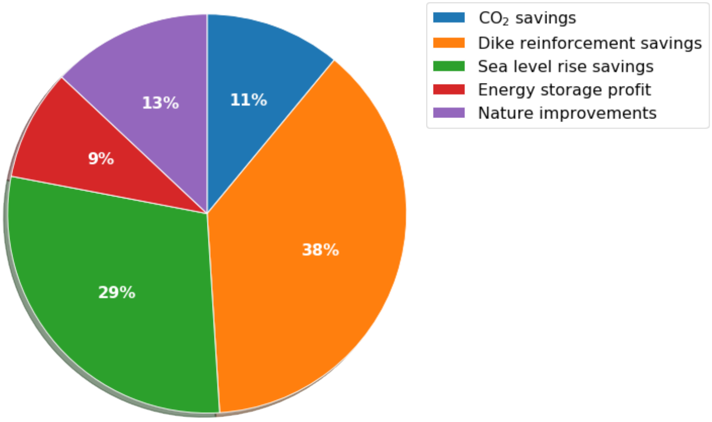


Figure 1.1: Distribution of profits in Dutch DELTA21 design in 2100

The concept of DELTA21 in the Netherlands is multi functional, which is beneficial. However, there are many other locations where this project can be successful. Such locations have more or less the same opportunities as the Haringvliet, but there can also be other needs in the area. An adjusted design of the project, with some other functions, is then even more attractive. The objective of this report is finding those abroad locations. The second chapter describes how those places are found and the chapters thereafter show all the steps made towards the best location.

2

Methodology

The goal of this report is finding suitable locations for the concept of DELTA21. More specifically, the goal is to find one abroad location with high potential for DELTA21. This location will be investigated further during an MSc Thesis. Part of the further research is making more elaborate designs for the locations. In Figure 2.1 the methodology of this report is shown. The steps are further explained in the paragraphs below.

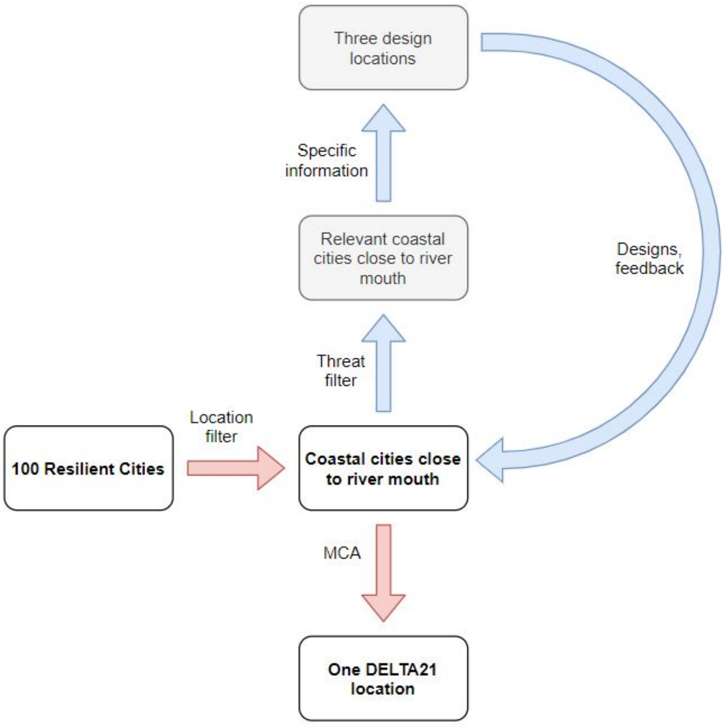


Figure 2.1: Methodology for this report

The starting point of this analysis is a list of the 100 participant cities of the Resilient Cities project. Information about these cities is more accessible than for other cities. Also, this choice forms the scope of this analysis. Although many other locations of interest are not considered, it is likely that one of the Resilient Cities is an appropriate location.

The 100 Resilient Cities list is filtered by the boundary conditions. The functions of DELTA21 in the Netherlands are based on the location of the project. With the function analysis from the Dutch DELTA21 concept, the boundary conditions are formulated and the cities are filtered. This first location filter can already reduce the list much.

The next step is to reduce the list even further. For this, information from the 100 Resilient Cities organisation is used. Relevant challenges or threats of the cities are determined, that influence the attractiveness of DELTA21 for a city in a positive or negative way. This is an important step, because the relevant threats can also be used as criteria for the eventual multi criteria analysis. After the threat selection, the cities are compared in terms of amount of relevant positive and negative threats. Those cities that have a low score here are removed from the list.

More specific information is needed for the remaining cities, so that a choice of three design cities can be made. Especially the peak discharge of the river near the cities is important. The peak discharge gives an indication of the dimensions of the storage lake and the effectiveness of energy storage. For cities with a lack of available information, closed projects from Royal HaskoningDHV can be used. In the reports of those projects, dimensions are determined based on measured data. The specific information also forms criteria for the multi criteria analysis.

Next, the three designs are made. These first designs contains some dimensions and the location of the structures. The choice of the cities is based on the order of magnitude of the peak discharge, population and the coast type. The idea is that the chosen cities are as different as possible to get a better view on the important factors that make a location suitable for DELTA21. Especially different river mouths make an interesting distinction between cities.

With the information gained in the previous step, the most attractive location for DELTA21 can be selected. The selection is done by a multi criteria analysis, in which the remaining cities after the threat selection take part. With the determined important factors, other cities can be selected here as well. The evaluation criteria are based on the relevant threats, the found specific information and the results of the three global designs.

3

Filtering cities based on location

This chapter is about finding an appropriate set of cities for further analysis. The cities should be at a suitable location and there should be enough available information about the cities. In fact, that information is used in the next chapters.

Figure 3.1: The 100 Resilient Cities network (Fastenrath, Acuto, Coenen, & Keele, 2019)

3.1. First list of cities

After consultation of Jasper Fiselier (supervisor and senior consultant at Royal HaskoningDHV), the first list for possible locations for the concept of DELTA21 is based on the member cities of 100 Resilient Cities (2019). 100 Resilient Cities is an initiative of the Rockefeller Foundation. The goal of this initiative is to support cities financially and exchange ideas and expertise. These cities have special challenges where the support is dedicated for. The list of all the participant cities is shown in Table 3.1. The cities are also shown in Figure 3.1. An important reason to choose for these locations is the higher chance of finding good information about those locations. The website of 100 Resilient Cities already gives some useful information about the challenges of all the cities.

Table 3.1: The 100 Resilient Cities

Accra, Ghana	Houston, USA	Pittsburgh, USA
Addis Ababa, Ethiopia	Huangshi, China	Porto Alegre, Brazil
Amman, Jordan	Jaipur, India	Pune, India
Athens, Greece	Jakarta, Indonesia	Quito, Ecuador
Atlanta, USA	Juarez, Mexico	Ramallah, Palestine
Bangkok, Thailand	Kigali, Rwanda	Rio de Janeiro, Brazil
Barcelona, Spain	Kyoto, Japan	Rome, Italy
Belfast, United Kingdom	Lagos, Nigeria	Rotterdam, the Netherlands
Belgrade, Serbia	Lisbon, Portugal	Salvador, Brazil
Berkeley, USA	London, United Kingdom	San Francisco, USA
Boston, USA	Los Angeles, USA	San Juan, Puerto Rico
Boulder, USA	Louisville, USA	Santa Fe, Argentina
Bristol, United Kingdom	Luxor, Egypt	Santiago de los Caballeros, Dominican Republic
Buenos Aires, Argentina	Greater Manchester, United Kingdom	Santiago (Metro), Chile
Byblos, Lebanon	Mandalay, Myanmar	Seattle, USA
Calgary, Canada	Medellin, Colombia	Semarang, Indonesia
Cali, Colombia	Melaka, Malaysia	Seoul, South Korea
Can Tho, Vietnam	Melbourne, Australia	Singapore, Singapore
Cape Town, South Africa	Mexico City, Mexico	St. Louis, USA
Chennai, India	Greater Miami and the Beaches, USA	Surat, India
Chicago, USA	Milan, Italy	Sydney, Australia
Christchurch, New Zealand	Minneapolis, USA	Tbilisi, Georgia
Colima, Mexico	Montevideo, Uruguay	Tel Aviv, Israel
Da Nang, Vietnam	Montreal, Canada	The Hague, the Netherlands
Dakar, Senegal	Nairobi, Kenya	Thessaloniki, Greece
Dallas, USA	Nashville, USA	Toronto, Canada
Glasgow, United Kingdom	Oakland, USA	Vejle, Denmark
Deyang, India	New Orleans, USA	Toyama, Japan
Durban, South Africa	New York City, USA	Tulsa, USA
El Paso, USA	Norfolk, USA	Vancouver, Canada
Guadalajara (Metro), Mexico	Panama City, Panama	Washington DC, USA
Haiyan, China	Paris, France	Wellington, New Zealand
Honolulu, USA	Paynesville, Liberia	Yiwu, China

3.2. Location filter

Based on the DELTA21 report of Waterveiligheid (Berke & Lavooij, 2018b), the following boundary conditions regarding the location are applicable:

- The location must be at the coast, because one of the two main functional requirements of DELTA21 in the Netherlands is coastal flood protection of the hinterland.
- The location should also be at a river mouth, because the other main functional requirement is limiting maximum the water level in upstream river locations.

Not all cities lie at the coast and at the mouth of a major river. Those are not convenient for a DELTA21 design and can be eliminated from the first list of 100 cities. The 36 remaining cities after applying this criteria are shown in Table 3.2. This filter is not applied as strictly as possible. Cities like Rome (Italy) and London (United Kingdom) are not really coastal cities but lie close to the coast. Also, there are cities like Accra (Ghana) still in the list. No major rivers flow through Accra, but the presence of some smaller rivers can make this location interesting as well.

Table 3.2: The 36 remaining cities

Accra, Ghana	Durban, South Africa	Oakland, USA
Bangkok, Thailand	Houston, USA	Paynesville, Liberia
Barcelona, Spain	Jakarta, Indonesia	Porto Alegre, Brazil
Belfast, United Kingdom	Lagos, Nigeria	Rome, Italy
Berkeley, USA	Lisbon, Portugal	Salvador, Brazil
Boston, USA	London, United Kingdom	San Francisco, USA
Bristol, United Kingdom	Los Angeles, USA	Singapore, Singapore
Buenos Aires, Argentina	Melbourne, Australia	Surat, India
Can Tho, Vietnam	Montevideo, Uruguay	Sydney, Australia
Chennai, India	New Orleans, USA	Thessaloniki, Greece
Chicago, USA	New York City, USA	Toyama, Japan
Christchurch, New Zealand	Norfolk, USA	Vancouver, Canada

Two other cities seem suitable for the DELTA21 project. These cities are Da Nang (Vietnam) and Melaka (Malaysia). However, there is no information available about the rivers in those cities. Because of the lack of river data, it is also more likely that other crucial information is missing about those locations. Based on Google Earth, those rivers do not seem to be major rivers, so these cities are not likely to be the best locations for DELTA21 anyway. Therefore, the cities are left out of the list.

4

Filtering cities based on threats

In the previous chapter, it was already mentioned that the 100 Resilient Cities all have challenges or threats wherefore the support of the foundation is intended. Those threats can be used to learn more about the situations in the remaining cities. First, these threats are listed and selected by relevance. Relevant threats are threats wherefore DELTA21 can be a solution. The opposite is also the case, those threats are a problem for the DELTA21 design. After the relevant threats are found, the remaining cities are compared using the selected threats. The complete comparison can be found in Appendix A.

4.1. Threats

100 Resilient Cities highlights multiple threats to the participant cities. These threats are shown in Table 4.1. The DELTA21 project can be of importance against those threats to help the cities improve. Such 'beneficial' threats are marked in blue. Of course, not all of the threats appear in each city. Those cities that have threats regarding the possible functions of DELTA21 will be selected for further analysis. Nevertheless, not all threats are beneficial for DELTA21. Not all threats can be dealt with by this project and some of those and some of those work against the project cost and time. Those threats are marked in orange. In total, 18 out of the 68 threats are selected for this analysis.

Table 4.1: Threats for the 100 Resilient Cities (favourable threats are in blue, unfavourable threats are in orange) (100 Resilient Cities, 2019)

Aging infrastructure	Invasive species
Aging population	Lack of affordable housing
Blizzard	Lack of green space
Climate change	Lack of investment
Coastal/tidal flooding	Lack of social cohesion
Corruption	Landslide
Crime/violence	Liquefaction
Cyber attack	Loss of biodiversity
Declining population/human capital flight	Political instability
Disease outbreak	Poor air quality
Displaced populations/migrants	Poor governance/regulatory climate
Drought	Population growth/overpopulation
Drug/alcohol abuse	Poverty
Earthquake	Power outage
Economic inequality	Rainfall flooding
Energy insecurity	Riot/civil unrest
Environmental degradation	Sea level rise/coastal erosion
Ethnic inequality	Severe storms
Extreme cold	Shifting macroeconomic trends
Extreme heat	Storm surge
Financial/economic crisis	Structural racism
Fire	Subsidence
Food insecurity	Terrorist attack
Hazardous material accident	Tornado
Homelessness	Traffic congestion
Hurricane/typhoon/cyclone	Traffic injuries
Inadequate education systems	Tsunami
Inadequate health systems	Uncontrolled urban development
Inadequate infrastructure	Undiversified economy
Inadequate public transportation systems	Unemployment
Inadequate sanitation systems	Urban blight
Informal housing/settlements	Volcanic activity
Infrastructure failure	Water insecurity
Insecure municipal finances	Youth disenfranchisement

Flooding threats are very important and can be helped by the storage of peak river discharges and the dikes around the storage lake. The storage lake of DELTA21 is capable of storing part of the extreme river discharges but also an amount of water due to storm surge in the sea. This means that rainfall flooding is relevant, because heavy rainfall causes high river discharges. High sea water levels can lead to coastal/tidal flooding, so this threat is also relevant. Causes of high sea water levels are severe storms (which leads to storm surge) and a hurricane/typhoon/cyclone.

Energy storage is one of the main functions of DELTA21, which should eventually create a more stable energy supply. The threat energy insecurity is therefore important, this should become less. A consequence of unstable energy supply is power outage, which should be less probable.

The third main function of DELTA21 is nature restoring or protection. Because of that, locations that are dealing with a loss of biodiversity are more attractive for the project. Other environmental threats are a lack of green space and poor air quality, but those threats cannot be solved directly by DELTA21. Notable is that none of the cities are given the 'loss of biodiversity' threat. Despite its importance, there cannot be made a selection with this threat.

Threats regarding the infrastructure can be tackled by the storage lake, which are aging infrastructure, inadequate infrastructure and infrastructure failure. On the dikes of the storage lake, a road can be constructed to improve the infrastructure. This is a possible secondary function of the DELTA21 area. The traffic-related threats are left out, because it is not likely that this extra road has a large impact on traffic congestion. The effect on traffic injuries is even more negligible. For some locations, drought is a challenge. The consequence of that is shortage of high quality water. Another possible secondary function of the project is the production of drinking water, by making use of the content of the storage lake.

The DELTA21 design is meant for the future, so the threats regarding climate change need to be taken into account as well. The area of interest might be affected to relative sea level rise, a combination of the threats sea level rise/coastal erosion and subsidence. The dikes might need adjustments because of the relative sea level rise but will also be a flood defense for the future.

There are also threats that are unfavourable for the project. The presence of those threats increases the project costs significantly which is undesirable. In earthquake sensible areas, all project parts need to be checked on this extra loading. This will eventually lead to a stronger and more expensive design. For tsunami sensible areas, it is even more difficult. The dikes cannot be designed for such loads because it is not cost effective, so a higher risk should be accepted. The threats political instability and poor governance/regulatory climate suggest that the government of the area of interest is less likely to support the project as much as in regions with a good and stable government. Support of the government is important from a financial point of view.

4.2. Threats per city

Now that the relevant threats are selected, the remaining cities can be compared using the present threats in the cities. The specific results of this comparison can be found in Appendix A. In the appendix, Table A.6 shows the amount of favourable and unfavourable threats for DELTA21 per city.

The amount of relevant threats varies a lot per city. There are fifteen relevant favourable threats selected for DELTA21. Cities that have less than six of those challenges, which means less than 40 %, do not seem to be very convenient for this project. However, the information of 100 Resilient Cities should be considered critically. For example Jakarta (Indonesia), a city that certainly has subsidence problems, does not have the subsidence threat. Keeping this in mind, it is more appropriate to set the threshold at a lower amount of relevant threats.

4.3. Threat filter

Cities with less than four favourable threats are removed from the list. The cities with four favourable but also unfavourable threats are removed as well. The reason for this is that the cities with the lowest 'allowable' amount of threats are not the most likely locations for DELTA21, certainly those with extra negative threats.

After the application of the threat filter, the list contains fifteen cities. The list is shown in Table 4.2. A lot of those cities lie in the United States and three of them are very close to each other. Berkeley, Oakland and San Francisco all lie in the Bay Area in California. The threats of those cities are similar as well.

