Tidal energy generation in Kalpasar

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by

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Preface

The thesis culminates my work in the field of tidal energy in order to complete my masters degree in Sustainable Energy Technology at TU Delft.

These last few months have quite easily been the biggest learning experience of my life, requiring me to constantly keep out of the comfort zone of what I knew before. The knowledge, the skills and the work ethic required in this work have made me grow as an engineer and as a person.

There are several people I would like to thank for helping me reach this point. First of all I would like to thank my committee for all the guidance they have provided in these months. Prof. Aarninkhoff, thank you so much for being so involved and providing your insights into the work during our meetings. Jeremy and Antonio, you have been excellent in supervising me and helping me at every stage of the work and I am very grateful. Christof, thank you for all your help in the turbines and also for all the feedback during our meetings.

I would also like to acknowledge Royal HaskoningDHV where I have worked for the duration of my thesis, especially the Rivers and Coasts Department. Thank you Michel for providing me this opportunity helping me throughout. Thank you to all my colleagues at office for helping me and providing a wonderful environment to work in. I would also like to thank Anton from Deltares, for your insights into Delft 3D modeling process.

Nothing is complete without thanking my family and my friends. The support has been tremendous and all the small and long talks have helped keep me motivated in this long and arduous journey.

Lastly, a special mention to Han and Rene, my two teammates in this Kalpasar project. We have had a wonderful time together and I am forever thankful for your help in making me understand this unfamiliar world of hydraulic engineering.

Dhruv Rajeev
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Abstract

In the future, two enormous challenges face humanity: decreasing the carbon emissions to mitigate the effects of climate change and supporting the growing energy demands in the developing regions of the world. These challenges highlight the need for a greater amount of implementation of renewable energy projects. This thesis tackles one such potential project, a tidal barrage power plant based in the Gulf of Khambhat off the Western coast of India.

For decades, a large multidisciplinary project in the Gulf of Khambhat has been considered, named the Kalpasar project. The project involves the closure of a part of the gulf, for multiple purposes such as freshwater storage, land reclamation etc. However there has been little progress in the last 20 years and multiple changes have been made to the initial design. Royal HaskoningDHV has been involved with the project and in 2017 created a research team to work on the various challenges being faced in the project. This research involves the modeling of the tidal energy generation component of the Kalpasar project.

The Gulf of Khambhat has a high tidal range of 8-11 m, and with the size of the tidal basin, a large amount of energy is theoretically available. However, only a fraction of this energy is expected to be extractable. A focus was placed on modeling the entire operation of the tidal barrage power plant and understanding the interactions of the local regime with the power plant.

Two operation modes were looked at for the tidal power plant: Ebb generation mode and 2 way generation mode. To simulate the operation of the power plant, a two dimensional (2D) model was created on Delft 3D to calculate the hydrodynamics of the flow passing in/out of the tidal basin, which factored the various elements such as the tidal constituents, the bathymetry and the location of the dam. Furthermore, the model required a user-defined input discharge in the form of a time series in order to simulate the opening and closing of the dam and account for the resistance to flow provided by the turbines.

A zero dimensional (0D) model is also created in order to compare against the 2D model and thus ascertain how the local conditions (the bathymetry) of the system can influence the tidal energy generation.

Based on the simulations, several details about the tidal barrage power plant could be ascertained. 2 possible locations are available for placing the turbines, where sufficient depths are present. The locations vary in the resultant tidal range available and also in the way the discharge empties/fills the basin. Based on the tidal range alone, the location on the far-right of the tidal basin is deemed ideal. The turbine's resistance to the flow also influenced the energy generation of the power plant. This influence was compared to the case without any resistance, and it was shown that in some scenarios, the resistance provided a positive influence on the energy generation. It was also shown that the barrage itself increases the tidal range available at the site.

The 2 biggest differences between the 2D and the 0D models were the shallowness of the basin and the presence of the tidal flats. These two factors negatively impact the energy generation in the area. The tidal flats in particular act as an obstruction to the flow, preventing a uniform filling and emptying of the basin during operation. The effects of these tidal flats are more pronounced as the water levels during operation drop. Due to this, a greater amount of energy is lost in the 2 way generation mode.

The removal of these tidal flats by dredging would create a more uniform depth withing the basin and would lead to a higher energy generation, with upto 34% increase seen in the

2 way generation scenarios.

Limitations remain in the models created and the representation of the flow. However, under conditions where there is no major obstruction to the flow as the basin empties and fills during operation, the 2D models can be used for calculating the energy generation. In the case of the Kalpasar project, this meant the 3 Ebb generation scenarios.

Further, the strengths of the 2D modeling process was seen. For any future tidal resource assessment, not modeling the local conditions could provide highly inaccurate values of the energy generation possible.

Contents

List of Symbols

Symbol	Unit	Description
A_{cross}	$[m^2]$	Turbine cross section area
A_{sluice}	$[m^2]$	Sluice opening area
A	$[m^2]$	Basin surface area
C_d	[-]	Discharge coefficient
D	[m]	Turbine diameter
e	[J]	Energy generation in 1 timestep
E	[J]	Energy generation
E_{year}	[GWh/yr]	Energy generation in a year
E_{max}	[GWh/yr]	Maximum energy generation in a year
E_{0D}	[GWh/yr]	Energy generation based on 0D mode
E_{2D}	[GWh/yr]	Energy generation based on 2D mode
g	$[\frac{m}{s^2}]$	Gravitation constant value
H	[m]	Head difference
H_{start}	[m]	Starting head for power generation in a turbine
H_{stop}	[m]	Stopping head for power generation in a turbine
h_{basin}	[m]	Elevation of the basin
h_{sea}	[m]	Elevation of the sea
h_{diff}	[m]	Difference in elevation between the basin and the sea
N	[-]	Number of turbines
N_s	[-]	Turbine specific speed
P	[W]	Power
P_{rated}	[W]	Rated Power
Q	$[\frac{m^3}{s}]$	Flow rate
ρ	$[\frac{kg}{m^3}]$	Density of seawater
η	[-]	Efficiency of turbine
7		

1

Introduction

The chapter provides a background for the thesis along with the research question addressed and the methodology.

In a world with a growing focus on new and developing renewable energy technologies and how they can be properly realized, tidal range power stands as an anomaly, having been successfully implemented at locations around the world for decades. And as society progresses with factors such as climate change and the energy crisis having a high priority, inevitably technologies such as this will receive increased attention and scrutiny.

The thesis involves the analysis of one such tidal power plant, proposed off the Western coast of India, in the gulf of Khambhat. The power plant is a part of a large, multi disciplinary project called the Kalpasar project which has been proposed by the Indian government since the 1970s.

1.1. Background

1.1.1. Global warming and energy

Global warming due to Greenhouse gases (GHG) is one of the greatest challenges the world is facing for the future, the impacts of which can already be seen. Sea levels are rising which threatens millions of people living in low-lying regions. Extreme weather phenomena, such as floods and droughts are becoming increasingly common (Pachauri, K., Meyer, L., Core Writing Team, 2015). Glaciers are melting at an unprecedented rate, with the Arctic ocean expected to be ice-free in the summer by the 2030s(Wang, Overland, 2012).

The major cause of global warming can immediately be traced down to the increased demand and use of energy by humans.

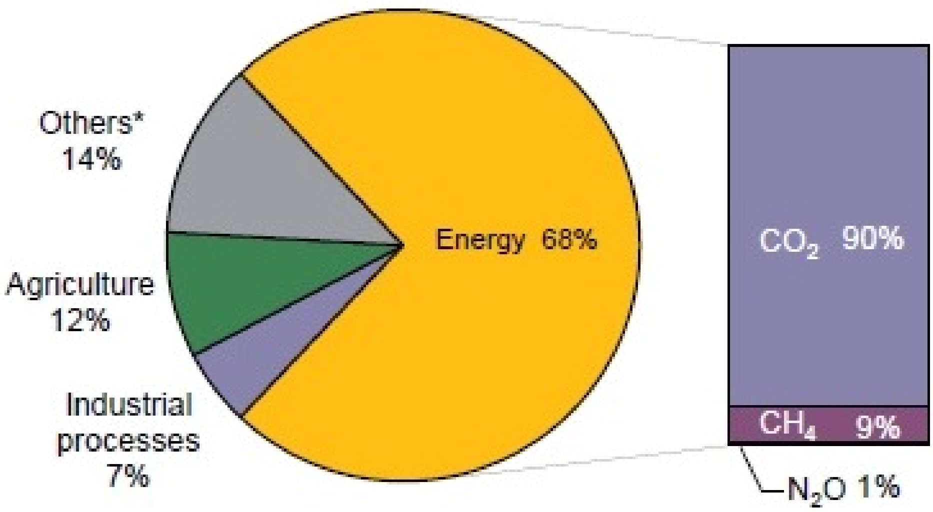


Figure 1.1: Greenhouse gas emissions and energy
(IEA, 2017)

This demand of energy is only increasing in the future. The Energy Information Administration estimates the total energy demand to increase by 28% by the year 2040, with the largest increase seen by developing countries. This is due to factors such as:

- Strong economic growth
- Rising population
- Shift of workforce from agrarian to industrial sector(EIA, 2017)

Moreover, the change in the oil prices remains another challenge. In recent years, the oil price rise in the 2000s or the oil glut of 2014-15 had severe incapacitating effects on several economies.

1.1.2. India

According to the International Energy Agency's report (IEA, 2015) on India, although it currently uses only 6% of the world's energy, it is India that is projected to have the greatest contribution to the global energy demand increase. India currently has an estimated 240 million people with no access to electricity, and several million more with insufficient energy access. With the growing population and rapid economic growth, the demand for energy is only expected to grow.

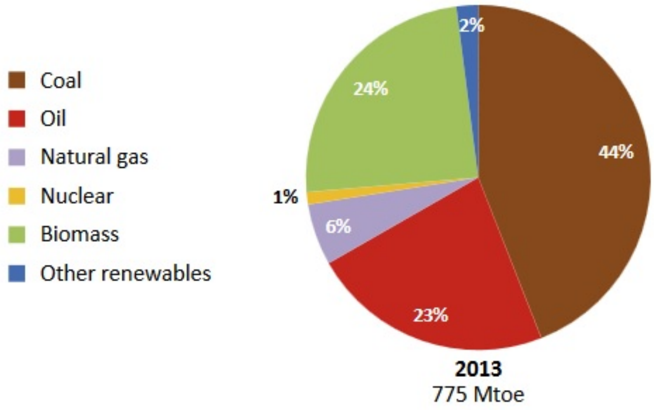


Figure 1.2: India's energy mix
(IEA, 2015)

In the current energy mix, India is heavily reliant on coal and oil, especially in the electricity sector. However, India recently has also agreed to honor the Paris agreement and has set ambitious targets to reduce their emissions by 2030 (Kwatra, S., 2015). India now faces the twin challenges of decreasing their emissions while also requiring to provide energy to its rapidly increasing population.
Among the states in India tacking this problem is Gujarat. Recently two big coal power plants in the state (Tata Power, Adani Power) are facing a lot of financial troubles because of the rising costs of coal and could face closure soon (Chatterjee, Bhatnagar). This phenomena could well extend to other coal plants in the state.
All these factors give rise to an increasing need to step up its energy production using renewable sources.

1.1.3. Kalpasar project

The Kalpasar project is a large interdisciplinary project to create a closure dam (a barrage) in the Gulf of Khambhat in India for multiple purposes. The vision is to create one of the largest freshwater lakes in the world. It will mainly provide water for agricultural, industrial and domestic use in the region of Saurashtra (at the west side of the gulf) located in the state of Gujarat, which suffers from severe water shortages.

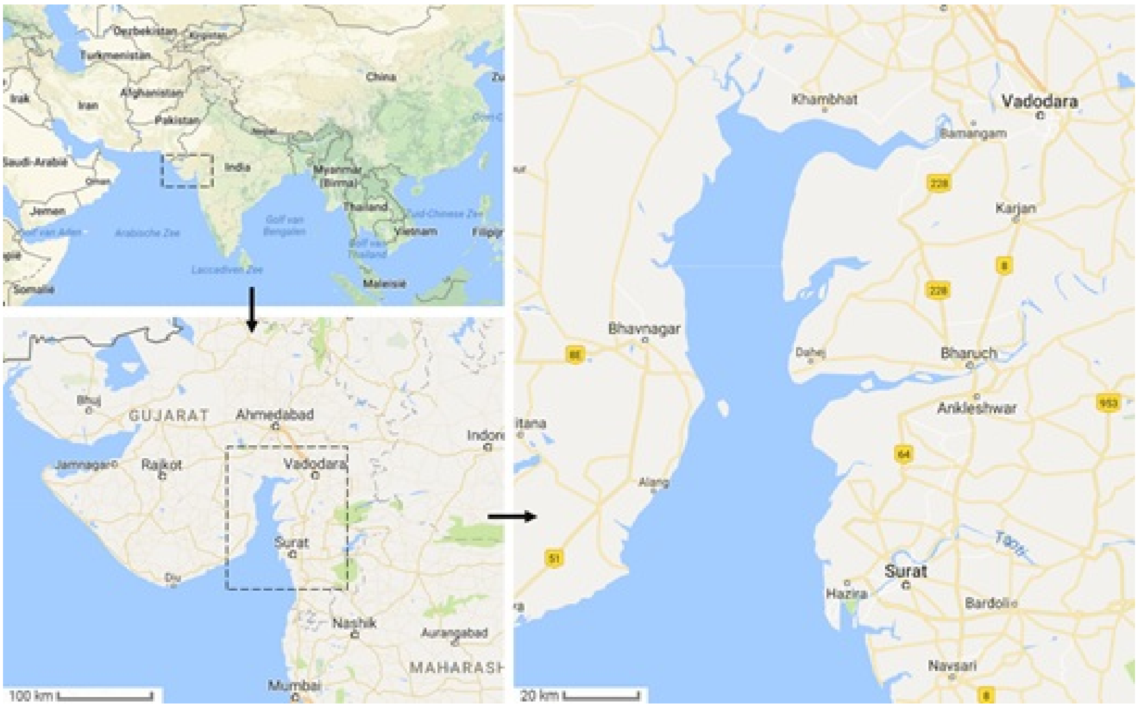


Figure 1.3: Location of Gulf of Khambhat

It was a project considered by the government of India since the 1970's, where they were looking for the possibility of reclamation of land in the saline delta. Since then, the government has been working on the feasibility and implementation of this project.

From the main pre-feasibility report of 1998, the objectives of the KALPASAR project are:

Primary

- Creation of a reservoir in the Gulf of Khambhat to store freshwater inflow from the rivers Narmada, Sabarmati, Mahi and Dhadar
- Use of the freshwater stored to meet the industrial and private demand in the future
- Creation of irrigation canal in Saurashtra using the freshwater obtained for agricultural production in the area

Secondary

- Creation of a separate tidal basin (saltwater) for the generation of electricity
- To reclaim the land off the coast of the bay which have been affected due to the salinity concentration
- Development of the ports in the area of the Gulf such as Bhavnagar, Dahej.
- Terrestrial transportation development by connecting the coast of Saurashtra with the East coast of Gujarat.
- Development of the freshwater fisheries department

Royal HaskoningDHV has been involved in this project since the 1990's, when a pre-feasibility study was made and delivered in 1998. However, since the report there has been little progress by the authorities in further research and development of the project.Over the course of the last two decades, there have been changes in priorities between the collective objectives of the KALPASAR project. The existence of a detailed project report has not been confirmed and the status of the feasibility studies is uncertain (Kapil Dave, 2017).

This is why in 2017, Royal HaskoningDHV has created a multidisciplinary research team consisting of students from universities in the Netherlands to revive the project and tackle challenges of the project with the updated conditions. From TU Delft, there are 3 students who will be investigating different technical challenges faced in the project, such as:

- Closure works strategy of the barrage
- Morphological response in the Gulf of Khambhat
- Feasibility of tidal energy

Furthermore, there are 2 students from VU Amsterdam and Radboud University who are investigating the cultural impact in such megaproject management and risk mitigation in project financing respectively. The research conducted by the students would be in the form of their master's theses in cooperation with the organization.
The focus of this thesis lies in the tidal energy component of the Kalpasar project.

Tidal energy in the Kalpasar project

The Gulf of Khambhat is known for its high tidal ranges of 8-11 m(Kalpasar, 1998). Moreover, the construction of the barrage across the Gulf of Khambhat creates the possibility of having a large reservoir of water with controllable water levels against the sea.

This tidal energy component in the Kalpasar project has received significant attention due to the benefits seen by the multiple stakeholders in the project. For the state and national government, the generation of energy through tidal power provides several benefits. The growing damage of climate change and the related climate agreements requires direct action by the governments. With the large potential at the site, the success of the tidal power plant could significantly contribute towards reaching these renewable energy targets. For the project developers, the tidal energy plant would act as an additional source of revenue, making it a valuable add-on for the Kalpasar project itself. Hence finding the feasibility of the tidal energy component is important

1.2. Problem definition

The feasibility of tidal energy can be influenced by several factors such as the environmental impacts, clashes with other objectives of the project or the economic costs. However, knowing the energy generated (and its associated revenue) is key to determining the feasibility.
Currently in the Kalpasar project, there are no boundary conditions for the tidal energy component such as:

- Having the maximum energy generation possible
- Keeping the cost of energy generation as low as possible
- A limit to the amount of energy generated (Ex: if there are limits to the amount of energy the local grid can take)

to name a few. These conditions may not necessarily be technical decided but they affect the design of the tidal power plant. Additionally, there is little information on the estimated energy generation with the updated location of the barrage.

The big problem being faced is that there is inadequate information for the proposed tidal power scheme in order to make a design. Since the boundary conditions are undecided and can affect the final decisions, this problem cannot be solved only technically. However, a more complete understanding on how a tidal power plant would operate in the Gulf of Khambhat would go a long way in determining feasibility of this component. This can be done by accurately modeling the entire tidal energy generation process in the area and knowing how individual components in the system influence the energy generation.

1.3. Research objectives

The main question that must be answered in this thesis is:

How can tidal energy generation be modeled in the Kalpasar project?

The main objective of the research is to *model the tidal power plant* and understand the response of the local regime (the tidal basin and the sea) when the power plant is constructed. It is crucial in knowing the energy generation capability of a tidal power plant in the Gulf of Khambhat. Apart from the benefits for the project, it is also beneficial to understand the process of the modeling such a system.

Another objective of the project is to *understand how individual parameters in the tidal power plant influence the energy generation*. The factors that will be analyzed in the research are:

- Local conditions of the proposed tidal basin
- The barrage
- The turbines

A final objective of the research is *to understand if there are any wider implications for the modeling of the tidal energy projects*. Although site conditions vary around the world, any observations made in the process of modeling or the results that could be applied elsewhere would be a valuable result.

1.4. Methodology

- **Phase:Literature study**
  The first part of the thesis involves the literature study of all the possible topics. First, all information about the Kalpasar project, its status and resulting boundary conditions for the thesis is collected. Reference cases for similar projects in tidal power will also be made. Research on the governing equations of the action of the turbines and the response of the basin is required in order to create the analytical models.

- **Phase: Modeling the basin**

  The modeling accounts for the largest proportion of the thesis. The basin is being modeled using a combination of the Delft 3D and MATLAB softwares to accurately represent the energy generation. Simulations will be made with varying conditions in the models to observe the response of the system.

- **Phase: Results and conclusions**

  From the model simulations, the results for different possible generating modes of the power plant will be made. Conclusions on the results of the modeling as well as the modeling process will be made for the Kalpasar project. Finally,possible recommendations for future work, limitations of the model and any possible implications for future tidal barrage modeling projects will be made.

1.5. Scope

Firstly, the scope of research of this thesis remains in the proposed tidal basin of the Kalpasar project. The near and far field effects of the sea side of the barrage will not be explored. Within the tidal basin, the focus of the research remains on the energy generation. The economics of the tidal power plant and the financing remain out of the scope.

The construction of the tidal power plant and the environmental effects associated with the power plant during construction and operation are not considered. This also extends to the electricity transmission of the energy generated. Aspects such as the power transmission lines, connections to the electrical grid and power ratings of transformers etc are not considered.

Only single basin schemes are being considered within the tidal barrage technology. Double-basin schemes are only a theoretical concept that provides a greater degree of flexibility and would be more beneficial for the purposes of energy storage than energy generation. Further details on the types of basin schemes can be found in C.2

2
Literature

The chapter details the literature reviewed for the necessary theoretical knowledge required for the thesis. This includes more details and the boundary conditions set in the Kalpasar project, the workings of tidal power and turbines used

2.1. Kalpasar project

2.1.1. History

Historically the Kalpasar project can be divided in three phases:

- Phase 1 Start Kalpasar project (1969-1988)
- Phase 2 Involvement Royal HaskoningDHV (1989-1999)
- Phase 3 Feasibility studies Kalpasar Department and EAG (2000-2017)

2.1.2. Phase 1

The project was first mentioned in the Gujarat State Gazetteers (Government of Gujarat, 1969), a newspaper from 1969. The newspaper stated that the government wants to reclaim land in the saline delta area. Advised by Dutch experts the government, speaks of a pilot Polder Plan; It would envisage the construction of a 40 kilometer (25 mile) long earthen dam with a 3 km (10.000 feet) long waste weir to prevent flooding from the rivers and to preserve rain water. The fresh water would wash away the salinity of the soil, therefore rendering it fit for cultivation.

In 1975, Prof. E. M. Wilson from the United Nation Mission introduced the option of a tidal power installation. It was presented in a report to the Central Electricity Authority for the construction of a dam between Ghogha and Dahej. In September 1986, the Central Design Organisation from the Irrigation Department in the Gujarat government prepared the design and cost estimate for constructing a 46 km long dam to store 3377 Million Cubic Meter (MCM) of water (Central Design Organisation, 1986).

2.1.3. Phase 2

In the year 1996, eight years after a Reconnaissance Report, the government of Gujarat entrusted the work of preparing a Pre-feasibility Report to Royal HaskoningDHV. The report, submitted in the year 1998, recommended to carry out six specific studies before starting a full feasibility report.

In year 1999, the report of the Six Specific Studies supplemented the knowledge gaps in the Pre-feasibility Report, making a suggestion to carry on several additional studies on certain important technical and economic aspects. The Six Specific Studies report is the last major report of Royal HaskoningDHV concerning the Kalpasar project. Together with the Pre-Feasibility Report also the most detailed (Kalpasar Department, 2017).

2.1.4. Phase 3

An Expert Advisory Group (EAG) consisting of international experts, has been installed to guide and coordinate the preparation of the feasibility report. They recommended to carry out more studies with respect to the construction of a Narmada Diversion Canal and a Barrage near Bhadbhut. The last documented meeting of the EAG was in 2012. The minutes from

this meeting state the initial design from the Pre-Feasibility Study from Royal HaskoningDHV has been altered. Most design alterations have been documented in the minutes as well, an example of these alterations is the shift of the alignment of the dam to a more northern position by 15 km (see figure 2.1). However no technical or economical feasibility studies can be found on this altered design. (de Jong, 2017).

Figure 2.1: (a) Initial project alignment and (b) New alignment

2.1.5. Boundary conditions

Based on the reports by Royal HaskoningDHV and the Kalpasar department in the past, certain boundary conditions of the project can be defined, such as:

- A barrage will be built across the Gulf of Khambhat to create a reservoir. This barrage is based on the New alignment (figure 2.1).
- The tidal energy generation requires an inner dam to be built to separate it from the freshwater basin.
- The main rivers flowing into the basin (Narmada, Mahi, Sabarmati) are on the Eastern shores and the North. Therefore the tidal basin is situated on the Western shore of the Gulf with no discharge into it.
- The primary objective of the Kalpasar project is the storage of freshwater. Therefore,a minimum freshwater requirement is necessary. Any increase in the area for the tidal basin decreases the area available for the freshwater basin. Hence a conservative limit to the surface area of the tidal basin was made From the Six Specific Studies report prepared (RHDHV, 1999). A maximum of around 300 sq. km (the surface area of the entire basin being 2000 sq. km) was kept.

