Grand Bahama after Hurricane Dorian

Interdisciplinary approach to Build Back Better

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Acknowledgement

We would like to express our deepest appreciation to all those who provided us the possibility to complete this report. A special gratitude we give to Manell Munroe, Administrative Assistant of the University of the Bahamas, whose contribution in stimulating suggestions and encouragement, helped us to coordinate this project, especially in setting up the experience.
Furthermore, we would also like to acknowledge with much appreciation the crucial role of Supervisor: Dr Carlton Watson, Dean of the University of the Bahamas, who gave access to necessary materials to complete this report.

A special thanks goes to the participants of the workshop in the Bahama,
[Students; Alexis Lightbourne, Breanne Grant, Emmitt Francis , Ernal Mckenzie, Kavon Knowles, KeVaughn Ellison, Matel McDonald, Shabernice Brown, Shanea Adderley Other; Dr. Nader Azab],
who helped us to assemble the parts and gave suggestions.

Last but not least, many thanks go to the heads of the project, Dr. F.L. Hooimeijer (Urbanism) and Dr ir Frans H.M. van de Ven (Water Management), who have invested their full effort in guiding the team in achieving their goals. We have to appreciate the guidance given by other supervisors as well; Dr. ir. R. Lanzafame (Hydraulic Engineering) and Ir. J. Schroën (Architectural Engineering)

Table of content

Management summary

The ambition to Build Back Better after a serious flood disaster is a complex challenge. A comprehensive, multi-disciplinary redevelopment planning process is required to reduce the flood risk and meanwhile create sustainable solutions that bring added value to society every day. General planning principles can be formulated on how to develop the physical conditions for flood resilience, while building a better place to live and work. Scoping and the charrette method are to be applied for pairing and integrating disciplinary results, to co-create Better plans in an interdisciplinary planning process. The disaster recovery on Grand Bahama, after the 2019 hurricane Dorian, was studied by a multidisciplinary team of students and staff to investigate how far Building Back Better was, or is to be, realized. This was done by confronting the practice of the reconstruction process and the resulting plans with the guiding principles for the physical concepts and interdisciplinary planning approach. Practice shows that Building Back Better is suffering from a lack of integration of disciplinary solutions, guided by existing planning regulations, practices and driven by the need for flood safety and by the urgency of the reconstruction works.

On September 1st, 2019, hurricane Dorian made landfall on the Abaco Islands with a Category 5. On September 2nd it hit the island of Grand Bahama with the same force and remained there for another day, finally pulling away from the island on September 3th. The wind speeds, up to 295 km/h, also impacted a storm tide of 6.1 to 7.6 m, covering a large part of Grand Bahama with sea water. Dorian also dropped an estimated 0.91 m of rain over the island.

The total devastation in the Bahamas amounted to US$3.4 billion, 282 people missing and at least 70 deaths, 10 of which were on Grand Bahama.

The island Grand Bahama, with 75.000 residents, suffered from multiple aspects: A king tide, storm surge and waves led to coastal flooding which then caused salt water intrusion into their drinking water aquifer. At least 60% of Grand Bahama was left submerged once Dorian had passed over the island. Extreme rain led to pluvial flooding and extreme wind speeds and tornado’s damaged buildings, infrastructure, trees and forests. There was an island-wide power outage, and an oil refinery was damaged. About 300 homes were destroyed or severely damaged. The income dip, population decrease and post- traumatic stress are substantial societal problems as secondary effects of the hurricane.

Grand Bahama can be divided in three zones, namely east, west and the town of Freeport. Freeport is a 560 km2 free trade zone on Grand Bahama Island. The Grand Bahama Port Authority (GBPA) operates the free trade zone, under special powers conferred by the government under the Hawksbill Creek Agreement, which was recently extended until August 3, 2054. GBPA and the national authorities are currently developing plans for the recovery of the island. The University of the Bahamas (UB) and TU Delft started assisting in this recovery process with an interdisciplinary design project. Some of the results are summarized in the next paragraphs.

The main vision for the reconstruction of Grand Bahama is to Build Back Better. This is done by taking an interdisciplinary approach and connecting engineering to spatial planning and design.
The proposed strategy reduces the risk by taking into account exposure and vulnerability of the general risk approach. The main point of the strategy is to create a resilient urban environment in which vital infrastructure like the airport remains functional. This is done by making a collective protection zone of the economic and social city centre of Freeport, a zone that also offers shelter. Individual protection and evacuation shelters will be given to residents, buildings and facilities in the less densely built areas, east and west of the city.
The strategy has three intervention layers: hydraulic engineering, “zoning & critical infrastructure” and resilient water householding. The hydraulic engineering layer proposes strategic dikes that connect natural heights in the town Freeport. This creates a zone that is safe from storm surges by a collective protection system and an ’outer dike’ area that requires individual protection systems. Based on this new topography the zoning & critical infrastructure layer proposes interventions per zone. The new safe zone in Freeport (comparable to the traditional mound “terp” and Dutch polders) will be the centre for critical infrastructure and offers shelter for people from outside this protected zone. Road infrastructure on the island will be improved to give better access to this centre. In the ‘outer dike’, east and west districts, individual protection needs to be scaled up by building regulations and by creating strategic evacuation centres. The layer of resilient water households considers groundwater resource protection, large scale rainwater management, the implementation of separate household and drinking water infrastructure, water purification and wastewater treatment facilities. In this proposal the focus is laid on the current situation.

This vision and strategy are developed in more detailed plans for three locations: the airport, the UB North Outside Campus and the UB town campus. Both the new airport building and the UB North Outside Campus are made out of ensembles of smaller buildings that are more resistant to the hard winds of the hurricane. They are made flood proof by lifting them on mounds. The UB In Town Campus is an historical building that also is made flood proof by placing a program on the first floor. The ground floor is flexibly used. All three buildings are designed as an evacuation point.

This report also discussed in Climate Resilient Urban Areas Governance, Design and Development in Coastal Delta Cities Chapter 5 Recovery capacity: to build back better by Frans H. M. van de Ven, Fransje Hooimeijer, and Piet Storm.

1 Introduction

1.1 Problem field

In the past, the Island of Grand Bahama has suffered from several tropical storms and hurricanes. Some of them have had a tremendous impact on the island. The recent hurricane Dorian caused significant damage and struck the island in different manners: high wind speeds and surge, together with significant amounts of precipitation over the island.

There is a high probability that the island of Grand Bahama will be struck again by a major hurricane. Furthermore, the hazards and uncertainties are rising every year as a consequence of climate change and sea level rise. Academic research is essential to develop new mitigation strategies and designs that reduce the flood vulnerability of Grand Bahama. Academic research can propose new concepts to design and build a more suitable architecture, in order to create protected and resilient spaces. This report elaborates on how the exposure of flooding in the Island of Grand Bahama in the Bahamas can be mitigated, considering the influences of extreme floods and winds to contribute to the definition of the approach how to Build Back Better. To do so, the research team, which consists of students coming from the Civil Engineering (CiTG) and Architecture in the Build Environment (ABE) faculties, proposes an interdisciplinary approach, addressing the different scales of research and intervention with specific goals, according to the area of expertise.

In the ideal situation after a hurricane passes over a region all the damage made by the hurricane will be restored and life continues as usual. Right now, the Grand Bahama is rebuilding after Hurricane Dorian, but the island doesn’t seem to be able to leave behind the events of Dorian. Not everything on the island gets rebuilt and after every hurricane the amount of the island's structures gets smaller. Furthermore, the impact of this hurricane was significant and the anxiety about a possible recurrence arose. The question arises what the concept of Building Back Better can mean for the Island.

Ties between researchers of TU Delft and The University of the Bahamas started an international project to exchange knowledge and develop suggestions to confine the damage of the next big hurricane.

The project is organized with the focus on interdisciplinary and international cooperation. The interdisciplinary goals centre around cooperation between the built and social environments (architecture, hydraulic engineering, psychology, sociology, building technology, urbanism) and the natural environment (water management, hydrology, physical geography, environmental engineering). The intersection of these disciplines would create a project (and its resulting outcomes) that facilitates integrated learning and foster multifaceted developments in Grand Bahama.

1.2 Problem statement

Dorian impacted the island much more than other hurricanes did. In the light of climate change with rising sea level and more frequent storms, it is not enough to consider building back what there already was and with the same methods. The problems arising from climate change, combined with urbanisation and sustainable economic development, are big and complex challenges to be addressed.