Table 4.2: The 15 remaining cities

Bangkok, Thailand	Chicago, USA	New Orleans, USA
Berkeley, USA	Christchurch, New Zealand	New York, USA
Boston, USA	Houston, USA	Norfolk, USA
Bristol, United Kingdom	Lagos, Nigeria	Oakland, USA
Can Tho, Vietnam	Melbourne, Australia	San Francisco, USA

5

Relevant cities

This chapter focuses more in depth on the fifteen remaining cities. First, more information is presented about those cities. This information was found by internet research and a reference project report from Royal HaskoningDHV. Thereafter, a selection of three cities is made for which a first design is developed.

5.1. City information

This section is about the gathered information about the cities. The information contains the populations and river discharges in the fifteen remaining cities. Relevant discharges for DELTA21 are the average discharge (Q_{avg}) and a peak discharge (Q_{peak}). The information can be found in Table 5.1. For most rivers, the mean discharge is known. The peak discharge is somewhat more complicated, but the exact value is not needed for the analysis. The order of magnitude of this discharge gives an idea about the variation of the river discharge and the possibilities of the storage lake in the eventual design. It is chosen to link the peak discharge to a return period of 100 years. In Appendix B, the method for finding the peak discharges is given.

Table 5.1: Populations (World Population Review, 2019) and river discharges in the fifteen cities

City and country	Inhabitants	River of interest	Average river discharge [m^3/s]	Peak river discharge [m^3/s]
Bangkok, Thailand	10,300,000	Chao Phraya	720	6767
Berkeley, USA	120,000	Sacramento	665	3254
Boston, USA	700,000	Charles	8	118
Bristol, United Kingdom	680,000	Lower Avon	22	273
Can Tho, Vietnam	1,500,000	Bassac	1700	16,500
Chicago, USA	2,700,000	Chicago	20	557
Christchurch, New Zealand	400,000	Waimakariri	250	729
Houston, USA	2,300,000	Buffalo Bayou	47	763
Lagos, Nigeria	13,900,000	Commodore channel	2000	10,000
Melbourne, Australia	4,900,000	Yarra	37	257
New Orleans, USA	400,000	Mississippi	16,790	42,253
New York, USA	8,400,000	Hudson	600	5492
Norfolk, USA	240,000	James	194	7637
Oakland, USA	430,000	Sacramento	665	3254
San Francisco, USA	880,000	Sacramento	665	3254

The table shows that the same river information holds for Berkeley, Oakland and San Francisco (Bay Area, USA). In the next section, three cities are selected based on the found information.

5.2. City selection for first designs

The three cities are selected based on the following criteria:

- The coast type at the locations of the cities should be sandy and mildy sloped. Such coast types are desired, because a lot of soil needs to be dredged at the location of the storage lake. Also, sand or other soil material is needed for the construction of the dikes around the lake. This material can be very costly, depending on the country. Moreover, a mild sloped coast implies that the cities have an altitude close to the sea level. The flood probabilities of such locations are often higher.
- The rivers near the cities should have a high peak discharge. A high peak discharge is preferred now, because that makes sure that DELTA21 is used occasionally for high discharges and energy storage is possible during the rest of the time.
- The city population should be high, which means that a lot of people are at risk when flooding occurs. Reducing the flood risk is a desired outcome of DELTA21.

After gathering relevant information about the remaining cities, an intermezzo follows with the aim of finding other important factors for the attractiveness of cities for DELTA21. The three selected locations are Bangkok (Thailand), Lagos (Nigeria) and New Orleans (USA). Those cities all have a quite sandy, mildly sloped coast. The coast types are not identical, but dredging and dike construction is considered to be possible at the locations. Besides the coast, the rivers near the selected cities all have a high peak discharge. Lastly, the city populations are high. The intention here is also to have three very different locations for global designs, since that results in more information for good evaluation criteria in the multi criteria analysis.

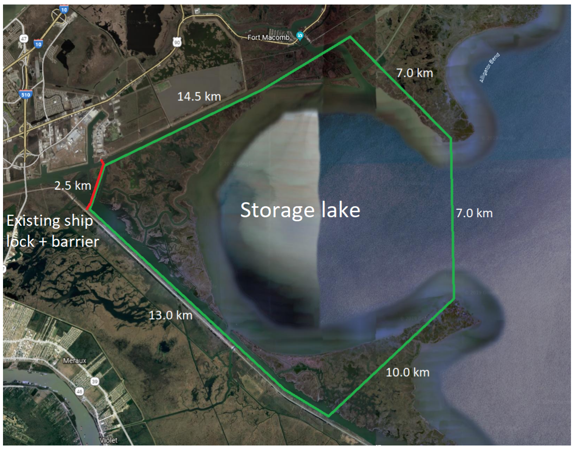
6

Three designs

This chapter shows the results of the rough designs for three of the locations. The chosen locations are Bangkok (Thailand), Lagos (Nigeria) and New Orleans (USA). Projections of the DELTA21 variants on the current cities are shown in Figure 6.1a (Bangkok), Figure 6.1b (Lagos) and Figure 6.1c (New Orleans). Dikes are shown in green and ship locks in red. In New Orleans there is an already existing barrier at the west side of the storage lake, this is also shown in red. The major characteristics of the designs per location are given in Table 6.1. Calculations corresponding to the values can be found in Appendix C. The dike profiles are visible in Figure 6.2a (Bangkok), Figure 6.2b (Lagos) and Figure 6.2c (New Orleans).

(a) Bangkok design projection

(b) Lagos design projection

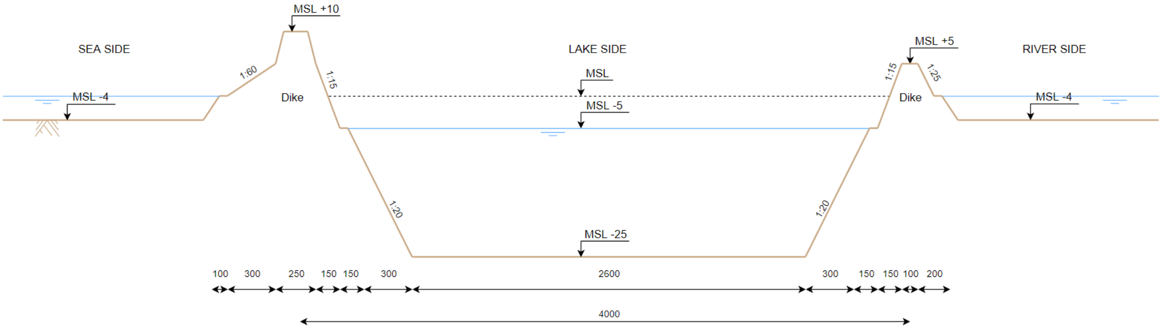


(c) New Orleans design projection

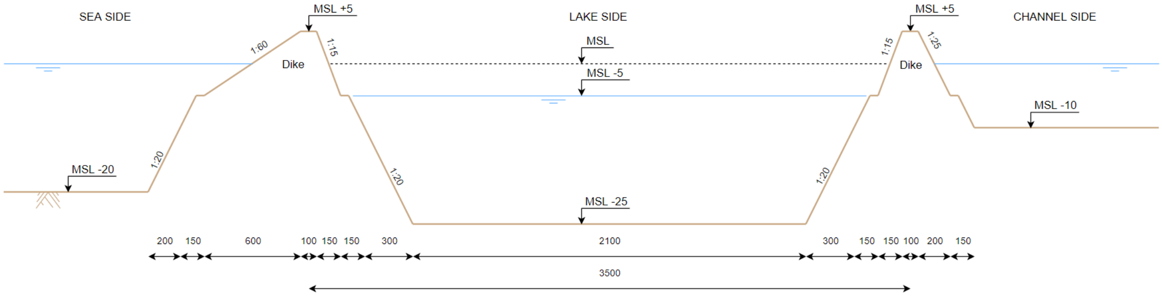
Figure 6.1: Projections of the DELTA21 variants over Google Earth

Table 6.1: Properties of the three designs

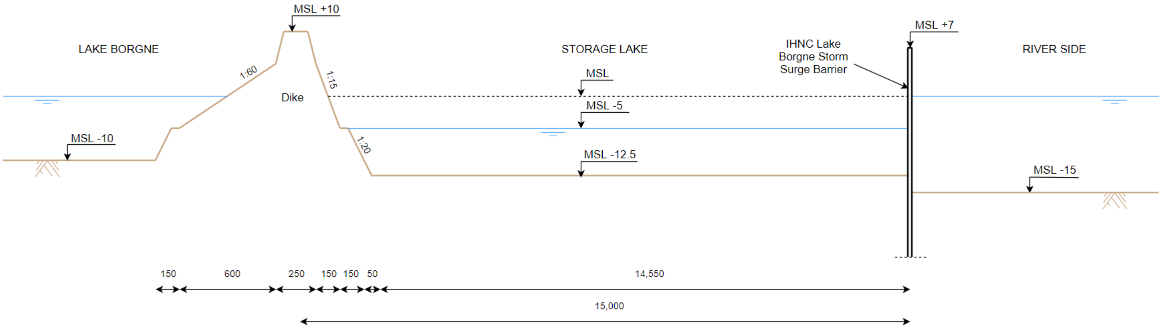
	Bangkok (Thailand)	**Lagos (Nigeria)**	**New Orleans (USA)**
Length storage lake [m]	6500	8000	15,000
Width storage lake [m]	4000	3500	12,500
Depth storage lake [m]	25	25	12.5
Storage capacity storage lake [10^6 m^3]	296	314	780
Amount of pumps (20 MW)	57	58	30
Total pump capacity [MW]	1140	1160	600
Peak discharge [m^3/s]	6767	10,000	7042
Pump discharge [m^3/s]	6858	7286	3932
Energy storage profit estimation [€/year]	140 million	142 million	63 million



(a) Bangkok dike profile



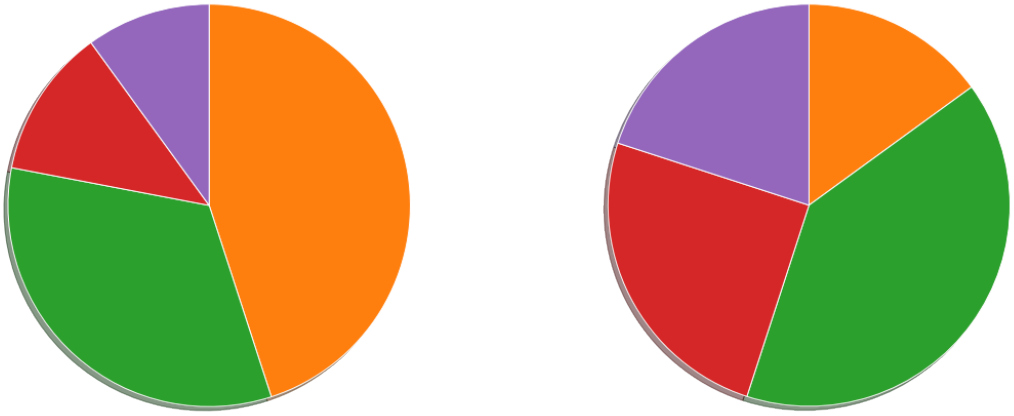
(b) Lagos dike profile



(c) New Orleans dike profile

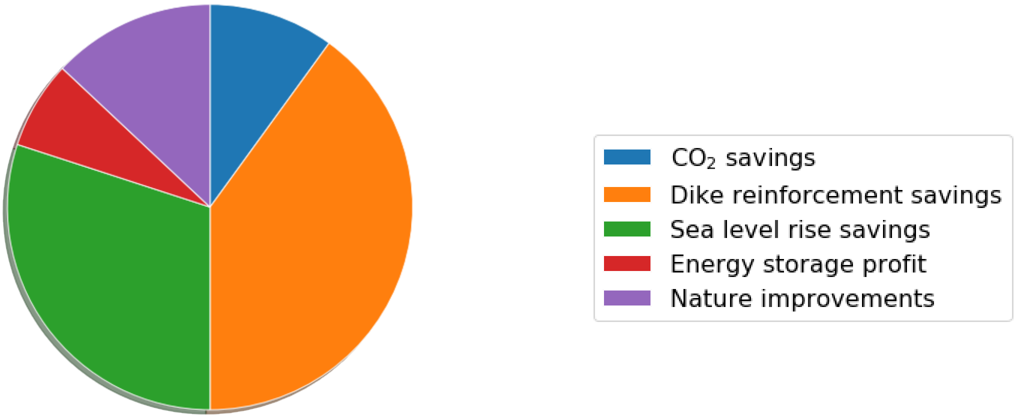
Figure 6.2: Dike profiles of the DELTA21 variants

The three designs all have different shapes and dimensions, especially the New Orleans design. Also, the importance of functions differs per location. The focus of the Lagos design is more on the energy storage, whereas the focus of the New Orleans design is more on processing high discharges. The Bangkok design is a mix of the other two designs, but looks more familiar to the Lagos design. For the three locations, pie charts are made as a comparison with the Dutch DELTA21 design. The pie charts are shown in Figure 6.3a (Bangkok), Figure 6.3b (Lagos) and Figure 6.3c (New Orleans).



(a) Bangkok pie chart

(b) Lagos pie chart



(c) New Orleans pie chart

Figure 6.3: Pie charts for the three locations of the DELTA21 designs

The created pie charts are a result of the found possibilities when the designs were made. In both Bangkok and Lagos, there is no CO$_2$ tax at the moment, leading to zero expected savings. Because of the announced dike reinforcement projects in Bangkok, the dike reinforcement savings here are probably even more important than in the Netherlands. The energy storage is in Lagos very important, but its contribution in Bangkok is also expected to be higher than in the Netherlands. The other important factor in Lagos are the sea level rise savings, one of the city's threats according to 100 Resilient Cities (2019). In New Orleans, the pie chart is comparable to the Dutch distribution. Less profit from energy storage is expected, because of smaller differences between the peak and off-peak energy prices. The larger area of the designed project here gives more opportunities for nature improvements in and around the storage lake.

7

Multi Criteria Analysis

With the information gained in the previous chapters, the multi criteria analysis is elaborated in this chapter. First, the criteria are specified and explained. Thereafter, those criteria are ordered by importance for the project, which makes it possible to assign a weighting factor to each criteria. The different cities are judged per defined criterion and the total score per city is obtained by summing up all the scores multiplied with the corresponding weighting factors. Appendix D gives explanations for the given grades.

7.1. Criteria definition

Using the gained knowledge from the previous steps, the criteria for the multi criteria analysis are:

- **Space for the project**
  Of course, more space for the project is beneficial. The larger the horizontal dimensions of the storage lake, the larger the storage capacity. The depth of the lake could be decreased when the storage capacity is high enough. A lower depth reduces the required pump capacity significantly. This was the case for the New Orleans design (a large storage lake).

- **Coast type**
  The ideal coast type is a trailing edge: this is a tidal influenced, mildly sloped and sandy coast. Such coast types can be found in West Europe, Southeast Asia and the east coast of the USA. The coast at Bangkok is such an example. This coast type is preferred because that often implies that there are densely populated areas near the coast. Coasts that are river-dominated are usually less civilized, because of a river delta. This is the case for New Orleans, where the river mouth of the Mississippi is located far away from populated areas. Rocky coasts with steeper slopes are also less attractive, because the soil in those areas is often too hard to construct the storage lake. Furthermore, steep coast slopes lead to large depth differences, that increases the dike construction costs.

- **Threats/opportunities**
  Using the information of 100 Resilient Cities, it was found that each city has certain related threats or opportunities. Some of those are relevant for DELTA21. Based on these threats, a first city selection was made. This time, the threats are accounted for but with different weights per threat and only as one criterion in the analysis. The city opportunities are especially useful for public investments: the more opportunities DELTA21 brings in the city, the more attractive DELTA21 is for support/investment.

- **Profits**
  From a business point of view, DELTA21 should be a project that is attractive to be a part of. Of course, the project will never be constructed by any contractor without profits. The profits are discussed with the pie charts that gave an expected profit distribution per location. Some of the mentioned profits are clearly very important, meaning that absence of such profits is not desirable. The most important profit part are savings from dike reinforcements. The second most important profit part are savings in case of sea level rise. This means that useful locations require flood protections. The presence of flood protections or plans for flood protections in the area are the key point here.

7.2. City grades

Each of the 36 cities from Chapter is now graded based on the four criteria. This means that the cities are given four criterion grades, which are between 1 and 5. Those grades are multiplied with the weight factors. The summation of the multiplied grades lead to the final city scores. An overview of the multi criteria analysis is shown in Table 7.1. The weight factors are given at the top of the table. Further explanation of the grades and determination of the weight factors is given in Appendix D.

Four of the participating cities have a final score that is 4 out of 5 or higher. These cities are Bangkok (Thailand), Can Tho (Vietnam), New Orleans (USA) and Surat (India). Based on this multi criteria analysis, Bangkok has the highest score (4.3 out of 5).