Although further optimization between the sizes of the tidal basin and the freshwater basin is possible, this would be difficult due to the varying estimates of the freshwater discharge which would finally be available and time consuming. Hence for the thesis, a more conservative value was chosen

2.2. Gulf of Khambhat

The Gulf of Khambhat is a region on the Western continental shelf of India, along the coast of the state Gujarat.

The gulf has a wide inlet of around 250 km and has a total length of 200 km, having an inverted funnel shape in the north east direction. Further upstream, the gulf rapidly decreases in width to distances of 25 km. The gulf is also distinguished by its shallow depths, only reaching a maximum of 30 m in the south. The northern part of the gulf has even lower water depths (<10 m) and has several large tidal flats (Satish Kumar S., Balaji R., 2015b). The Eastern side of the gulf has discharges from the 3 major rivers: Narmada, Mahi, Sabarmati of which the Narmada river accounts for the largest discharge.

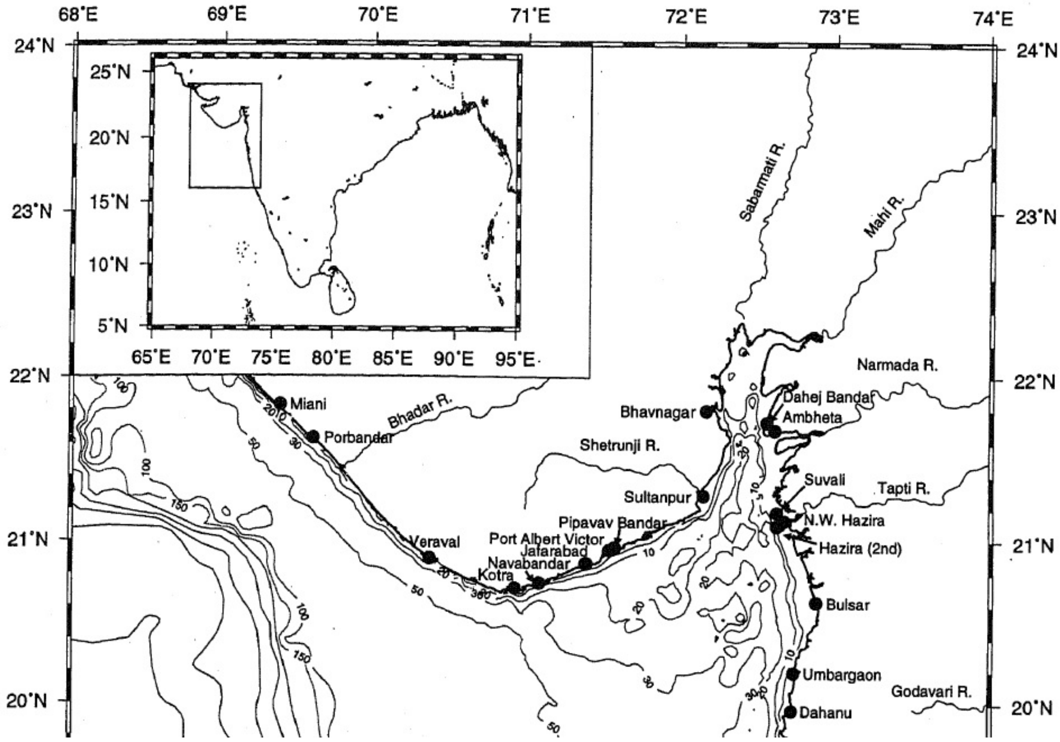


Figure 2.2: Gulf of Khambhat
(Unnikrishnan A., Shetye S.R., et al, 1999)

With growing economic activities in the area (oil and gas industry, fisheries, shipping), several studies have been made on the characteristics of the flow regime in the area(Satish Kumar S., Balaji R., 2015a). The region has a characterized mixed semidiurnal movement with high tidal ranges, reaching over 10 m in the Northern part of the bay, near Bhavnagar. These high tidal ranges are the combined effect of several factors such as:

- The reduction of the breadth and depth of the channel along the inward direction.
- The bottom friction acting as a dampener on the propagating tidal wave
- Reflection of tidal wave (Giardino A., Elias E., et al, 2013)

2.3. Tidal power

The motion of tides have been known to us for a long time and have historically been used in water mills for hundreds of years. At high tide, water would be stored and during low tide, the potential of the water body due to the height difference would be converted into mechanical work for grinding the grains
However, the use of tides for the generation of electricity has been far more recent. Research was being conducted into the technology in the 20th century, but it was only in 1966 when the first operational tidal power plant was set up in La Rance, France. Since then, there has been a slow growth of the technology due to varying reasons (Kempener and Neumann, 2014).

The history of tidal power has been dominated by three projects. The world's first tidal barrage project was constructed in La Rance, France in 1966. The location has naturally high tides, reaching upto 13.5 m in spring tide. The facility has a 240 MW capacity, run by 10 MW reversible turbines (EDF, 2009). The power plant operates both ways with pumping to enhance the performance. Until recently it was the world's largest tidal power plant until the Sihwa plant in South Korea, which became operational in 2012. The plant operates during the flood tide and has a capacity of 254 MW. Another tidal power plant was constructed in 1984 in Annapolis, Canada. The power plant consists of a single 20 MW turbine which only generates energy during the Ebb tide.

Figure 2.3: (a) Sihwa and (b) La Rance (Pacific Northwest National Laboratory)

Tidal power plants of much smaller capacities have also been set up in other parts of the world, such as Jiangxia (China), Kislaya Guba (Russia). In recent years, extensive research into the fields of tidal stream power and tidal lagoons has been made, leading to the proposal of several tidal projects. UK, for example has an estimated theoretical potential of 92 GW power (Estate, 2012) and is in the forefront of several proposed projects, such as:

- The Severn barrage, with research conducted estimating over 15.6 TWh/yr energy generation (from a possible 8.6 GW capacity) (Xia, 2012).
- Swansea bay, where there is a proposal to create a tidal lagoon instead of a barrage with a capacity of 320 MW.
- In 2010, the Meygen project was announced in Northern Scotland, with the development of a tidal stream project of upto 398 MW using 1.5 MW tidal turbines

2.4. Power generation

The two types of tidal energy technologies that are most promising currently are:

- Tidal stream: Tidal stream technology utilizes the currents formed in the ocean due to the tidal movements. In a principle similar to wind energy, turbines are placed in the ocean to extract the kinetic energy of the currents through the turbines, and is most economical at sites with with tidal currents formed (> 2 m/s). This field has made enormous progress in the last few decades towards commercialization of the concepts. Most of the turbines have been set up in the UK, which has high tidal current velocities. The technology still has high initial costs and a relatively high levelized cost of electricity (EUR 0.25-0.47/ kWh) (Kempener and Neumann, 2014) but is still actively looked upon due to the relatively lower environmental impacts

- Tidal barrage: Tidal barrage is the use of dam-like structures to store water and use the potential energy of the water. This form of energy is similar to conventional hydroelectricity, which also utilizes the potential energy of water. The turbines are placed within the dam and when a water level difference exists between the basin and the water body outside it, the flow of the water powers the turbines to produce electricity. The typical tidal power plant consists of the embankment, sluices, turbines and ship locks.

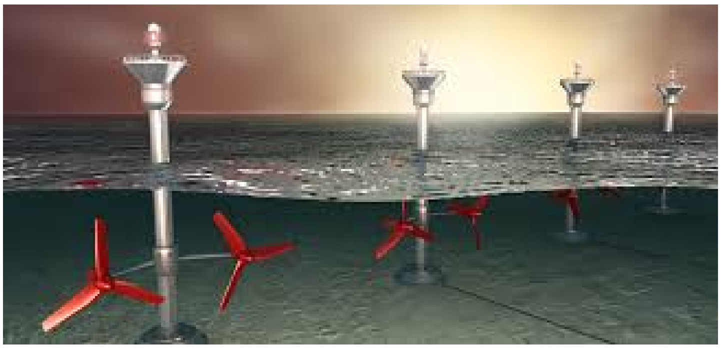


Figure 2.4: Tidal stream turbine

In recent times, a variation of this form of technology, called tidal lagoons have been researched on. Unlike a tidal barrage, a tidal lagoon would not block the entire tidal estuary.
The construction of a tidal barrage requires a high initial investment. However, such structures are built with lifetimes exceeding 50 years. The cost of electricity for tidal barrages varies with the tidal resource available for the site. However, the 2 big tidal barrage projects; La Rance and Sihwa have a levelized cost of electricity of 0.04 and 0.02 EUR/kWh respectively(Kempener and Neumann, 2014) which are competitive with the costs of fossil fuels.

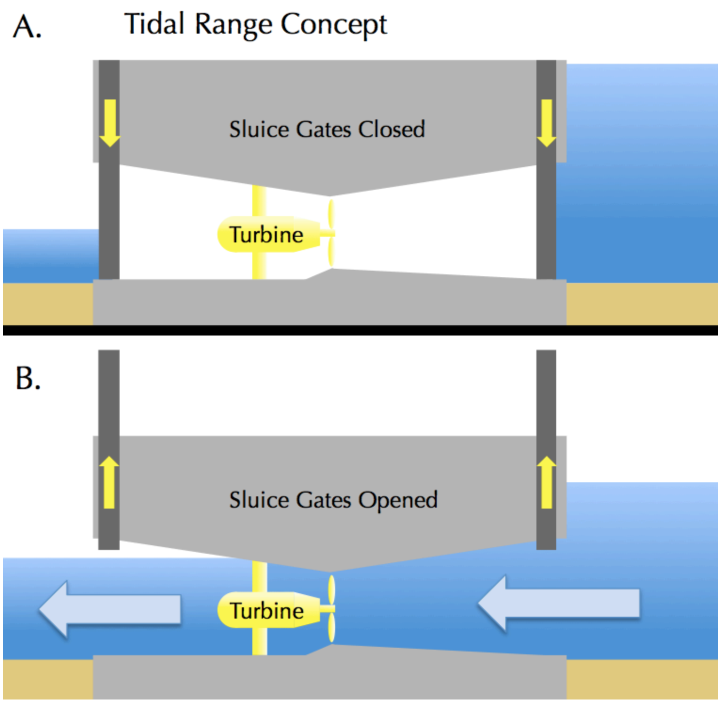


Figure 2.5: Tidal range

Among these technologies, *tidal barrage power will be used for the Kalpasar project.* This is due to the high tidal range being formed in the Gulf of Khambhat and the fact that a proposal for the construction of the barrage across the Gulf of Khambhat for other purposes already exists. The barrage is integral to separating the saltwater and freshwater.

Given a tidal basin, the theoretical potential for energy generation using a tidal barrage is measured by the formula:

$$E = A * \rho * g * H^2 \tag{2.1}$$

This theoretical potential is based on several assumptions, amongst which the main ones are:

1. An instantaneous filling and emptying of the basin (which implies infinite flow rates passing between the tidal basin and the sea)

2. Turbines having a 100% efficiency of conversion of mechanical energy to electrical energy.

For the Gulf of Khambhat, the surface area of the basin (A) is approximately 300 sq. km, the mean tidal range of 9.5 m is chosen. With this the potential available in 1 tide is 1.31 $*10^{14}$ Joule. Given that there are 2 tides in a day and 365 days in the year, the **potential energy production** possible is calculated to be 9.93 $*10^{16}$ J or 27602 GWh/yr.

However, such a high potential only exists because of the crucial assumption of infinite flow rates, which is physically impossible. With finite flow rates, only a part of the tidal range is obtained within the operation of the tidal barrage.

Tidal barrage operation

The tidal barrage utilizes the tidal cycle (more information in C.1) in order to create the head difference between the basin and the sea. The water levels in the basin are controlled by opening and closing the turbines and/or sluices to the basin at selected times. Based on the operation sequence, there are 3 main power generation methods by using a barrage:

- **Ebb generation:** In this method, during the flood tide the gates for the basin are opened, allowing the water to enter and raise the basin water levels. As the sea starts receding (and its water level drops), the gates are closed and a 'holding' period is enforced, where the basin is closed off from the sea and its high water level stays the same. Once a sufficient head is created between the tidal basin and the sea, the water is allowed to discharge into the sea only through the turbines, which then converts the potential energy into electricity. When the basin is emptied, energy production stops and the basin is allowed to be filled again during the next flood tide.

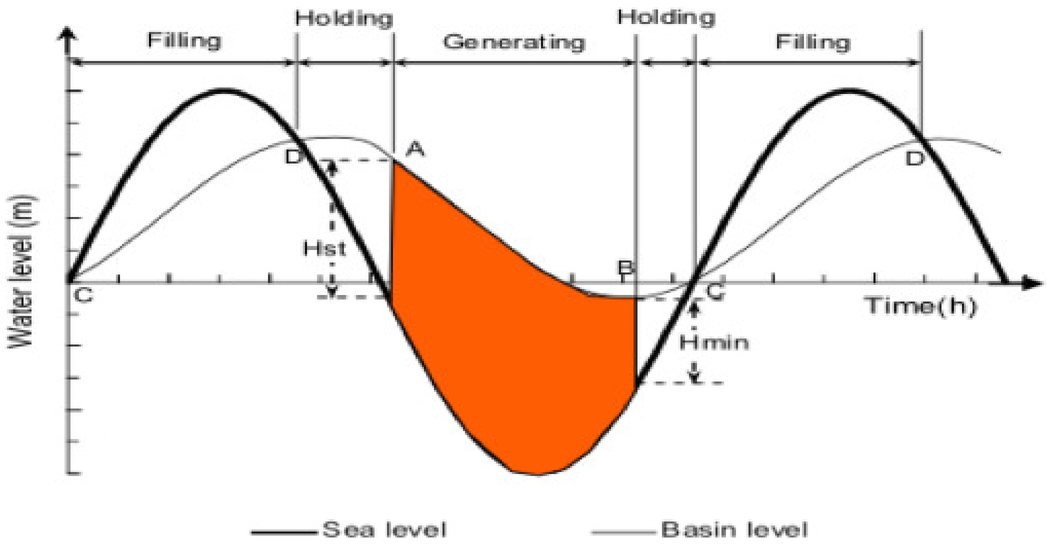


Figure 2.6: Ebb generation

- **Flood generation:** Similar to ebb-generation, but with inverted operational timings. The gates to the basin are closed during low tide, keeping the water level low and constant inside the tidal basin as the sea levels rise. During the flood tide, the water will pass to the basin through the turbines. Due to the smaller volume of the basin (compared to the sea), the water level would rise faster as compared to ebb-generation, resulting in the head difference between the sea and the tidal basin dropping quicker. This causes a decreased capacity for energy generation as compared to the Ebb generation mode.

- **Two way generation:** This method harvests energy during both ebb and flood tides, resulting in an increased period of electricity generation. This means that at the end of the ebb tide and the flood tide, the gates of the basin are closed for a small time (holding period) while a head difference is created between the sea and the basin. This method of power generation requires reversible turbines (capable of converting flow from both directions).

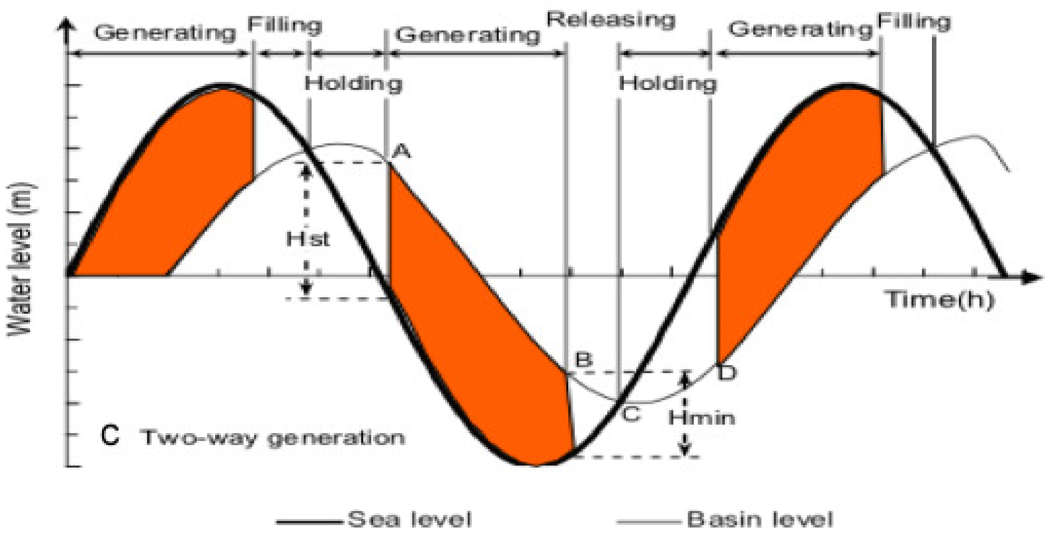


Figure 2.7: 2 way generation

Ebb generation requires a simpler (and cheaper) construction and can provide a higher amount of energy for a given installed capacity. However, 2 way generation schemes can provide energy at a more distributed rate throughout the day, which is preferred for electricity transmission. Of these generating modes, Ebb generation and 2 way generation are widely preferred over Flood generation when the main priority is energy generation. The Sihwa power plant remains the exception in using a Flood generation scheme because of a greater importance in water quality.

In the Kalpasar project, *Ebb and 2 way generation* modes will be looked at further.

2.5. Turbines

Tidal power has a few different necessities compared to most forms of hydropower, with seawater having an increased density and having a variable and a very low head(<10 m). These differences are translated into the designs of the turbines for the operation of the tidal power plants. Nonetheless the principle of energy generation remains the same as traditional hydropower turbines, with certain turbines being capable of being used in operation for both forms of energy generation. The principle for energy extraction remains a function of the

head developed between the basin and the sea.
Below rated power, at a given time t

$$h_{diff}(t) = h_{basin}(t) - h_{sea}(t) \tag{2.2}$$

$$Q(t) = \mu * A_{cross} * \sqrt[2]{2 * g * h_{diff}(t)} \tag{2.3}$$

$$P(t) = \eta * Q(t) * \rho * g * h_{diff}(t) \tag{2.4}$$

One such form of turbines which are suitable for these low head applications are the Kaplan turbine, which is a reaction turbine. The two turbines which are currently in use for the tidal range sector are:

- Bulb turbines: A bi-directional flow turbine, it consists of a horizontal axis Kaplan turbine placed in a compact unit which also consists of the generator. The bulb turbine has an adjustable runner and inlet guide vanes in order to efficiently guide the water at the optimum angles for varying heads and flow rates (Voith). Due to this, the bulb turbine has a relatively flat efficiency curve for most of the turbine operating range, with peak efficiencies reaching 90%. However, when the turbine is operating in the reverse mode (flow from the opposite direction), the efficiencies drop to 69.34% .

  Bulb turbines are the most widely used form of turbines in tidal barrages. The La Rance and Sihwa tidal plant use bulb turbines of 10 MW and 25.4 MW capacity. These turbines have operated in La Rance for over 40 years. They have a proven record and very attractive option, especially in two way generation schemes where the full utilization of the turbines can be achieved. However, the complexity of the turbine increases the costs of the turbine itself

- Straflo: The Straflo turbine is an axial turbine which works on a similar operating head as the bulb turbine. It consists of fixed runner blades and a generator placed on the outer rim (outside the flow). The efficiency of these turbines are lower than a bulb turbine due to the fixed runner blades, which also restrict the generation to one direction. However, the simpler nature and lesser moving parts of the Straflo turbine significantly reduce the costs of the turbine. Currently, the use of the Straflo turbines in tidal power is restricted to the Annapolis plant, where one 18 MW turbine has been installed(Waters, Aggidis, 2015).

A variation of the bulb turbine has been created, with an additional guide vane placed. This improves the efficiency in the reverse mode from 69.34% to 80% but the efficiency in the forward mode drops to 84% (Wang, Zheng, et al, 2013). This variation is expected to lead the turbine costs.

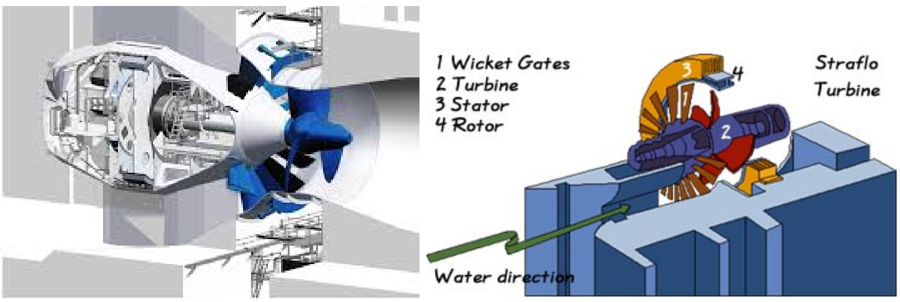


Figure 2.8: (a) Bulb and (b) Straflo turbine

Both the Bulb and the Straflo turbine have been proven technologies for decades and have high efficiencies. Investors are also not keen to try new and unproven turbine configurations

with minimal gains in terms of energy generation. Due to these factors, not much innovation has taken place in the field of tidal range turbines. However, an increased focus on the fish friendliness and other environmental effects has shifted the focus recently.
Rolls Royce has also worked on a conceptual turbine specifically for the Severn Barrage in the UK (Rolls Royce, Atkins, 2010).This turbine has been created for turbine heads below 5 m and capable of operating under high efficiencies in both modes of generation.

Apart from these turbines, a few theoretical turbines have also been proposed, such as Rushhydro's vertical axis turbine, Archimedes screws etc. These turbines have been created as alternatives due to the challenges the traditional turbines face in terms of fish friendliness and simple construction but do not have the same power capacity or efficiency.

In the final project, the actual turbines chosen will not only be based on the efficiency of energy generation but also the costs of the turbines, as this is a significant expense in the tidal power plant. However for the research objectives, the electrical section of the turbines will not be observed closely and it is the interactions of the turbines with the flow passing which is more important. Hence, *standard Bulb turbines and Straflo turbines have been chosen* because detailed manufacturer data is available on actual operation of these turbines.

At the power plant level, the two most important parameters calculated are the annual energy production(E_{year}) and the capacity factor(cf) , based on the output of the turbines. The annual energy generation is a summation of the energy generated by all the turbines in the year.

Another important factor is the capacity factor. It is the ratio of the actual energy production in the year to the maximum energy generation possible in the year. It is an effective measure of how thoroughly the designed capacity of the power plant is being utilized.

$$e(t) = P(t) * dt \tag{2.5}$$

$$E = \sum e(t) \tag{2.6}$$

$$E_{year} = E * \frac{Time_{year}}{Time_{simulation}} \tag{2.7}$$

$$E_{max} = P_{rated} * Time_{year} \tag{2.8}$$

$$cf = \frac{E_{year}}{E_{max}} \tag{2.9}$$

2.6. Highlights

Based on the literature in the previous sections, a summary of the most important points are highlighted below:

- The barrage is placed in the northern section of the Gulf of Khambhat, which is characterized by a tidal range of over 10 m and shallow depths of less than 10 m
- The alignment of the closure dam is fixed and the surface area of the proposed tidal basin is limited to 300 sq. km.
- The type of tidal energy technology chosen is tidal barrage energy, which utilizes the potential energy of the tides.
- Within the tidal barrage scheme, 2 generation modes (Ebb and 2 way) are looked at for further consideration.
- Bulb and Straflo turbines will be used in the models due to the data present from manufacturers about their flow characteristics in existing tidal energy projects.