Furthermore, the context of Grand Bahama doesn’t arrive from a tradition of big scale collective and public plans for safety and infrastructure. Therefore, other than a design for a standard reconstruction of the island, there needs to be a reflection on the methods, governance approaches and the attitude towards natural disasters. At the moment, the majority of the prevention measures explained and distributed to the people of the Bahamas focus on the individual scale. Although this approach is absolutely essential, there is a need for a project that considers long-term and regional solutions, to answer the complex challenges arising from extreme weather and the everyday socio-economic reality of the Bahamas.

The complexity of the issue calls for interdisciplinary cooperation. The impact of hurricanes has consequences in different extensions and affects the island in various ways. Therefore, the disciplines of hydraulic engineering, water management, urbanism, architecture, and building technology will work together in order to provide essential guidelines and potential answers to the current challenges.

1.3 Research Question

The main focus of the research relates to the Task 4b.2 from the Building Back Better created by the United Nations Office for Disaster Risk Reduction, in support of the Sendai Framework for Disaster Risk Reduction 2015-2030: Conduct a pre-disaster recovery planning (PDRP) among all stakeholders, namely, the assessment on the organization capacity to manage recovery, reconstruction and rehabilitation needs in the aftermath of Hurricane Dorian. The investigation into how hurricane events and consequent flooding have impacted the island of Grand Bahama in spatial and temporal scales, is the basis to explore solutions for mitigation. At the same time, the project tackles the needs and issues of the daily scenario. Suggestions and guidelines are developed for the governmental spheres of The Bahamas, providing inputs for the decision- and policy-making for the protection of Grand Bahama from the hazard of a hurricane event, as or more devastating than Hurricane Dorian. The main question which is supporting this aim is:

How to rebuild a more resilient Grand Bahama and improve the quality of daily life on the island as defined by the concept Build Back Better?

This question will be answered by following a project approach and methodology which is based in field research, desk research, action research and research by design. The investigation into how to design Build Back Better is delivering insight in the concept itself and lines of approach towards the specific case of Grand Bahama.

In chapter 3, the report analyses the external and internal factors that provoke or amplify the damages of the urban and natural environment. The project then proposes design solutions of the elements which have the power to lead towards a resilient situation, allowing eventually the mitigation of negative impacts of extreme natural phenomena, this can be found in chapter 4.

2 The project approach and methodological framework

This research draws the hypothesis that interdisciplinary design is at the base of Building Back Better. Interdisciplinarity is considered the outcome and intertwining of knowledge and products. Interdisciplinary design is the integration of sectoral responsibilities, goals, approaches and solutions (Hooimeijer et al., 2021).

The approaches and methods for this project aims at creating conditions to support Building Back Better and have been developed at the Delft University of Technology during the "living labs" in Tokyo and Tohoku, Japan, which have been subject to storm surge and tsunami hazards. For three consecutive years workshops were conducted for groups of students from many disciplines, to learn from the reconstruction of Japanese cities after disasters, and apply these insights together with Dutch design principles, to hypothetical reconstruction of Japanese and Dutch cities for increased disaster resilience and liveability. This project incorporated interdisciplinary design into its MSc-level education of civil engineers and spatial designers, focusing on the development of an appropriate understanding of interdisciplinary design and tools to reach it. A deep comprehension of the build environment in the previous workshops and case studies provided important highlights on the steps to follow, the priorities to take, and the scales of intervention to take into account, from the regional and urban aspects, to the detailing of the building's architecture.

First important aspect of setting up the multidisciplinary student groups was setting up staff members to intensively guide the groups. Then the projects followed the three main phases of the interdisciplinary process: analysis & synthesis, design, and conclusion as described in the theory framework and were built on the interdisciplinary conditions, also described above. In the ensuing, each phase is elaborated on. Furthermore, the combination of the specific disciplinary research methods of each discipline enriched this interdisciplinary approach.

2.1 The approach

This project is done by a multidisciplinary group of students for which interdisciplinary working is activated by specific conditions:

- Taking the same project location, shared analysis,
- Group building through excursion and other activities,
- Regular presentations and meeting between students work,
- Workshops with scoping and charrette methods,
- Taking interdisciplinary mentors in mentor teams,
- Define specific interdisciplinary subjects that are to be addressed collaboratively.

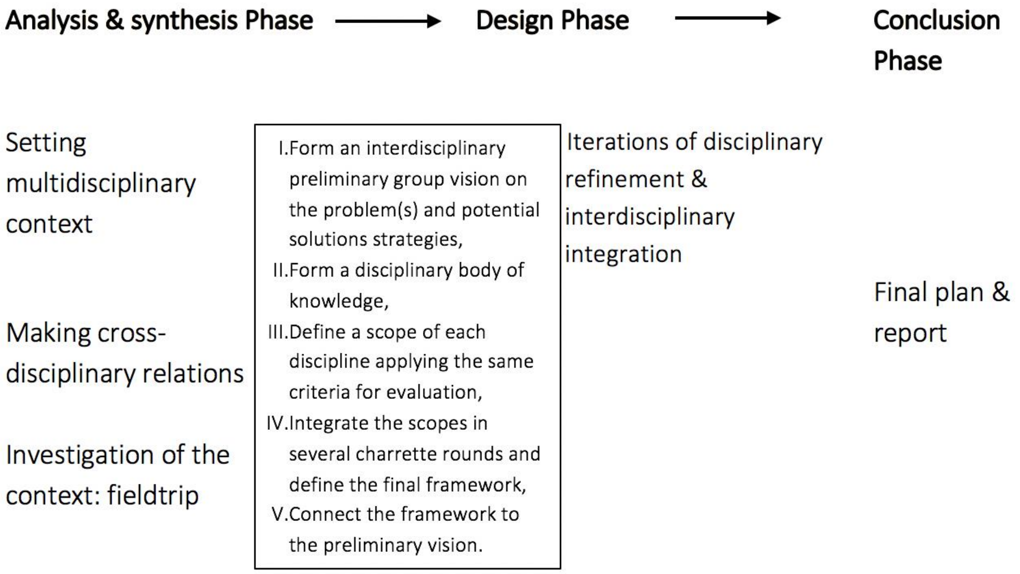
Next to the conditions the case itself offers the interdisciplinary context. The interdisciplinary approach that is used is developed by Hooimeijer et al. (2021) describing the following steps is indicated in Fig 1.

The main research question of this project is leading the research of exponents of each involved discipline that have formulated the outcomes they expected for the research and the other disciplines. These goals help gather and process information and allow us to understand the relationship between the five participating disciplines: water management, hydraulic engineering, urbanism, architecture, and building technology. Within this framework, several topics and perspectives have been discussed.

Urbanism envisions ways to create new urban plans and designs to ensure ecological, economic, and social resilience in the Bahamas. It also envisions long-term scenarios that aim towards prevention and risk mitigation in extreme situations and at the liveability of the urban and natural environment in the short term and daily. Therefore, the context of the project is crucial.

Architecture indicates conceptualizations of interventions, makes the narrative, materializes it in a built form. Architecture is never the solution, but a trigger to change in the larger picture over a more extended period.

Building Technology offers insight on small scale solutions. It connects with the bigger scale when understanding what the ecological, economic, and social selection criteria of the matrix of strategies may be addressing hurricane and flood proof interventions on structure and envelope of a building.



I. Form an interdisciplinary preliminary group vision on the problem(s) and potential solutions strategies,
II. Form a disciplinary body of knowledge,
III. Define a scope of each discipline applying the same criteria for evaluation,
IV. Integrate the scopes in several charrette rounds and define the final framework,
V. Connect the framework to the preliminary vision.

Fig:1 Visualization of the applied interdisciplinary approach

Hydraulic Engineering creates new possibilities for the other disciplines, by means of large and/or small interventions that affects the scale of hazards and that reduces impact on the environment, and improves the liveability in the areas. Hydraulic Engineering studies on how circumstances influence the flow of water in large water bodies, like rivers and oceans, and how this affects the environment.

Water management supports by giving insight on how to design with water, and making the water work for you. The drainage of excessive and supply of required amounts of water, while considering multi-functional use of the required infrastructure in order to improve life quality in a resilient manner.