Table 7.1: Multi criteria analysis for 36 cities

City	Space for the project	Score * 0.1	Coast type	Score * 0.2	Treats/ opportunities	Score * 0.3	Profits	Score * 0.4	Total score
Accra, Ghana	2	0.2	4	0.8	2	0.6	4	1.6	**3.2**
Bangkok, Thailand	4	0.4	5	1.0	3	0.9	5	2.0	**4.3**
Barcelona, Spain	2	0.2	4	0.8	3	0.9	2	0.8	**2.7**
Belfast, United Kingdom	2	0.2	2	0.4	2	0.6	2	0.8	**2.0**
Berkeley, USA	2	0.2	1	0.2	4	1.2	3	1.2	**2.8**
Boston, USA	2	0.2	4	0.8	4	1.2	3	1.2	**3.4**
Bristol, United Kingdom	3	0.3	2	0.4	3	0.9	2	0.8	**2.4**
Buenos Aires, Argentina	5	0.5	5	1.0	2	0.6	3	1.2	**3.3**
Can Tho, Vietnam	1	0.1	5	1.0	3	0.9	5	2.0	**4.0**
Chennai, India	2	0.2	5	1.0	2	0.6	5	2.0	**3.8**
Chicago, USA	4	0.4	5	1.0	3	0.9	2	0.8	**3.1**
Christchurch, New Zealand	2	0.2	1	0.2	3	0.9	2	0.8	**2.1**
Durban, South Africa	2	0.2	5	1.0	2	0.6	3	1.2	**2.8**
Houston, USA	5	0.5	4	0.8	3	0.9	4	1.6	**3.8**
Jakarta, Indonesia	2	0.2	5	1.0	2	0.6	4	1.6	**3.4**
Lagos, Nigeria	2	0.2	4	0.8	3	0.9	3	1.6	**3.1**
Lisbon, Portugal	2	0.2	4	0.8	2	0.6	2	0.8	**2.4**
London, United Kingdom	3	0.3	2	0.4	3	0.9	2	0.8	**2.4**
Los Angeles, USA	4	0.4	1	0.2	2	0.6	2	0.8	**2.0**
Melbourne, Australia	3	0.3	4	0.8	3	0.9	3	1.2	**3.2**
Montevideo, Uruguay	5	0.5	5	1.0	2	0.6	3	1.2	**3.3**
New Orleans, USA	5	0.5	3	0.6	5	1.5	4	1.6	**4.2**
New York, USA	2	0.2	4	0.8	4	1.2	4	1.6	**3.8**
Norfolk, USA	4	0.4	4	0.8	5	1.5	3	1.2	**3.9**
Oakland, USA	2	0.2	1	0.2	3	0.9	3	1.2	**2.5**
Paynesville, Liberia	2	0.2	4	0.8	2	0.6	1	0.4	**2.0**
Porto Alegre, Brazil	3	0.3	4	0.8	1	0.3	2	0.8	**2.2**
Rome, Italy	4	0.4	5	1.0	3	0.9	2	0.8	**3.1**
Salvador, Brazil	4	0.4	4	0.8	2	0.6	1	0.4	**2.2**
San Francisco, USA	2	0.2	1	0.2	3	0.9	3	1.2	**2.5**
Singapore, Singapore	2	0.2	5	1.0	3	0.9	3	1.2	**3.3**
Surat, India	4	0.4	5	1.0	2	0.6	5	2.0	**4.0**
Sydney, Australia	2	0.2	4	0.8	1	0.3	2	0.8	**1.7**
Thessaloniki, Greece	3	0.3	3	0.6	2	0.6	3	1.2	**2.7**
Toyama, Japan	2	0.2	5	1.0	2	0.6	2	0.8	**2.6**
Vancouver, Canada	3	0.3	1	0.2	2	0.6	4	1.6	**2.7**

8

Conclusion, discussion and recommendations

In this chapter, the conclusions are made from results of the Multi Criteria Analysis. These conclusions are also discussed. Finally, some recommendations are given.

8.1. Conclusion

The first part of the report eventually lead to three DELTA21 designs. While making the designs, knowledge was gained about the important factors of the success rate of DELTA21. An obvious found criterion here was the available project space. Also the coast type was found to be an important criterion, because it gives an indication for the expected soil composition. A good soil composition is necessary for the dredging and dike construction. The third found criterion were the treats or opportunities at the locations. Like the DELTA21 concept in the Netherlands, the project is aimed to be multi functional. Multi-functionality is crucial for public investments and support of the involved actors. Finally, the most important criterion were the expected profits. This is the essential point for the business case and is mostly depending on the savings from dike reinforcements (both for the current and the future situations).

In terms of grades, the city with the highest MCA score is Bangkok (Thailand). Especially the expected savings on dike reinforcements lead to the high grade. This city was also expected to be the best city because it was chosen as one of the three cities to make a first design for. After the made designs, the size of the storage lake in Bangkok could be increased compared to the first design. The local mean depth here is only 4 m, which is shallow. Bangkok's design was most elaborated because of high traffic delays in the city. A road over the DELTA21 elements can be an extra function of DELTA21 here.

Good alternatives for Bangkok are Can Tho (Vietnam), New Orleans (USA) and Surat (India). In Can Tho, there is only one disadvantage. This is the space for DELTA21. From current satellite images, the space for the project is estimated less than 10 km^2 near Can Tho. This city was initially chosen from the 100 Resilient Cities list, because it was located quite close to the coast and along a major river. The best location here would be at the mouth of the Bassac river, but this is 80 km southeast of Can Tho.

Unlike Can Tho, the estimated space is large in New Orleans. The benefits of DELTA21 in New Orleans are probably similar to DELTA21 in the Netherlands. There have already been constructed many flood defences near this city. Like the western part of the Netherlands, neighbourhoods of the city are below sea level. The coast type is less attractive here, because the Mississippi river's mouth is in a delta form. This means that DELTA21 can be placed at the mouth of only one branch of the river.

Surat is a surprising alternative, because this city was not selected when the city threats were analysed. Like Bangkok and Can Tho, Surat has a monsoon climate, leading to high rainfall and river discharge variations. The flood risk definitely needs to be improved here. Because of the low score from the threats/opportunities, a different type of flood defence probably suits this city better.

8.2. Discussion

This section presents the points of attention of this report. First of all, what should be realised is that the starting point of the report was a list of hundred cities with a high expected probability of information availability. Obviously, this decision excludes many other interesting locations. Chinese cities, for example, are barely discussed here. The aim of the report is to find an attractive location, but the worldwide best location is impossible to find.

Important in the multi criteria analysis is that not all factors are included. The project costs cannot be determined in this stage, that would give a better idea about the consequences of different shapes and sizes of DELTA21. The most important part of the profit is the savings on dike reinforcements. For the Netherlands, those savings are estimated in the Energie report (Berke & Lavooij, 2017). However, such estimations are hard to make for different areas, especially when there is no plan available of the country about improving the flood safety.

The grades from Table 7.1 could not always be made objectively. Especially for the profits grade, because this grade was mainly based on future predictions for the locations. For almost every location there was flooding news available where new measurements were discussed. However, the costs of these measurements were still unknown. The space for the project criterion was also graded with a small amount of subjectivity. The reason for that is the fact that the exact location of DELTA21 in those cities was still unknown. Some time was spent on finding more exact locations, but not as much as for the three design cities.

One of the functions of DELTA21 could also be drainage rainwater. This was not analysed. Drainage systems in cities are complex, that makes it difficult to argue whether DELTA21 can be an addition to the drainage system. In general, many cities from the multi criteria analysis have problems with rainwater drainage. Bangkok is one of those cities, so drainage problems would not lead to a radical change in the results.

Something that was not discussed as well was the nature improvement of DELTA21 abroad. For that, more ecological information is needed of the specific design locations. This report is written from an engineering point of view, meaning that there was no experience with this subject. Also, the report only contains three first designs; ecology is considered to be too specific for that.

There is a practical reason for giving alternative cities for DELTA21. In Bangkok, it might be the case that the project cannot be executed due to regulations. For example, the coast near the Chao Phraya river mouth has mangrove vegetation. Mangrove is a vulnerable tree species so construction processes could be prohibited in this area. Another problem could be that the Thai government is not willing to cooperate for the project. Public private partnership is considered to be necessary for success of DELTA21.

Lastly, this report is written by a student, so there was few experience with this kind of analyses. It is possible that illogical assumptions are made for the city selections. The first part of the report, eventually leading to the three designs, was a learning process for the author. The expected result was a better combination of criteria for the multi criteria analysis.

8.3. Recommendations

For abroad possibilities of DELTA21, Bangkok is the recommended city. In further research, it is important to find a clear overview of the benefits of the project here. The benefits should be compared to the estimated project cost. Apart from the benefits, the regulations in Bangkok need to be investigated. When both outcomes are positive, the dimensions of the elements of DELTA21 have to be determined more specifically, of course. As a starting point, the dimensions given in this report can be used. Another point of interest is the drainage system in the city and the improvements that can be done to it, as mentioned in the discussion.

Bangkok may not be a good location after further research. As mentioned in the conclusion, the focus could be shifted to those locations. In the case that the given cities turn out to be not good enough for DELTA21, the found criteria of the multi criteria analysis could be used for a new city selection.

A

Threats per city

This appendix shows the 36 location-wise filtered cities with their threats or challenges, relevant for DELTA21. Table A.1 shows the threats related to flooding. The threats related to energy are shown in Table A.2. None of the remaining cities have the threat loss of biodiversity, this threat is therefore not shown in the tables. The threats regarding the secondary functions are shown in Table A.3 and the future threats in Table A.4. Finally, Table A.5 shows the unfavourable threats. The summation of the threats per city is shown in Table A.6. The presented tables are based on information from 100 Resilient Cities (2019).

A summation of the threats per city is done in Chapter 4, to reduce the list of 36 cities. In Chapter 7, the threats are used as one of the criteria for the multi criteria analysis. This analysis is also performed with the 36 cities from the tables presented below.

Table A.1: Overview of flooding related challenges per city (100 Resilient Cities, 2019)

City	Coastal flooding	Hurricane/ typhoon/ cyclone	Rainfall flooding	Severe storms	Storm surge
Accra, Ghana	🟦		🟦		
Bangkok, Thailand	🟦		🟦		
Barcelona, Spain	🟦		🟦		
Belfast, United Kingdom	🟦				
Berkeley, USA	🟦		🟦		🟦
Boston, USA	🟦		🟦	🟦	🟦
Bristol, United Kingdom			🟦		
Buenos Aires, Argentina			🟦		
Can Tho, Vietnam	🟦		🟦		
Chennai, India		🟦			
Chicago, USA			🟦	🟦	
Christchurch, New Zealand	🟦		🟦		
Durban, South Africa			🟦		
Houston, USA		🟦	🟦	🟦	
Jakarta, Indonesia	🟦		🟦		
Lagos, Nigeria			🟦		
Lisbon, Portugal			🟦		
London, United Kingdom	🟦		🟦		
Los Angeles, USA			🟦		
Melbourne, Australia	🟦		🟦		
Montevideo, Uruguay			🟦		
New Orleans, USA	🟦	🟦	🟦	🟦	
New York, USA	🟦		🟦	🟦	
Norfolk, USA	🟦	🟦	🟦	🟦	🟦
Oakland, USA	🟦		🟦		🟦
Paynesville, Liberia			🟦		
Porto Alegre, Brazil			🟦		
Rome, Italy	🟦		🟦		
Salvador, Brazil			🟦		
San Francisco, USA				🟦	
Singapore, Singapore	🟦		🟦		
Surat, India					
Sydney, Australia					
Thessaloniki, Greece			🟦		
Toyama, Japan	🟦		🟦		
Vancouver, Canada					

Table A.2: Overview of energy related challenges per city (100 Resilient Cities, 2019)

City	**Energy insecurity**	**Power outage**
Accra, Ghana		
Bangkok, Thailand		
Barcelona, Spain		
Belfast, United Kingdom		
Berkeley, USA	🟦	
Boston, USA		
Bristol, United Kingdom	🟦	
Buenos Aires, Argentina		
Can Tho, Vietnam		
Chennai, India		
Chicago, USA		
Christchurch, New Zealand		
Durban, South Africa		
Houston, USA		
Jakarta, Indonesia		
Lagos, Nigeria	🟦	
Lisbon, Portugal		
London, United Kingdom		
Los Angeles, USA		
Melbourne, Australia		
Montevideo, Uruguay		
New Orleans, USA		
New York, USA		🟦
Norfolk, USA		
Oakland, USA		
Paynesville, Liberia		
Porto Alegre, Brazil		
Rome, Italy		
Salvador, Brazil		
San Francisco, USA		
Singapore, Singapore		
Surat, India		
Sydney, Australia		
Thessaloniki, Greece	🟦	🟦
Toyama, Japan		
Vancouver, Canada		

Table A.3: Overview of threats regarding the possible secondary functions (100 Resilient Cities, 2019)

City	**Aging infrastructure**	**Drought**	**Inadequate infrastructure**	**Infrastructure failure**
Accra, Ghana	🟦			🟦
Bangkok, Thailand	🟦	🟦		
Barcelona, Spain				🟦
Belfast, United Kingdom	🟦			🟦
Berkeley, USA	🟦	🟦		🟦
Boston, USA	🟦			🟦
Bristol, United Kingdom	🟦		🟦	🟦
Buenos Aires, Argentina	🟦			🟦
Can Tho, Vietnam		🟦		
Chennai, India	🟦			🟦
Chicago, USA	🟦			🟦
Christchurch, New Zealand	🟦			
Durban, South Africa		🟦		
Houston, USA	🟦			
Jakarta, Indonesia				
Lagos, Nigeria				🟦
Lisbon, Portugal	🟦			🟦
London, United Kingdom				🟦
Los Angeles, USA	🟦	🟦		🟦
Melbourne, Australia	🟦	🟦		
Montevideo, Uruguay				🟦
New Orleans, USA	🟦	🟦		🟦
New York, USA	🟦		🟦	🟦
Norfolk, USA				
Oakland, USA	🟦	🟦		
Paynesville, Liberia				🟦
Porto Alegre, Brazil				
Rome, Italy				🟦
Salvador, Brazil				
San Francisco, USA	🟦	🟦	🟦	🟦
Singapore, Singapore				
Surat, India	🟦	🟦		
Sydney, Australia				🟦
Thessaloniki, Greece				🟦
Toyama, Japan				
Vancouver, Canada	🟦			🟦

Table A.4: Overview of future challenges per city (100 Resilient Cities, 2019)

City	Sea level rise/coastal erosion	Subsidence
Accra, Ghana		
Bangkok, Thailand		
Barcelona, Spain		
Belfast, United Kingdom		
Berkeley, USA	🟦	
Boston, USA	🟦	
Bristol, United Kingdom		
Buenos Aires, Argentina		
Can Tho, Vietnam	🟦	
Chennai, India		
Chicago, USA		
Christchurch, New Zealand	🟦	
Durban, South Africa		
Houston, USA		
Jakarta, Indonesia		
Lagos, Nigeria	🟦	
Lisbon, Portugal	🟦	
London, United Kingdom		
Los Angeles, USA		
Melbourne, Australia	🟦	
Montevideo, Uruguay	🟦	
New Orleans, USA	🟦	🟦
New York, USA	🟦	
Norfolk, USA	🟦	🟦
Oakland, USA	🟦	
Paynesville, Liberia		
Porto Alegre, Brazil		
Rome, Italy	🟦	
Salvador, Brazil		
San Francisco, USA	🟦	
Singapore, Singapore	🟦	
Surat, India	🟦	
Sydney, Australia		
Thessaloniki, Greece		
Toyama, Japan	🟦	
Vancouver, Canada	🟦	

Table A.5: Overview of unfavourable threats per city (100 Resilient Cities, 2019)

City	Earthquake	Political instability	Poor governance/ regulatory system	Tsunami
Accra, Ghana	🟧			
Bangkok, Thailand				
Barcelona, Spain				
Belfast, United Kingdom		🟧		
Berkeley, USA	🟧			
Boston, USA				
Bristol, United Kingdom				
Buenos Aires, Argentina				
Can Tho, Vietnam				
Chennai, India				
Chicago, USA				
Christchurch, New Zealand				
Durban, South Africa				
Houston, USA				
Jakarta, Indonesia	🟧			
Lagos, Nigeria				
Lisbon, Portugal	🟧			🟧
London, United Kingdom				
Los Angeles, USA	🟧			🟧
Melbourne, Australia				
Montevideo, Uruguay				
New Orleans, USA				
New York, USA				
Norfolk, USA				
Oakland, USA	🟧			
Paynesville, Liberia				
Porto Alegre, Brazil	🟧			🟧
Rome, Italy	🟧			
Salvador, Brazil				
San Francisco, USA	🟧			
Singapore, Singapore				
Surat, India				
Sydney, Australia				
Thessaloniki, Greece	🟧			
Toyama, Japan	🟧			
Vancouver, Canada	🟧			

In Table A.6, the summation of the city threats are given. In Chapter 4, the cities with four or more favourable threats are selected for further analysis. Cities with only four favourable threats but also unfavourable threats are not selected.