3 Model setup

The chapter describes the modeling process of the power plant set up in the Delft3d and MATLAB softwares. The various components of the models in each case are described, such as the basin, the turbines and the operation of the plant. It is described how these components are simulated. Finally, the expected results of the models are explained

3.1. Modeling process

One of the main objectives of the thesis is modeling tidal energy generation at the site. This tidal resource available is a complex function not only of the natural conditions existing (bathymetry, local tidal regime) but also as a factor of the energy conversion capability of the tidal power plant.

The power that can be generated from a tidal power plant in a time step t can be expressed by the equation:

$$P(t) = \eta * Q(t) * \rho * g * h_{diff}(t) \tag{3.1}$$

Where

η is the efficiency of the turbines,
$h_{diff}(t)$ is the height difference between the water levels in the tidal basin and the sea
$Q(t)$ is the flow rates passing between the basin and the sea
ρ is the density of the sea water (assumed constant throughout the model)
And g being the gravitational acceleration (9.81 $m^2/$s).

In the modeling process, it is important to map the hydrodynamic interactions within the system and the influence of the hydraulic components (the gates, turbines, sluices, barrage) with the localized water levels. In order to do this multidimensional models are often used for analysis, such as three dimensional (3D) or two dimensional (2D) models (Neill S.P, Angeloudis A., et al , 2018). The main difference between the 2D and 3D models lies in the fact that in 2D models, only a single vertical layer of flow is taken during computation and the vertical acceleration is considered negligible. Due to this the computational time of each simulation also decreases. Depending on the type of analysis required, either the 2D or the 3D model can be considered appropriate.

In the system, fluid parameters such as salt concentration, temperature or density differences are not relevant and the fluid is considered homogeneous throughout the vertical direction. Due to this, a 2D simulation is considered appropriate, for which the Delft3D software is used.

Delft 3D is a program suite used for multidimensional hydrodynamic and transport simulations which calculates non-steady flow and transport phenomena that result from various forces. Separate modules are used for calculation of the hydrodynamics (FLOW), wave action

(WAVE), water quality, morphology (MOR).

Delft 3D FLOW is used for the simulation of unsteady flow and transport phenomena in 2D (depth averaged) or 3D systems. The system is discretized into a grid and the Navier Stokes Equations are solved for each element. These equations solved under the shallow water and Boussinesq assumptions (Deltares, 2014).

3.2. 2D model

In the 2D model, the following components are required to be modeled and integrated into the final system.

- The sea (and the tidal regime in the area)

- The barrage (closure dam)

- The flow through the turbines and the sluices

- The opening/closing of the barrage (the operation sequence)

3.2.1. Sea

The water levels available on the sea side of the barrage are predominantly a function of the tidal regime. However, the location of the barrage and the location of the dam opening also have an influence on the resulting tidal range.

Deltares, a research institute in the field of water had created a model of the Gulf of Khambhat to understand the tidal characteristics by creating a numerical model on Delft 3D. With the permission of Deltares, this model was used for providing valuable information about:

- The local bathymetry

- Manning's coefficient (for the bottom roughness)

- The tidal constituents (Factors depicting the multiple influences on the tidal motion in the area)

The model was a part of a tidal modeling study by Deltares which was validated versus tidal measurements in the area (Giardino A., Elias E., et al, 2013). This model was used as a platform for the creation of the tidal basin model in the area. Using this model, the tides were modeled on Delft 3D. At the boundary of the model, the required information about the tidal constituents were taken from the TOPEX global database.

Figure 3.1: Model domain of the Gulf of Khambhat

3.2.2. Barrage

The coordinates of the outer barrage (the closure dam for the Gulf) was provided by Royal HaskoningDHV enclosing an area of around 2000 sq. km. Based on the minimum freshwater requirement of the project provided by the company, a tidal basin was chosen on the Western part of the bay, sharing the Southern wall with the planned barrage.

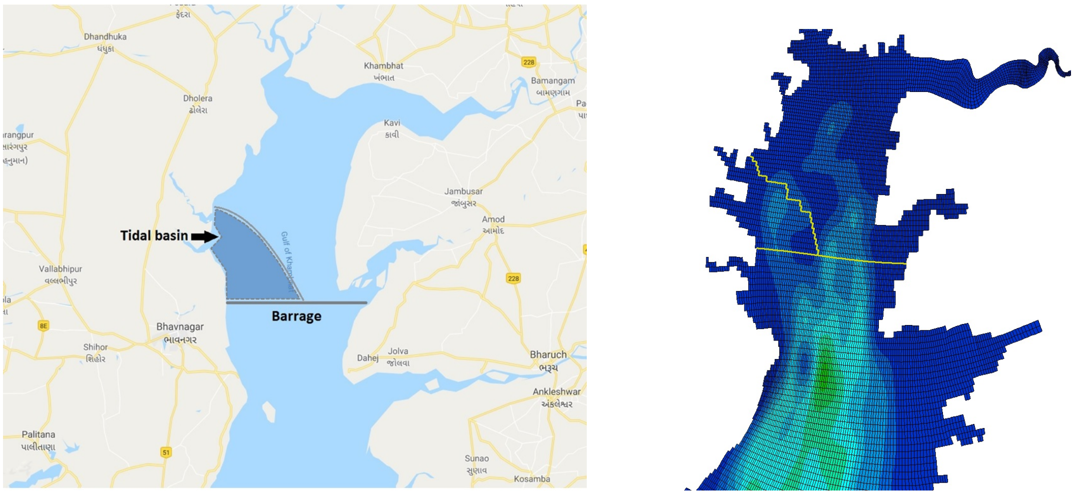


Figure 3.2: (a) Schematic of the barrage and tidal basin and (b) Simulation on Delft 3D

Thin dams have been used in Delft 3D to simulate the barrage. These thin dams prohibit any flow passing between the 2 cells on either side of it but do not reduce the surface area of the tidal basin itself due to its infinitely small thickness.

3.2.3. Turbines and sluices

The turbines and the sluices are placed in the openings in the barrage and they are used to control the flow between the tidal basin and the sea. Additionally, the turbines produce electricity as flow passes through it. The sluices are not used in 2 way generation mode, since during both ebb and flood tides, water has to pass through the turbines to generate energy. However, it is used in the Ebb generation mode in order to have a high water level available.

In the 2D model, the turbines and the sluices represent a resistance to the flow as it passes through. For the sluices, the discharge can be calculated as:

$$Q(t) = A_{sluice} * C_d * \sqrt[2]{2 * g * h_{diff}} \tag{3.2}$$

where C_d is the discharge coefficient of flow passing through the sluices. For the model it was kept constant at 0.9.
For the turbines, ideally the discharge through the orifice (turbine opening) would be:

$$Q(t) = \sqrt[2]{2 * g * h_{diff}(t)} * \pi * D^2 * /4 \tag{3.3}$$

However, practically the turbines itself imparts some form of resistance to flow passing between the sea and the tidal basin. This resistance is calculated through the Q-H curves of a turbine, which are given by turbine manufacturers.

A report in the University of Idaho complied information of several existing hydroelectric projects using bulb turbines and plotted their characteristics in the form of experience curves (Kpordze C.S.K, Warnick C.C, 1983).

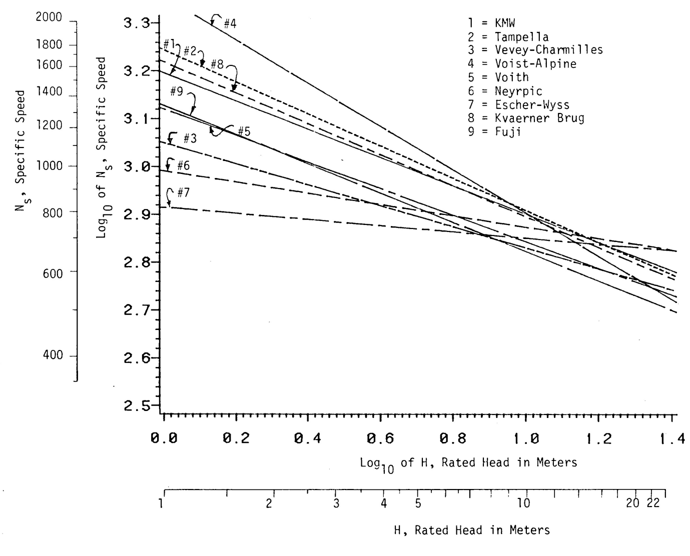


Figure 3.3: Data of the head vs the specific speed
(Kpordze C.S.K, Warnick C.C, 1983)

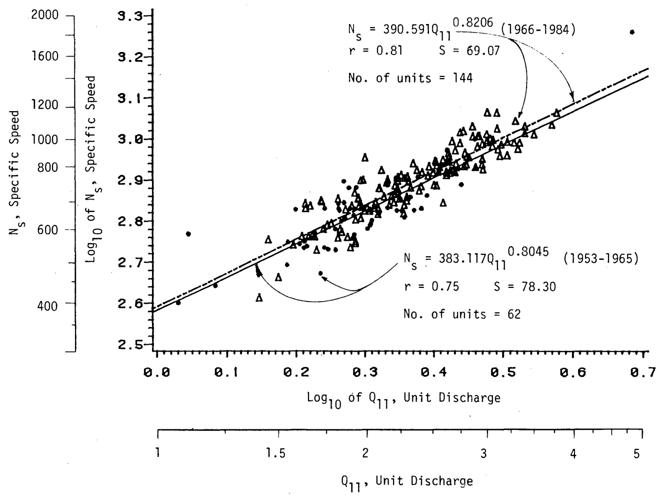


Figure 3.4: Data of the unit discharge vs the specific speed
(Kpordze C.S.K, Warnick C.C, 1983)

As can be seen in figures 3.3 and 3.4, empirical relations of the flow rates and the head as a function of the specific speed have been made. Combining these relations, we can get a direct relation between the flow rates and the head in the form of:

$$Q(t) = \pm 5.238 * |h_{diff}|^{0.0.1542} * D^2 \tag{3.4}$$

A 7.6 m diameter and 5.8 m rated head was chosen for the turbines, based on the configurations of the turbines used in the Annapolis power plant. (Nova).

The plot in figure 3.5 shows the reduction in flow rate from the ideal case.

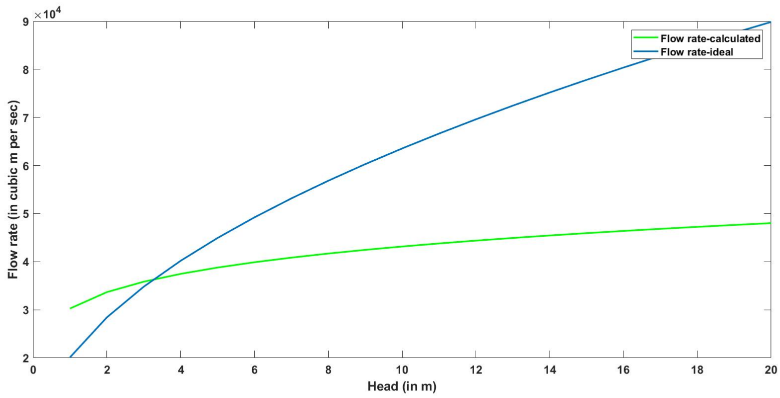


Figure 3.5: Demonstration of ideal vs calculated discharge

Based on this, the flow rate at rated speed was calculated and through this the rated power (or 'design' power) was calculated to be 20 MW. This matches the capacity of the turbines used at Annapolis. Factors such as the starting and stopping heads, turbine efficiencies were taken based on literature on the tidal plants in Sihwa and La Rance.

Below the rated head, the power output from the model is calculated as:

$$P(t) = n * Q(t) * h_{diff}(t) * \rho * g * \eta \tag{3.5}$$

while at/above rated head, rated power is generated for that time step.

$$P(t) = N * P_{rated} \tag{3.6}$$

A summary of the characteristics of these turbines in the simulations are:

Parameter	Value
Rated head	5.8 m
Starting head	1.5 m
Stopping head	0.5 m
Diameter	7.6 m
Rated power	20 MW
η_{forw} (Bulb turbine)	0.9
η_{rev} (Bulb turbine)	0.6934
η (Straflo turbine)	0.84

Table 3.1: Turbine configuration

3.2.4. Operation

The final element in the 2D model is the opening and the closing of the gates. In figure 3.6, the different stages of the plant can be seen for both ebb and 2 way generation. The basin levels are controlled by the the turbines and the sluices (for ebb generation). The 4 stages can be classified as:

- **Flood:** For 2 way generation, the turbines are opened and generate electricity as water passes from the sea to the basin. In Ebb generation mode, the gates are opened, but no energy is produced.
- **Holding:** The basin is completely closed to generate a head difference as the sea recedes.
- **Ebb:** Not to be confused with the Ebb generation mode. During ebb stage, the turbines are opened (for both 2 way and ebb generation) and as water recedes to the sea, electricity is generated
- **Hold for flood:** Similar to the holding stage, the basin is closed as the water levels in the sea rise.

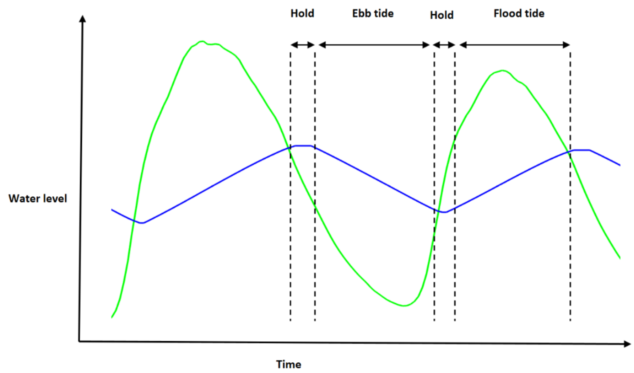


Figure 3.6: Cycle of the 4 operation stages in the power plant

To optimize the operational timings of these 4 stages, the opening and closing of the basin is condition-based on the head difference between the sea and the basin instead of basing it on the time of the day. The turbines also require a minimum starting and stopping head (H_{start} and H_{stop} respectively) before power generation can begin. These stages are simulated in the MATLAB program using a switch case between the 4 cases based on the conditions, ensuring the cycle remains intact.

Stage	Condition required
Flood	h_{basin}<h_{sea}
Wait	h_{basin}>h_{sea}
Ebb	h_{basin}-H_{start}>h_{sea}
Hold for flood	h_{basin}-H_{stop}<h_{sea}

Table 3.2: Conditions for switching stages in tidal cycle

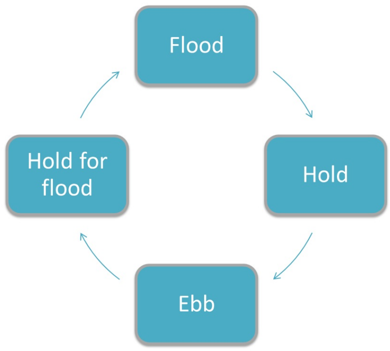


Figure 3.7: Cycle of the 4 operation stages in the power plant

Unfortunately, the periodic opening and the closing of the gates of the barrage cannot be implemented in Delft 3D *during the simulation*. However, the software allows the input of a time varying discharge into the tidal basin . This discharge can be user defined and can be used as a controller for the tidal basin, with a value of zero at the discharge being the equivalent of a closed gate for that particular time step.

Predicting the discharge

To simulate the effects of the turbines and the opening/closing of the dam, the discharge in/out of the basin is predicted. The method involves keeping the basin completely closed during the simulation and placing a discharge inlet in the basin from the sea, the resulting system acts as an underwater pipeline which can be controlled by the user. It bypasses the thin dam, allowing interaction of flow between the sea and the basin. To physically represent the resistance to the flow due to the action of the turbines, the reduction of the flow rates must be calculated separately before being provided as an input in the model.

This time varying discharge has to be added as a separate input file within the software and cannot be computed using Delft 3D itself. To predict the values, the MATLAB software is used to create a zero dimensional (0D) model.

3.3. 0D model

MATLAB is a programming language used for the visualization and computation of problems, used to create a 0D model. A 0D model is a model where the parameters being analyzed (in this study: the water level of the basin) only varies with respect to time and has no spatial variation.

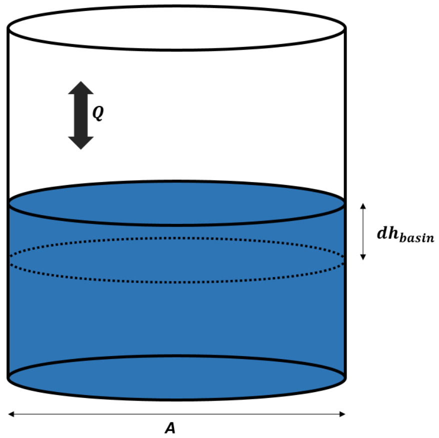


Figure 3.8: Representation of a zero dimensional basin

This zero dimensional basin effectively acts as a column of water, with a surface area (A), discharge in/out of the basin (Q) and a change in the basin height (dh_{basin}) as shown in figure 3.9. The column of water has no perceivable depth, and there is no difference in the value of dh_{basin} within the surface area of the basin.

Modeling the basin

For an incompressible flow passing through a fixed cross section, the continuity equation can directly be used. The discharge in/out of the basin is the sum of the capacity of the turbines and the sluices (in 2 way generation it only depends on the capacity of the turbines due to the absence of sluices in the operation)

The turbine and sluice discharge equations are described in 3.2.3. In the ebb tide, flow going out of the basin is positive while in the flood tide, the flow entering the basin is given a negative sign.

For each time step, the change in basin level is calculated by:

$$dh_{basin}(t) = \frac{Q(t) * dt}{A(t)} \tag{3.7}$$

and thereby

$$h_{basin}(t+1) = h_{basin}(t) + dh_{basin}(t) \tag{3.8}$$

3.3.1. Scenarios

In order to understand the operation of the tidal power plant, 6 scenarios were chosen for simulating. This comprises of 3 models to simulate Ebb generation mode, with a fixed number of turbines (50) and an increasing number of sluices. The other 3 scenarios simulate the 2 way generation mode have no sluices and an increasing number of turbines:

Generation mode	Number	Turbine	Sluices
	1.	50	-
• 2 way	2.	75	-
	3.	100	-
	4.	50	30
• Ebb	5.	50	60
	6.	50	100

Table 3.3: Scenarios for 2 way and ebb generation

3.4. The validity of the models

The 2D model takes into account the local conditions. It is a more accurate representation of reality as compared to the 0D model. However, in order to understand what local conditions affect the energy generation possible in the Gulf of Khambhat, the particular part of the 2D model cannot be dissected and analyzed.

This requires a comparison with the 0D model, where these local conditions are not present. Thus a comparative analysis is required between the 2D and the 0D model on the basis of their energy generation. Knowing the the magnitude of these differences is also important in understanding whether the local conditions plays a significant enough role in the energy generation. If it does not, a case could be made for using the 0D models for mapping the tidal resource in an area since the models are much faster and easier to construct.

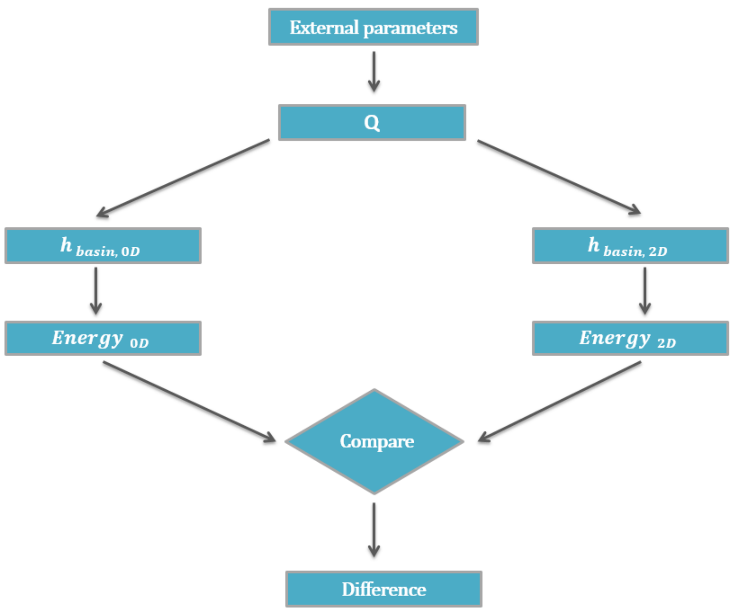


Figure 3.9: Comparison of the 0D and the 2D models

Further, it is noted than both models are connected by a common parameter: the discharge (Q). The input discharge in the simulation is predicted in the 0D model and is forced into the 2D model simulations. This means that in the 2D model, the basins are forced to empty/fill at a predetermined time and cannot be changed if the actual basin levels are not optimal.

In order to know if predicting the discharge in the 2D model is a feasible method of modeling the barrage operation, the response of the tidal basin water levels is also analyzed with respect to the sea levels at the side to check for any physical inaccuracies, such as if the basin levels exceed the High tide or Low tide water levels of the sea. It is also important to understand (if any) under what conditions is the feasibility of the model possible.

4

Results and discussion

The various results of the 2 models are detailed here. These include finding the optimal locations of the turbines along the barrage, estimating the effect of the barrage itself on the tidal resource, and what the influences of the local conditions are on the energy generation in the Gulf of Khambhat.

4.1. Turbines

4.1.1. Turbine placement

A crucial factor to determine is the placement of the turbines along the outer dam.

In figure 4.1, the bathymetry at and just south of the tidal barrage is shown. The area is characterized by the presence of 2 deep channels (shown in light blue). The channel on the right has depths of upto 15 m while the channel on the left is shallower with depths of upto 6 m. Along the remaining parts of the barrage, extremely shallow depths are present in the form of intertidal areas. These regions are not submerged during the entire tidal cycle and are hence not feasible to place the turbines.

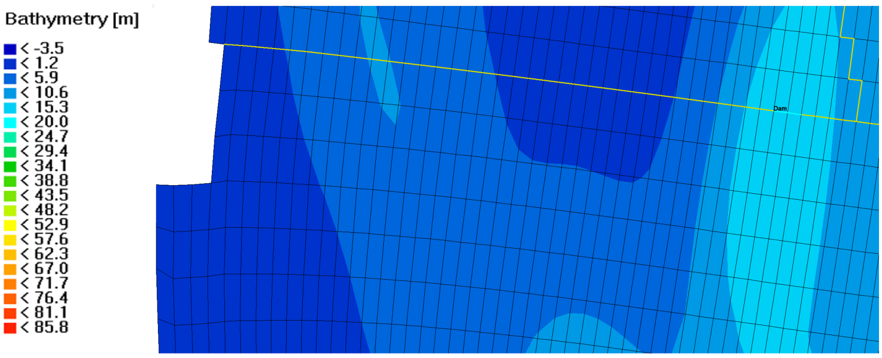


Figure 4.1: Bathymetry just outside tidal barrage

The tidal range at both locations was looked at, with the results shown below:

In figure 4.2, that when the turbines are placed on the left channel, the resulting tidal range does not exceed more than 5-6 m, only half of the 10 m which has been seen in the location (Satish Kumar S., Balaji R., 2015b). This is because of the depth. Even though technically the water level is capable of reaching uptill -5 m (5 m below MSL), there is a high resistance to flow provided by the sea bed as the water levels drop.