2.2 Methodology

The process of thinking and working that is followed throughout the research is explained in this section. It identifies and explains the research framework that was developed to carry out the research. Particularly, the conceptual framework is defined as a "network of interlinked concepts that provide a comprehensive understanding of a phenomenon or phenomena" (Jabareen, 2009). The conceptual framework is employed to create dialogues between theories and concepts that are integrated in the problem statement, assumptions and finally in the design proposals.

Architecture is the smallest of the scales of research and intervention, supported by Building Technology. Nonetheless, the scope includes the insights of the other disciplines. Such scope addresses two main scenarios (extreme and daily conditions) and is translated into space in two main contexts (protected and non-protected areas). Starting with an analysis of the existing conditions of the infrastructure of Grand Bahama and the typical architecture, we suggest a series of concepts and spatial exercises that aim to face the resulting wind and water conditions of the analysis, therefore, providing the first design operations for the next step, the module proposal. The module responds to the two scenarios introduced before, and aims to create social cohesion and an overall goal.

Urbanism addresses the question with a systematic approach, by connecting the above-mentioned disciplines into a holistic vision. Therefore, it addresses multiple scales of analysis and intervention and multiple scenarios that includes the factor of space and time. In this way, it is possible to imagine scenarios that take into account the usual and extreme situations of the territory and to project them in a long-term vision. The analysis of the context starts from defining the problems and needs of the present time, focusing on the natural and infrastructural environment as backbones of the island's resilience. The vision and design that follow suggest a series of spatial proposals that take the existing patterns and fabrics as starting points and build new strategic interventions upon them, so to assure their maximum performance and to avoid side effects that could harm both the natural and social infrastructure.

Hydraulic Engineering focuses on protecting people and ecology in areas against hazards such as coastal and fluvial flooding, erosion or sedimentation. Usually this is done by large interventions which should be maintained. The long-term benefits make these solutions attractive.

Water management is the discipline that connects water with people; designing the drainage of excessive and supply of required amounts of water. Consequently, it addresses multiple scales of analysis and intervention in multiple scenarios, to create or find a balance between inhabitants and the ecological surrounding. The discipline preference to see this balance in consequences and action. The action being, implementation of water management measures like levees, excavation of channels or rainwater storage.

2.2.1 Scoping model and charrette approach

In order to accomplish a successful interdisciplinary outcome, the scoping model and charrette approach has been used. To engage the participating disciplines in information and concepts integration the **scoping model** (Hooimeijer et al., 2018) is carried out according to the **charrette method** (Lennertz and Lutzenhiser, 2014).

The **charrette method** suggests a series of steps where disciplines are twinned in sub-group discussions and the size of each sub-group is gradually increased until the final session, when one large group discussion is held with all disciplines.

The scoping model is an orchestration of data into information from a (mono)disciplinary analysis and design to an interdisciplinary analysis and design. What is important is that the different disciplines use comparable values to be able to explain and merge their chosen concepts with ones from other disciplinary perspectives. In the scoping model the first step is performing the (mono)disciplinary analysis concepts and/or measure sets selected per discipline and as such evaluated along the lines of the value system that is agreed on beforehand. Different disciplines use this value system to be able to explain and merge their chosen concepts with the ones from the other disciplinary perspective. Afterwards disciplines discuss their scopes and merge them. The last two steps are discussed in a group of three and finally again with all the disciplines present. Each step creates new combined scopes with integrated measure sets or concepts. This co-creative approach can be applied at different spatial scales, to confront large scale planning ideas with small scale, much more detailed plans to test the feasibility of the ideas as visualized in Fig 02.

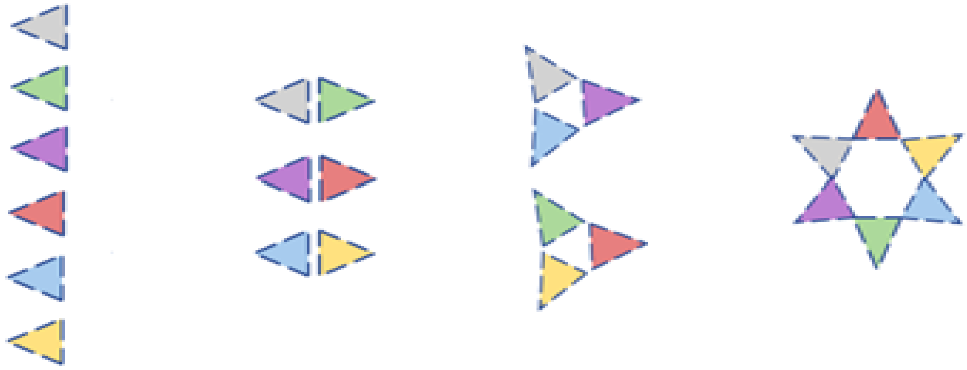


Fig 02: Schematic representation of the charette approach.

2.2.2 Three-point Approach

In order to apply appropriate measures with respect to flood risk, the three-point approach (Fratini et al., 2012) is used. The three-point-approach is an important concept for Building Back Better (Fernandez, 2019). Point one is initiated by designing a facility that offers protection for a storm event with respect to predictively hardened conditions such as climate change and the number of impermeable surfaces. Point two represents a situation where this protection level is exceeded by applying an event of lower occurrence rate: The protection system fails. This point emphasizes the need for a design aimed at minimizing the damage of that failing system, by maximizing its coping and recovery capacity. The third point represents the every-day situation. Instead of being a hindrance, the protection facilities should provide added value to society every day. Multi-functionality of the protection measures is essential, meaning that additional to flood prevention the required construction efforts for flood protection ought to be merged with other essential societal or economic tasks or services in a living community. This is visualized in Fig 03.

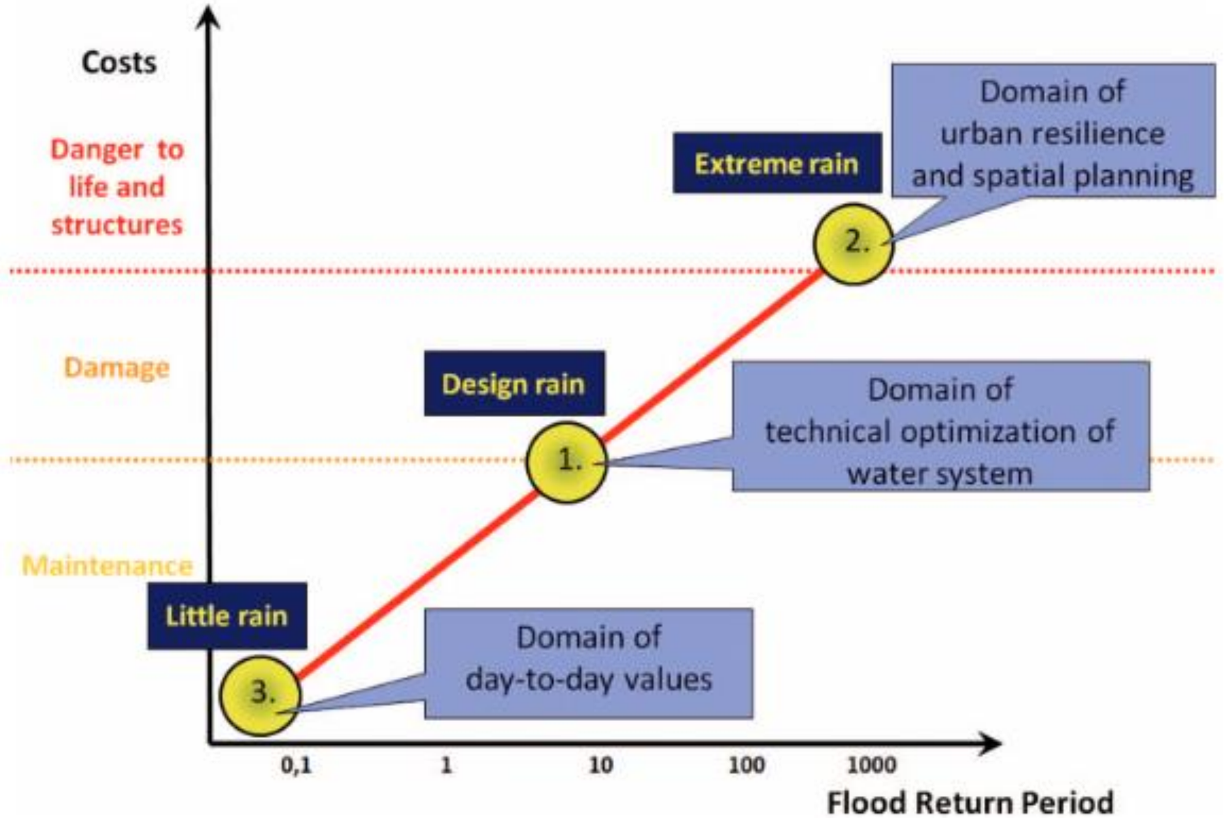


Fig 03: Graphical representation of the three-point-approach (Fratini, 2012)