Table A.6: Amount of relevant threats per city

City	Favourable threats	Unfavourable threats
Accra, Ghana	4	1
Bangkok, Thailand	4	0
Barcelona, Spain	3	0
Belfast, United Kingdom	3	1
Berkeley, USA	8	1
Boston, USA	7	0
Bristol, United Kingdom	5	0
Buenos Aires, Argentina	3	0
Can Tho, Vietnam	4	0
Chennai, India	3	0
Chicago, USA	4	0
Christchurch, New Zealand	4	0
Durban, South Africa	2	0
Houston, USA	4	0
Jakarta, Indonesia	2	1
Lagos, Nigeria	4	0
Lisbon, Portugal	4	2
London, United Kingdom	3	0
Los Angeles, USA	4	2
Melbourne, Australia	5	0
Montevideo, Uruguay	3	0
New Orleans, USA	9	0
New York, USA	8	0
Norfolk, USA	7	0
Oakland, USA	6	1
Paynesville, Liberia	2	0
Porto Alegre, Brazil	1	2
Rome, Italy	4	1
Salvador, Brazil	1	0
San Francisco, USA	6	1
Singapore, Singapore	3	0
Surat, India	3	0
Sydney, Australia	1	0
Thessaloniki, Greece	4	1
Toyama, Japan	3	1
Vancouver, Canada	3	1

B

Discharge graphs

This appendix gives more information about the peak discharges mentioned in Section 5.1. First, the codes are shown to construct graphs of discharge return periods. Thereafter, the resulting graphs are given that lead to the peak discharges.

B.1. Codes

The construction of the discharge graphs as well as finding the peak discharges in Section 5.1 are shown in this section. The Python code for the peak discharge of the Sacramento river is shown in Listing B.1. This code suits as an example of the used codes for the American locations. For all these discharges, tab-separated data files from USGS were used. The plotting part was also used for Bangkok (Thailand), Christchurch (New Zealand) and Melbourne (Australia). For those locations, the daily data (in tab-separated text files) had to be converted. An example of this is shown in Listing B.2.

```
# Importing packages
import numpy as np
import matplotlib.pyplot as plt
from pandas import read_csv
from IPython.display import display
import pandas as pd
from scipy import stats
import matplotlib
matplotlib.rcParams.update({’font.size’: 16})

# Loading the data from USGS
df = read_csv(’sacramento.txt’, delimiter=’\t’, skiprows=72, parse_dates=[2], index_col
    =[2])
maxdis = df[’peak_va’] * 0.0283168466
ecdf = maxdis.rank() / (len(maxdis)+1)

# Constructing the figure
plt.figure(figsize=(10,8))

# Plotting the empirical discharges and return periods
plt.plot(maxdis, 1/(1 - ecdf), ’ko’)

# Plotting the GEV fitted discharges and return periods
x = np.linspace(0, 4000)
c, loc, scale = stats.genextreme.fit(maxdis)
plt.plot(x, 1/(1 - stats.genextreme.cdf(x, c, loc, scale)))

# Changing the layout of the graph
plt.axvline(stats.genextreme.ppf(0.99, c, loc, scale), ls=’dashed’, ymax=2/3, color=’C3
    ’)
plt.axhline(100, ls=’dashed’, xmax=0.81, color=’C3’)
plt.xlabel(’Discharge [m$^3$/s]’)
plt.ylabel(’Return period [years]’)
plt.yscale(’log’)
plt.ylim(1,1000)
```

```
plt.xlim(0,4000)
plt.yticks([1, 10, 100, 1000], ['1', '10', '100', '1000'])

# Finding the peak discharge
print(stats.genextreme.ppf(0.99, c, loc, scale))
```

Listing B.1: Finding peak discharges with USGS data

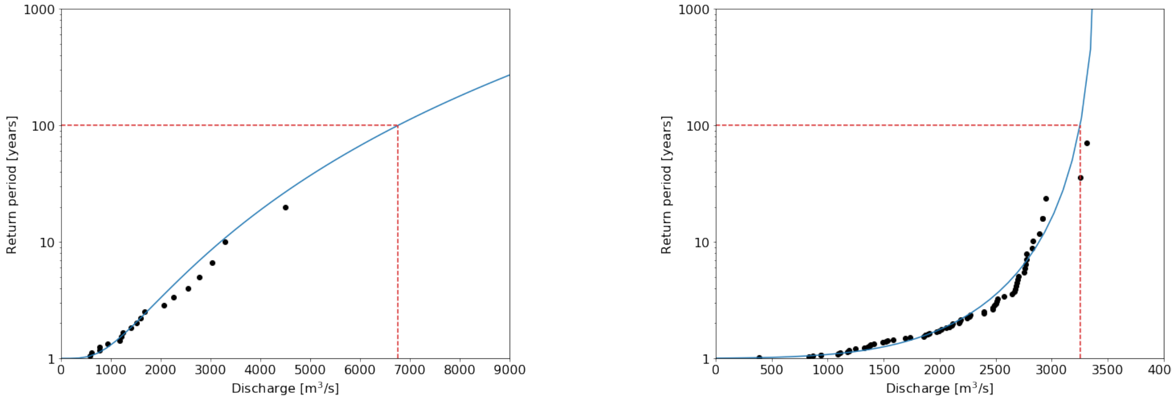
```
# Importing the daily data and collecting the maximum values per year
maxdis = pd.DataFrame({'year':[],'discharge':[]})
for i in range(1981, 2000):
    textfile = str(i) + '.txt'
    df = read_csv(textfile, delimiter='\t', index_col=[0], parse_dates=[0])
    dis = pd.DataFrame({'year':[str(i)],'discharge':[df['Discharge'].max()]})
    maxdis = maxdis.append(dis)

# Exporting the yearly maximum data to a CSV file
maxdis = maxdis.set_index('year')
export = maxdis.to_csv(r'C:\Users\909552\Documents\Python Scripts\chao_phraya.csv',
    index=True)
```

Listing B.2: Converting daily mean data to yearly maximum data

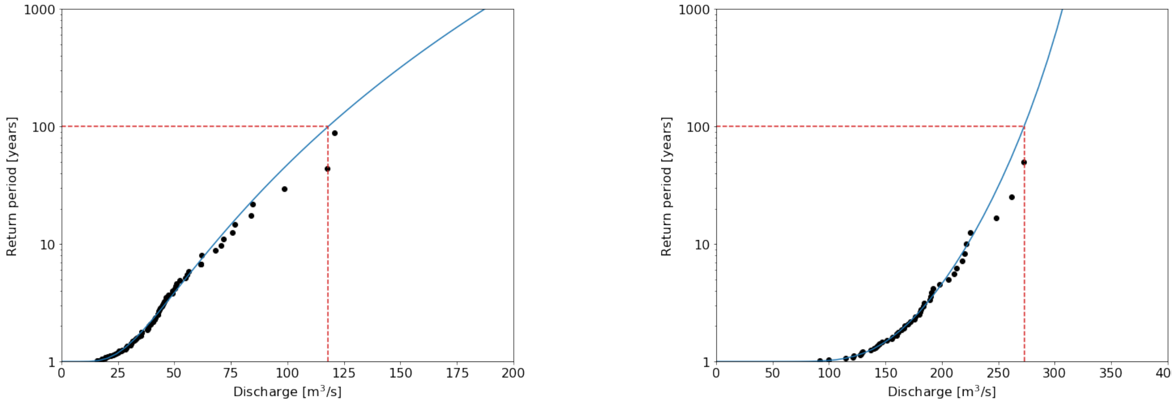
B.2. Graphs

The output of the codes shown in Listings B.1 and B.2 is a graph. For most locations, the resulting graphs of the discharges with the corresponding return periods are shown in Figure B.1.



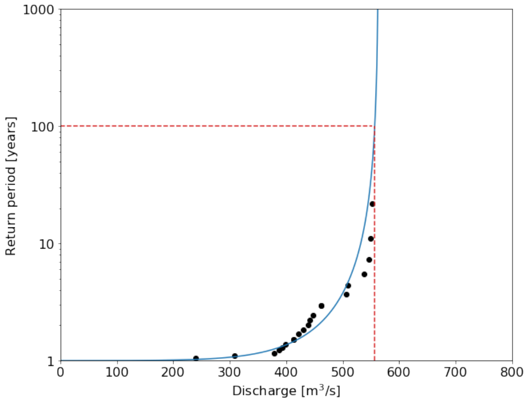
(a) Chao Phraya (Bangkok) graph based on daily data (Thai Royal Irrigation Department, 2004)

(b) Sacramento (Bay Area) graph based on yearly data (USGS, 2017c)

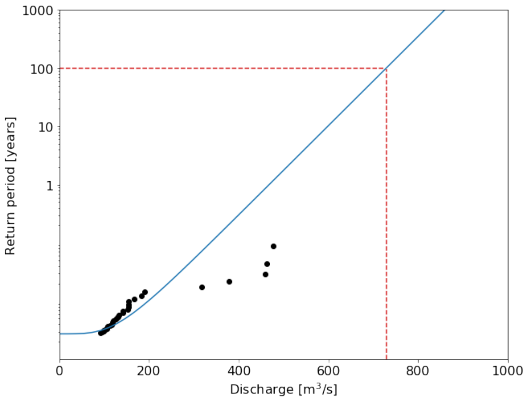


(c) Charles (Boston) graph based on yearly data (USGS, 2018a)

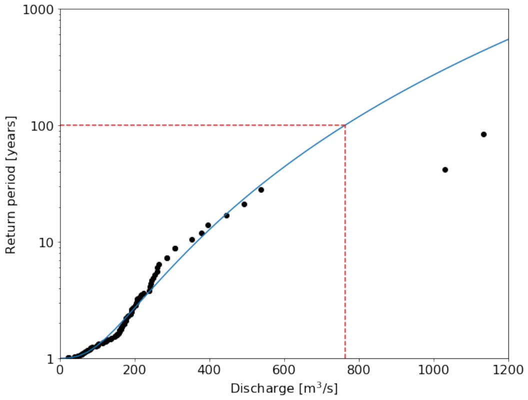
(d) Lower Avon (Bristol) graph based on yearly data (National River Flow Archive, 2018)



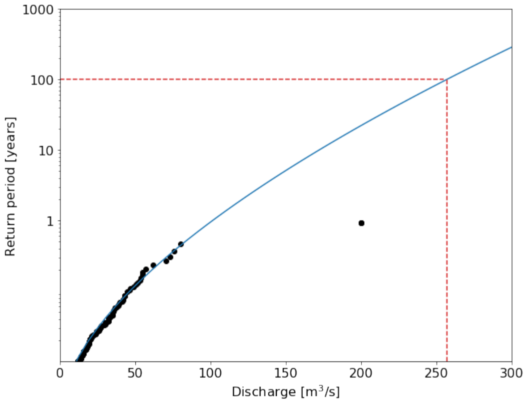
(e) Chicago (Chicago) graph based on yearly data (USGS, 2005)



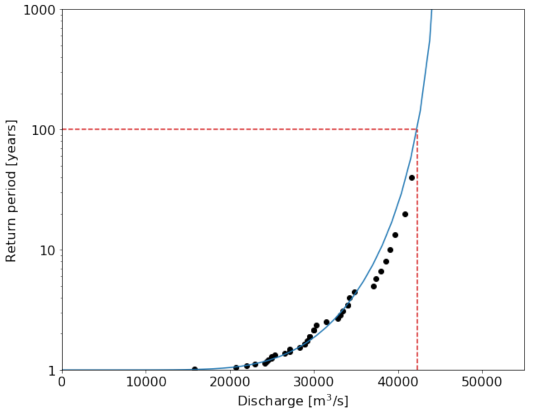
(f) Waimakariri (Christchurch) graph based on daily data (Environment Canterbury, 2019)



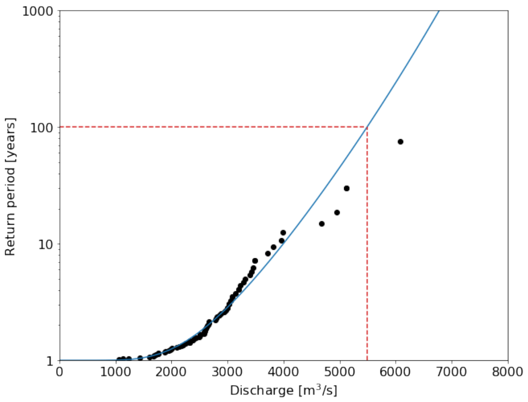
(g) Buffalo Bayou (Houston) graph based on yearly data (USGS, 2017b)



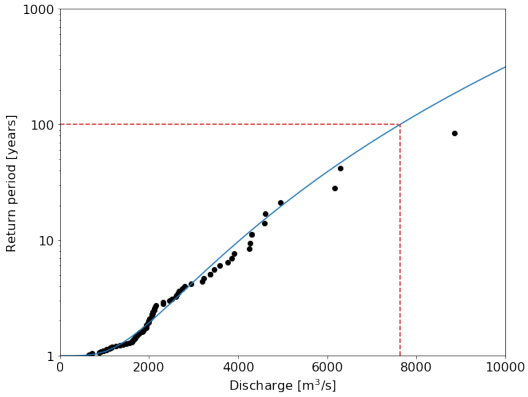
(h) Yarra (Melbourne) graph based on daily data (Melbourne Water, 2019)



(i) Mississippi (New Orleans) graph based on yearly data (USGS, 2018c)



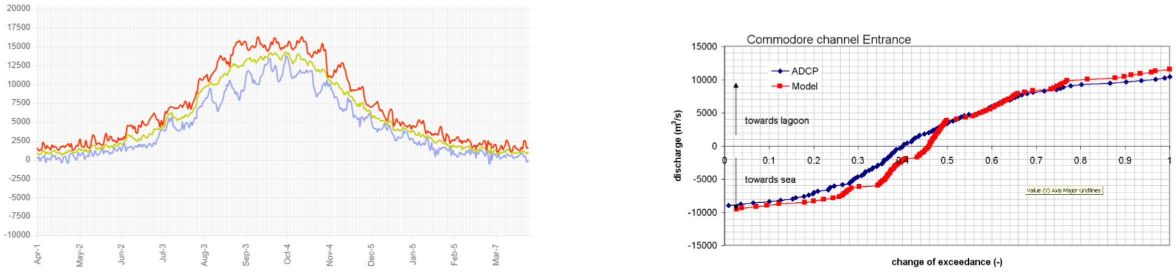
(j) Hudson (New York) graph based on yearly data (USGS, 2018b)



(k) James (Norfolk) graph based on yearly data (USGS, 2017a)

Figure B.1: Yearly maximum discharges of the rivers with return periods

Figure B.2 contains the graphs for the other locations (Can Tho and Lagos), where no discharge data was available. A rough discharge estimation was made from these figures.



(a) Minimum, average and maximum discharge between 1960 and 2009 of the Song Hau at Can Tho in blue, green and red, respectively (in m^3/s) (Mekong River Commission, 2009)

(b) Cumulative probabilities of discharge in the Commodore Channel (Lagos) (Scholl & Reneerkens, 2011)

Figure B.2: Alternative graphs used for determining the peak discharge

C

Elaborations of designs

This appendix contains the elaborations of the three designs made for Bangkok (Thailand), Lagos (Nigeria) and New Orleans (USA).

C.1. Bangkok design

This is one of the three sections containing first designs. It contains a first design for DELTA21 in Bangkok. Parts of this design are the specific location, dimensions of the storage lake and the required power of the pump elements. The first design gives a good indication whether Bangkok is suitable or not for DELTA21.

Current situation

The flood safety of Bangkok definitely needs to be improved. The severe floods of the Chao Phraya river in 2011 were mainly caused by a combination of heavy rainfall and poor management. In addition, the ground level of Bangkok is just a few meters above the sea level and the gradient of the river is low. The coast of Bangkok is characterized by its large tidal ranges, but also by the differences in rainfall between the monsoon and the dry season. In the dry season, the sea water flows into the Chao Phraya during high tide. The problems of this are a shrinkage of the volume of fresh water during the dry periods and higher river water levels. During the wet season, the river discharges are much higher, also leading to increased river water levels. The latter situation is most critical for Bangkok.

In 2011, the maximum water level in the Chao Phraya reached MSL +2.53 m in Bangkok. Because of that, the Thai government decided to improve the drainage system and the flood protection. The drainage system should function with rain intensities up to 60 mm/h. Parts of the improved drainage system are canals, pipes, pumping stations, retention areas and a flood control center. The flood protection system is improved by reinforcing several dikes and increasing dike heights. Canals are dredged to obtain more drainage efficiency. The new dike heights are between MSL +2.50 m and MSL +3.50 m. The costs are estimated at 70 billion baht (2 billion euro) (Phamornpol, 2012).

Location

The mouth of the Chao Phraya seems suitable for the project in terms of space. Its width just upstream from the mouth is 650 m. At the location of the mouth the river is roughly 3,000 m wide. The west side of the river is far less civilized compared to the east side. At the river banks there are industry terrains and small harbours. Non built-up areas consist of mangrove and agriculture. Although the Chao Phraya transports a lot of sediment, there are no (sandy) beaches located near the river mouth. The dominant wind direction is either SW or NE. This means that the most likely direction from where the high water comes is SW. In combination with the lower amount of industry and harbours on this river side, the west side of the river mouth is chosen as the location for a first design of DELTA21 in Bangkok (Figure C.2). The southernmost building along the west river bank is the Phra Chulachomklao Fort. South of this fort is enough space for constructing the storage lake. The average water depths in the area are not larger than 4 m (Figure C.1), meaning that no extreme wave conditions are expected.