This problem is not prevalent in figure 4.3, where the presence of the deep channel runs far south of the site of the powerhouse, providing less resistance to flow during low tide than

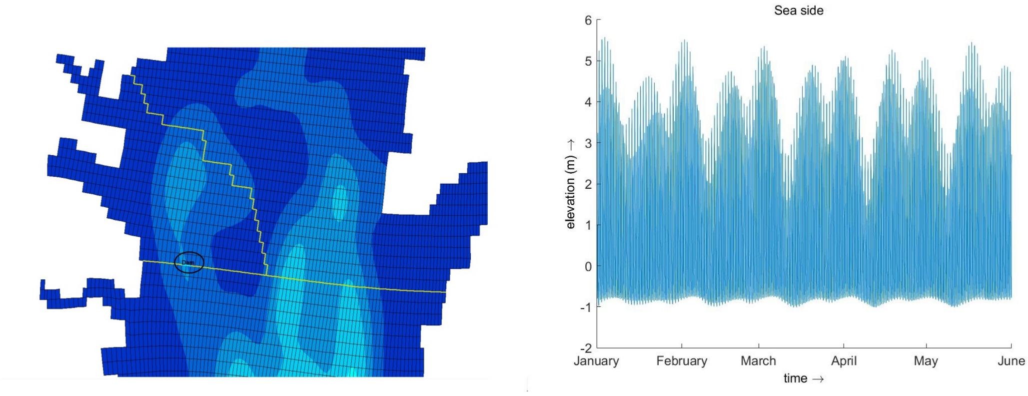


Figure 4.2: (a) Position of turbines and (b) corresponding water levels at left channel

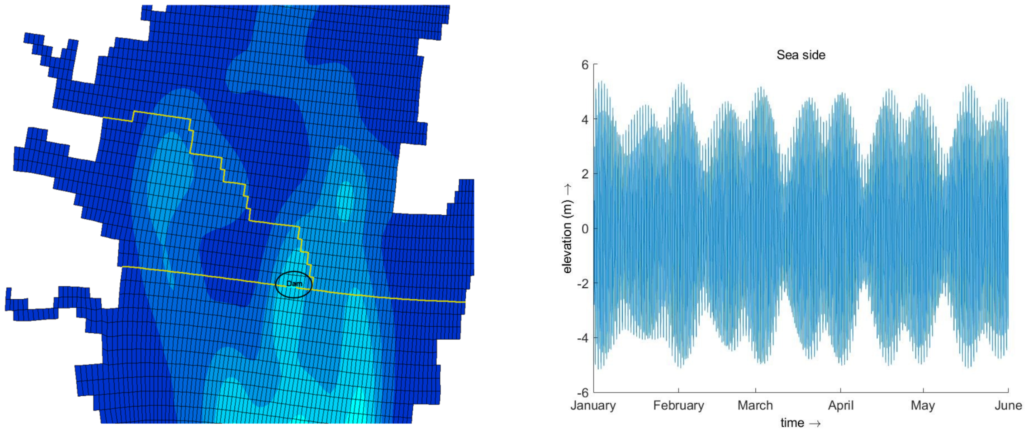


Figure 4.3: (a) Position of turbines and (b) corresponding water levels at right channel

the other sides and allowing the complete tidal movement of the location. Thus at high tide the water levels can rise to + 5 m and drop to - 5 m MSL during low tide, giving a tidal range of 10 m.

If the assessment of tidal energy generation were only based on the tidal range available, the location on the right channel is ideal. However, the channel on the left can also be used for energy generation.

4.1.2. Turbine resistance

As mentioned in section 3.2.3, it cannot be assumed that flow passes between the turbines without any resistance provided by the turbine itself. This resistance causes a smaller discharge to pass through the turbines for a given head difference as compared to an ideal case (an orifice in the dam with the surface area of a turbine).

This has the effect of a slower filling and emptying of the tidal basin throughout the simulation. With the given equation for the calculation of power

$$P(t) = n * Q(t) * h_{diff}(t) * \rho * g * \eta \tag{4.1}$$

This turbine resistance could have a positive or a negative impact on the power generation. Although the turbine resistance would decrease the discharge flowing through the turbines($Q(t)$), a slower change in the height of the tidal basin could be beneficial.

Since the sea levels rise and fall uninterrupted on the other side of the barrage, this could lead to an increased head difference ($h_{diff}(t)$) between the aforementioned basin and the sea.

An analysis was conducted where the energy production was compared to a case where no resistance is provided by the turbines as discharge passes (in eqn 3.3) .

Generation	Turbine	Sluices	$E_{Q,real}$	$E_{Q,ideal}$	Ratio $(E_{Q,real})/(E_{Q,ideal})$
	50	-	3200	3117.3	1.026
• 2 way	75	-	4783	4641.3	1.03
	100	-	6315.2	6097.2	1.035
	50	30	3022.6	2955.3	1.022
• Ebb	50	60	3452	3447	~1
	50	100	3717.6	3751.8	0.99

Table 4.1: Effect of turbine resistance on energy production, compared to the ideal case (Energy values given in GWh/yr)

The results of table 4.1 give an interesting picture. In every scenario of 2 way generation, the energy generation is actually higher when the presence of the turbine resistance is accounted for in the model.This highlights the increased effect of the head difference to the energy generation as compared to the flow rate passing through the turbines. This is also seen when the number of turbines increases, the ratio of the power generation to the ideal power generation becomes higher.

For the 2 way generation, it can be seen that with an increasing number of sluices, the ratio drops and at 100 sluices the ideal generation is higher. This is due to the fact that with an increasing number of sluices, the amount of discharge flowing in and out of the tidal basin becomes less dependent on the turbines, especially so because in the model of the sluices, the resistance to flow provided is less than that of turbines. Hence, the advantage of the increased head difference seen in 2 way generation is nullified.

The positive or negative influence on the energy generation cannot be generalized for other tidal power plants since it is a function of the cross sectional area of the discharge, the resistance provided by the turbines and the sluices and also the basin surface area itself. However, these results do show the need to account for the turbine resistance in the modeling process.

4.2. Effect of barrage on tidal range

Another important detail was in understanding whether the dam itself had any effect on the tidal range generated at the turbine opening. Simulations were made in Delft 3D at the location on the right channel without the barrage. This was compared against a simulation where the barrage has been placed along with the turbines in the openings.

The results in 4.5 show an increase in the water levels at high tide and a decrease in the water level at low tide, increasing the net tidal range available. Initially, the maximum tidal range available is 9.3 m. This increase is around 0.4 m in the neap tide and 1 m in the spring tide, increasing the maximum tidal range to 10.5 m.

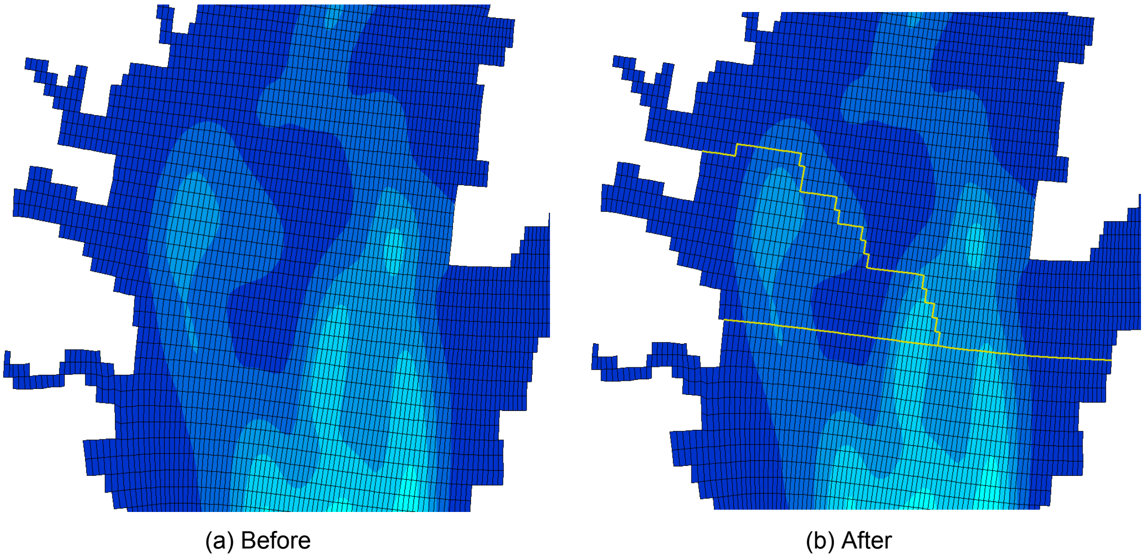


Figure 4.4: Gulf of Khambhat (a) before and (b) after the placement of the barrage

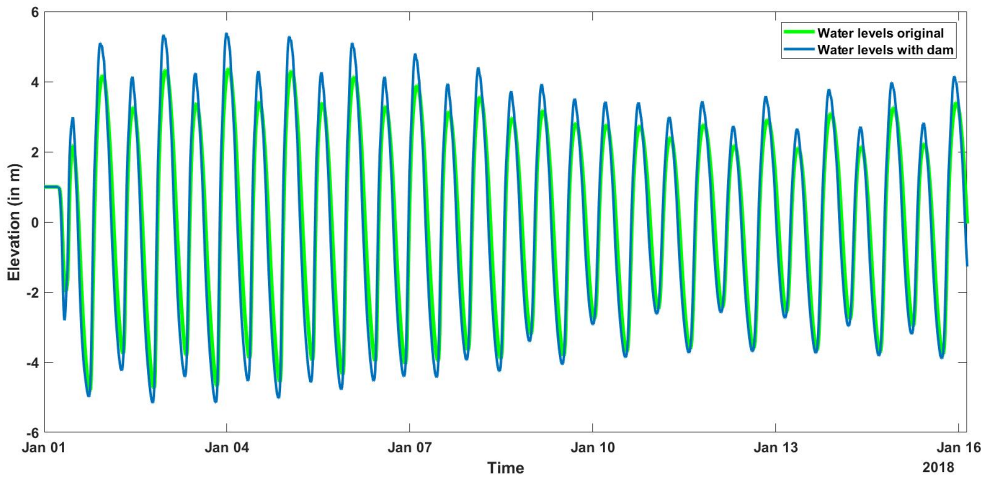


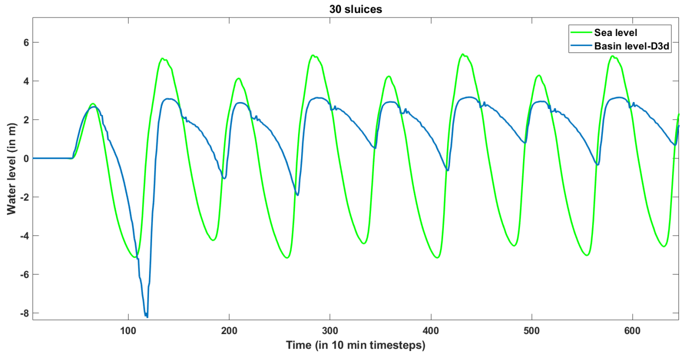
Figure 4.5: Tidal range with and without the dam

4.3. Energy generation in the 2D model

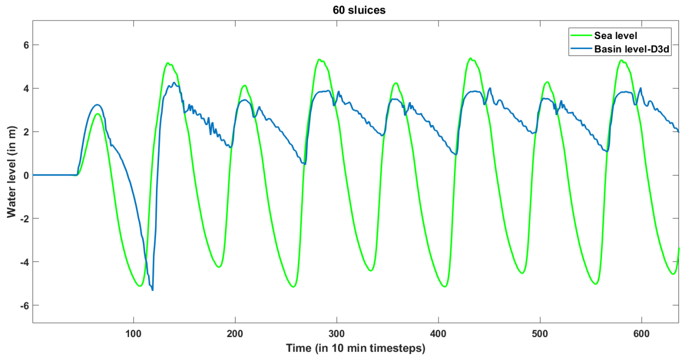
The energy generation for the 2D model was calculated for all 6 scenarios, with the discharge location chosen on the right channel. From the predicted discharge, the simulation was made on Delft3D and the tidal basin levels were measured.

Generation	Turbine	Sluices	E_{2D} (GWh/yr)	Capacity factor
	50	-	2718.3	0.3103
• 2 way	75	-	3271.4	0.249
	100	-	4080	0.233
	50	30	2291	0.262
• Ebb	50	60	2955	0.337
	50	100	3298	0.3765

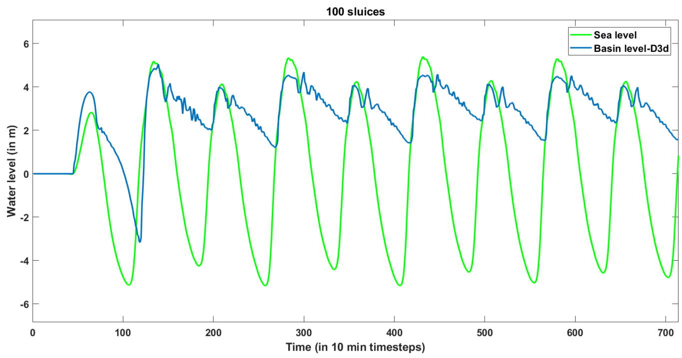
Table 4.2: Energy generation based on 2D model



(a) 30 sluices

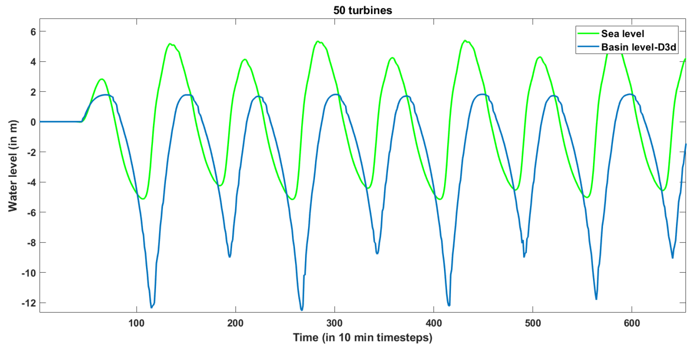


(b) 60 sluices

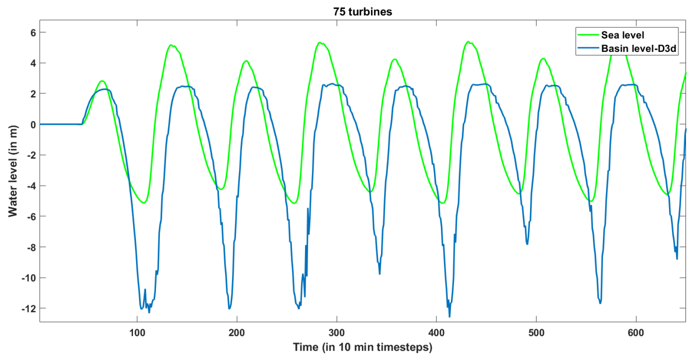


(c) 100 sluices

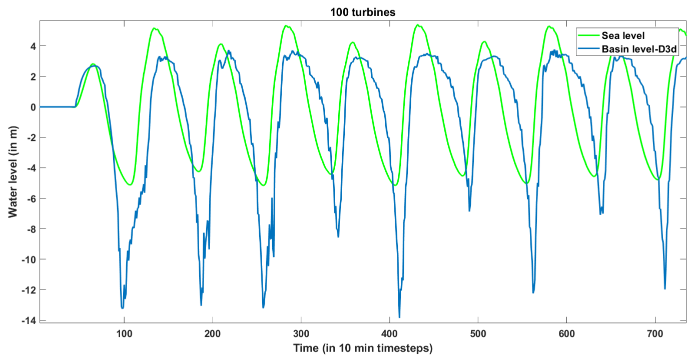
Figure 4.6: Basin levels vs sea levels for Ebb generation scenario with 50 turbines-2D model



(a) 50 turbines



(b) 75 turbines



(c) 100 turbines

Figure 4.7: Basin levels vs sea levels for 2 way generation scenario-2D model

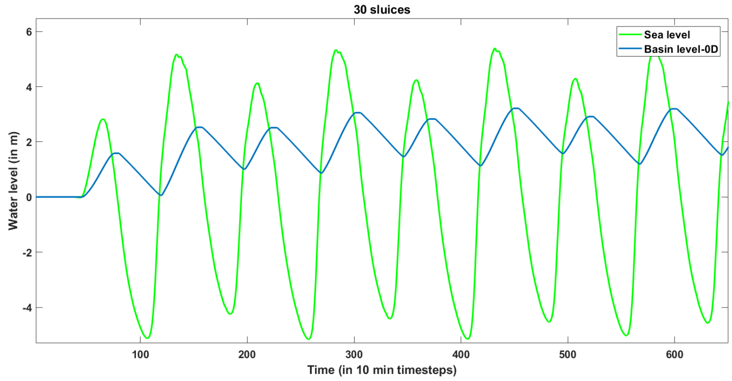
The figures above show the response of the tidal basin when the discharge is added to the 2D model. Inaccuracies are present in the representation of the 2 way generation scenarios (in figure 4.7), which are addressed in greater detail in the next chapter (section 5.1).

However, the trends present in the energy generation and capacity factor can be seen in table 4.2. All the Ebb generation scenarios have the same installed capacity with 50 turbines. But with an increasing number of sluices, the energy generation increases. This is because with the increased total cross sectional area of the sluices, a greater amount of water fills the basin, resulting in an increased head difference between the basin and the sea during energy generation in the ebb tide. This is also seen in the increase in the capacity factor.

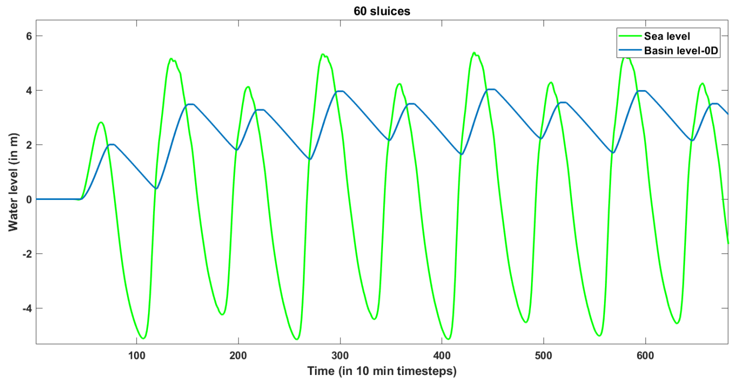
For the 2 way generation scenarios, with an increasing number of turbines, the energy generation increases but not proportional to the increase in the number of turbines (or increase in the capacity of the power plant) and this is reflected in the drop in the capacity factor of the power plant. It can also be seen how during most parts of the operation, the basin water levels in the Ebb generation scenarios remain higher than mean sea level. This is because the sluices during operation are only opened during the flooding of the tidal basin, not emptying.

4.4. 0D model

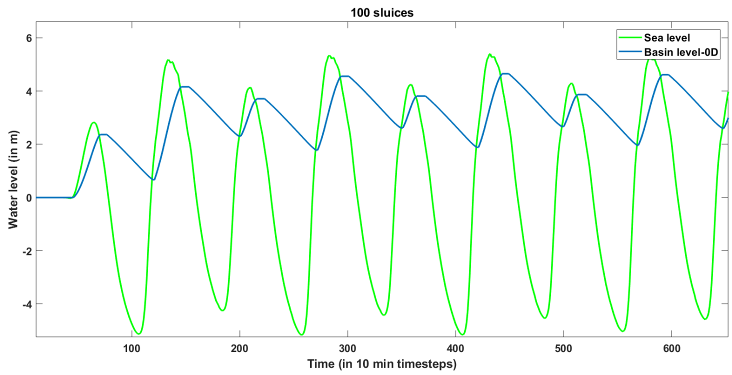
Next, the 0D model was run for the same six scenarios, with the results presented in figures 4.8 and 4.9.



(a) 30 sluices

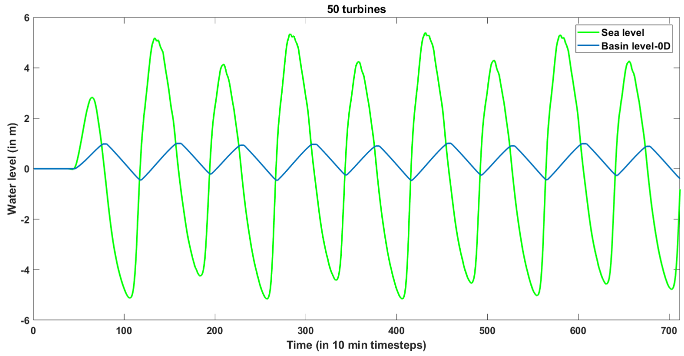


(b) 60 sluices

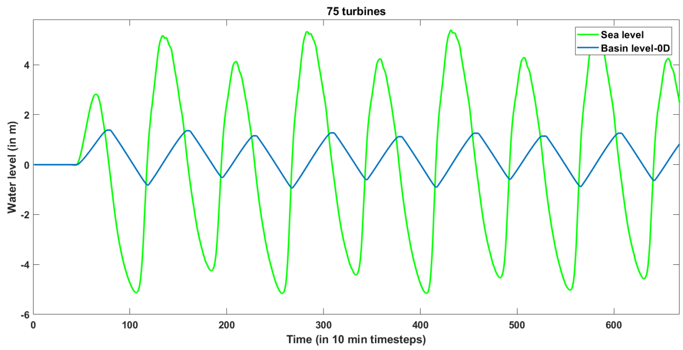


(c) 100 sluices

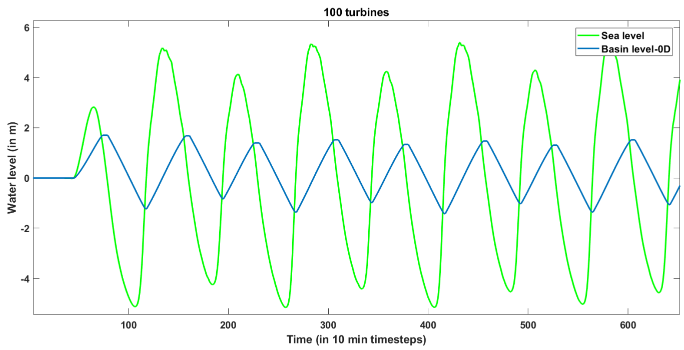
Figure 4.8: Basin levels vs sea levels for Ebb generation scenario with 50 turbines-0D model



(a) 50 turbines



(b) 75 turbines



(c) 100 turbines

Figure 4.9: Basin levels vs sea levels for 2 way generation scenario- 0D model

In the 2 way generation scenarios, the water levels during operation oscillate around the MSL, with an increase in turbines only increasing the elevation at high water and decreasing the elevation at low water.

In the Ebb generation scenarios, similarities can be seen with 4.6, where the water levels stay higher and rarely drop to MSL. The differences between the 2D model and the 0D model are elaborated below.

4.5. Differences in model

The table below shows the energy generation from this 2D model compared with the 0D model, with the parameter *Ratio* showing the relative value of the 2D generation compared with the 0D model.

Generation	Turbine	Sluices	E_{2D} (GWh/yr)	E_{0D} (GWh/yr)	Ratio $(E_{2D})/(E_{0D})$
• 2 way	50	-	2718.3	3200	0.8492
	75	-	3271.4	4783.6	0.684
	100	-	4080	6315.2	0.6461
• Ebb	50	30	2291	3022.6	0.758
	50	60	2955.2	3452	0.8561
	50	100	3298	3717.6	0.8871

Table 4.3: Energy generation differences between the models

The energy generation calculated from the 2D model is lower than the analytical (0D) model in each scenario, showing there are some fundamental differences. In section 3.4 it is described how the comparison of the models is required in order to understand what local conditions affect the energy generation.