2.3 Conceptual Framework: Build Back Better

The aftermath of a natural disaster is a great challenge that communities face in terms of procedures and decision-making, where saving lives and protecting the essential infrastructure becomes a priority. As the United Nations Office for Disaster Risk Reduction (UNISDR) states, the countries and communities impacted by natural disasters are often much better equipped to face a better (re)construction process and build back better during the period of recovery and rehabilitation when they have taken actions to strengthen recovery capacities and decision-making effectiveness prior to the onset of the disaster (UNISDR, 2017, p4). Furthermore, the united Nations General Assembly in 2016 defined Build Back Better (BBB) as “The use of the recovery, rehabilitation and reconstruction phases after a disaster to increase the resilience of nations and communities through integrating disaster risk reduction measures into the restoration of physical infrastructure and societal systems, and into the revitalization of livelihoods, economies, and the environment” (UNGA, 2016).

The UNISDR lists this concept as part of the Sendai Framework and labels it as Priority 4B, focusing its interest on recovery, rehabilitation, and reconstruction. Throughout this research, the aim is to provide an understanding of - and guidelines to support - the main ideals that Build Back Better entails, focusing our attention on the aftermaths of Hurricane Dorian on the island of Grand Bahama. In order to understand and explain the concept of BBB and to make it operational the research build a framework of understanding out of the following building blocks:

- Interdisciplinary design
- Concept of vulnerability
- The multi-layer safety approach
- Resilient city

2.3.1 Interdisciplinary design

Interdisciplinary design is the integration of sectoral responsibilities, goals and solutions (Hooimeijer et al.,2020). To target a better future with the concept Building Back Better, the complexity of the problems caused by the hurricane needs the interaction and synergy between fields of knowledge in order to get a better understanding of problems, or to produce better answers to the problems.

This research takes the interdisciplinary design approach that covers the disciplines of water management, hydraulic engineering, urbanism, architecture and building technology. The main goal is to create guidelines in which the fields are synergized towards Building Back Better.

How do the disciplines involved in this report relate to BBB? Water is always a relevant agent in communities. Knowing hazards arising from the lack or abundance of water during and after events will aid recovery capacities and decision-making effectiveness prior to the onset of the disaster. To ensure

that communities work with water and not against water is the approach to Building Back Better. Hydraulic engineering works on a regional scale to define the quantities of water that enter the system. Water management needs to focus on an urban scale to be able to handle the quantity of water entering the system. To integrate and evaluate solutions from water management in the landscape, architecture and urbanism are crucial on both the urban and the building scale.
The effects that a hurricane can have on the ocean and the hydrologic cycle are immense. Hydraulic interventions can be used to reduce the loads that affect the solutions of other disciplines and increase the threshold capacity of the flood protection. In good coordination with urbanism, water management, and architecture these interventions can lead to new and better solutions.

Architecture becomes a relevant agent within the Build Back Better approach as provider for both preventive and disaster-relief infrastructure, where the future hurricane hazards can be controlled through a series of spatial interventions, hand by hand with urbanism, water management, and hydraulic interventions, combining or “translating” the approaches that other disciplines have in the spatial order, in a more suitable architecture for the island. The UNISDR suggests, regarding the responsibilities in Building Back Better, that “systems for permitting”, contracting, and human resource distribution that certify or otherwise ensure architects and engineers are adequately licensed to design and construct resilient structures greatly improve the likelihood that Build Back Better philosophies are upheld as recovery proceeds” (UNGA, 2016). These resilient structures, therefore, become our main interest as architects and designers in the smaller intervention-scale of this research.

2.3.2 Concept of Vulnerability

The concept of vulnerability can be explained in four different capacities to minimize its adverse consequences: the threshold -, coping -, recover and adaptive capacity (De Graaf et al., 2017). The threshold capacity is the amount of load (exposure) a solution can withstand before it fails and damage occurs. Once this threshold is exceeded, the functionality of the solution fails or is at least reduced. A good example of threshold capacity is a levee; it keeps the water out up to a certain flood level, but fails when this is exceeded. So, in other words, how much is Freeport supposed to withstand? To completely prevent damage from larger hurricanes, which have a lower frequency of occurrence, a larger threshold capacity is needed. This may need larger interventions which have a higher cost and more impact on everyday life. The choice of the threshold level is a design solution and is influenced by the conditions, therefore by the probable size of the hurricane.

Instead of completely preventing the flooding, a solution can also be found in dealing with flooding by reducing damage and ensuring effective emergency processes in order to minimize the damage when flooding occurs. This latest can be done e.g., by protecting the critical infrastructure and clear emergency plans. In these plans the organization and responsibility for disaster management should be clear. Also, the communication with inhabitants is an important part of it.

In case of flooding, damage needs to be restored to become in an equivalent state as before the emergency. The capacity of a society to recover quickly and effectively from these incidents can be described in the recovery capacity. The recovery capacity consists of reconstructing buildings, infrastructure, and dikes and the capacity to quickly reactivate a functioning water supply and sanitation system. Improving the recovery capacity will reduce damages and cost as a result of a slow rebuilding/repairing and economic slow-down. For this, a speculative approach on architectural and infrastructural solutions were implemented, reducing the vulnerability and improving the daily life conditions on the island.

The fourth and last capacity is the adaptive capacity, which is focused on the flexibility to anticipate uncertain future developments and catastrophic, not frequently occurring, disturbances which affect the society. By having sufficient space, resources and an effective decision-making system in place a more flexible solution can be realized.

The concept of vulnerability-reduction is key to the concept of BBB when it comes to proposing design solutions. By proposing new approaches in the context of Grand Bahama, new vulnerabilities will arise again from the design solutions themselves. The new vulnerabilities should be analysed and addressed, if not with final design solutions, with guidelines for their governance and for the future management of the structures.

2.3.3 The multi-layer safety approach

The concept of multi-layered safety allows the design measures to reduce the risk of flooding divided in three practices. The first one, prevents flooding from the sea or from rivers, with the use of collective infrastructures, such as dikes and levees. The second layer is about the prevention of damage and casualties in case of flooding, including pluvial flooding. This means that the built environment should be planned and designed in a way that it can withstand flooding. The third layer is about preparedness. In case the first two layers fail, the third one allows to manage the emergency and save people’s lives (EU, 2005) The layers can have been visualised in Fig 04. The context of Freeport and in general of the Island of Grand Bahama, is foreign to this collective perspective of risk mitigation. On the island, there has been an investment mainly on the second layer, although on the very small scale of the singular building.

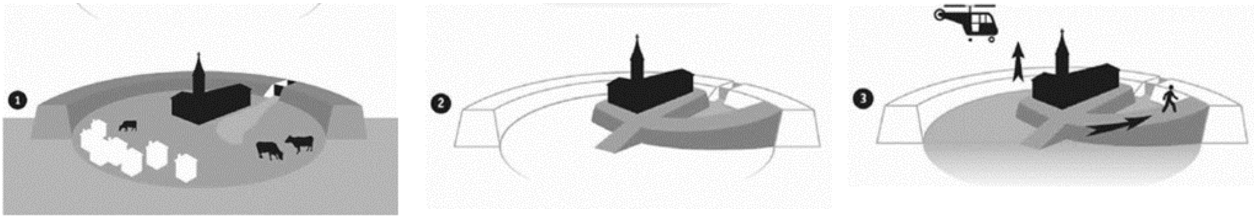


Fig 04 Flood protection measures will be based on a multi-layer safety approach; (1) preventive measures; (2) spatial planning and (3) emergency plans (Ritzema,2017).

Throughout this report, the project is evolved by addressing all three layers that become fundamentally interconnected through the initial spatial planning and the strategy common to all the involved disciplines (Leskens, 2015).