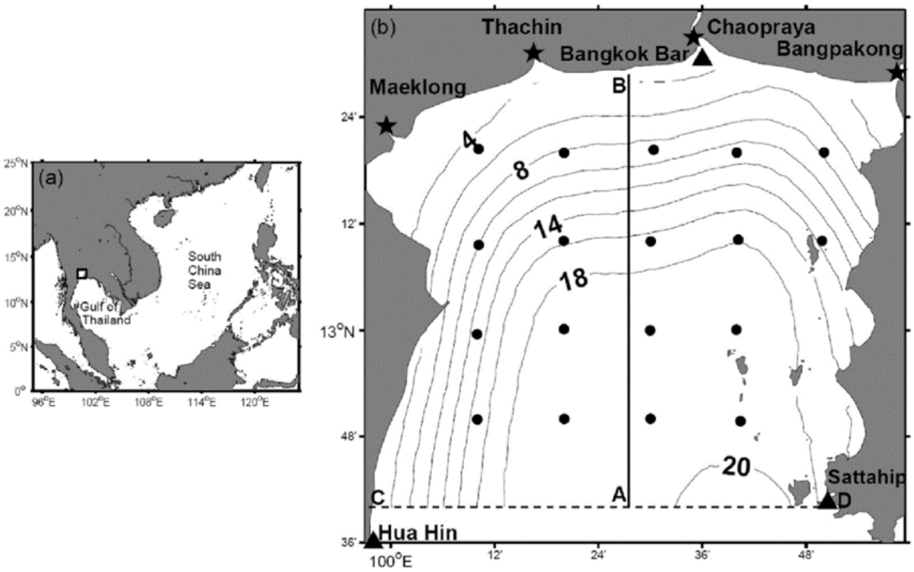


Figure C.1: Bathymetry in the Bay of Bangkok (Yua, Guoa, Morimotoa, & Buranapratheprat, 2018)

Dimensions of storage lake

To make sure that vessels do not encounter problems regarding the width of the river, there should be about 650 m space for a navigation lock and a separate flood defense between the dikes of the storage lake and the east river bank. This is namely also the river with upstream of the mouth. In case of high enough river discharges, the flood defense is open. During the dry season the flood defense is closed more often, to prevent the seawater from flowing in the river.

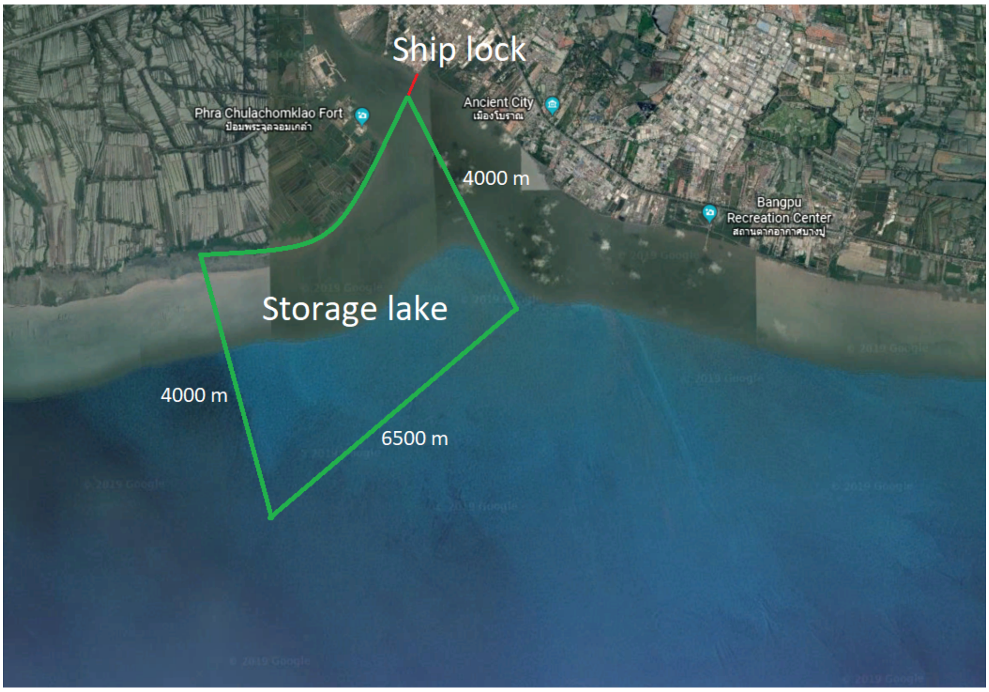


Figure C.2: First design DELTA21 in Bangkok with some dimensions

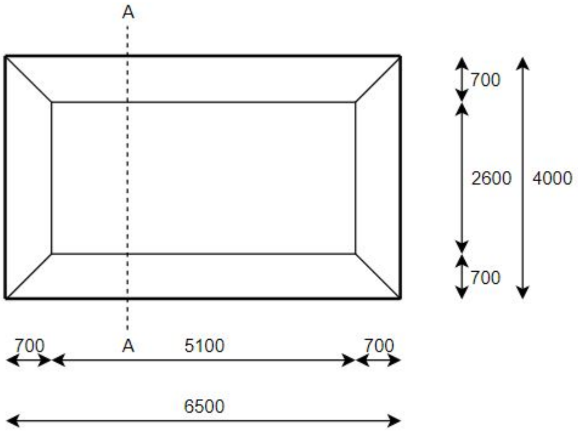


Figure C.3: Top view of the simplified lake (distances in m)

Figure C.2 shows some general dimensions of the storage lake. These dimensions are measured at the top of the surrounding dikes. The lake is approximated by the rectangle shown in Figure C.3. In the first design, some principles of the Dutch DELTA21 design are used. For example, the dike height is assumed to be 10 m above the mean sea level. Although the tidal ranges in this area are much larger than in the Netherlands, the water depths are lower here resulting in lower wave heights. Both locations lie in a sheltered area with respect to the oceans. Figure C.4 shows a cross-section of the Bangkok storage lake, based on the dike profiles from the report Waterveiligheid (Berke & Lavooij, 2018b). The dikes at the river side are 5 m lower than at the sea side. Both sides of the dikes contain underwater dams, for a better sand supplementation. The cross-sectional area that needs to be dredged is shown in red and the cross-sectional area that must be supplemented is shown in green. For simplification it is assumed that the current water depth in the area is constant (4 m).

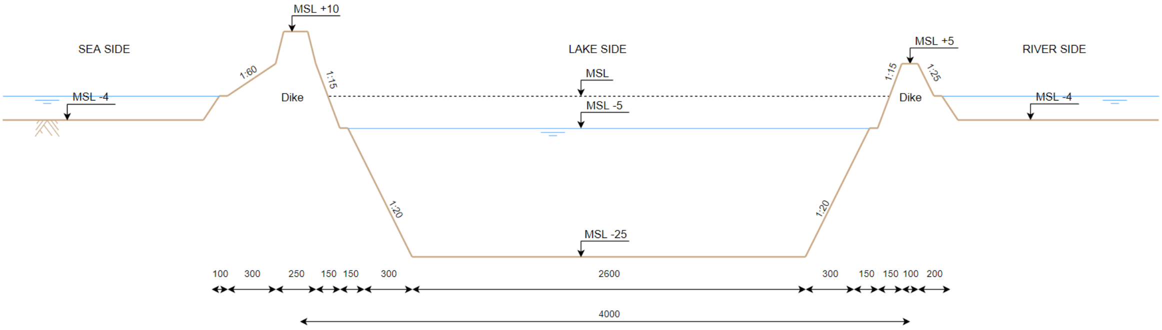


Figure C.4: Cross-section A-A: Dike profile of Bangkok storage lake (distances in m)

With the first dimensions from Figures C.3 and C.4 the storage volume of the storage lake can be calculated. This is done by calculating the difference between the maximum water volume (V_{high}) and the minimum water volume (V_{low}) in the lake:

$$V_{storage} = V_{high} - V_{low} = d_{high} \cdot (d_{high} \cdot i + L) \cdot (d_{high} \cdot i + B) - d_{low} \cdot (d_{low} \cdot i + L) \cdot (d_{low} \cdot i + B) \tag{C.1}$$

where:

$V_{storage}$ [m^3] = Storage capacity of the storage lake
V_{high} [m^3] = Maximum water volume in the storage lake
V_{low} [m^3] = Minimum water volume in the storage lake
d_{high} [m] = Maximum water depth
d_{low} [m] = Minimum water depth
i [-] = Inner dike slope
L [m] = Length bottom of storage lake
B [m] = Width bottom of storage lake

For a simplification of the calculations, a constant inner dike slope of $i = 1:20$ is assumed. This means that $L = 5100$ m and $B = 2600$ m. The highest water level is at MSL -5.0 m, in that case the water depth is 20 m. The lowest water level is at MSL -22.5 m, then the water depth is 2.5 m. With Equation C.1, the storage volume is:

$$V_{storage} = 20 \cdot (20 \cdot 20 + 2600) \cdot (20 \cdot 20 + 5100) - 2.5 \cdot (20 \cdot 2.5 + 2600) \cdot (20 \cdot 2.5 + 5100) = 296 \cdot 10^6 \text{ m}^3$$

Pump capacities

In the Dutch DELTA21 design, the pumps that transport the river water from the storage lake to the sea should be able to empty the storage lake in 12 hours. With this criterion, the DELTA21 design is able to process high discharges during a longer period. Then, the capacity of DELTA21 is not limited to the storage capacity of the storage lake. For the first Bangkok design, the same criterion is applied. The required average discharge is calculated as follows:

$$Q_{avg} = \frac{\Delta V}{\Delta t} \tag{C.2}$$

where:

Q_{avg} [m^3/s] = Required average discharge
ΔV [m^3] = Volume difference
Δt [s] = Time interval

As mentioned before, $\Delta t = 12$ hours. The volume difference is $\Delta V = V_{storage} = 296 \cdot 10^6$ m^3. Using Equation C.2, the average required discharge to the Bay of Bangkok is:

$$Q_{avg} = \frac{296 \cdot 10^6}{12 \cdot 3600} = 6849 \text{ m}^3/\text{s}$$

The assumption that the lake has to be emptied in 12 hours can be checked by using the peak discharge of the Chao Phraya (6767 m^3/s), determined in Section 5.1. The time to fill the storage lake when the peak discharge occurs and the flood defense is closed is:

$$\Delta t = \frac{\Delta V}{Q_{peak}} = \frac{296 \cdot 10^6}{6767} \approx 12 \text{ h}$$

The peak discharge from Section 5.1 is almost identical to the calculated average discharge of the pumping station. Therefore, the Chao Phraya can fill the lake in the same time when the peak discharge occurs. With the average discharge, the total required pump capacity can be determined. This is done by the following formula:

$$P = \frac{Q \cdot \rho_w \cdot g \cdot \Delta H}{\eta} \tag{C.3}$$

where:

P [W] = Total required pump power
Q [m^3/s] = Discharge
ρ_w [1000 kg/m^3] = Density of water
g [9.81 m/s^2] = Gravitational acceleration
ΔH [m] = Water level difference
η [-] = Pump efficiency

The pump efficiency η is estimated to be 0.90 or 90 %. Usually, the efficiency of hydropower stations is very high, which is an important reason to choose for pumped hydropower storage. The highest water level in the storage lake is 5 m below the mean sea level and the lowest water level is 22.5 m below the mean sea level. In case of high tide, the sea level is about 1.5 m higher than the mean sea level. The design water level difference is therefore 15.25 m, based on the mean water level in the storage lake. Using Equation C.3, the required total pump capacity is:

$$P = \frac{6849 \cdot 1000 \cdot 9.81 \cdot 15.25}{0.90} = 1138 \text{ MW}$$

The same pump type as in the Netherlands is applied here with an individual pump capacity of 20 MW. The required total pump power of 1138 MW can therefore be realized with 57 pumps. The total pump capacity of 57 pumps is 1140 MW.

Energy storage profit

Based on the methodology in the report Energie (Berke & Lavooij, 2017), the yearly profit from the energy storage in the lake is calculated. The principle of the energy storage is to pump water out of the lake during off-peak hours and to sell generated energy during peak hours. The amounts of energy involving pumping and generating are calculated as follows:

$$E_{pump} = P \cdot t \tag{C.4}$$

$$E_{turbine} = \eta \cdot P \cdot t \tag{C.5}$$

where:

E_{pump} [kWh] = Energy required for pumping
$E_{turbine}$ [kWh] = Energy gained from generating
P [kW] = Total pump power
η [-] = Efficiency
t [h] = time interval

The pumps/turbines can either be used for pumping or for generating. This means that the water can be pumped to the sea during half of the year, so $t = 4380h$. The amount of used and generated energy by the pumps/turbines per year are:

$$E_{pump} = 1140 \cdot 10^3 \cdot 4380 = 4.99 \cdot 10^9 \text{ kWh}$$

$$E_{turbine} = 1140 \cdot 10^3 \cdot 4380 \cdot 0.90 = 4.49 \cdot 10^9 \text{ kWh}$$

The amount of profit from the energy storage is calculated as follows:

$$\text{Profit} = E_{turbine} \cdot p_{peak} - E_{pump} \cdot p_{off-peak} \tag{C.6}$$

where:

Profit [€/year] = Amount of profit from energy storage per year
p_{peak} [€/kWh] = Unit cost of energy during peak hours
$p_{off-peak}$ [€/kWh] = Unit cost of energy during off-peak hours

During peak hours, the energy price in Thailand is 4.12 - 4.35 baht/kWh (0.12 - 0.13 €/kWh). During off-peak hours, the Thai energy price is 2.61 - 2.66 baht/kWh (0.08 €/kWh) (Praiwan, 2018). Therefore, the amount of profit given the energy prices in Thailand has a value of:

$$\text{Profit} = 4.49 \cdot 10^9 \cdot 0.12 - 4.99 \cdot 10^9 \cdot 0.08 \approx 140 \text{ million €/year}$$

Traffic congestion

Not only flooding is a problem for Bangkok. The city is one of the world's most congested cities because of a lack of roads and traffic capacities. The severity of the traffic jams is illustrated by Figure C.5. The figure shows the traffic delays in the south of Bangkok, around the DELTA21 location. Although Figure C.5 is a snapshot, the traffic was checked multiple times on different days. With other snapshots during the evening rush hours, the same conclusions could be made from the traffic delays as presented below.

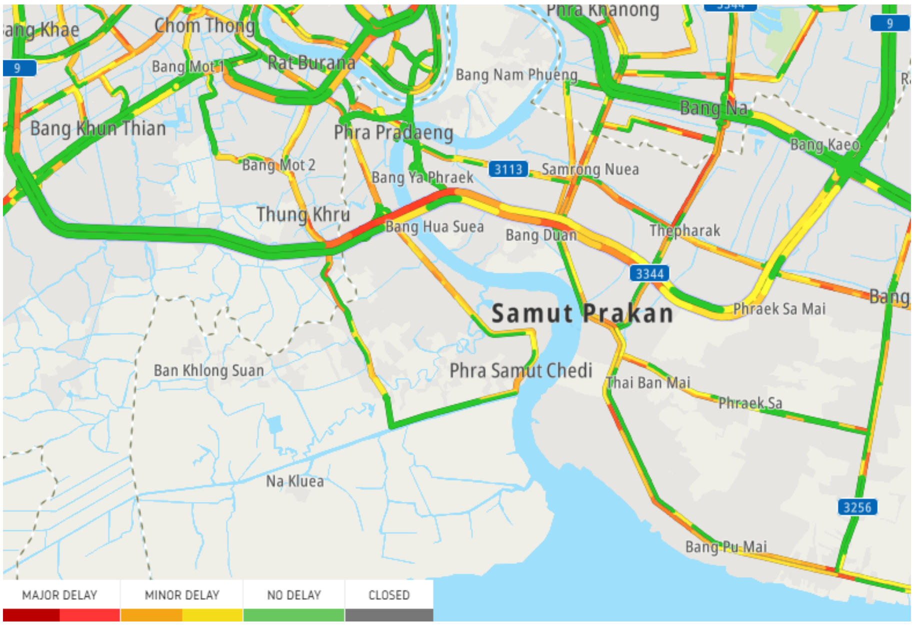


Figure C.5: Traffic congestion in south Bangkok during the evening rush hours on November 12 2019 (TomTom, 2019)

Especially the southernmost bridge over the Chao Phraya, the Kanchanaphisek Bridge, experiences high traffic intensities resulting in major traffic delays. This bridge seems to be a bottleneck in the current Bangkok traffic network. There are few alternatives to cross the Chao Phraya river south of the city centre. All the traffic with origins and destinations south of this bridge has to drive over the bridge. DELTA21 can provide a solution for this problem. It could be possible to construct a road on top of the northern dike and the ship lock (Figure C.6).