The local conditions influencing the energy generation have been detailed below:

4.5.1. Tidal flats

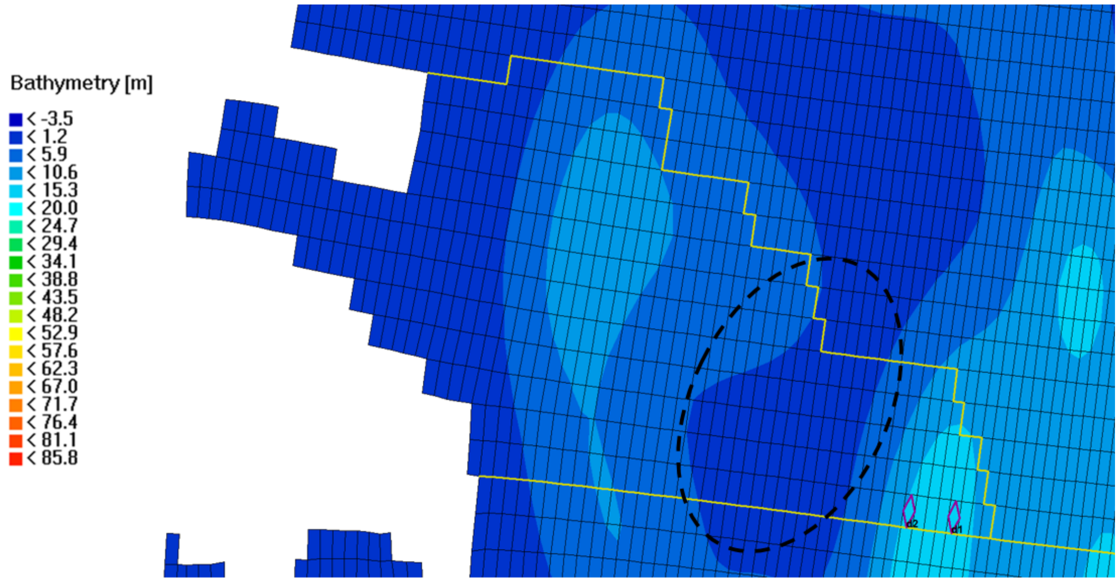
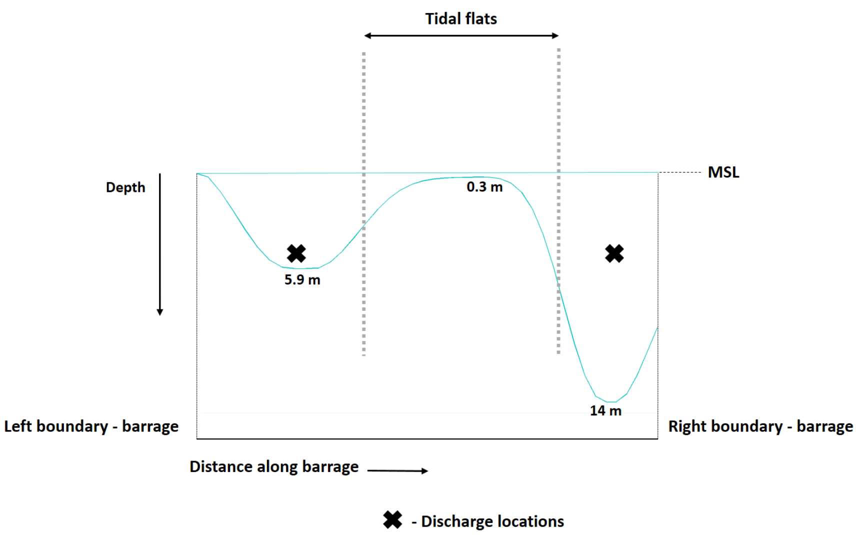
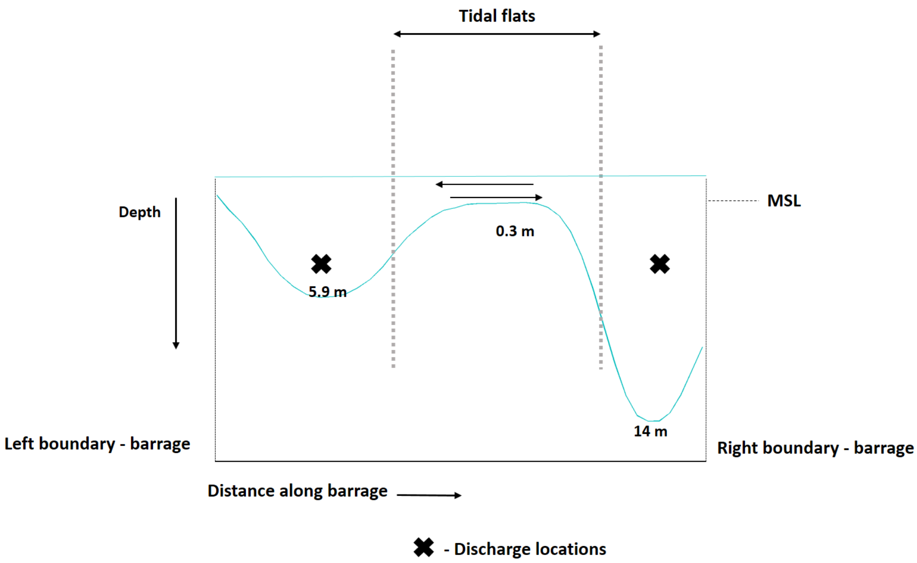


Figure 4.10: Tidal basin and the tidal flats (in the highlighted region)

The first factor is the presence of the tidal flats, highlighted in figure 4.10. These tidal flats are coastal wetlands, regions of extremely shallow depths (< 3 m). These tidal flats occupy a significant area within the tidal basin. The proximity of these tidal flats is problematic due to the rapid change in the depth of the tidal basin, acting as a partial obstruction to the flow.



(a) Mean Sea Level



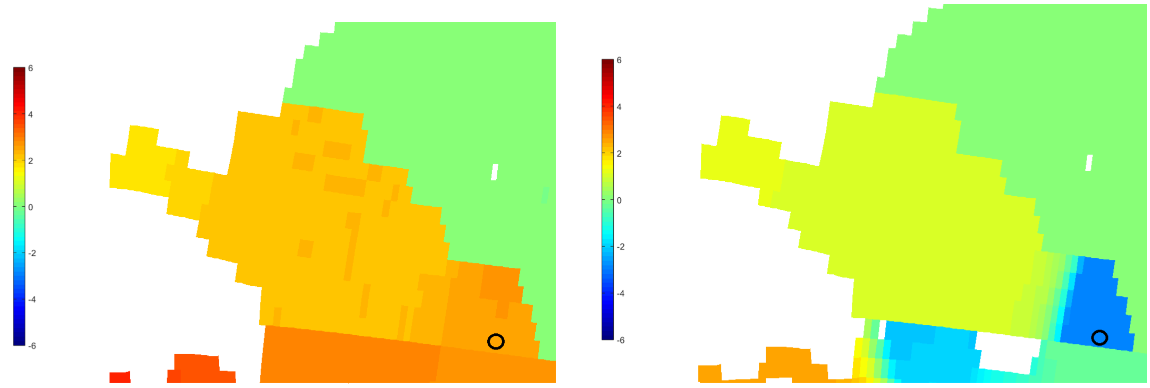
(b) High water

Figure 4.11: Depth profile along the dam alignment

The figure 4.11 shows the depth profile of the tidal basin along the dam alignment, with the 2 possible points of discharge shown. In 4.11a, it can be seen how in the region of the tidal flats, the depth below the free surface is low and the effective cross sectional area for water to pass through is small, leading to a certain degree of decoupling of the 2 basins formed on the left and right of the tidal flat, with the basin on the right of the tidal flat having a much smaller surface area. Although flow occurs over the tidal flats, the magnitude is much smaller.

At higher water levels (in 4.11b), the obstruction to the flow is smaller, allowing the water from the (either) discharge point to fill the entire basin more uniformly.

This can be seen in figure 4.12, which shows the response of the tidal basin during one of the Ebb generation scenarios. In this, the discharge point is highlighted on the far-right.



(a) Flood tide (b) Ebb tide

Figure 4.12: Top view of tidal basin during different water levels

During the ebb tide, as the water levels are supposed to drop, the tidal flats prevent the water from the other side of the basin to reach the discharge point. However, the mass of water that is supposed to empty out of the basin is fixed at that timestep. This results in more water being taken near the immediate vicinity, causing a much greater drop in the water levels near the discharge point than on the other side of the tidal flats. This can be seen in 4.12b where there remains an imbalance of the water levels in different part so of the basin. On the right (where the discharge point is placed), the water levels go till -3 m elevation, while in the other side of the basin, the water levels drop very slowly and remain around + 1 m in elevation.

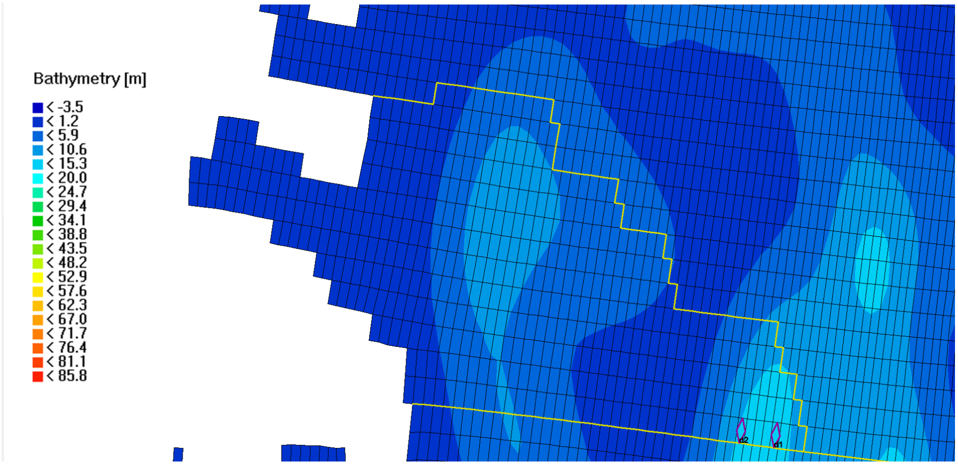
During the flood tide, the effect of the obstruction of the flow is less pronounced, and can be seen in figure 4.12a where the water levels of the entire basin are more uniform.

The effect of this tidal flats can also be seen in the 6 scenarios presented. In the Ebb generating mode scenarios, the water levels during operation predominately remain high, rarely dropping below sea level. Due to this, the negative influence of the tidal flats is smaller. With an increasing number of sluices, the water levels during operation continue to rise, leading to smaller differences in the energy generation compared with the 0D models.

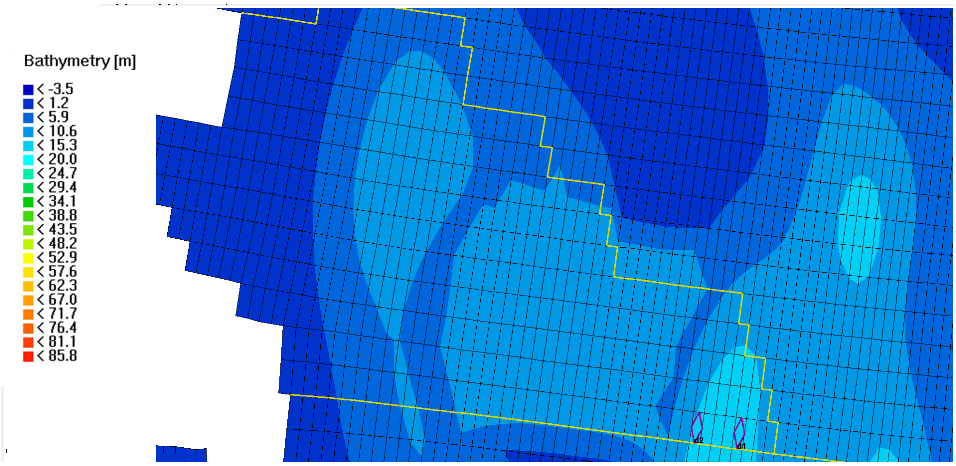
Whereas for the 2 way generation scenarios, the opposite occurs. During Ebb tide, the water levels drop to lower elevations with an increasing number of turbines since an increased cross sectional area is available for the water to discharge out of. Due to this, the effect of the tidal flats increases and it can be seen in table 4.3 that the ratio drops with a higher number of turbines.

Dredging

The presence of the tidal flats severely restricts the energy generation possible at the site. An option of dredging (digging of the seabed) at roughly the site of the tidal flats was looked at. The intention is to only dredge deep enough in order to have a more uniform water depth across the entire tidal basin . This decreases the resistance to flow provided by the sudden change of the water depth at the tidal flats. A further simulation was carried out at Delft 3D with a modified bathymetry. At roughly the regions where the tidal flats existed, the depth was increased by 6 m.



(a) Original bathymetry



(b) Modified bathymetry

Figure 4.13: Bathymetry of basin before and after 6 m dredging

The simulation was conducted for the 2 way scenario with 100 turbines since this was the simulation with the biggest obstruction to the flow. The result gave a value of 5484.6 GWh/yr, a 34% increase in the annual energy generation as compared to the current (undredged) model. The basin levels in both 2D and 0D models were compared in 4.14, showing a much more similar response of the tidal basin to the discharges.

For Ebb generation, the simulations with the dredging did not vary much. A comparison of the basin levels in the 0D and 2D models was made in figure 4.15 for the scenario with 100 sluices. The resulting energy production only increased by 6.76% to 3521.8 GWh/yr. This was an expected result since the tidal flats provided a smaller obstruction to the flow to the Ebb generation scenarios due to the higher water levels during operation.

4.5.2. Depth and bottom roughness

The second factor is the low depth. In addition to the presence of the tidal flats, the entire tidal basin is situated in extremely shallow waters. The deepest section of the tidal basin is a channel on the edge of the tidal basin, where the turbines are placed. At this location, the depth of the bed does not exceed 15 m. Under such depths, the shallow water assumptions apply and the frictional forces play a role in the conservation of momentum equations (in section B.1.2). The bottom friction of the seabed provides a resistance to the flow and controls the water levels and currents at that location. (Satish Kumar S., Balaji R., 2015a).

The bottom friction is an intrinsic property of the flow over a seabed and cannot be avoided. However, the cumulative effect of the tidal flats and the bottom roughness can be checked

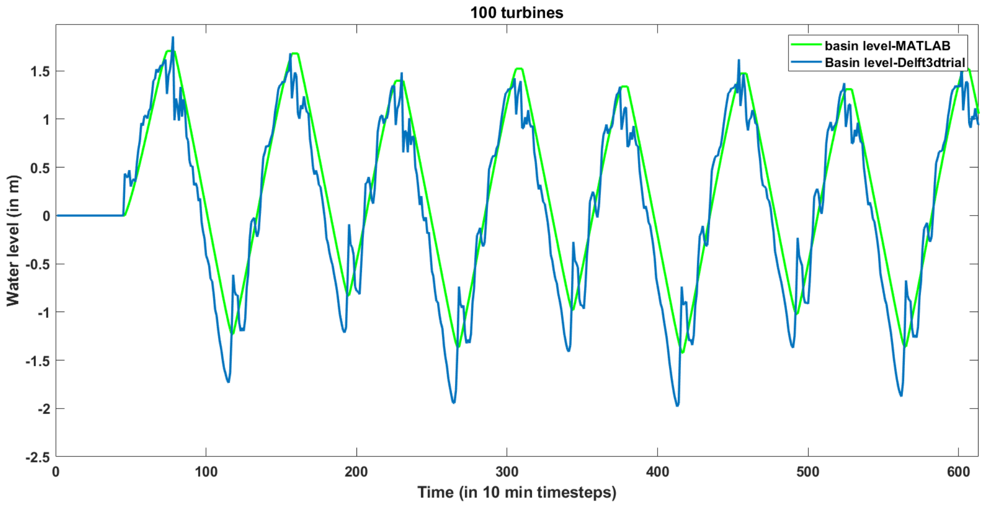


Figure 4.14: Basin levels of 2 way generation scheme after dredging

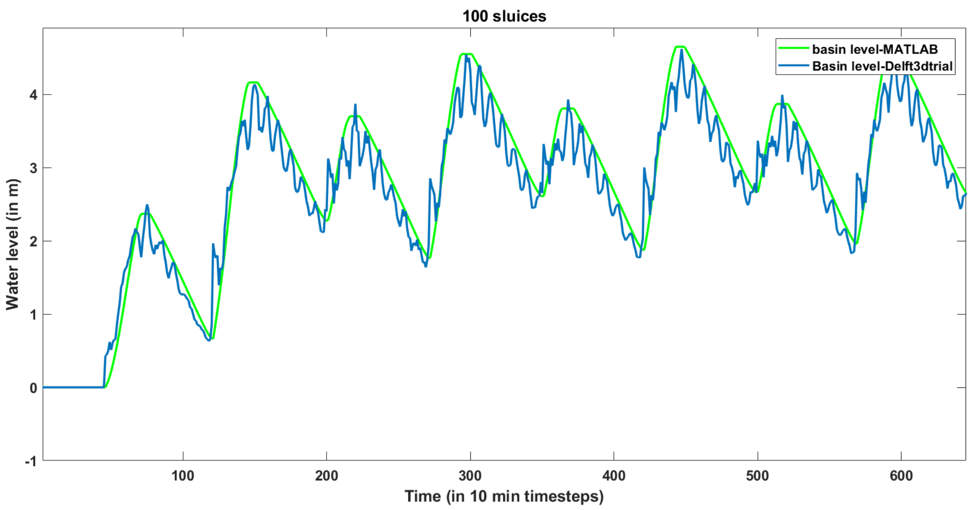


Figure 4.15: Basin levels of Ebb generation scheme after dredging

on the 2D model.

In order to do this, a **hypothetical case** is modeled where these 2 effects are negated in the 2D model and the results compared against the 0D model. It must be stressed that these models do not represent a physically possible generation scheme in the tidal plant. These simulations have been carried out to observe the response of the basin and quantify the effect of these factors on the energy generation.

The depth of the entire tidal basin was increased by 100 m in Delft 3D. By doing so, the tidal basin is now deep and the effects of the bottom friction are negligible on the water level. Furthermore, by increasing the depth by 100 m, the tidal flats are also completely submerged.

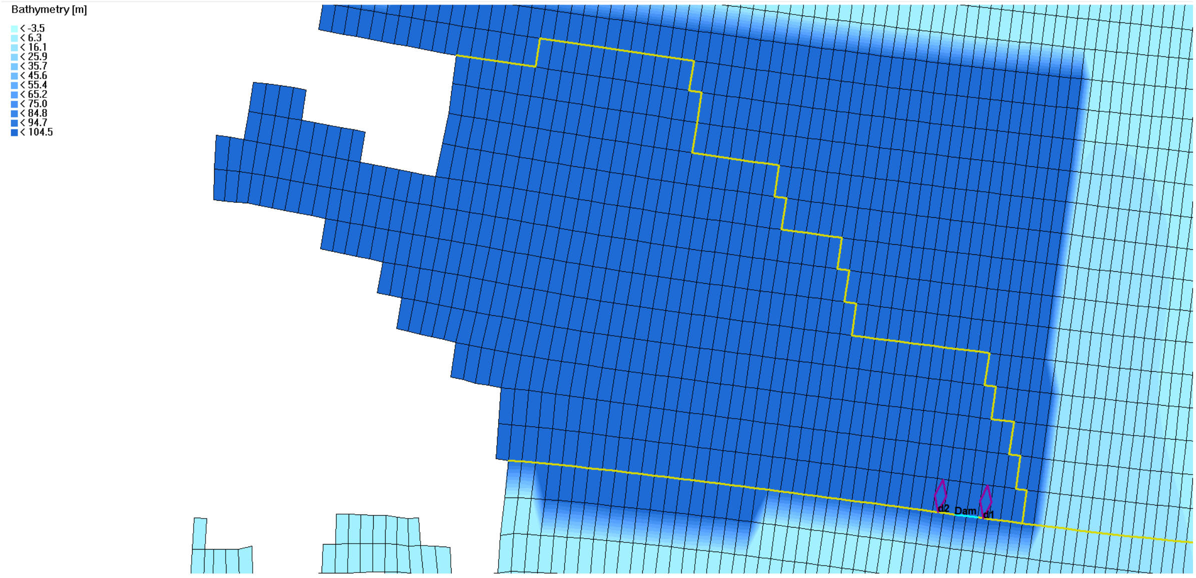
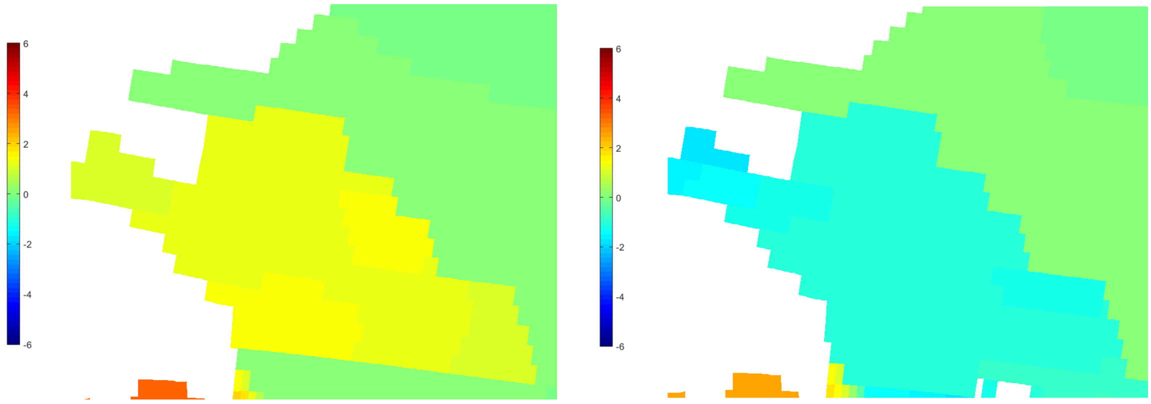


Figure 4.16: Simulation with increased depth



(a) Flood tide

(b) Ebb tide

Figure 4.17: Top view of basin with increased depth

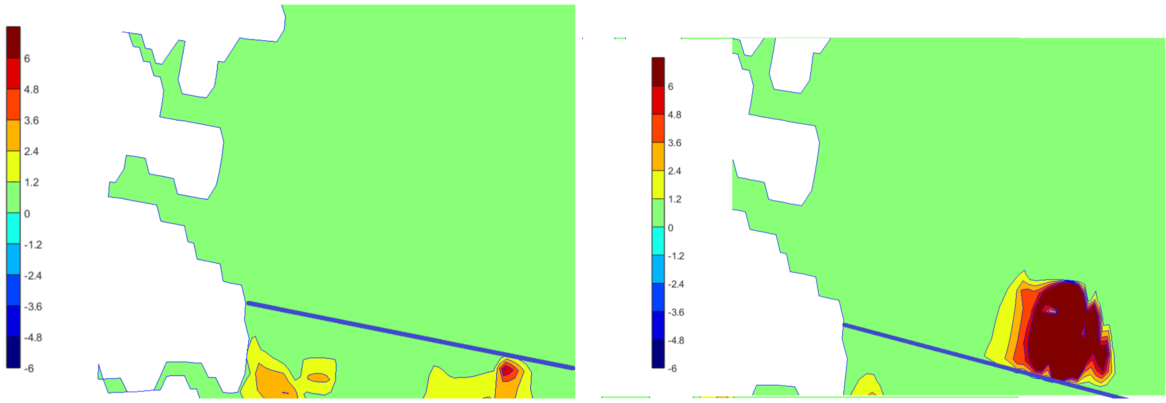
The difference in increasing the depth can also be seen in terms of the shear forces acting against the sea bed (which dissipates energy). In figure 4.18, a comparison of the shear forces present in the tidal basin bed is shown for the same scenario at the same point in the tidal cycle. At an increased depth, the shear forces acting have a negligible magnitude.