This approach is used in the project by envisioning different scenarios, including that of the daily life, of the Dorian situation and of a possible future event that is double as strong as Dorian. By doing so, an understanding of the various needs that arise with different weather and flood conditions becomes clear and allows for the definition of the three layers in the new proposal.

2.3.4 Resiliency

Resilience is a concept that has recently gained attention in post-disaster contexts. It is originally a concept used in social ecology and psychology in the 1970s, with a clear meaning: the ability to recover from a negative event. As Suzuki et al. (2016) suggest, this concept is gaining attention again in the 21stcentury and used in a wider sense as natural disasters have occurred throughout the world, becoming a keyword.

In the context of the Bahamas and precisely of Freeport Island, the project defines strategies and sites to answer the needs for resiliency. They have been individuated in Mileti's (1999) definition, where he states that: ''Local resiliency with regard to disasters means that a locale is able to withstand an extreme natural event without suffering devastating losses, damage, diminished productivity, or quality of life and without a large amount of assistance from outside the community''.

2.3.5 Flood Risk reduction tactics

Only four flood risk reduction tactics are available to reduce the risk of flooding.

These four tactics are:

1. Improvement of the drainage system by creating storage
2. Increasing ground level to avoid flooding or lower the level to create storage
3. Adapt the buildings so that they can take a larger exposure
4. Adapting people by investing in preparedness, awareness, evacuation, etc.

In most cases a combination of tactics will be used to protect an area and its population from flooding. Each of the four tactics can be used to provide safety, but a combination of the tactics is often more robust and therefore recommendable. A multi-disciplinary dialogue with the local stakeholders is required to find a desirable balance, taking societal and economic costs and benefits into account.

2.3.6 BBB Framework

Table 1 depicts the concepts and scales mentioned in the previous pages, and the relation between them. These relations give life to the framework of Building Back Better that this research proposes.

Table 1: used concepts and their correlation

	Vulnerability	Multi-layer safety approach	Flood risk reduction tactics	Resiliency
Building scale	Damage of buildings	Prevention of damage and casualties in case of flooding	Tactic 3: Adapt the buildings so that they can take a larger exposure	Raised buildings, robust elements for every residential building.
Urban scale	Damage of built environment, higher population density and exposure to flood risk	Preparedness for future flooding, evacuation plans	Tactics 1 and 4: Improve the drainage system by creating storage; adapt people by investing in preparedness, awareness, evacuation	Flexibility of the urban environment, fast recovery
Natural scale	Flooding of the island and damage of existing (eco)systems	Collective and individual scale protection, evacuation routes and preparedness to leave.	Tactic 2: Increasing ground level to avoid flooding or lower the level to create storage	Fast recovery of economic and social systems
Interdisciplinary design	Understanding the points of contact and conflicts among the involved disciplines	Understanding the relationship between scales and involved disciplines	Seek a balance between the four tactics	Systemic and holistic attitude towards the problem

In the following chapters, the report analyses the external or internal factors that provoke or amplify the damages of the urban and natural environment. The project then proposes design solutions of the elements which have the power to lead the physical and governmental dimensions of the island towards a resilient reality, allowing eventually the mitigation of negative impacts of extreme natural phenomena.

3. Analysis of natural, urban and building scale

Grand Bahama is the most northern island in The Bahamas and its second most populous island. The major city on the Island, Freeport, is regarded as the nation’s second largest city. The pine forest that dominated the island three decades ago made way for a thriving port city with an industrial centre and tourist area. This increase came from the Hawksbill Creek Agreement of 1955, the Government of The Bahamas granted 50.000 acres of land with an option of a further 50.000 to American financiers, which created the Grand Bahama Port Authority (Knowles, 2019).

The island Grand Bahama, just like the rest of the country, lies in Hurricane Alley where many hurricanes are formed (Goudzari, 2006; APnews, 2019). After each hurricane that hits the island a decline in population follows, not only because of the loss of life, due to the hurricane and its aftermaths, but also due to loss of work and/or homes. After each hurricane the cost of maintenance increases per person due to this decline in population. The increase in costs makes it less likely for people to return and to rebuild, making the population spiral even further into decline. A solution must be found to make the island more resilient and building for future prosperity. This solution must be found in the near future, before the population can’t be stopped from spiralling down. The context of Freeport and in general of the Island of Grand Bahama, is foreign to this collective perspective of risk mitigation. On the island, there has been an investment mainly on the second layer of the multi-layer safety approach, although on the very small scale of the singular building.

In this chapter, the characteristics of the region of Grand Bahama are explained on three scales: natural, urban and building scale. The first one comprehends the analysis of the natural environment of the island, including the topographic characteristics, the list of natural resources and ecosystems. An analysis is presented of the natural scale that defines the natural hazards threatening the island during an extreme weather event. The urban scale looks at the existing built environment, understanding the functioning and liveability of the island through the analysis of public space, urban form, connectivity and transportation. Finally, the building scale mainly addresses the analysis of the residential function, understanding how the extreme scenario performs on the scale of a household.

3.1 Natural scale

3.1.1 The geology, bathymetry and topography of Grand Bahama

The bases for the Bahamian island were formed by the North American and Caribbean plates when the supercontinent Pangea broke apart or by bacteria and sand that travelled across the Atlantic Ocean from the Sahara Desert. On these rocks two carbonate banks were formed. Which is now at a depth of five kilometre. The northern bank is called Little Bahama Bank and the other one the Great Bahama Bank (Lytle, 2006; Scarinci, 2016).

On top of these rocks carbonate sediments are deposited. They consist mainly of limestone but also Lower Cretaceous dolostone and evaporites, which are sedimentary deposits that result from the evaporation of seawater (Lytle, 2006; Vacher & Quinn, 2004, p. 98). On top of this limestone Coral reefs have grown which helped to form the islands (Scarinci, 2016) Since the last 2000 to 3000 years the sea level remained stable the coral reef growth could catch up with the sea level. And thereby form a barrier for sediment transportation which enhances the growth and stability of the islands (Vacher & Quinn, 2004).

This sediment - and the water pressure (also known as Lithostatic pressure) on top of the carbonate banks result in vertical stresses in the soil. This may exceed the strength of the limestone which results in compromising the platform. Which lead into subsidence of the passive margin and therefore in subsidence of the grand Bahama island (Freemann-Lynde et al., 1981, p. 38). The last 300.000 years all the banks in the Bahama subsidize for about 1 to 2 meter per 100.000 years (Vacher & Quinn, 2004, p. 96).

The development of shape of the Grand Bahama, the morpho dynamics, are highly influenced by the hydrodynamic conditions. In general, if the flow becomes less energetic, the flow velocity and wave height will decrease, and this will enhance sedimentation and growth of the island (Bosboom & Stive, 2015). The island Abaco in the west forms a natural barrier that usually protects Grand Bahama for a large wind and waves and thus results in a low energetic hydrodynamic environment. The consequence is that Grand Bahama is a large broad and low island which mostly is below 5 m below mean sea level. Being in the lee side of Abaco results also in an extensive flatland across the northern part. Which is known as the Little Bahama Bank. And the high part of the island is formed by aeolian processes, wherein the wind creates a high ridge (Vacher & Quinn, 2004, pp. 98, 151). The contour lines of the topography, from the Grand Bahama Port Authority, and bathymetry, are combined visible on Fig 05 and Fig 06.

An increase in water depth also affects the morphodynamics. This increase in water depth can be expressed in a relative sea level rise. Which is the summation of the land subsidence and the sea level rise (Bosboom & Stive, 2015). The consequence of the relative sea level rise is rapid large-scale erosion. Which can be expected for many Bahamian islands if there is a sea level rise (Vacher & Quinn, 2004). Based on Google Earth Engine it can be concluded that at least since 1984 the island is stable. At some locations there is some sedimentation, as visible at the breakwater at the Xanadu beach channel (Google Earth Engine, n.d.). It can be concluded that there is no urgent land retreat due erosion that should be considered, since the priority of the solution lies in the near future.

As mentioned above, Grand Bahama consists mainly of Limestone. This is a very porous material and thus is easily eroded by rainfall and runoff from the surface. Which results into a large possibility for the formation of caves. On the outer edge of the island the limestone can dissolve since there is both fresh and saltwater. Which also leads to cave formation (Lytle, 2006). The porosity and permeability of the Limestone on Grand Bahama is highly variable (Ehrenberg et al., 2006). At 15 ft to 20 ft above mean sea level marine deposits are changed from loose sand to a fully altered rock. This increases the density and reduces the porosity of the soil. Due to groundwater movement channels can form in this soil which result in a high conductivity. These channels quickly fill with coarse granular calcite crystals if there is no water movement through these channels (Ministry of Overseas Development, 1977).