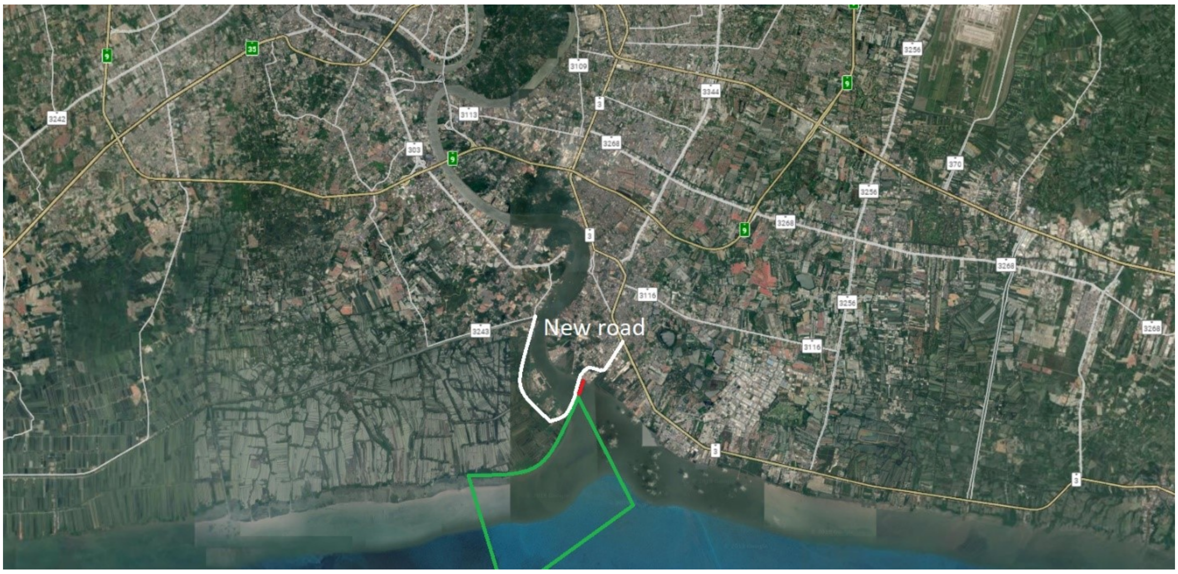


Figure C.6: New suggested road (white) as part of DELTA21 in Bangkok (dikes in green, ship lock in red)

This road serves as an alternative connection over the Chao Phraya in case of traffic delay on the Kanchanaphisek Bridge. The most convenient road type is therefore an access road, with a maximum speed limit between 50 and 80 km/h. In this area, smaller roads are already present. These roads are suitable locations for the new road, which prevents demolition of the surrounding buildings.

C.2. Lagos design

The second location for a first design of the project is Lagos (Nigeria). The main water ways through this city are part of the Lagos lagoon. Part of the discharge to this lagoon is from the Ogun river, a river that flooded recently in the more upstream city Abeokuta. However, this river does not have the right characteristics for DELTA21. Especially the width is too small. Therefore, the first design is made for another location than the river mouth. Again, this chapter consists of the most attractive location, first estimates of the dimensions of the storage lake and pump capacities and a profit estimation for the energy storage.

Lagos has especially problems regarding erosion of the coast. One of the measures against this phenomenon is the construction of Eko Atlantic. Eko Atlantic forms a neighbourhood for the richer inhabitants of Lagos. The built shoreline consists of large blocks that lower the erosion. DELTA21 can be the project that extends this shoreline protection. A major issue in the country is frequent power outage. According to data from The World Bank (2019), 78 % of the Nigerian companies experience electrical power outages, with on average 32.8 power outages in firms in a typical month. These numbers are high compared to the Thailand (the country of the first design). The energy storage function is therefore more important in Lagos.

Location

The best location for DELTA21 in Lagos is near the channel between the Lagos lagoon and the Atlantic Ocean, because the discharge in this channel has a high order of magnitude. The dikes of the storage lake should function as a flood protection, so DELTA21 must be located at the channel entrance. The main wind direction in Lagos is SW. Therefore, the west side of the channel entrance is assumed to be the most effective location considering flood protection. The other reason to choose for the west side is because of the construction of Eko Atlantic on the east side of the channel entrance. Eko Atlantic is a form of land reclamation, that suggests that sand suppletion and dredging is possible in the region. In Figure C.7, the bathymetry in the area of interest is shown. It can be observed the differences in depth are high, because of the navigation in the channel and a steep coastal slope. This is advantageous for the deep storage lake, but the surrounding dikes require more supplementation of sand.

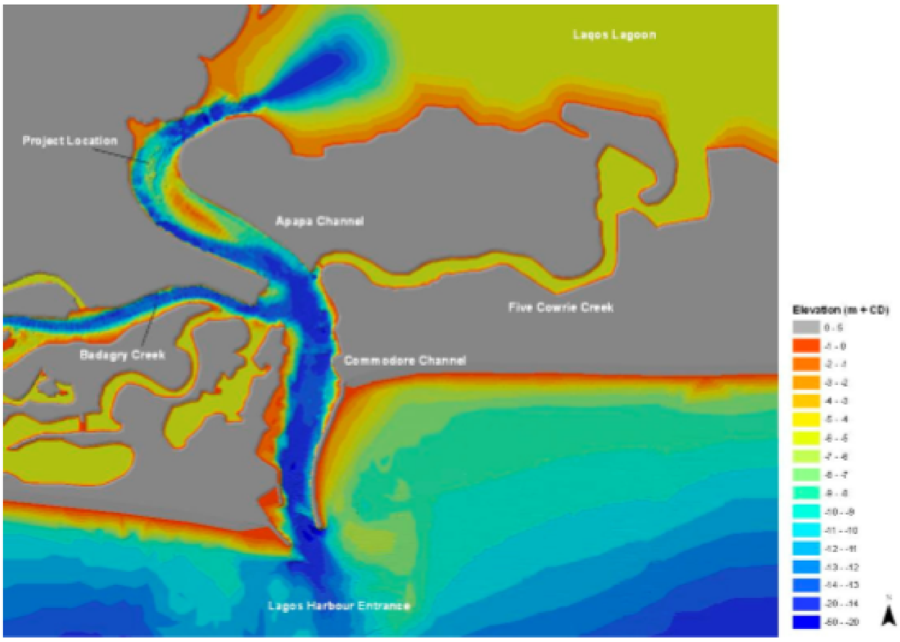


Figure C.7: Bathymetry near the coastline of Lagos and the lagoon entrance (Scholl & Reneerkens, 2011)

Dimensions of storage lake

Since the energy storage function is very important for the DELTA21 design in Lagos, the storage capacity of the storage lake should be large. Lagos has an altitude of about 40 m above the mean sea level, meaning that coastal flooding is less critical here. Because of the steep coastal slope, the lake has a more oblong shape. The locations of the dikes (in green) and the ship lock (in red) are shown in Figure C.8. This figure also includes some first dimensions. For the calculations, the simplified lake is shown in Figure C.9.

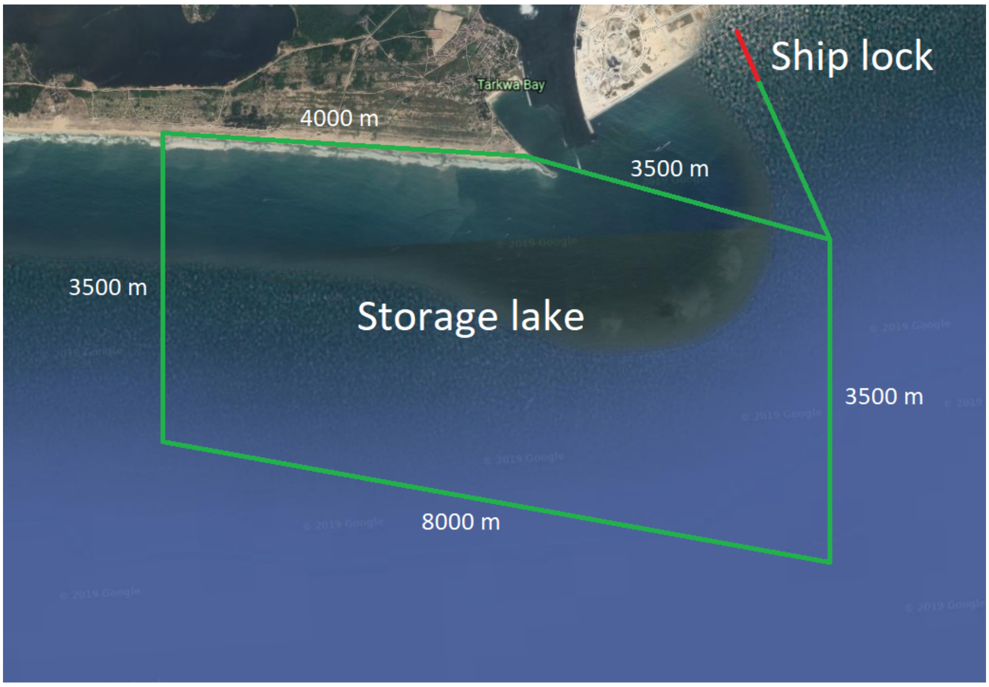


Figure C.8: First design DELTA21 in Lagos with some dimensions

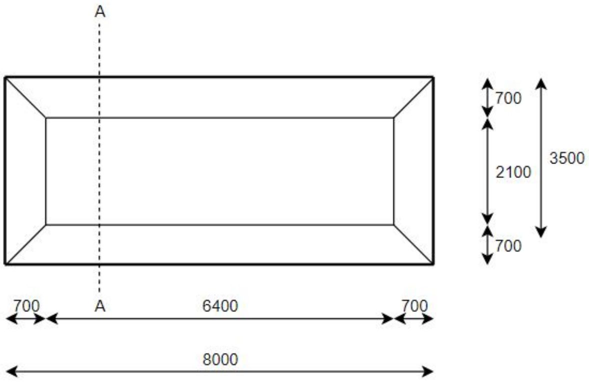


Figure C.9: Top view of the simplified lake (distances in m)

The initial assumed dike height is 5 m above the mean sea level. However, special attention should be made for the shore protection along the outer dikes of the lake. The slope of the outer dike is quite mild, to minimize the effects of plunging waves. A cross-section of the dikes and the lake is shown in Figure C.10. Again, this design is based on the Dutch design (Berke & Lavooij, 2018b). In the cross-section, an sea depth of 20 m and a lagoon depth of 10 m are assumed (based on the bathymetry from Figure C.7).

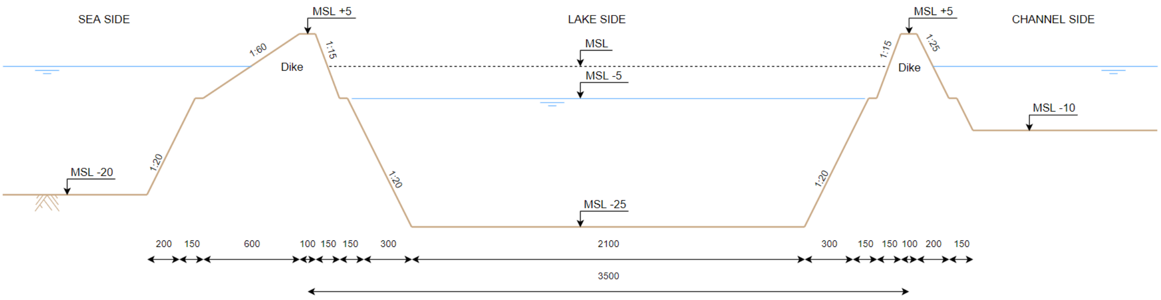


Figure C.10: Cross-section A-A: Dike profile of Lagos storage lake (distances in m)

With the first dimensions from Figures C.9 and C.10 the storage volume of the storage lake can be calculated (using Equation C.1). For a simplification of the calculations, a constant inner dike slope of 1:20 is assumed. The storage volume is the water volume difference between water levels at MSL -5.0 (V_{high}) and MSL -22.5 m (V_{low}):

$$V_{storage} = 20 \cdot (20 \cdot 20 + 6600) \cdot (20 \cdot 20 + 2100) - 2.5 \cdot (20 \cdot 2.5 + 6600) \cdot (20 \cdot 2.5 + 2100) = 314 \cdot 10^6 \text{ m}^3$$

Pump capacities

Also for the Lagos DELTA21 design, the requirement of emptying the storage lake in 12 hours time is used. With Equation C.2, this leads to the following required discharge to the ocean:

$$Q_{avg} = \frac{314 \cdot 10^6}{12 \cdot 3600} = 7274 \text{ m}^3/\text{s}$$

The assumption that the lake has to be emptied in 12 hours can be checked by using the peak discharge in the Commodore channel (10,000 m^3/s), determined in Section 5.1. The time to fill the storage lake when the peak discharge occurs and the flood defense is closed is:

$$\Delta t = \frac{\Delta V}{Q_{peak}} = \frac{314 \cdot 10^6}{10,000} \approx 9 \text{ h}$$

The peak discharge from Section 5.1 is higher than the found required discharge from the lake to the ocean. This is assumed to be non-problematic, because the probability of flooding of the channel is low (since Lagos has an altitude of about 41 m above the mean sea level). With the average discharge, the total required pump capacity can be determined. Since the lagoon is brackish, the salinity of the water is assumed high. This means that the density of the water here is about 1025 kg/m^3. The highest water level in the storage lake is 5 m below the mean sea level and the lowest water level is 22.5 m below the mean sea level. In case of high tide, the sea level is about 0.5 m higher than the mean sea level. The design water level difference is therefore 14.25 m, based on the mean water level in the storage lake. Using Equation C.3, the required total pump capacity is:

$$P = \frac{7274 \cdot 1025 \cdot 9.81 \cdot 14.25}{0.90} = 1158 \text{ MW}$$

The same pump type as in the Netherlands is applied here with an individual pump capacity of 20 MW. The required total pump power of 1158 MW can therefore be realized with 58 pumps. The total pump capacity of those pumps is 1160 MW.

Energy storage profit

Like for the design in Bangkok, the yearly profit from the energy storage in the lake is calculated. The principle of the energy storage is to pump water out of the lake during off-peak hours and to sell generated energy during peak hours. The pumps/turbines can either be used for pumping or for generating. This means that the water can be pumped to the sea during half of the year, that is 4380 hours. With Equations C.4 and C.5, the amount of used and generated energy by the pumps/turbines per year are:

$$E_{pump} = 1160 \cdot 10^3 \cdot 4380 = 5.08 \cdot 10^9 \text{ kWh}$$

$$E_{turbine} = 1160 \cdot 10^3 \cdot 4380 \cdot 0.90 = 4.57 \cdot 10^9 \text{ kWh}$$

In Nigeria, the electricity prices are relatively low. There are no peak and off-peak prices in the country yet. In the future, those prices might be introduced in Nigeria. For the future scenario, the peak and off-peak electricity prices in Cameroon are used. This neighbouring country has a comparable average electricity price. In Cameroon, the peak electricity price is 85 XAF/kWh (0.13 €/kWh) and the off-peak price is 60 XAF/kWh (0.09 €/kWh) (GET.invest, 2012). For the profit calculation, Equation C.6 is used. The amount of profit per year given the energy prices in Cameroon has a value of:

$$\text{Profit} = 4.57 \cdot 10^9 \cdot 0.13 - 5.08 \cdot 10^9 \cdot 0.09 \approx 142 \text{ million €/year}$$

Although the amount of profit per year is not much higher than for the design in Bangkok, the energy storage is more important in the Lagos design. Therefore, the question is whether this design has enough benefits. Most benefits in the Dutch design come from savings on dike reinforcements. In Lagos, such plans are not yet published. Future land-protecting projects are expected to be meant against sea level rise, one of the threats of Lagos (Appendix A).

C.3. New Orleans design

The final city that is analysed more in-depth is New Orleans (USA). Despite many engineering projects along the Mississippi river, the chances of a big flooding are still not negligible. The order of magnitude of the peak discharge shows that such events would have an enormous impact on New Orleans. In the following sections, a first design for a project like DELTA21 is presented. This design contains the exact location, storage lake sizes and required pump capacities.

New Orleans is not only located along one of the worlds largest rivers, but has also very low altitudes relative to the sea level. Some neighbourhoods of the city lie several meters below the sea level, like many cities in the Netherlands. Living here is made possible by many engineering projects. In fact, the city is also a form of land reclamation. One of those is the construction of the Lake Borgne Surge Barrier northeast of the city. This barrier was built after the catastrophic consequences of hurricane Katrina in 2005. This structure should be able to protect the city against a new hurricane.

Location

Since the mouth of the main Mississippi River is more than 100 km downstream of New Orleans, a different location for DELTA21 is considered. The location of interest is next to the existing IHNC Lake Borgne Surge Barrier (Figure C.11). A smaller branch of the Mississippi river is connected to lake Borgne here. The bathymetry of the lake is shown in Figure C.12.