The results of the simulation were:

Generation	Turbine	Sluices	E_{2D} (GWh/yr)	E_{0D} (GWh/yr)	Ratio $(E_{2D})/(E_{0D})$
	50	-	3140	3200	0.9813
• 2 way	75	-	4689	4783	0.9782
	100	-	6115	6316	0.968
	50	30	2907	3022.6	0.965
• Ebb	50	60	3306	3452	0.958
	50	100	3556.4	3717.6	0.9566

Table 4.4: Energy generation-increased basin depth

With an increase in the depth, the filling and the emptying of the tidal basin is much more



(a) Increased depth (b) Normal depth

Figure 4.18: Shear forces present in the tidal basin

uniform. The results of this are reflected in table 4.4. The ratio of the energy generation from the 2 models almost equal to 1, with the 0D model having slightly higher energy values in all 6 scenarios. The comparison of the response of the water levels in the basin is shown in 4.19 for the Ebb generation mode(other scenarios shown in section A.2.3), where the basin water levels in Delft3D largely follow the predicted response during the tidal cycle.

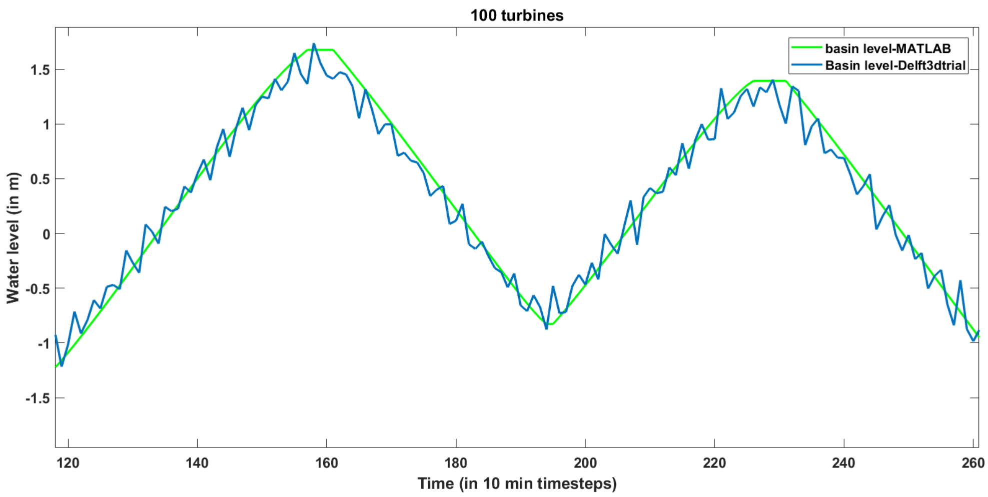


Figure 4.19: Basin levels with a 100 m increased depth

With these simulations, it can be seen that the 1) tidal flats and the 2) shallow depth cumulatively account for almost all the influence of the local conditions in the Kalpasar project. When these 2 factors are removed, there is a near convergence between the 0D and the 2D models, which has been seen for both the energy generation and the water levels response.

5 Discussion

The chapter highlights discussions on the validity of the models created and the design considerations for the Kalpasar project

5.1. Model validity

The first point of consideration is understanding the validity of the models created and understanding the limits.

2D model

As mentioned in section 4.3, inaccuracies are present in the 2D model in its representation of the 2 way generation scenarios.

It can be seen in figure 5.1 that during the ebb tide, the basin levels go below the sea and between time t_1 and t_2, the basin level continues to reduce even as the sea rises. This increases the power generation during each flood tide due to the increased head difference available now.

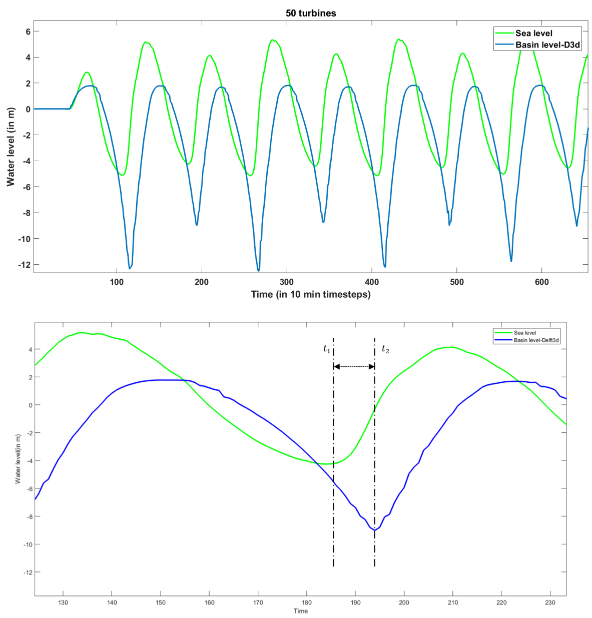


Figure 5.1: (a) Basin levels on Delft 3D for 2 way generation, 50 turbines with (b) closeup of one cycle

This development is impossible during the actual operation of the plant because at the end of the ebb tide, the gates close. Even if the gates are open, the flow of water would now be into the basin, increasing the water level from time t_1. However, due to the nature of the program, the discharges and the opening/closing of the gates are predicted and cannot be analyzed at each time step.

The simulation requires a form of control for the gates separating the sea and the tidal basin which would be based on the head difference created. This condition should ideally be evaluated at each time step in order to determine when the gates are opened and closed. However, in the current Delft 3D there exists no method to change the conditions continuously during the simulation. To tackle this problem, the discharge passing between the gates (and thus the opening/closing) was predicted for each time step.

This method was successful in representing the response of the tidal basin for all the Ebb generation scenarios since the basin response is more uniform at higher water levels. However, it remained unsuccessful for 2 way generation. In the simulations, the gates would ”remain open” and water would leave the basin even when the water levels of the sea are higher. This had a serious effect in exaggerating the energy generation possible for those 3 scenarios.

Due to this, the real energy generation for the 2 way scheme would be even lower than that computed by the 2D model. This same phenomena has been observed in all three scenarios for 2 way generation.

The complete value of the amount of energy difference in the 2 way generation (compared to the 0D model) cannot be calculated using the current model. What is clear that for 2 way generation mode, even the 2D model on Delft 3D has overestimated the energy generation in the power plant

Simulations were also conducted with the discharge point now located on the left channel of the basin. With all 3 scenarios of 2 way generation, the basin water levels still dropped below the low tide and hence the model is still not a valid representation

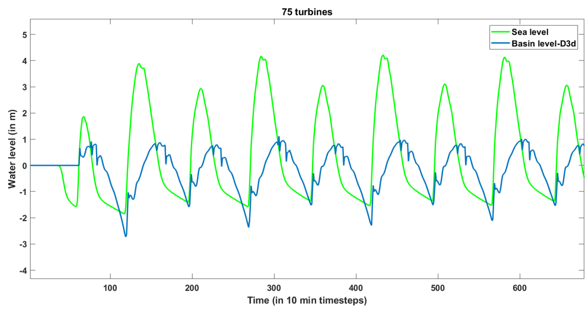


Figure 5.2: 2 way scenario with turbines placed on the left channel

However, with a greater area of the basin present on the left side, the drop in the basin water levels is smaller due to a more uniform emptying of the basin. The energy generation predicted by the 2D models would not be very different than the real values.

To conclude, the 2D model built can be used for modeling tidal energy projects under the condition that *within the operating water levels of the design, there is no major obstruction to the flow filling up and emptying the tidal basin.* In the Kalpasar project this is only valid in the 3 Ebb generation scenarios with the discharge placed in the right channel, not the 3 2-way generation scenarios.

In the dredging simulations and the simulations with the increased depth, these inaccuracies are no longer present since the basin depths are more uniform now.

0D model

In 4.5.2, only when the basin is significantly deep and there are no obstructions like the tidal flats, there is a high degree of convergence between the 2D and the 0D models.

Until such conditions are present in real locations around the world, the 0D models cannot be used for modeling because the local conditions have a significant influence on the energy generation.

5.2. Design considerations- Kalpasar project

Based on the results of all the simulations, some design considerations can be looked at for the Kalpasar project:

- In the current tidal basin, the 2 locations of discharge (left and right channel) provide different advantages. In the channel on the right, the maximum tidal range is available of 10 m. However, due to its proximity with the tidal basin, the volume of water that enters/exits the basin is much lower than expected, which impacts the energy generation. In the channel on the left, only a tidal range of around 5 m is available. But by being connected to a larger part (surface area) of the tidal basin, the emptying of the basin is more uniform.

  Picking an optimal location for the placement of the turbines is thus dependent on several parameters and cannot be just one location for all schemes. For the Ebb generation schemes, the filling/emptying of the basin is not a problem. Hence the deciding factor would only be the available tidal range, which is greatest in the channel on the right. This can also be seen in the simulations, where the energy generation in all 3 Ebb generation mode scenarios was significantly higher with the discharge located on the right channel.

  For the 2 way generation schemes, the decision is not straightforward. A conclusive decision cannot be made for the 2 way generation scenarios because of the inaccuracies present in the model when the discharge is placed(especially on the right channel). The inaccuracy cannot be quantified and hence an estimate cannot be made. Improvements are required in the modeling process in order make a clear decision

- However, a clear characteristic of the flow in the basin can be seen in the form of the tidal flats. It can be seen that it has a negative impact on the energy generation. The simplest recommendation for the project could be to only use Ebb generation as an operation mode in the tidal power plant and design it to keep the water levels during operation high. This decreases any obstruction to the flow caused during the tidal cycle. This creates a more efficiently running power plant for a given installed power capacity.

- However, if the 2 way generation schemes are to be looked at, dredging should be considered as an option. In section 4.5.1, it is shown how dredging the tidal flat regions by 6 m would help increase the energy generation of the power plant. However, this was a very rough simulation without taking into account how this would affect the coastal environment and the natural processes associated with it in the region. The risks involved in the option remain unknown.

  Also apart from the increased energy generation, the sand dredged can also be used for the construction of the barrage. A detailed study into the scope and impact of the dredging in the tidal basin would be highly beneficial.

6
Conclusions

The chapter summarizes the work done within the thesis. First the research objectives and their respective results are highlighted. Next the recommendations for any further improvements or research are provided.

The thesis explores the possibility of tidal energy generation in the Gulf of Khambhat, on the Western coast of India. The region has high tidal variations, with the tidal range having magnitudes of over 10 m. This is part of a large project named Kalpasar which proposes creating a barrage to close a part of the sea for multiple other purposes such as freshwater storage, terrestrial transportation etc.

- The main objective of the thesis was to *model the tidal power plant in the Kalpasar project*

A two dimensional model of the entire system was made using a combination of Delft 3D and MATLAB softwares. This required modeling several components such as:

- The Gulf of Khambhat and the motion of the tides.
- The location of the barrage and the tidal basin.
- The modeling of the discharge through the turbines and the sluices and the electricity conversion of the turbines.
- The operational sequence of the opening and closing of the gates of the turbines and sluices.

These components were modeled, integrated into the final system and simulated together to obtain the resulting energy generation. The key element in the modeling of the tidal power plant is **coupling the opening/closing of the tidal basin with the hydrodynamics of the flow**. In the thesis, this was done by predicting the opening/closing time during the simulation and implementing it in Delft 3D using an user-input discharge.

The method can be accurate for calculating the energy generation with some tolerances and under some conditions. The main condition is that within the operating water levels within the tidal basin, there shouldn't be a significant obstruction to the discharge flow. This interrupts the emptying/filling of the entire tidal basin

Moreover, a number of assumptions were taken in the modeling of the system, thought to have little effect in representing the real energy generation (in section B.2.1). However, this does mean that a small degree of variation must be assumed in the final values of the energy generation.

- Secondly, the *influence of individual parameters on the tidal energy generation* was checked, with the following conclusions:

1. Local conditions: The tidal flats and the shallow depth of the basin have a significant influence on the hydrodynamics of the flow passing between the tidal basin and the sea. They have a negative impact in the energy generation in the tidal power plant.

   The effect of these local conditions varies depending on the water levels of the tidal basin during operation, with a greater negative effect when the water levels are low.

2. Turbines: The location of the turbines has to be chosen carefully because along most of the barrage, the depth is too shallow. Although a tidal range of 10 m is observed in the northern part of the Gulf, it is only available in the right edge of the tidal basin. Another possible location exists on the left side of the basin, but with a reduced tidal range of 5 m. Depending on the operation sequence of the power plant, either of these 2 locations is optimal for energy generation and must be considered during the final design.
   The resistance to the flow provided by the turbines also has a small influence on the energy generation of the power plant. In some scenarios, this influence can also be positive and increase the energy generation (when compared to the flow passing through the opening in the barrage).

3. Barrage: A comparison of the tidal range available was made with and without the presence of the barrage. It can be seen tha the construction of the barrage along the Gulf of Khambhat increases the tidal range available

- The last objective of the thesis was to know if *any wider implications can be seen for future modeling of tidal power plants*

One of the most important takeaways from the research is in highlighting the strengths of the use of 2D modeling for tidal barrage energy projects, even at the preliminary stage of the resource assessment. At different potential tidal energy sites worldwide, elements such as the water depths, inter tidal areas, seabed conditions and the tidal constituents differ.

It cannot be assumed that the components of the tidal power plant do not affect the tidal resource it is trying to extract. This form of interaction with the power plant cannot be observed by 0D modeling.

Such important data about the local conditions is lost. This can lead to an overestimation of the energy generation capabilities by a significant amount.

6.1. Model improvements and further research

- Currently 1 grid cell is scaled at 450 m * 1350 m. The grid cell resolution can always be refined for greater accuracy. This would also be more crucial in any future research on the near field effects at the location of the discharge.

- In the models, even when the effects of the tidal flats and the shallow depth were removed, there were still differences in the energy generation of 2% to 5% between the 2D and the 0D models. These differences could be explained by other factors which were not quantified, such as the wave forcing or the effects of the Coriolis acceleration. The inclusion of these factors would make the understanding of the 2D model more accurate.

- In the previous section, it was mentioned how important controlling the opening and closing of the basin during the simulation is. Real time control (RTC) tools are available as an add-on to the Delft 3D software for his purpose. Deltares has a software package named WANDA which was primarily designed to support the design processes in pipeline systems. However, it can also be coupled with Delft 3D to act as a controller for the turbines and the sluices. The coupling of this software with Delft 3D for future tidal barrage projects would be highly recommended for an accurate representation of the flow.

- During the research simulations, the tidal basin bathymetry was kept at a constant state and the simulation time was kept short at 5 months. However, the tidal plant is expected to have a lifetime of possibly upto 100 years. With this time period, the bathymetry is expected to change, especially considering that with the construction of the tidal basin and the position of the powerhouse, the dynamics of the flow of water and sediments in the region would be highly different than before. A detailed study of how the bathymetry of the basin and the sediment transport changes is crucial to understand in order to know if the energy generation changes over time.

- Currently, a lot of uncertainty lies in various parts of the Kalpasar project. The freshwater availability is one key factor which could have a key influence on the energy generation capability of the project. With the fixed alignment of the dam, the freshwater basins and the tidal basins are competing within a fixed amount of surface area. Since the primary purpose of the Kalpasar project remains freshwater storage, the maximum size of the tidal basin during the research was kept at a conservative value of 300 sq. km. Further research on the status of the availability of freshwater for the lifetime of the dam would help calculating the maximum basin area possible and help maximize the energy generation

A

Appendix: Supplementary figures

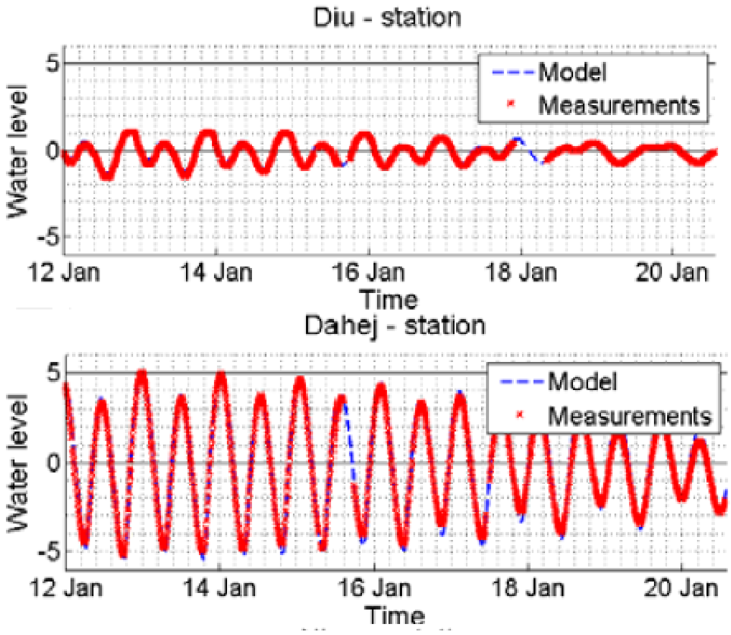


Figure A.1: Deltares model vs measured values at local stations

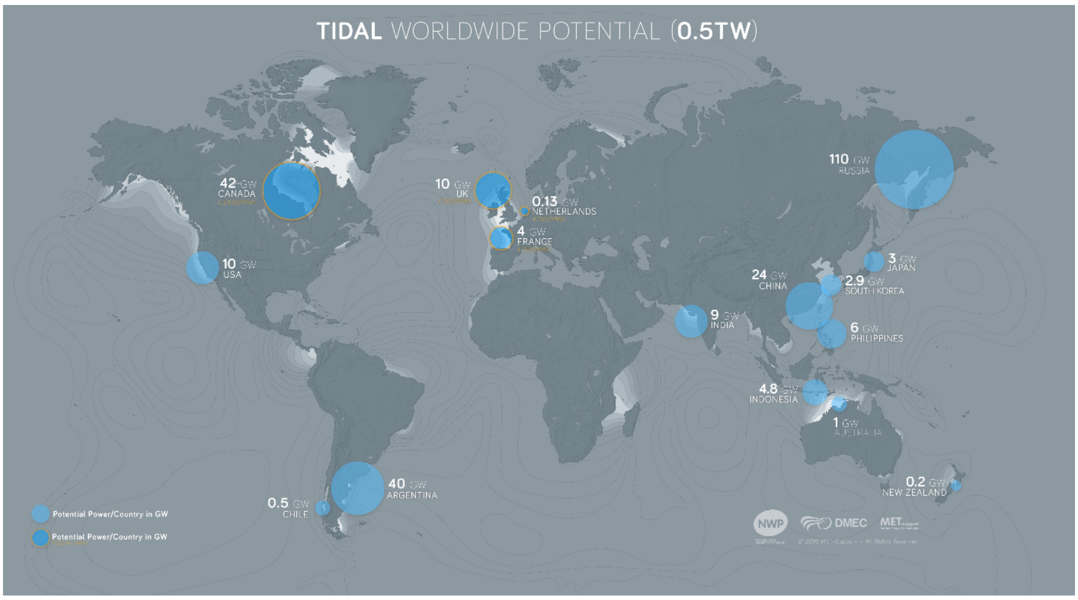
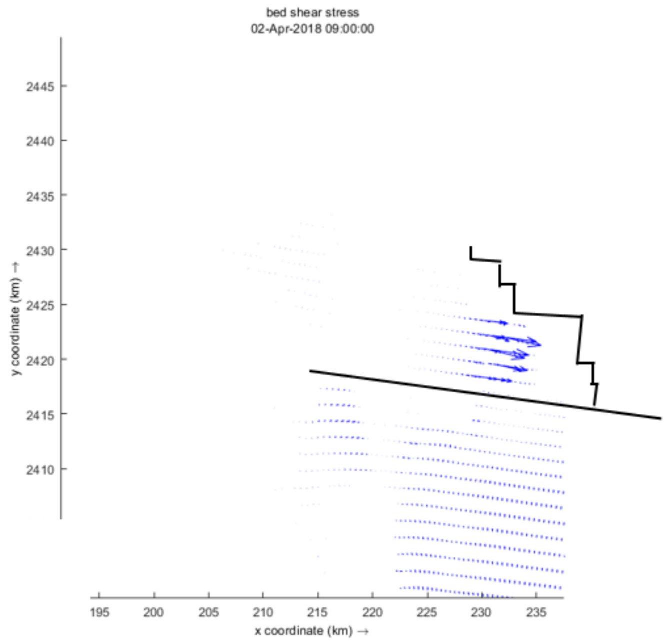