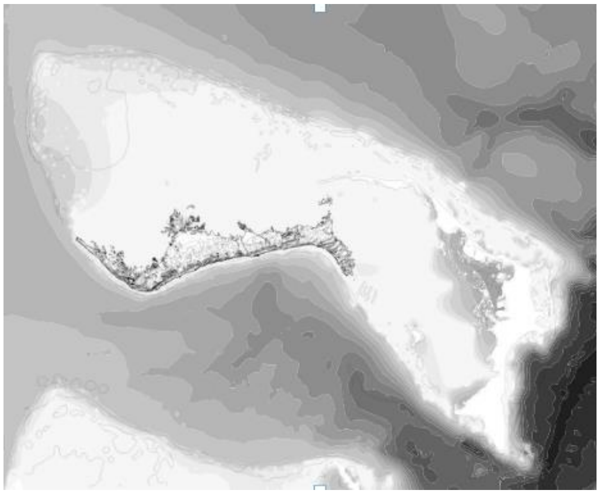


Fig 05 Ground height of Little Bahama Bank. Note, data from Grand Bahama Port Authority and Office of Coast Survey.

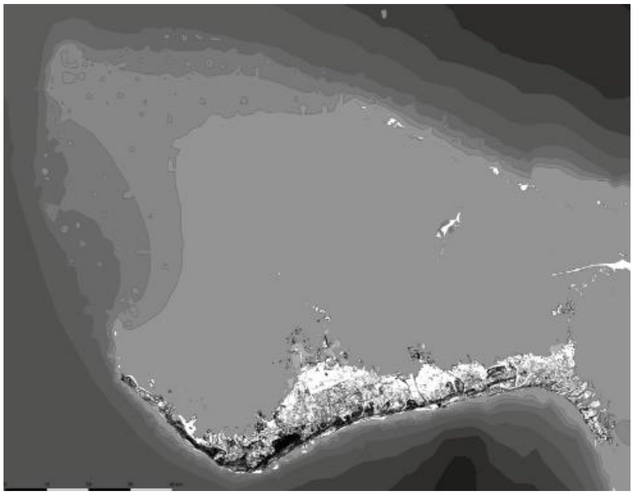


Fig 06: Ground height with contour lines of the west side of Little Bahama Bank. Note, data from Grand Bahama Port Authority and Office of Coast Survey.

3.1.2 Conditions Dorian

Dorian was one of the most powerful Caribbean storms on record, a category 5 hurricane with winds up to 185 mph (BCC News, 2019). It stalled over the islands Grand Bahama and Great Abaco for 30 hours (Packard, 2019), becoming the worst recent disaster in the nation's history. Radar pictures of the flooding are indicated in Fig 07.

The flooding of the island during Dorian is the result of the high storm tide. The storm tide is the total observed seawater level rise above mean sea level, which consists of the astronomical tide and the storm surge (Liu, 2019). The astronomical tide during Dorian was 3 ft. This was unfortunately the largest tide of the year, which is called a king tide (Buckingham, 2019).
The storm surge was relatively large, due to the onshore winds over shallow water towards Grand Bahama Island (NHC , 2019). The storm surge was in general up to 16 ft above mean sea level and in some locations up to 20 ft, according to the Grand Bahama Port Authority. Due to the flooding, the Grand Bahama's international airport was under 6ft of water (BCC News, 2019).

Near the coast, the storm surge was accompanied by large and destructive waves (NHC , 2019). These waves are offshore generated by the Hurricane and propagate towards the shore. The offshore significant wave heights are approximately 10 to 14 m, with a wave period of circa 13 seconds (Chung-Sheng et al., 2003, p. 1). In a spectrum of varying wave heights, the significant wave height is the one wherein one third of the waves is higher (Holthuijsen, 2007)

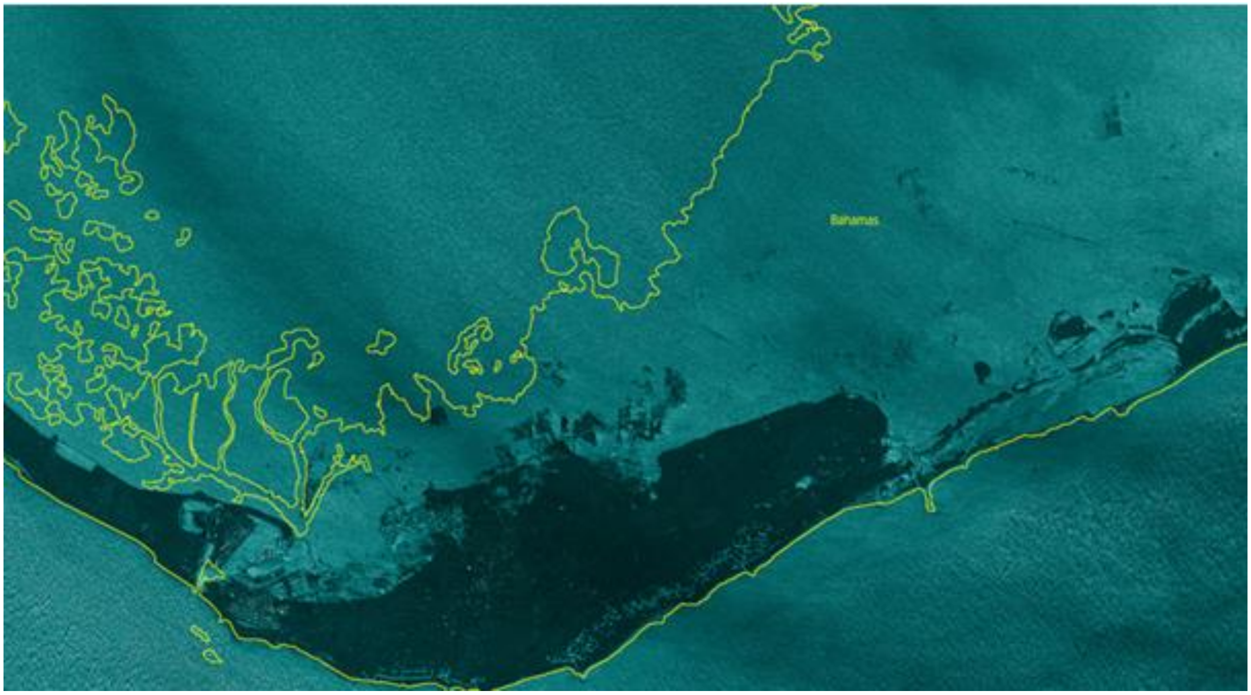


Fig 07: Grand Bahama Island during Hurricane Dorian. The image was taken 2 September 2019 and uses radar to penetrate the cloud cover. Areas that appear nearly black are not flooded (ICEYE, 2019).

Grand Bahama is one of the few islands in the Bahamas with pine trees due to fresh groundwater. The surge of saltwater that flooded the island infiltrated into this freshwater resource. Tainting fresh groundwater with salt causes lasting ecological and economical damage according to the Bahama National Trust (BHT).

In the early hours of Tuesday, September 3 2019, Hurricane Dorian was stationary over the island of Grand Bahama for 18 hours, most of the time as a category 5 hurricane. As seen in Fig 08 the total accumulation of rains over parts of Grand Bahama exceeded 36 inches according to NASA satellite-based estimates (NASA, 2019). Hurricanes with comparable rain intensity are expected to take place once every 15 years. This is taken from approximations of the Central Pacific Hurricane Centre with respect to occurrence rates of hurricanes on the coast of Florida (Central Pacific Hurricane Centre, 2020).