Figure C.11: Location of the DELTA21 design in New Orleans

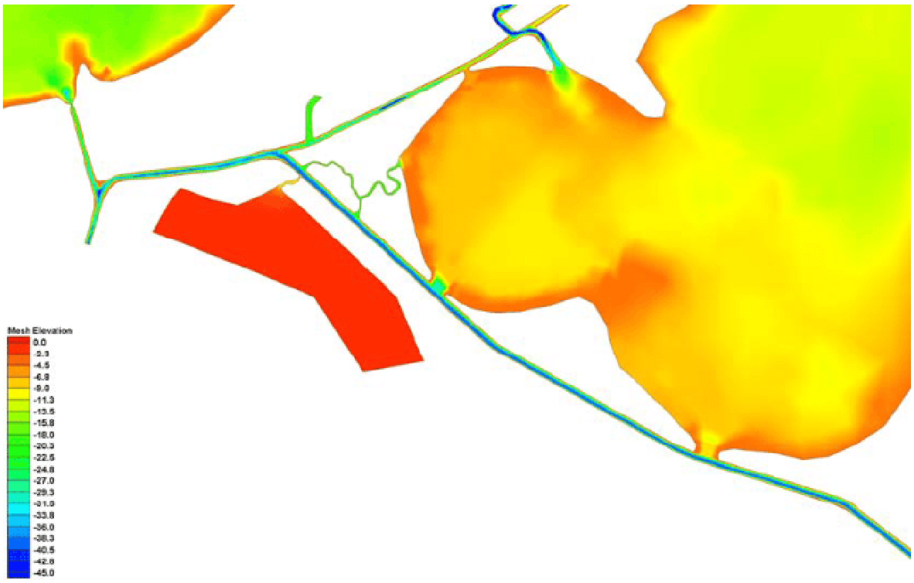


Figure C.12: Bathymetry of Lake Borgne and surroundings (Martin, McAlpin, & McVan, 2010)

Dimensions of storage lake

Figure C.13 shows the first design with some dimensions of DELTA21 in New Orleans. The storage lake is located in a current swamp, where the altitude is about equal to the mean sea level. Once again, the shape of the storage lake is simplified. The top view of the simplified lake is shown in Figure C.14.

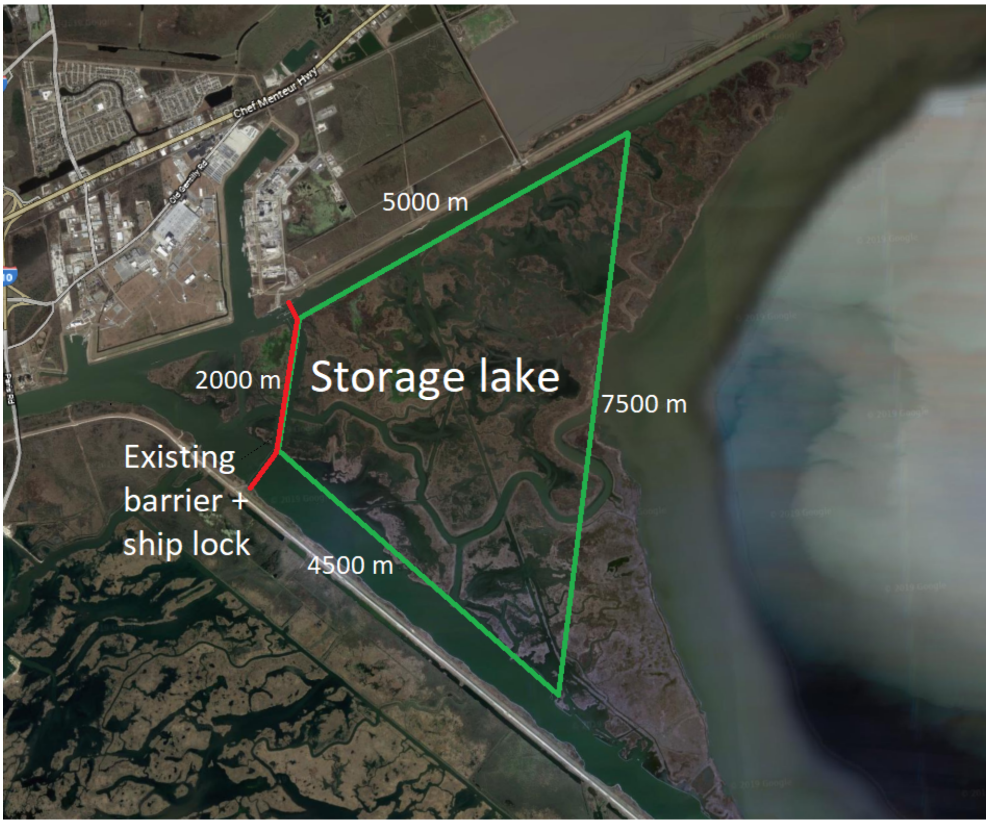


Figure C.13: First design DELTA21 near New Orleans with some dimensions

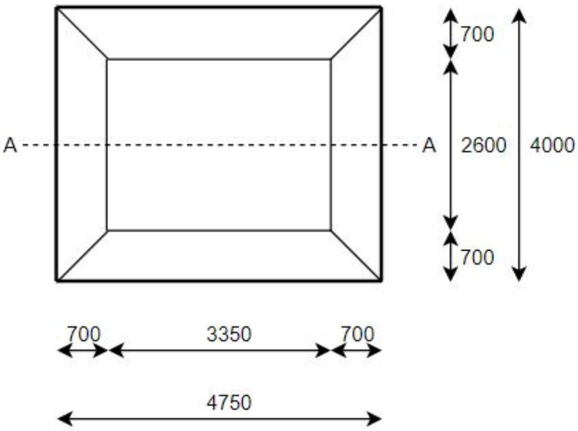


Figure C.14: Top view of the simplified lake (distances in m)

Lake Borgne has a mean depth of approximately 10 meters. The depth of the river/canals near the barrier is 15 meters. The top of the barrier is at MSL +7 m, which is slightly higher than the top of the smaller dikes (at MSL +5 m). The top of larger dike, on the west side of the storage lake, is estimated at MSL +10 m. The altitude of New Orleans is namely comparable to Dutch altitudes, where the same dikes are used. Hurricanes are present in the area, but probabilities of failure are accepted in the USA. Figure C.15 shows a cross-section

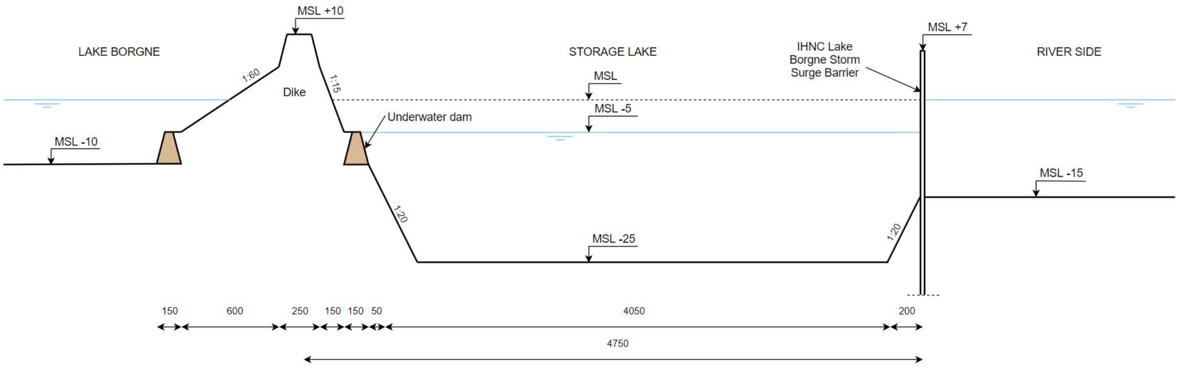


Figure C.15: Cross-section A-A: Dike profile of New Orleans storage lake (distances in m)

The storage capacity of the lake can be calculated based on the first dimensions given in Figure C.14 and C.15. For a simplification of the calculations, a constant inner dike slope of 1:20 is assumed. With Equation C.1, the storage volume is the water volume difference between water levels at MSL -5.0 (V_{high}) and MSL -22.5 m (V_{low}):

$$V_{storage} = 20 \cdot (20 \cdot 20 + 2600) \cdot (20 \cdot 20 + 3350) - 2.5 \cdot (20 \cdot 2.5 + 2600) \cdot (20 \cdot 2.5 + 3350) = 202 \cdot 10^6 \text{ m}^3$$

Pump capacities

Also for the New Orleans DELTA21 design, the requirement of emptying the storage lake in 12 hours time is used. Using Equation C.2, this leads to the following required discharge to the ocean:

$$Q_{avg} = \frac{202 \cdot 10^6}{12 \cdot 3600} = 4687 \text{ m}^3/\text{s}$$

The assumption that the lake has to be emptied in 12 hours can be checked by using the peak discharge in the branch of the Mississippi river. The peak discharge in the Mississippi river is 42,253 m^3/s, determined in Section 5.1. The width of the branch is about one third of the with of the Mississippi and approximately one third of the branch flows into lake Pontchartrain instead of lake Borgne. An estimate of the discharge near the storage lake is then $Q_{peak} = \frac{1}{4} \cdot \frac{2}{3} \cdot 42,253 = 7042 \text{ m}^3/\text{s}$. The time to fill the storage lake when the peak discharge occurs and the flood defense is closed is:

$$\Delta t = \frac{\Delta V}{Q_{peak}} = \frac{202 \cdot 10^6}{7042} \approx 8 \text{ h}$$

The peak discharge is higher than the found required discharge from the storage lake to lake Borgne. When the peak discharge occurs during a longer period, this design is not able to process the river water. To get an idea of the critical period that the river discharge exceeds the pump discharge, a graph is made. This graph is a critical discharge recording for which the entire storage lake is filled. Just at that moment, the discharge returns to non-critical values and the lake can be emptied. The assumed shape of the (Q,t)-curve is parabolic and has the following formula:

$$Q(t) = a \cdot t^2 + b \tag{C.7}$$

This formula should give the discharge difference between the occurring discharge trough the Mississippi branch and the pump discharge to Lake Borgne. In other words, the value of $Q(t)$ gives the rate of change of the available storage volume in the storage lake. The pump discharge is $Q_{pump} = 4687 \text{ m}^3/\text{s}$. In order to find the parameters a and b, two equations are needed. First of all, at the top of the curve, the discharge should be equal to the maximum difference. That is the peak discharge ($Q_{peak} = 7042 \text{ m}^3/\text{s}$) minus the pump discharge. Second, the area under the (Q,t)-curve between the time moments that $Q(t) = 0$ is equal to the storage capacity, $V_{storage} = 202 \cdot 10^6 \text{ m}^3$. These equations are as follows:

$$Q(t = 0) = Q_{peak} - Q_{pump} = 7042 - 4687 = 2355 \text{ m}^3/\text{s} \tag{C.8}$$

$$\int_{t_1}^{t_2} Q(t)\,\mathrm{d}t = V_{storage} = 202 \cdot 10^6\ \mathrm{m}^3 \tag{C.9}$$

For the second equation, the definition of the zero-crossing points t_1 and t_2 is:

$$t_{1,2} = \pm\sqrt{-\frac{b}{a}}$$

Application of Equations C.8 and C.9 leads to $a = -7.34$ and $b = 2355$. This results in the following (Q,t)-relation:

$$Q(t) = -7.34 \cdot t^2 + 2355 \tag{C.10}$$

For the output graph, the found relation in Equation C.10 is converted back to total discharges. This is done by adding the pump discharge to the relation. Then, the times are converted from seconds to hours. The chosen point of the origin is moved to the left, so that the peak discharge occurs at $t = 20$ h. The resulting graph is shown in Figure C.16.

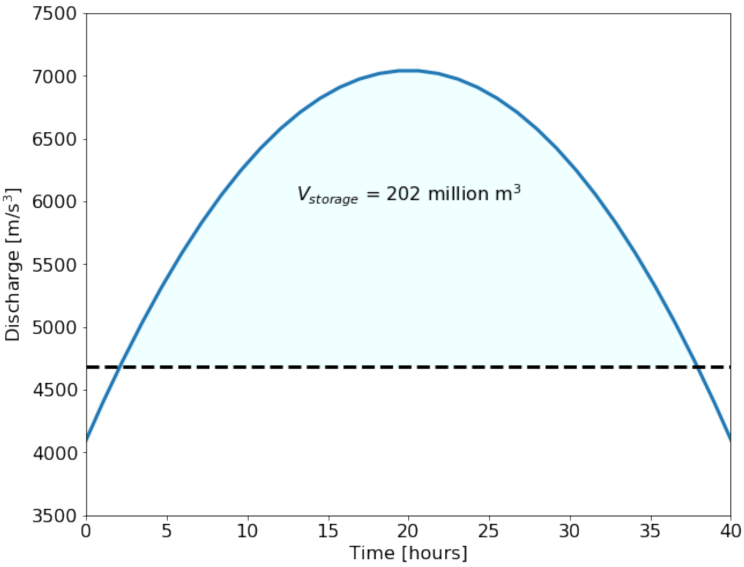


Figure C.16: Critical situation: the river discharge is higher than the pump discharge

From the graph it can be concluded that the critical period of the river discharge being higher than the pump discharge is about 37 hours. In terms of peak discharge graphs, that period is quite short.

Using the earlier determined average discharge, the total required pump capacity can be determined. The Mississippi contains fresh water, so the water density is assumed to be 1000 kg/m^3. The highest water level in the storage lake is 5 m below the mean sea level and the lowest water level is 22.5 m below the mean sea level. In case of high tide, the sea level is about 0.25 m higher than the mean sea level. The design water level difference is therefore 14.0 m, based on the mean water level in the storage lake. Using Equation C.3, the required total pump capacity is:

$$P = \frac{4687 \cdot 1000 \cdot 9.81 \cdot 14.0}{0.90} = 715\ \mathrm{MW}$$

The same pump type as in the Netherlands is applied here with an individual pump capacity of 20 MW. The required total pump power of 715 MW can therefore be realized with 36 pumps. The total pump capacity of 36 pumps is 720 MW.

Energy storage profit

With the same methodology as the other two designs, the yearly profit from the energy storage in the lake is calculated. Again, Equations C.4 and C.5 are used. The amounts of used and generated energy by the pumps/turbines per year are:

$$E_{pump} = 720 \cdot 10^3 \cdot 4380 = 3.15 \cdot 10^9 \text{ kWh}$$

$$E_{turbine} = 720 \cdot 10^3 \cdot 4380 \cdot 0.90 = 2.83 \cdot 10^9 \text{ kWh}$$

In Louisiana there is currently no peak and off-peak electricity price yet. However, it is likely that those prices will exist in the future. For the first calculation, the electricity prices in California are used. The peak price in California is 0.286 $/kWh (0.26 €/kWh) and the off-peak price is 0.235 $/kWh (0.21 €/kWh) (Pacific Gas and Electric, 2019). With Equation C.6, the amount of profit per year given the energy prices in California has a value of:

$$\text{Profit} = 2.83 \cdot 10^9 \cdot 0.26 - 3.15 \cdot 10^9 \cdot 0.21 \approx 75.7 \text{ million €}$$

Important in the calculations is that there is also a partial-peak energy price in California. Using or generating energy in the partial-peak periods results in more costs. Compared to the other designs, it is the question whether this storage lake is able to make profit by using the different energy prices.

Alternative design

From Figure C.16 it can be observed that the first design is limited in the process of peak discharges during a longer period. More pumps are needed than assumed or the depth of the lake must be increased. Furthermore, the orientation of the area west of the barrier looks convenient for a different kind of storage lake. The alternative design covers a larger area and is shown in Figure C.17 with the main dimensions. For the calculations, the lake was simplified to the shape shown in Figure C.18.