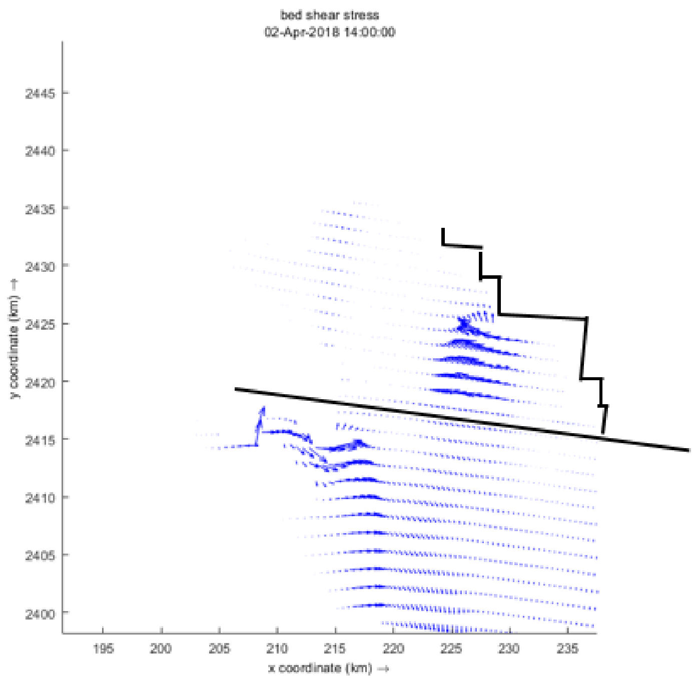
Figure A.2: Worldwide tidal potential

A.1. Shear stresses acting on basin

A.1.1. Actual location

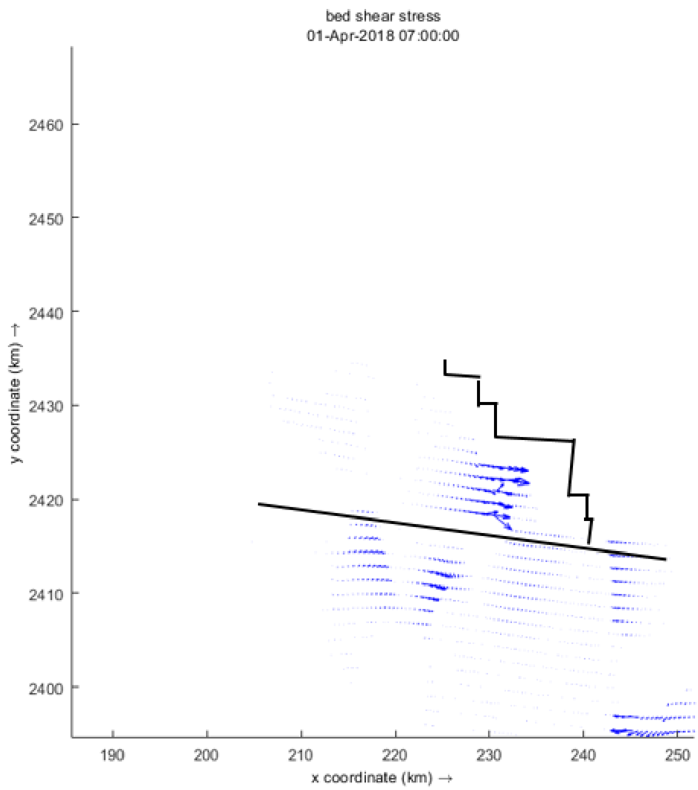


(a) 50 turbines-Ebb

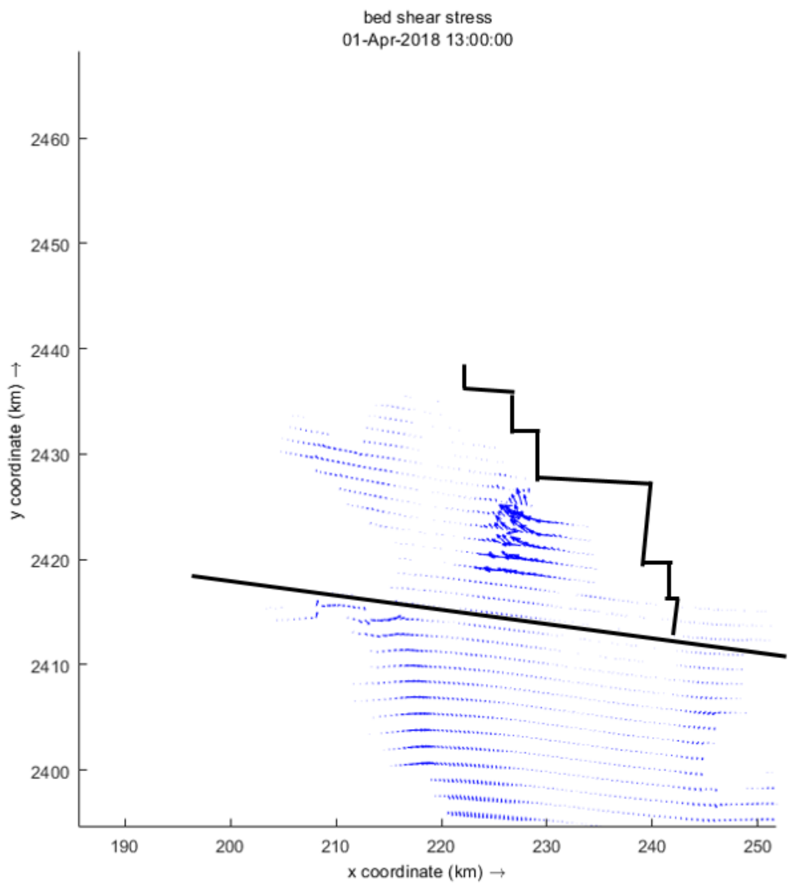


(b) 50 turbines-Flood

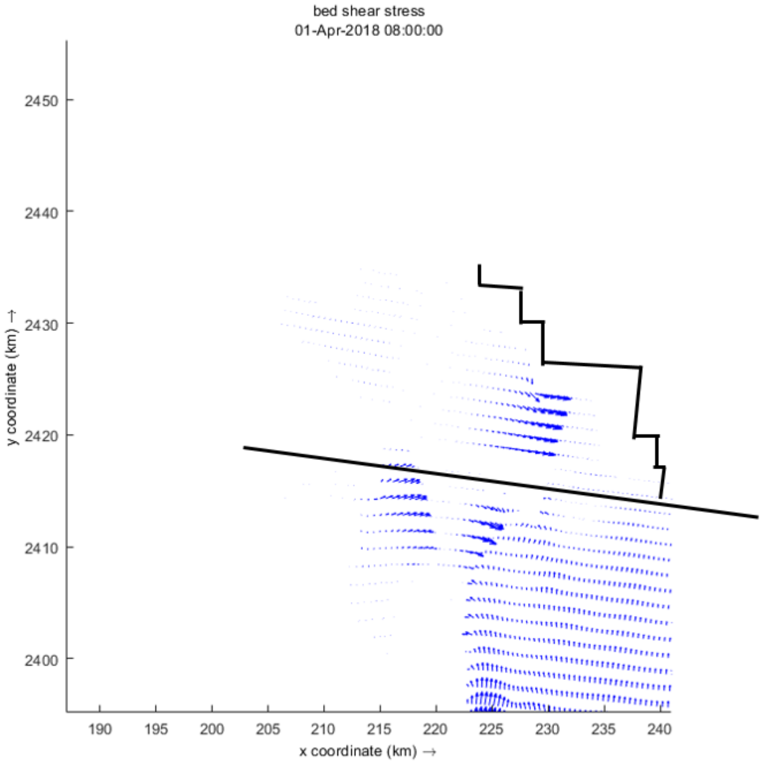
Figure A.3: Shear forces acting on basin for 2 way generation -50 turbines



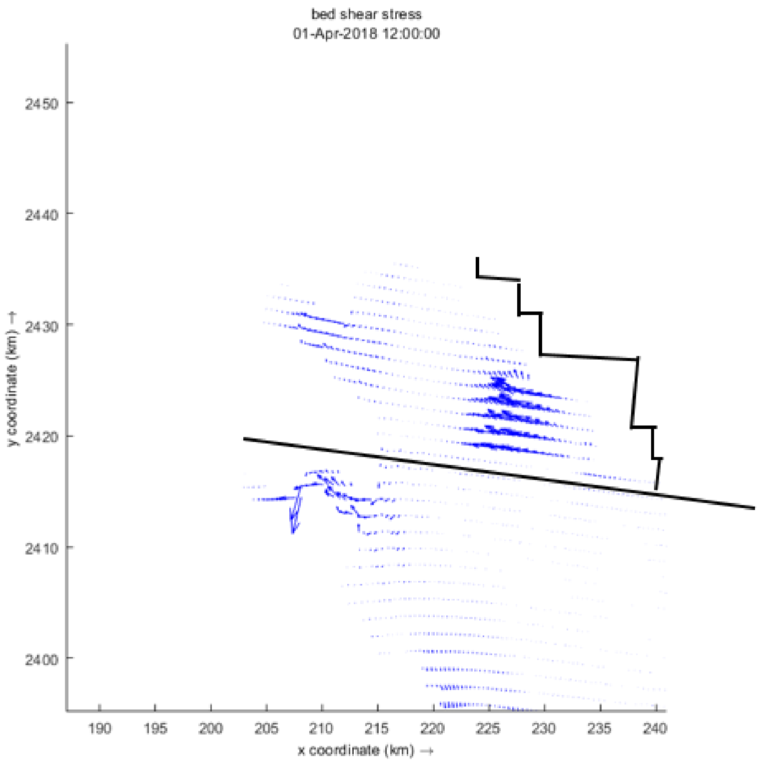
(a) 75 turbines-Ebb



(b) 75 turbines-Flood

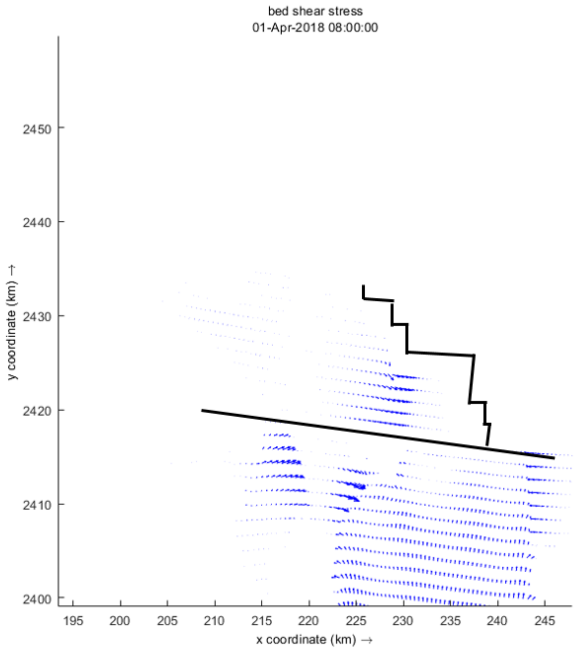


(a) 30 sluices-Ebb

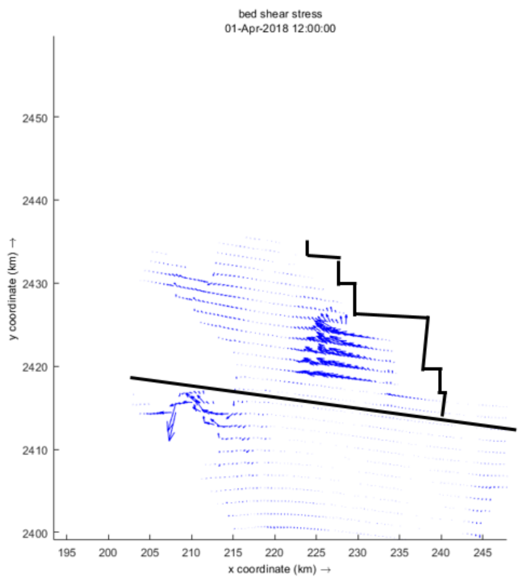


(b) 30 sluices-Flood

Figure A.5: Shear forces acting on basin for Ebb generation -30 sluices



(a) 60 sluices-Ebb

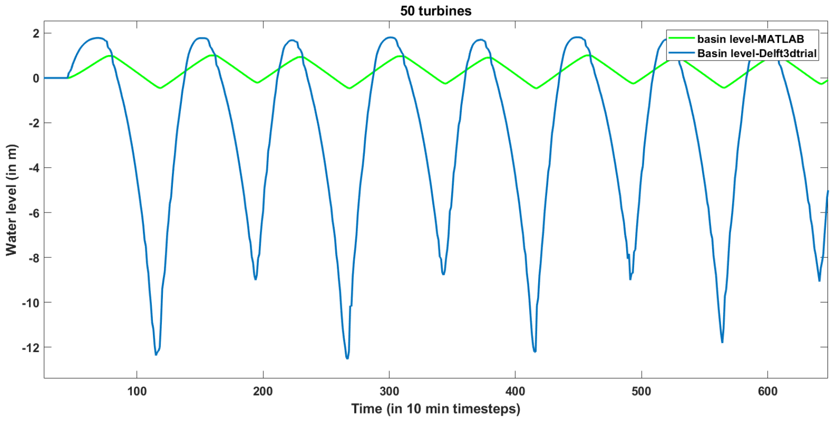


(b) 60 sluices-Flood

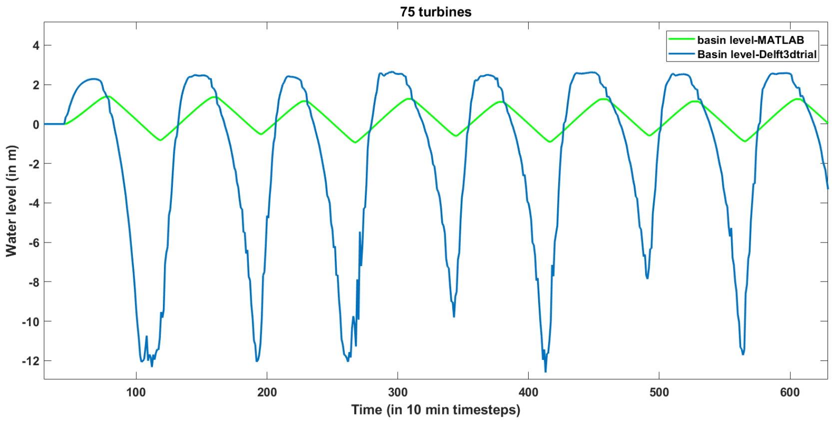
Figure A.6: Shear forces acting on basin for Ebb generation -60 sluices

A.2. Tidal basin levels

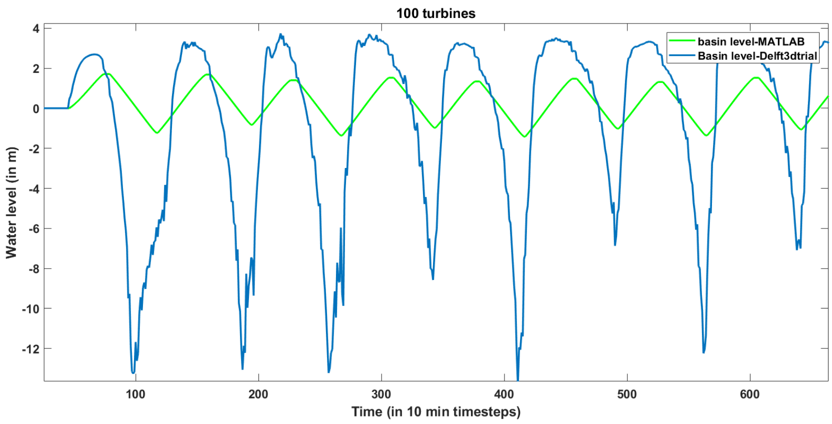
A.2.1. Location of discharge-right channel



(a) 50 turbines

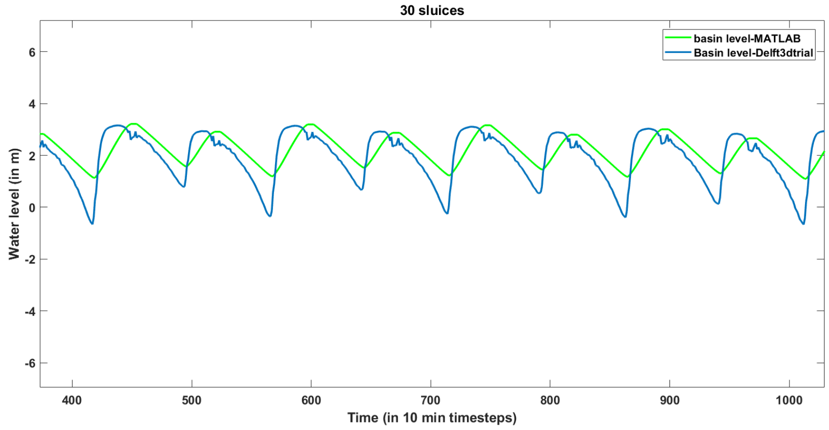


(b) 75 turbines

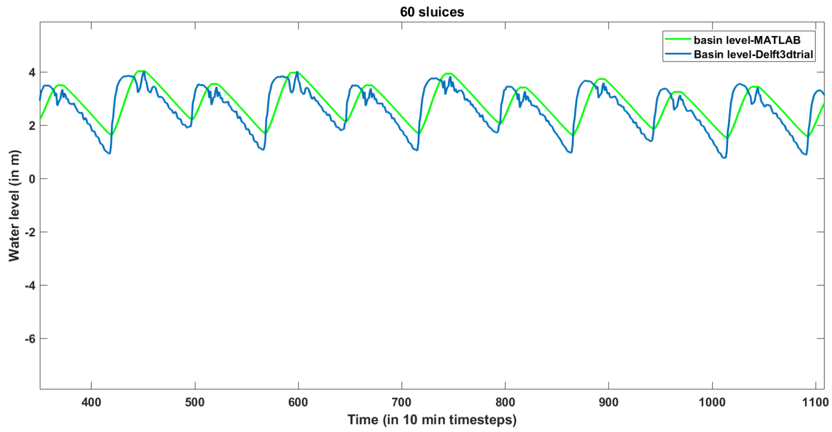


(c) 100 turbines

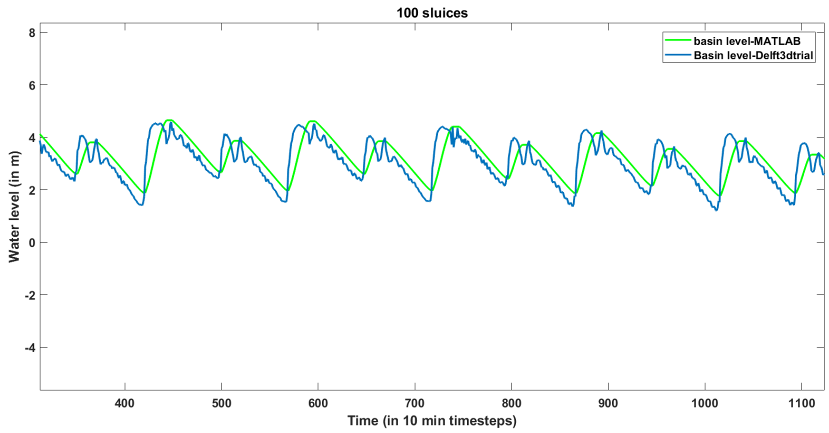
Figure A.7: Basin levels comparison- 0D (green) vs 2D (blue)



(a) 30 sluices



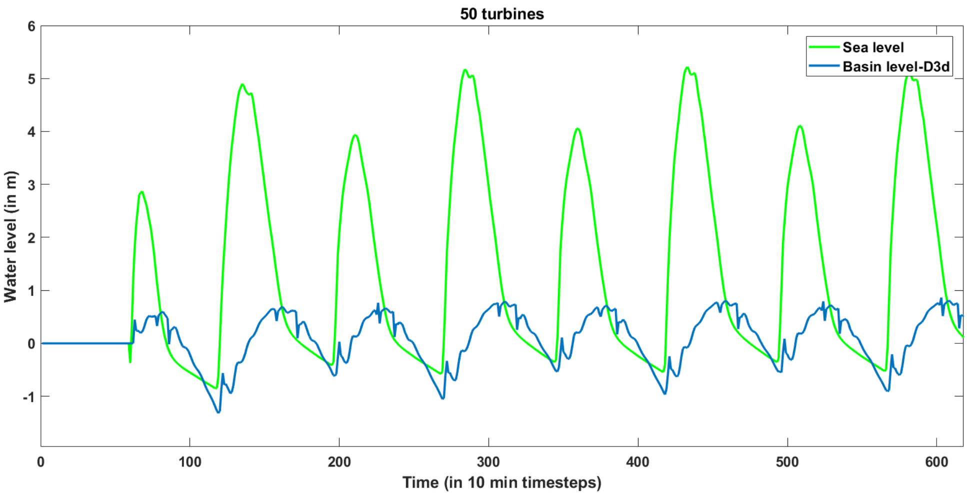
(b) 60 sluices



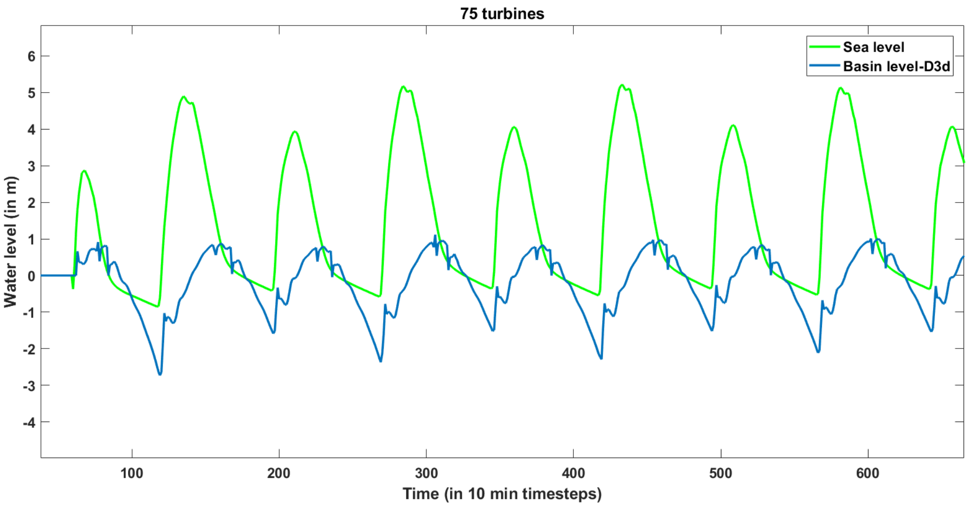
(c) 100 sluices

Figure A.8: Basin levels comparison- 0D (green) vs 2D (blue)

A.2.2. Location of discharge at left channel

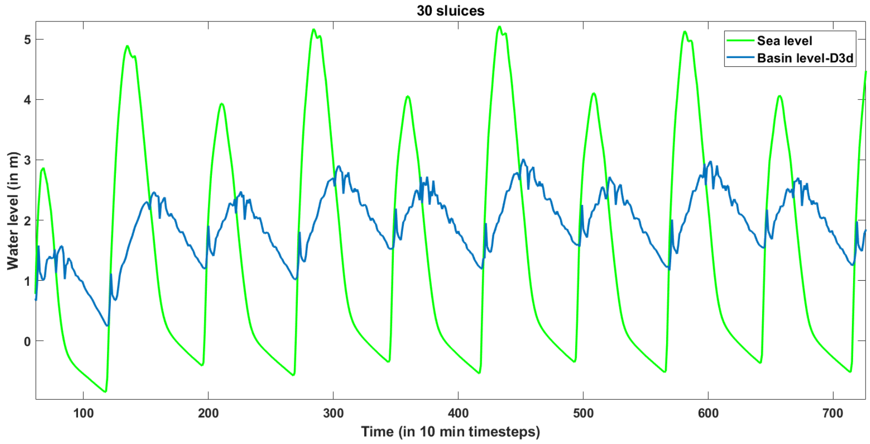


(a) 50 turbines

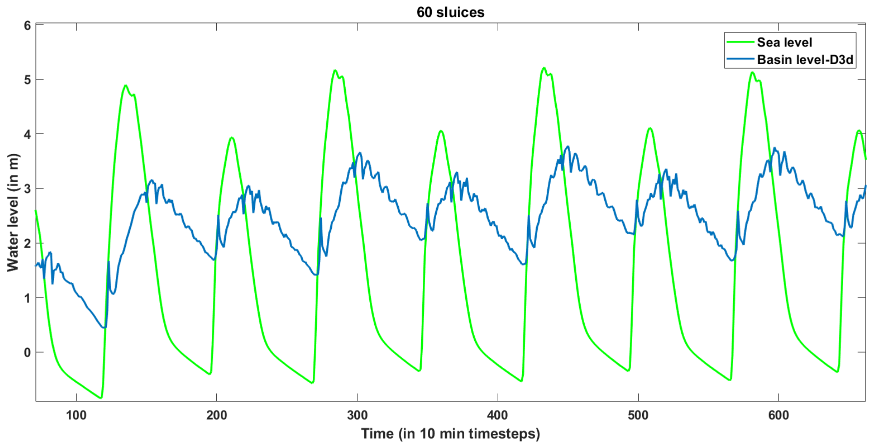


(b) 75 turbines

Figure A.9: Basin levels vs sea levels for 2 way generation



(a) 30 sluices



(b) 60 sluices

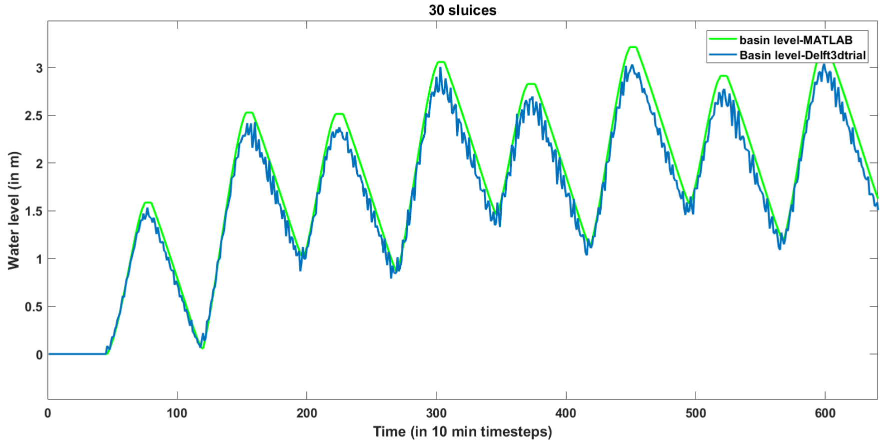
Figure A.10: Basin levels vs sea levels for Ebb generation

Turbines	Sluices	E_{2D}(in GWh/yr)	E_{0D}(in GWh/yr)	$\frac{E_{2D}}{E_{0D}}$	Cf for 2D model
50	-	834	1450	57.4%	0.0953
75	-	936.7	2173	43%	0.0713
100	-	1192	2765	43%	0.068