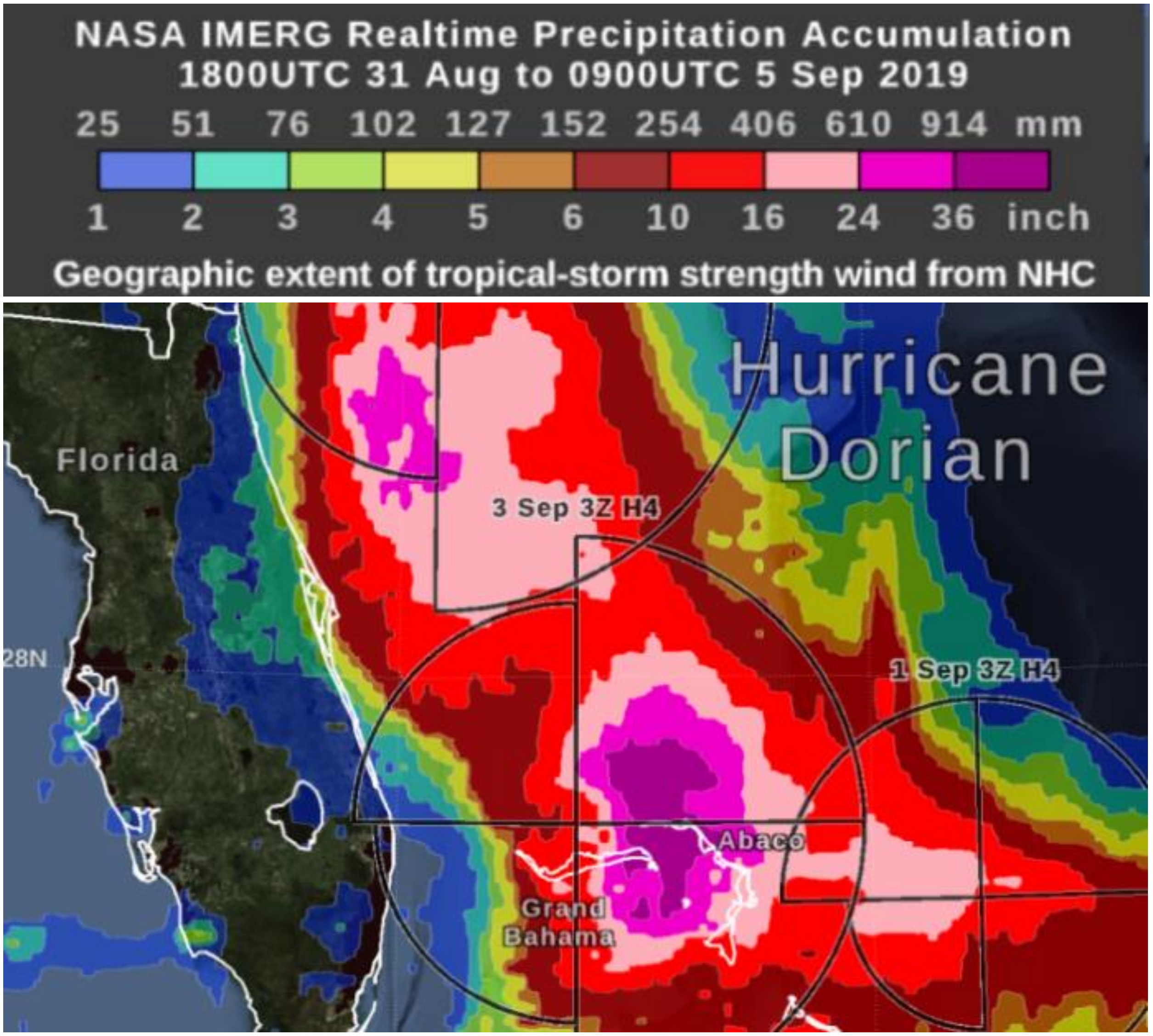


Fig 08: Nasa Realtime Precipitation Accumulation 18:00 ETC 31 Augustus to 09:00 UTC 5 September 2019 (Detail NASA,2019)

3.1.3 The hazards threatening the island

Based on the analysis of the island, the hurricane and the important physical processes, an overview and understanding of the hazards can be made. This hazard overview can optimize a solution, ensuring prosperity on the island.

Storm surges and waves

The topographic features and the bathymetry around Grand Bahama play a major role in the storm surge and the waves that reach the island. As mentioned above in chapter 3.1.1, Grand Bahama is protected from wind and waves that come from the east, due to Abaco. The same holds for the West, due to the short distance with the coast of Florida. On the south side the water level is very deep and can reach up to 2000 m. Just offshore the water depth is already 128 m. As will be explained in this chapter, the result is that this side of the island is mainly affected by large waves. While the northern part consists of a very large shoal. This shoal protects the northern side of the island for large waves but significantly increases the extent of a storm surge.

Wave behaviour and interactions

When the wind blows over the water surface, energy is transferred from the air towards the surface waves. There are different mechanisms for this energy transfer but the main result is that this leads to growing of waves which have different sizes (Miles, 1961). These waves propagate towards the shore with a certain speed, the phase speed. This velocity is dependent on the water depth. If the water depth is larger, the wave propagates faster. This has several effects.

If a wave propagates under an angle towards the coast the part closer to the shore has a lower water depth. As a result, the more offshore part of the waves travels faster towards the coast. The result is that the waves rotate and travel (almost) perpendicular to the coast (also named shore normal) at the coastline. This process is called refraction and is illustrated on Fig 09 (Holthuijsen, 2007).

Fig 09: Refraction of waves (Holthuijsen, 2007, p. 202).

When the water depth is slowly decreasing, the shape of the wave itself starts to influence the wave propagation speed. At the wave crest the water depth is slightly larger than at the wave through. This is visible in Fig 10. As a result, the wave crest propagates faster than the wave through and the wave itself starts to deform. The front of the wave becomes steeper resulting in the wave breaking. In this breaking turbulence processes result in energy dissipation (Holthuijsen, 2007). This dissipation is due to deformation of the whirls/eddies resulting is smaller rotating motions where viscous shear stresses convert the kinetic energy in thermal heat by viscous shear stresses (Uijttewaal, 2020).

Based on these principles, where the water depth influences the stability of the waves, information about the distribution of the waves can be determined. Since larger waves are more affected by these principles, , they will therefore break at deeper waters. As a result, the distribution of waves heights near the coast can be determined by the water depth rather than the offshore wave height. This is useful for designing solutions where the significant wave height (H_s) is commonly used. This is the wave height wherein one third of the waves is higher (Holthuijsen, 2007).

In shallow water the significant wave height (H_s) is half the water depth (h). There is shallow water if the water depth is 20 times smaller than the wavelength. The wavelength (L) is the length of the crest and trough and can in shallow be determined by the phase velocity (c) and the wave period (T): $L = cT = \sqrt{gh}T$(Holthuijsen, 2007).

If the steepness increases, a larger part of the wave is reflected. The wave can be completely reflected if this wave hits a vertical wall. The reflected wave, which propagates offshore, interacts with the waves that propagate towards the shore. As a result, the water surface level will be elevated even further and the flow velocities will locally increase significantly. This means that a hydraulic intervention interacts with the hydrodynamics around the structure. The resulting conditions can lead to erosion, undermining and eventually failing of the structure itself (Bosboom & Stive, 2015)

The type of waves, breaking or not breaking, and the corresponding amount of reflection depends on the slope of the bottom. This is usually expressed in the dimensionless Iribarren number. Which is actually the slope steepness versus the wave steepness (Schiereck & Verhagen, 2019, p. 156).

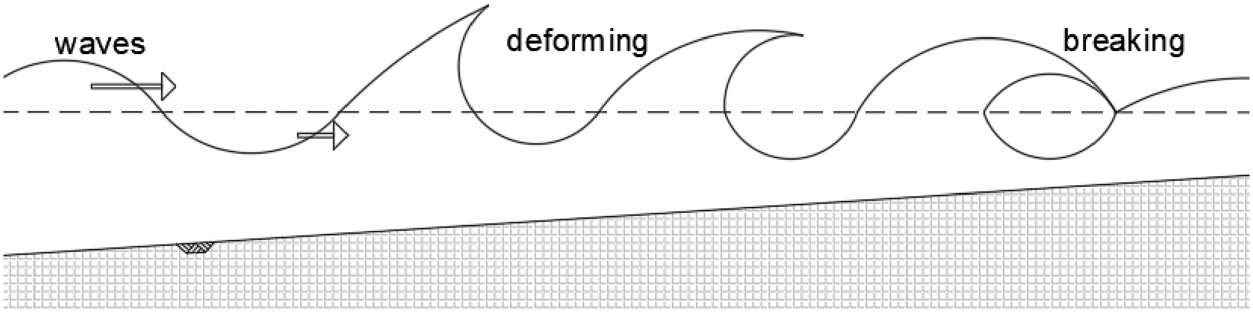


Fig 10: Indication shoaling, deformation of waves.