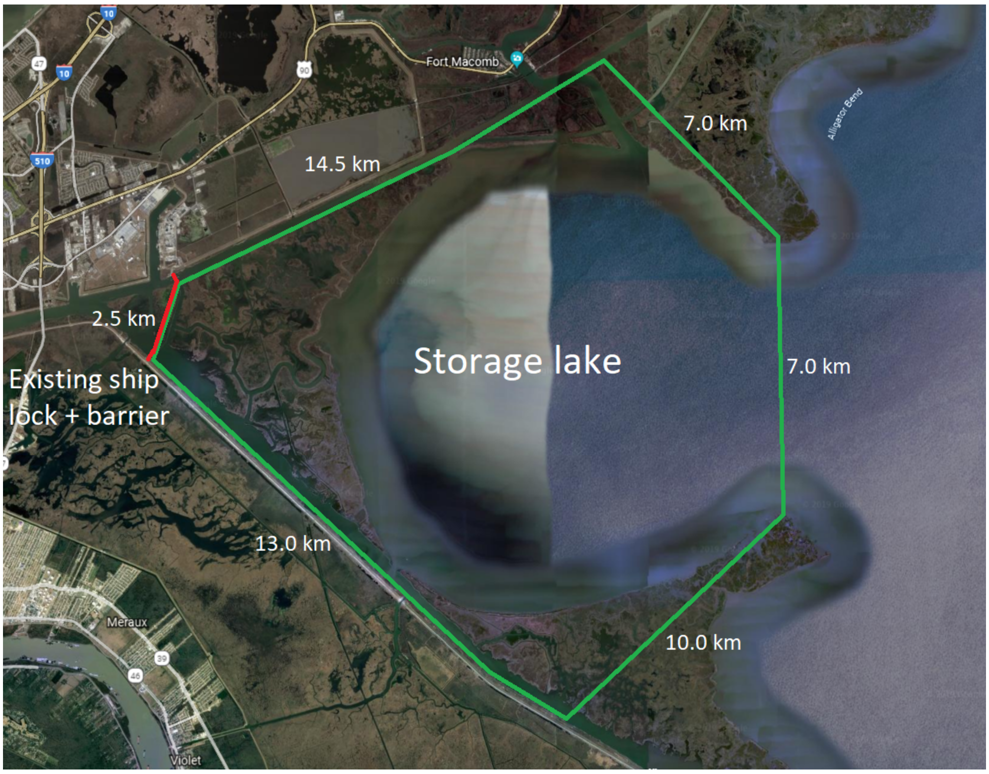


Figure C.17: Alternative design of DELTA21 in New Orleans with some dimensions

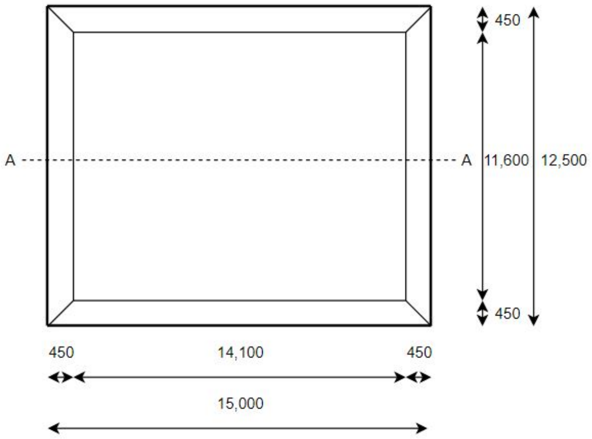


Figure C.18: Top view of the simplified lake of the alternative design (distances in m)

The large area of this storage lake implies that a smaller depth is needed for comparable storage volumes as for the other designs. The bottom of the lake is at MSL -12.5 m, with water levels between MSL -10 m and MSL -5 m. Like in the first design, the top of the dike is at MSL +10 m. The resulting dike profile is shown in Figure C.19.

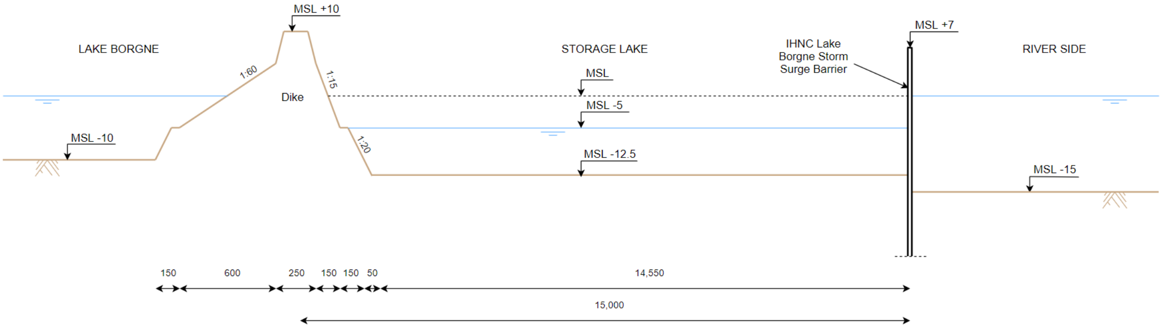


Figure C.19: Cross-section A-A: Dike profile of alternative New Orleans storage lake (distances in m)

Once again, the storage capacity of the lake can be calculated based on the first dimensions given in Figure C.18 and C.19 with Equation C.1 and a dike slope of $i = 1:20$:

$$V_{storage} = 20 \cdot (20 \cdot 20 + 2600) \cdot (20 \cdot 20 + 3350) - 2.5 \cdot (20 \cdot 2.5 + 2600) \cdot (20 \cdot 2.5 + 3350) = 780 \cdot 10^6 \text{ m}^3$$

Still, the storage volume is much larger compared to the other designs. Decreasing the depth even further is unbeneficial, because the current ground level in the area is about MSL -10 m. When the lake is emptied in 12 hours time, the average discharge from the storage lake to Lake Borgne with Equation C.2 is:

$$Q_{avg} = \frac{780 \cdot 10^6}{12 \cdot 3600} = 18,048 \text{ m}^3/\text{s}$$

Given the peak discharge of $Q_{peak} = 7042 \text{ m}^3/\text{s}$, it is not necessary to design the pumps based on the emptying criterion. Therefore, the peak discharge is taken as the required average discharge. The time to fill the storage lake when this peak discharge occurs is:

$$\Delta t = \frac{\Delta V}{Q_{peak}} = \frac{780 \cdot 10^6}{7042} \approx 31 \text{ h}$$

The resulting time is quite long, so the lake is even able to process discharges with higher return periods. Using Equation C.3 and the same values for η and ρ as for the first design and an average water level difference of 7.75 m (including 0.25 m tidal set-up), the required power of the pump station is:

$$P = \frac{7042 \cdot 1000 \cdot 9.81 \cdot 7.5}{0.90} = 595 \text{ MW}$$

Given the required total pump capacity, 30 pumps are used, leading to a total pump capacity of 600 MW. The energy amounts of pumping and generating per year can be calculated again with Equations C.4 and C.5 and result in $E_{pump} = 2.63 \cdot 10^9$ kWh and $E_{turbine} = 2.37 \cdot 10^9$ kWh. Based on the energy prices in California and Equation C.6, the profit per year is then:

$$\text{Profit} = 2.37 \cdot 10^9 \cdot 0.26 - 2.63 \cdot 10^9 \cdot 0.21 \approx 63.1 \text{ million €/year}$$

The amount of profit from the energy storage is less than for the first design. Less pumps are needed here, but the amount of pumps can be increased if more energy storage profit is desired.

D

Multi Criteria Analysis

This appendix contains the reasons for the presented grades of the multi criteria analysis in Chapter 7.. The grades that were given are integer numbers between 1 and 5. Thereafter, the grades were multiplied with the weight factor of the criterion. The determination of the weight factors is given in Table D.1. The weight factors are calculated as follows:

$$\mathrm{WF}_i = \frac{S_i + 1}{\Sigma(S_i + 1)} \tag{D.1}$$

where:

WF_i = Weight factor of criterion i
S_i = Total score of criterion i, from Table D.1

Table D.1: Weight factor determination for the criteria

	Space for the project	**Coast type**	**Threats or opportunities**	**Profits**
Space for the project		1	1	1
Coast type	0		1	1
Threats or opportunities	0	0		1
Profits	0	0	0	
Total	0	1	2	3
WF	0.1	0.2	0.3	0.4

Table D.2 gives the explanations for the given grades. Per criterion, location descriptions are given that lead to a score between 1 and 5. The grades were given by comparing the cities to the given descriptions.

In Table D.2, the weighted threat sum is mentioned as a reference for the threat criterion grading. The explanation of this is given in Table D.3, where the weighted threat sum is calculated for the cities. The threats are counted using Tables A.1, A.2, A.3, A.4 and A.5 from Appendix A. Then, the weighted threat score is found by summing up the weighted threats. The weight per threat type is shown at the top of the table.

Table D.2: Grade specifications for the multi criteria analysis

Criterion	**Score = 1**	**Score = 2**	**Score = 3**	**Score = 4**	**Score = 5**	**WF**
Space for the project	Estimated space is less than 10 km^2	Estimated space is 10-30 km^2	Estimated space is about 30 km^2 (like in the Netherlands)	Estimated space is 30-100 km^2	Estimated space is more than 100 km^2	0.1
Coast type	Rocky coast types with steep slopes, close to a plate border	Other non-beneficial coast types, such as karst coasts or archeic coasts	River dominated delta coasts	Lagoon coasts	Sandy, mildly sloped estuary coasts far from plate borders	0.2
Threats or opportunities in the city	Weighted threat sum is lower than 2	Weighted threat sum is 2-6	Weighted threat sum is 7-11	Weighted threat sum is 12-16	Weighted threat sum is higher than 16	0.3
Profits	No present flood protections or plans for constructing flood protections. The discharge variation of the river is low.	Flood protections are present, but there are no plans for constructing new flood protections or reinforcing existing protections. The discharge variation of the river is quite low.	No present flood protections, but there are future plans for constructing flood protections. The discharge variation of the river is around the average of the considered rivers.	Flood protections are present. Plans for new flood protections and reinforcement of current protections have an estimated cost lower than in the Netherlands (300 million €/year, € 2.1 billion in 2100). The discharge variation of the river is quite high.	Flood protections are present. Plans for new flood protections and reinforcement of current protections have an estimated cost higher than in the Netherlands (300 million €/year, € 2.1 billion in 2100). The discharge variation of the river is high.	0.4

Table D.3: Weighted threat scores per city

City	**(* 3) Flooding threats**	**(* 2) Energy threats**	**(* 1) Secondary function threats**	**(* 2) Future threats**	**(* -2) Unfavourable threats**	**Weigthed threat score**
Accra, Ghana	2	0	2	0	1	**6**
Bangkok, Thailand	2	0	2	0	0	**8**
Barcelona, Spain	2	0	1	0	0	**7**
Belfast, United Kingdom	1	0	2	0	1	**3**
Berkeley, USA	3	1	3	1	1	**14**
Boston, USA	4	0	2	1	0	**16**
Bristol, United Kingdom	1	1	3	0	0	**8**
Buenos Aires, Argentina	1	0	2	0	0	**5**
Can Tho, Vietnam	2	0	1	1	0	**9**
Chennai, India	1	0	2	0	0	**5**
Chicago, USA	2	0	2	0	0	**8**
Christchurch, New Zealand	2	0	1	1	0	**9**
Durban, South Africa	1	0	1	0	0	**4**
Houston, USA	3	0	1	0	0	**10**
Jakarta, Indonesia	2	0	0	0	1	**4**
Lagos, Nigeria	1	1	1	1	0	**8**
Lisbon, Portugal	1	0	2	1	2	**3**
London, United Kingdom	2	0	1	0	0	**7**
Los Angeles, USA	1	0	3	0	2	**2**
Melbourne, Australia	2	0	2	1	0	**10**
Montevideo, Uruguay	1	0	1	1	0	**6**
New Orleans, USA	4	0	3	2	0	**19**
New York, USA	3	1	3	1	0	**16**
Norfolk, USA	5	0	0	2	0	**19**
Oakland, USA	3	0	2	1	1	**11**
Paynesville, Liberia	1	0	1	0	0	**4**
Porto Alegre, Brazil	1	0	0	0	2	**-1**
Rome, Italy	2	0	1	1	1	**7**
Salvador, Brazil	1	0	0	0	0	**3**
San Francisco, USA	1	0	4	1	1	**7**
Singapore, Singapore	2	0	0	1	0	**8**
Surat, India	0	0	2	1	0	**4**
Sydney, Australia	0	0	1	0	0	**1**
Thessaloniki, Greece	1	2	1	0	1	**6**
Toyama, Japan	2	0	0	1	1	**6**
Vancouver, Canada	0	0	2	1	1	**2**

References

100 Resilient Cities. (2019). *Cities Archive.* Retrieved 16-09-2019, from `https://www.100resilientcities.org/cities/`

Berke, L., & Lavooij, H. (2017). *DELTA21 en Energie* (Tech. Rep. No. Deelstudie 2). DELTA21.

Berke, L., & Lavooij, H. (2018a). *DELTA21 en Natuurherstel* (Tech. Rep. No. Deelstudie 3). DELTA21.

Berke, L., & Lavooij, H. (2018b). *DELTA21 en Waterveiligheid* (Tech. Rep. No. Deelstudie 1). DELTA21.

Environment Canterbury. (2019). *Water - River stage flow data for individual site.* Retrieved 15-10-2019, from `http://data.ecan.govt.nz/Catalogue/Method?MethodId=79&SiteNo=66401#tab-data`

Fastenrath, S., Acuto, M., Coenen, L., & Keele, S. (2019). *What next after 100 Resilient Cities funding ends?* Retrieved 07-10-2019, from `http://theconversation.com/what-next-after-100-resilient-cities-funding-ends-116734`

GET.invest. (2012). *Cameroon, Energy Sector.* Retrieved 8-11-2019, from `https://www.get-invest.eu/market-information/cameroon/energy-sector/`

Martin, S. K., McAlpin, T. O., & McVan, D. C. (2010). *Hydrodynamic and Salinity Analysis of Conceptual Surge Barrier Designs in the Lake Pontchartrain Region* (Tech. Rep. No. ERDC/CHL TR-10-9). US Army Corps of Engineers.

Mekong River Commission. (2009). *Historical and Time Series Data.* Retrieved 15-10-2019, from `http://portal.mrcmekong.org/charts/chart`

Melbourne Water. (2019). *Rainfall and river levels.* Retrieved 15-10-2019, from `https://www.melbournewater.com.au/water/rainfall-and-river-levels#/reader/229143B`

National River Flow Archive. (2018). *NRFA Station Peak Flow Data for 53018 - Avon at Bathford.* Retrieved 15-10-2019, from `https://nrfa.ceh.ac.uk/data/station/peakflow/53018`

Pacific Gas and Electric. (2019). *Time-of-Use rate plans.* Retrieved 8-11-2019, from `https://www.pge.com/en_US/small-medium-business/your-account/rates-and-rate-options/time-of-use-rates.page`

Phamornpol, K. (2012). Flood Mitigation and Management in Bangkok Metropolitan Area. *Bangkok Metropolitan Administration.*

Praiwan, Y. (2018). *ERC launches off-peak power stimulus effort, Large factories targeted to reduce energy load.* Retrieved 29-10-2019, from `https://www.bangkokpost.com/business/1483185/erc-launches-off-peak-power-stimulus-effort`

Scholl, O., & Reneerkens, M. (2011). *Oando Jetty design conditions, Apapa Nigeria* (Tech. Rep. No. Project number 9W6386.21). Royal HaskoningDHV.

Thai Royal Irrigation Department. (2004). *River Discharge Observation: Daily Data.* Retrieved 14-10-2019, from `http://hydro.iis.u-tokyo.ac.jp/GAME-T/GAIN-T/routine/rid-river/disc_d.html`

The World Bank. (2019). *World Bank Open Data.* Retrieved 8-11-2019, from `https://data.worldbank.org/`

TomTom. (2019). *Bangkok traffic report.* Retrieved 12-11-2019, from `https://www.tomtom.com/en_gb/traffic-index/bangkok-traffic`

USGS. (2005). *Peak Streamflow for the Nation, USGS 05536995 Chicago Sanitary and Ship Canal at Romeoville, IL.* Retrieved 10-10-2019, from `https://nwis.waterdata.usgs.gov/usa/nwis/peak/?site_no=05536995`

USGS. (2017a). *Peak Streamflow for the Nation, USGS 02037500 James River near Richmond, VA.* Retrieved 10-10-2019, from `https://nwis.waterdata.usgs.gov/usa/nwis/peak/?site_no=02037500`

USGS. (2017b). *Peak Streamflow for the Nation, USGS 08074000 Buffalo Bayou at Houston, TX.* Retrieved 10-10-2019, from `https://nwis.waterdata.usgs.gov/usa/nwis/peak/?site_no=08074000`

USGS. (2017c). *Peak Streamflow for the Nation, USGS 11389500 Sacramento River at Colusa, CA.* Retrieved 10-10-2019, from `https://nwis.waterdata.usgs.gov/usa/nwis/peak/?site_no=11389500`

USGS. (2018a). *Peak Streamflow for the Nation, USGS 01104500 Charles River at Waltham, MA.* Retrieved 10-10-2019, from `https://nwis.waterdata.usgs.gov/nwis/peak?site_no=01104500`

USGS. (2018b). *Peak Streamflow for the Nation, USGS 01358000 Hudson River at Green Island, NY.* Retrieved 10-10-2019, from `https://nwis.waterdata.usgs.gov/usa/nwis/peak/?site_no=01358000`

USGS. (2018c). *Peak Streamflow for the Nation, USGS 07374525 Mississippi River at Baton Rouge, LA.* Retrieved 10-10-2019, from `https://nwis.waterdata.usgs.gov/usa/nwis/peak/?site_no=07374000`

Wallpaper Flare. (n.d.). *HD wallpaper: Bangkok In Twilight Cityscape Chao Phraya River In Thailand.* Retrieved 11-12-2019, from `https://www.wallpaperflare.com/bangkok-in-twilight-cityscape-chao-phraya-river-in-thailand-ultra-hd-wallpapers-for-desktop-mobile-phones-and-laptop-3840x2160-wallpaper-sinua`

World Population Review. (2019). *World City Populations 2019.* Retrieved 18-11-2019, from `http://worldpopulationreview.com/world-cities/`

Yua, X., Guoa, X., Morimotoa, A., & Buranapratheprat, A. (2018). Simulation of river plume behaviors in a tropical region: Case study of the Upper Gulf of Thailand. *Continental Shelf Research*(153), 16-29.