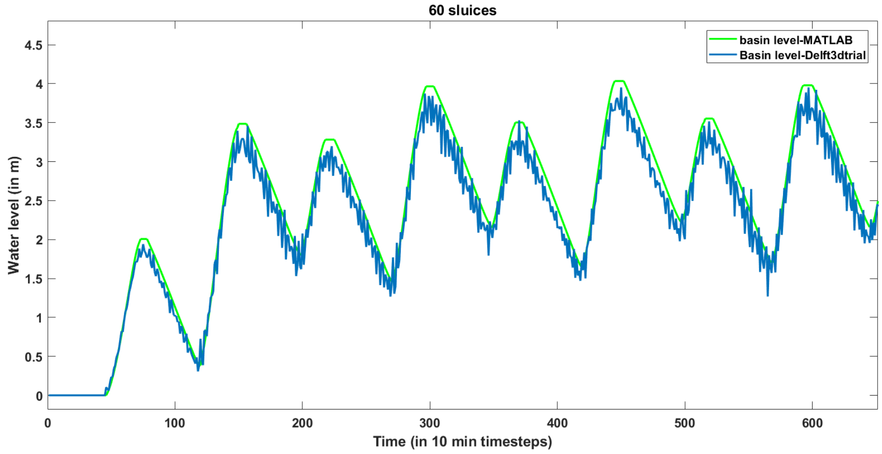
(a) 30 sluices

Figure A.11: Table of 0D vs 2D models for the 2 way generation schemes

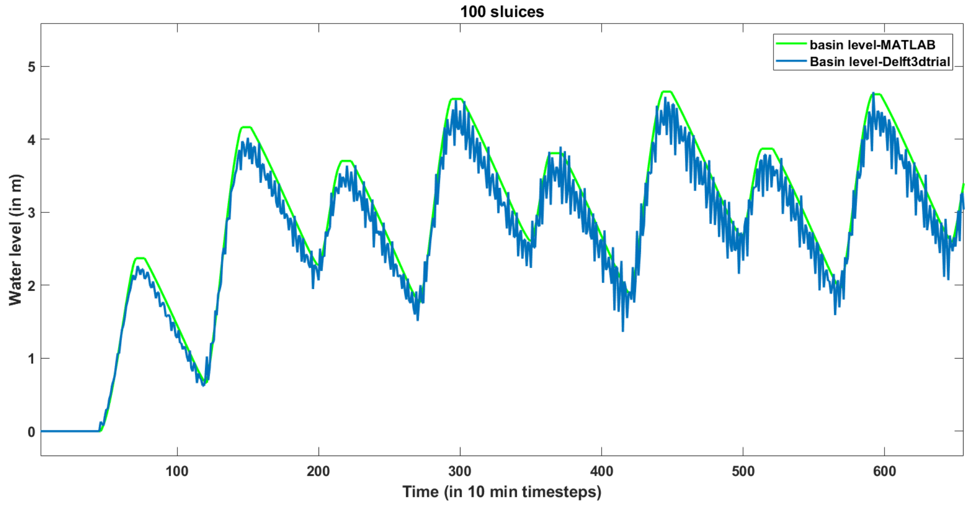
A.2.3. Simulation with increased depth



(a) 30 sluices

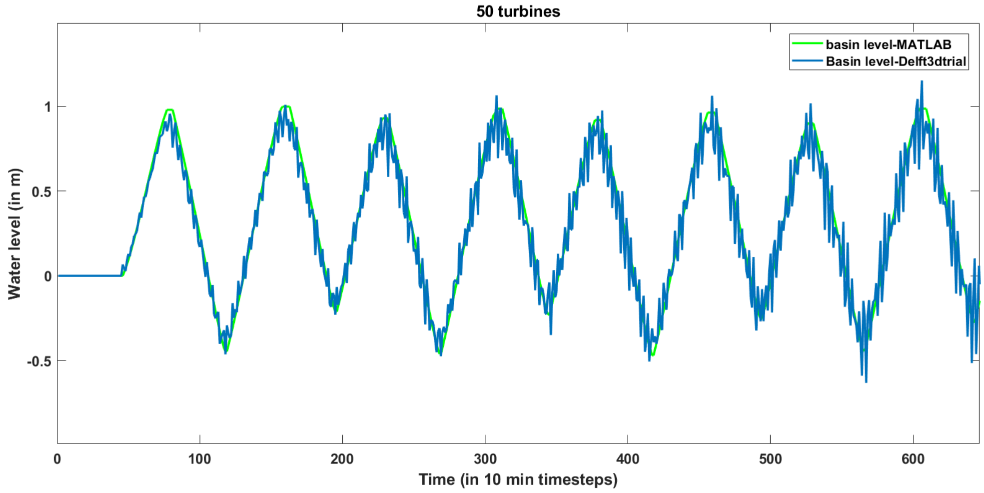


(b) 60 sluices

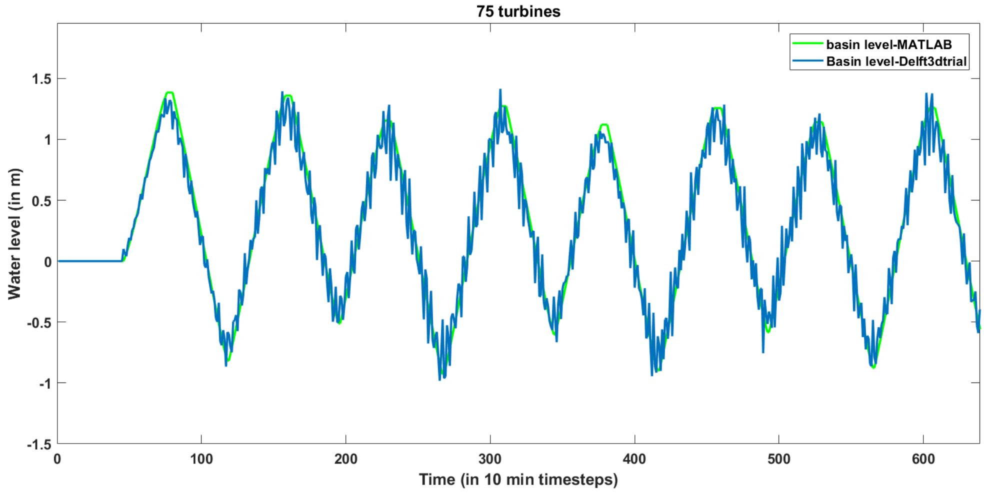


(c) 100 sluices

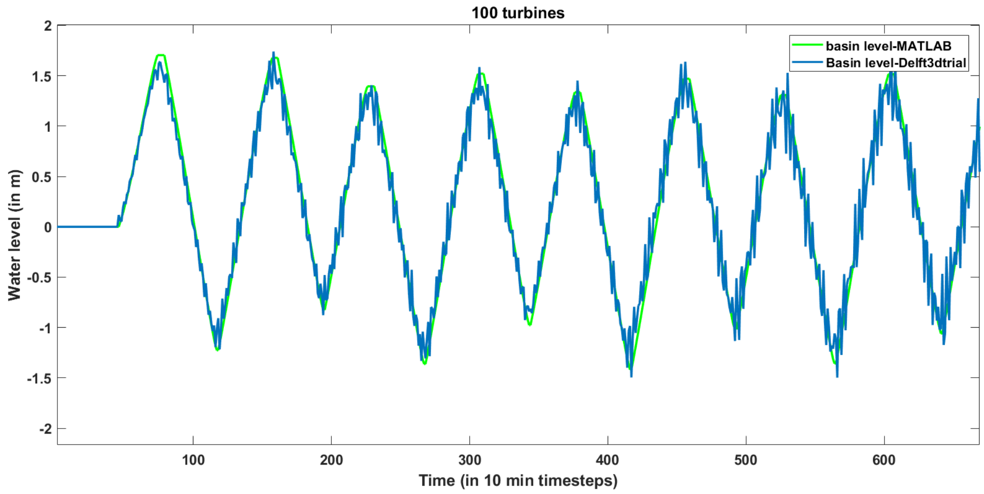
Figure A.12: Basin levels comparison for Ebb generation- 0D (green) vs 2D (blue)



(a) 50 turbines



(b) 75 turbines



(c) 100 turbines

Figure A.13: Basin levels comparison for Ebb generation- 0D (green) vs 2D (blue)

B

Appendix: Delft 3D model

Symbol	Description
x,y,z	Spatial coordinates in the longitudinal, lateral and vertical direction
u,v,w	velocity vectors in the longitudinal, lateral and vertical direction
t	time
p	Pressure
Re	Reynolds number
Pr	Prandtl number
τ	Shear stress tensor
E_t	Total energy
q	heat flux
δ	Surface elevation from MSL
R	Hydraulic radius (~ water depth)
C_{2D}	2D Chezy coefficient
n	Manning's bottom friction parameter

B.1. Governing equations

Delft3D-FLOW is a multi dimensional modeling software used to solve the unsteady flow and transport phenomena. The system of equations consists of the horizontal equations of motion, the continuity equation, and the transport equations for conservative constituents. The 2D model of the operation is solved using this. In the program, the conditions of flow for each timestep is solved using the Shallow Water Equations with a depth averaged velocity since it is a 2D simulation. These equations are derived from the three dimensional Navier-Stokes equations for incompressible free surface flow.

B.1.1. Navier Stokes equations

The Navier Stokes equations are a series of equations used to describe the motion of viscous fluids. It consists of non-linear PDE's that have 4 independent variables, x,y,z representing the spatial coordinates and t representing the time. The equations represent the conservation of mass (continuity), the conservation of momentum(for all 3 dimensions) and the conservation of energy (Hall, 2015).

Continuity:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \tag{B.1}$$

Momentum:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re}(\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}) \tag{B.2}$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re}(\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}) \tag{B.3}$$

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho wv)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re}(\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}) \tag{B.4}$$

Energy:

$$\begin{aligned}\frac{\partial(E_t)}{\partial t} + \frac{\partial(uE_t)}{\partial x} + \frac{\partial(vE_t)}{\partial y} + \frac{\partial(wE_t)}{\partial z} &= -\frac{\partial up}{\partial x} - \frac{\partial vp}{\partial y} - \frac{\partial wp}{\partial z} - \frac{1}{Re * Pr}(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}) \\ &+ \frac{1}{Re}(\frac{\partial}{\partial x}(u\tau_{xx} + v\tau_{xy} + w\tau_{xz}) + \frac{\partial}{\partial y}(u\tau_{xy} + v\tau_{yy} + w\tau_{yz}) + \frac{\partial}{\partial z}(u\tau_{xz} + v\tau_{yz} + w\tau_{zz}))\end{aligned} \tag{B.5}$$

The equations represent the total momentum in the system as a sum of *the pressure, viscous forces and external body forces*.

B.1.2. Shallow water Equations

The Shallow Water Equations are a set of equations used to describe the flow of an incompressible fluid that have been depth integrated from the Navier Stokes equations. They are a derivation of the Navier Stokes equations in the case when the horizontal scales are much larger than the vertical scales. The assumptions of the Shallow Water Equations are:

- Hydrostatic pressure is predominant and the vertical accelerations are negligible.
- Manning's equation and Chezy equation are used to describe the resistance effects.
- Fluid is incompressible.
- Streamline curvature is small

The Shallow Water equations consist of an equation for the mass balance (equation B.6) and equations for the momentum balance (equations B.7 and B.8). In its conservative form,

$$\frac{\partial \delta}{\partial t} + \frac{\partial uR}{\partial x} + \frac{\partial vR}{\partial x} = 0 \tag{B.6}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial h}{\partial x} + \frac{\tau}{\rho R} = 0 \tag{B.7}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial h}{\partial y} + \frac{\tau}{\rho R} = 0 \tag{B.8}$$

B.1.3. Bottom friction

On the left hand side of the momentum balance equations, the first terms signify the local acceleration, the second and third terms signify the advective accelerations, the fourth term signifies the pressure gradient(NPTEL, 2012). The fifth term signifies the shear forces acting due to the bottom friction. In Delft 3D FLOW, the shear stress for 2D averaged flow is assumed by using the quadratic law:

$$\tau = \frac{\rho g U^2}{(C_{2D})^2} \tag{B.9}$$

Where C_{2D} is the Chezy coefficient, a bottom friction parameter used which can be calculated in multiple methods. In the current model, it has been calculated using the Manning's formula:

$$C_{2D} = \frac{R^{\frac{1}{6}}}{n} \tag{B.10}$$

From equations B.9 and B.10, it can be seen that the shear force acting is directly proportional to the Manning's coefficient chosen for the bottom friction.

B.2. Model configuration

The Delft 3D model used for the purpose of the hydrodynamic simulations consists of a Master Definition File (MDF), which is connected to a number of attribute files, each file containing different forms of information about the system. During the simulations, the MDF file calls upon each of these files.

Some of the important attribute files are:

File extension	Description
.dep	Depth of water
.grd	Curvilinear grid
.enc	Grid enclosure
.thd	Location of thin dams
.bnd	Boundary definitions
.bca	Astronomical flow conditions
.src	Location of discharge
.dis	Discharge data
.obs	Data on observation points (for collecting results)

Table B.2: Attribute files in Delft 3D

Most of these attribute files remain fixed in all the simulations conducted. In the simulations where the depths were increased, the .dep files were changed. The main differences between all the simulations lied in the .src and .dis files. These files were used to define the discharge, which is given as an input by the user. The values of these changed depending on the number of turbines, sluices, discharge location and depth.

B.2.1. Set conditions

All water levels mentioned are calculated with respect to the Mean Sea Level (MSL).

The models are made for 2 operating modes of tidal barrage power plants: Ebb mode and 2 way production mode. For the ebb mode, Straflo turbines are being used while for 2 way generation, Bulb turbines are being used.

The following scenarios were executed to compare the MATLAB and Delft3D models:

Generation mode	Number	Turbine	Sluices
• 2 way	1.	50	-
	2.	75	-
	3.	100	-
• Ebb	4.	50	30
	5.	50	60
	6.	50	100

Table B.3: Scenarios for 2 way and ebb generation

For the sluices, the discharge area for a single sluice(A_{sluice}) has been kept constant at 100 sq. m. The different simulations in the 'Ebb' generating mode only change the number of sluices.

In the model, 2 grid cells along the thin dam are reserved for the placement of the turbines and sluices. With each grid cell having a longitudinal distance of 450 m, 900 m is kept open for the placement.

With the presence of 13 tidal constituents, the largest of which has a time period of 27 days, a minimum 1 month simulation time was required. However, the simulations are being carried out from January till June for a reference year, a period of 5 months. This simulation time is sufficient for checking any transient errors which might be insignificant in the first month.

In both models, there were a number of common assumptions taken:

- No vertical layers of water were considered in the tidal basin or in the sea during simulations
- The opening and closing of the gates takes 1 timestep, or 10 minutes.
- Constant density and temperature of water
- The efficiency of a particular turbine does not change with a varying load

Some of other parameters which were fixed in the Delft 3D model are listed below:

Parameter	Value
No. of grid cells	488
Grid resolution	450 m * 1350 m
Simulation time	5 months
History interval (for output results file)	10 min
Type of forcing	Astronomic
Roughness formula used	Manning
Manning's value (for both axes)	0.016
Advection scheme for momentum	Flood
Type of discharge	In-Out
Discharge interpolation	Linear

C

Appendix: Supplementary theory

C.1. Tides

Tides are the combined action of the sun and moon's gravity on the ocean, with the moon having the greater influence. As the moon revolves and rotates around the earth, the increased gravitational force of the moon causes the water levels to rise in the region nearest to the moon (until a maximum called high tide). After this point is reached, the water levels fall while the force is receding, until a low point is reached(NOAA).

The tidal movement can be described in 4 stages:

1. **Ebb tide:** The fall in the water levels in the sea, causing the sea to recede from the coastal regions.
2. **Low tide:** The minimum water elevation in the region, at the end of the Ebb tide. From this point, the flood tide begins
3. **Flood tide:** The rise in the sea levels until high tide is reached.
4. **High tide:** The maximum water elevation in the region, at the end of the flood tide. Once this point is reached, the Ebb tide begins again.

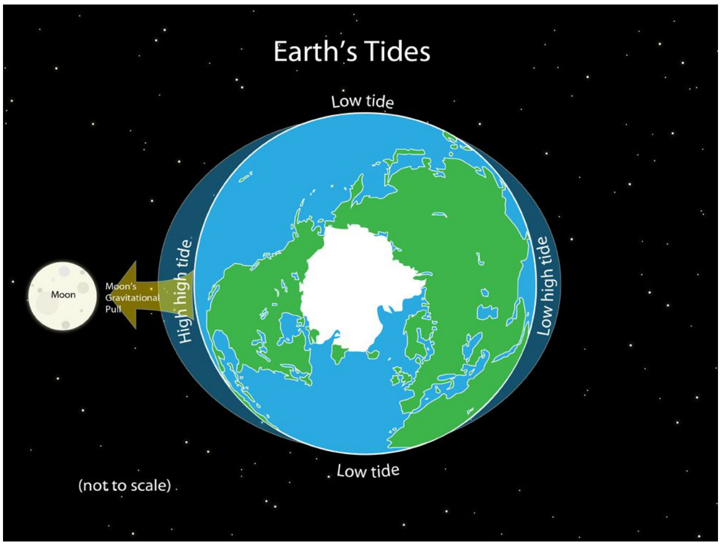


Figure C.1: Tide movement

The flow of tides can be classified as diurnal or semidiurnal. Most locations on earth have semidiurnal tidal movements, meaning the presence of two high and two low tides during the day. However, on the Gulf of Mexico and the eastern Russian coast, there is only one tide cycle. There are also mixed semidiurnal tides, which are defined as non-uniform amplitudes of the tidal range during the semidiurnal movement. This non uniform amplitudes are due to the relative positions of the sun. During full moon and new moon, the sun and the moon are alligned, causing the gravitational pull of the sun to be added to the gravitational pull of the moon. This is called *spring tide*, with the tidal range having an amplitude slighlty larger than normal. During the first and third moon quarter, the gravitational pull of the sun and the moon are at right angles to each other, causing the forces to partially cancel out. This results in the *neap tide*, where the tidal range is smaller than the normal value.

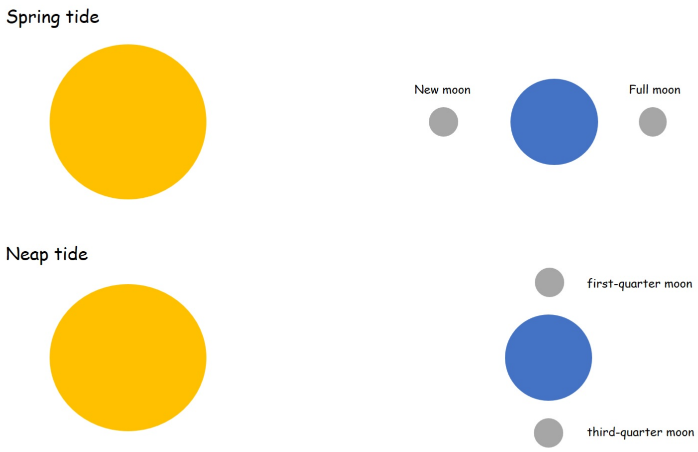


Figure C.2: Spring and neap tides
(NOAA)

C.2. Basin schemes in tidal barrages

Although there are only a few existing tidal barrage energy projects, multiple concepts have been theorized for future use. Based on the tidal basin, the two schemes proposed for tidal energy generation are:

1. Single basin schemes: Consists of a single closure dam used to separate the sea from the tidal basin formed. The barrage comprises of the sluices and the turbines, with the head difference formed between the basin and sea used for energy generation.

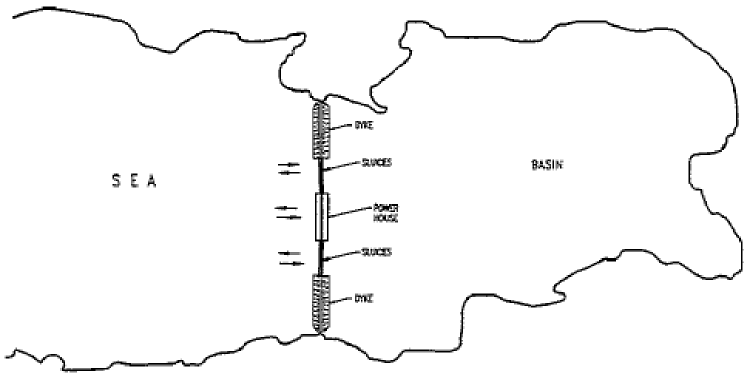
   During operation, flow passes between the tidal basin and the sea. It passes through the openings in the barrage where the turbines are placed. As flow passes the turbines convert this to electricity.

2. Double basin schemes: Consists of 2 tidal power basins, both being separated by the sea with their own barrage and sluices in order to control the water level in that basin. The 2 basins are also separated by each other with another dam, with the turbines being placed at this dam.

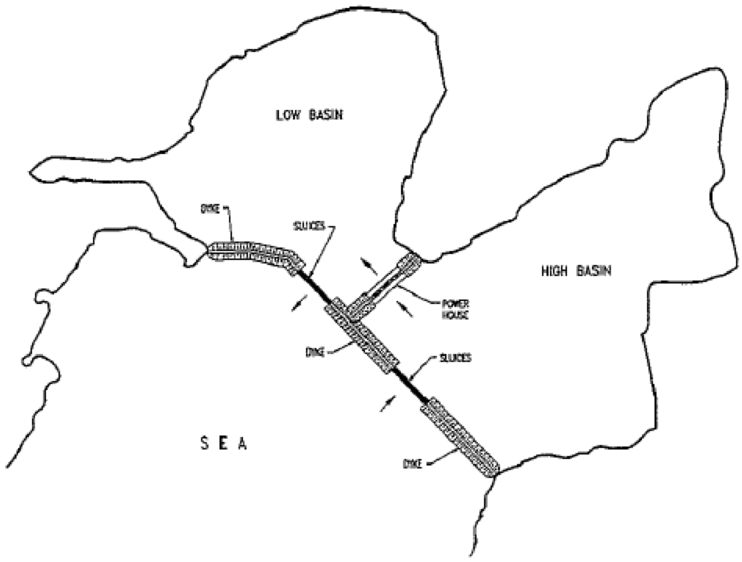
   During operation, one basin is opened to the sea close to the high tide, ensuring a high water level is kept. Similarly for the second basin, the water levels are kept low by opening the sluices during low tide. Additionally, the volume capacity of the 2 basins are optimized such that there is a head difference between the 2 basins throughout. To operate the power plant, the dam linking the two basins is opened and water flows through the turbines from the high water basin to the low water basin.

   (Kalpasar, 1998)

The double basin schemes offer a greater level of customization in the operation and power generation timings since water levels on both basins can be controlled. This leads to the power plant is no longer completely dependent on the duration of the tides for energy production. This is especially useful in schemes where the use of energy storage is required.



(a) Single basin scheme



(b) Double basin scheme

Figure C.3: Different tidal power basin types

However, double basin schemes utilize less energy from the tides compared to the single basin schemes and are more expensive to construct and operate due to their greater complexity.

All the existing tidal barrage plants use single basin schemes. The focus of these projects has been on maximizing the energy production and keeping the costs low, for which the simple design of the single basin schemes are ideal.

D

Appendix: Terms and abbreviations

Term	Description
Barrage	A type of dam which consists of gates. The regulation of water levels is done by the opening or closing of the gates instead of the crest level (in weirs)
2D model	Two dimensional model on the Cartesian plane, with only one vertical layer of flow
0D model	Dimensionless modeling, with the only variation in the parameters being based on time
GWh/yr	Gigawatt-hours per year. It is a measure of the energy generation in a year. 1 GWh/yr=$3.6*10^{1}2$ J
TWh/yr	Terawatt-hours per year. 1000 GWh/yr make one TWh/yr
EUR/KWh	Euro per kilowatt-hour. It is a measure of the price of electricity paid for a unit of energy
MSL	Mean Sea Level
head	difference in elevation between 2 points. Used as a measure of energy in incompressible fluids
Discharge	Flow passing through a cross section
Discharge coefficient	Ratio of actual discharge vs theoretical discharge for an orifice
Bathymetry	The underwater depths of a body, such as ocean floors or lakes
Dredging	Process of removing silt from the floor of an ocean or river body. Used for

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