Storm surge behaviour

The wind of the hurricane pushes the water in the direction of the wind. Since the wind direction varies within the hurricane, the location of the hurricane plays an important role in the water movements and the potential threat of a storm surge. Based on the physics, the bathymetry and topography at and around Grand Bahama the behaviour and the corresponding threat of a storm surge for Grand Bahama is derived in the coming subchapter.

If the wind blows over a water body, there is an exchange of momentum with the underlying water. This can be interpreted as a shear stress that results in a flow/movement of the water. If the wind blows towards the shore, the water will move towards the shore as well. Here the water piles up. This results in a surface level elevation, a set-up. At the high-water site, the water pressure is higher than at the location with a lower water level. Which means that there is a horizontal water pressure gradient, which acts as a force on the water. As a result of this force the water wants to flow in an offshore direction. Near the bottom, the wind force is neglectable. The result is that the flow is in an offshore direction at the bottom. At the water surface the wind force is dominant, so the flow direction remains in onshore direction. The result of these flow directions is a return current which is visible on Fig 11. It should be mentioned that the breaking waves, which propagate towards the shore, result into an additional shear stress on the surface which increase the onshore current at the water surface and thereby enhance the set-up and thereby also the return current (TU Delft, 2020). However, in hurricane conditions this is a small contribution and is therefore not elaborated further.

The flow over the bed is subject to bottom friction which acts as a force against the flow direction. As shown on Fig 12, this force acts in the same direction as the wind force and will thereby enhance the set-up. This set-up is not instantaneous but will grow in time. The storm surge is at his maximum when the wind force, the friction force and the force due to the water set-up are in equilibrium (TU Delft, 2020).

If the bed level is lower, thus the water depth is larger, the (maximum) set-up will be smaller. This is due to the fact that the offshore force acts over a larger area. As a result, the water level gradient has to be smaller to counteract the onshore forces. Next to this, the bed friction force stands up to the flowrate squared. This flow rate is dependent on the water depth. If the water depth is larger, the flow velocity of the return current will decrease. Therefore, also the bed friction force will decrease. As a result, the force due to the water level gradient will be smaller (TU Delft, 2020).

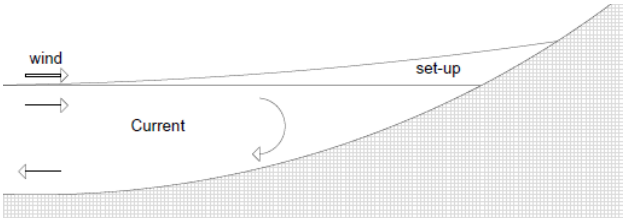


Fig 11: key concept of a storm surge

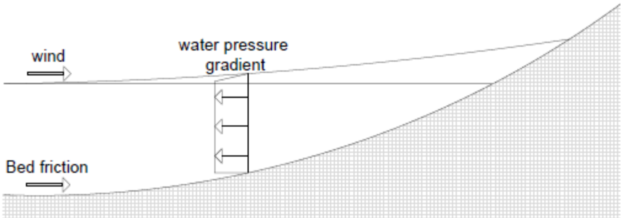


Fig 12: Force balance of a water set-up

In this process stratification is not considered. A separation of the lighter fresh rain water and denser saline ocean water can result in an additional set-up. The necessary water depth of fresh water to counteract the wind and friction force is larger than that of saline water (Pietrzak, 2020). It is expected that the large waves, and the corresponding breaking, will result in sufficient mixing.

The shape of the island should be taken into account. The above reasoning is based on a longshore uniform straight coast. If the coast is not straight, the accumulated water may flow to an adjacent location with a lower set-up. However, this is not always the case. Especially in the case of Dorian. Here the location of the hurricane resulted not only into the northern wind over the shallow water, which resulted in a large storm surge. But also, the unfavourable shape of the island resulted in a larger storm surge. It acts as a funnel where the wind blows in. As a result, the water can barely flow away. On Fig 13 the wind velocities are visible. The red arrow shows the wind direction towards the coast.

Next to this, it is important to conclude that it is not possible that there is a storm surge on both sides of the island. The onshore wind at one location will result in an offshore wind at the other side of the island. Due to this offshore wind the surface water will flow away from the island. This will result in a lowering of the water level.

Based on the same kind of reasoning of the storm surge it can be concluded that at the south side of the island, due to the large water depth, this set-up is negligible. As a result, the south side of the island can be used as a safe area for flooding.

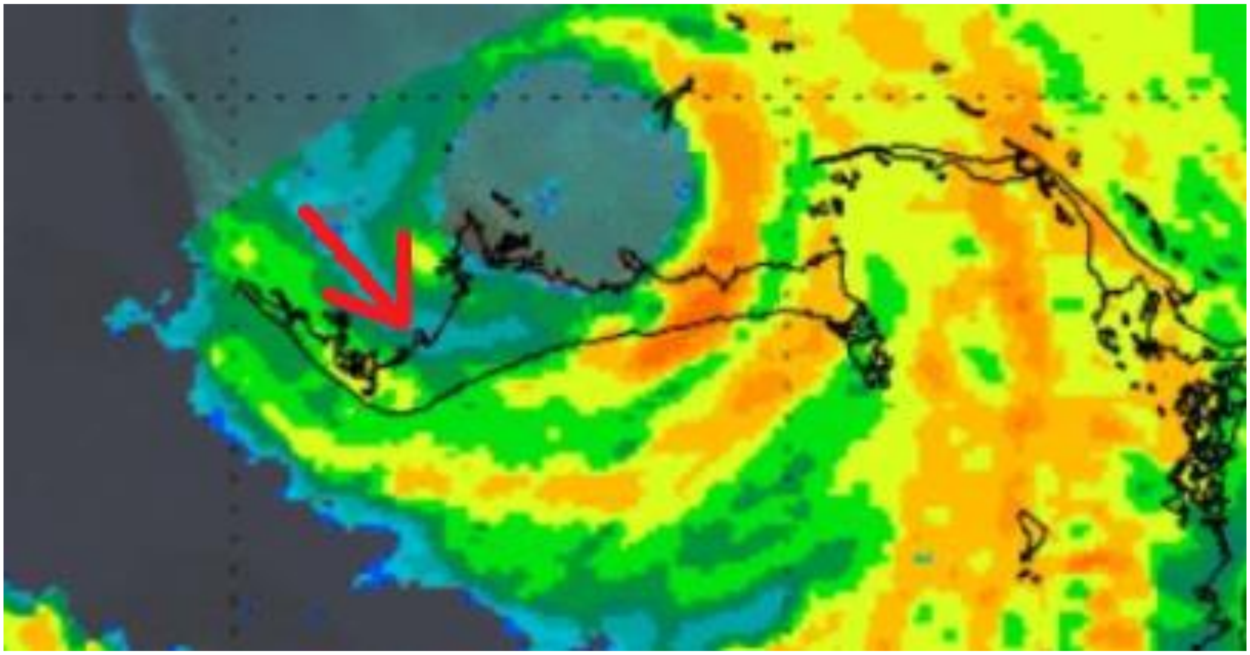


Fig 13: Wind speed and direction arrow at 2019-09-02 18.45 hr. Based on a video from McNoldy, 2019.

Precipitation and flooding

The direct hazard of rain is pluvial flooding. This occurs when an extremely heavy downpour of rain saturates drainage systems, the excess water cannot be absorbed creating a flood on the surface level and the capacity of the water system is exceeded.

To evaluate the hazards of the precipitation three different rain scenarios were constructed, i.e. Normal, Dorian and Extreme ("Double") Dorian, in line with the 3-point approach, chapter 2.2.2 . These three scenarios are used to monitor the performance of the system.

1. During normal events, rainfall on Grand Bahama is minimal compared to the rainfall during a hurricane. Data provided by Grand Bahama Port Authority showed that average annual rain scenarios lead to an average accumulation of 0,25 mm per day. This data was however insufficient to allow for a statistical analysis. To have a potent overview of a normal storm event, this study used a storm that has been abstracted from the hourly precipitation data from New Orleans and Galveston (see appendix 9.1) . This detailed data was used as the climate and latitude are similar to that of Grand Bahama. The resulting peak intensity for a normal rain scenario is expected to be i=3,8mm/h. An event of that intensity is expected to take place twice a year consequently T=½ yr.

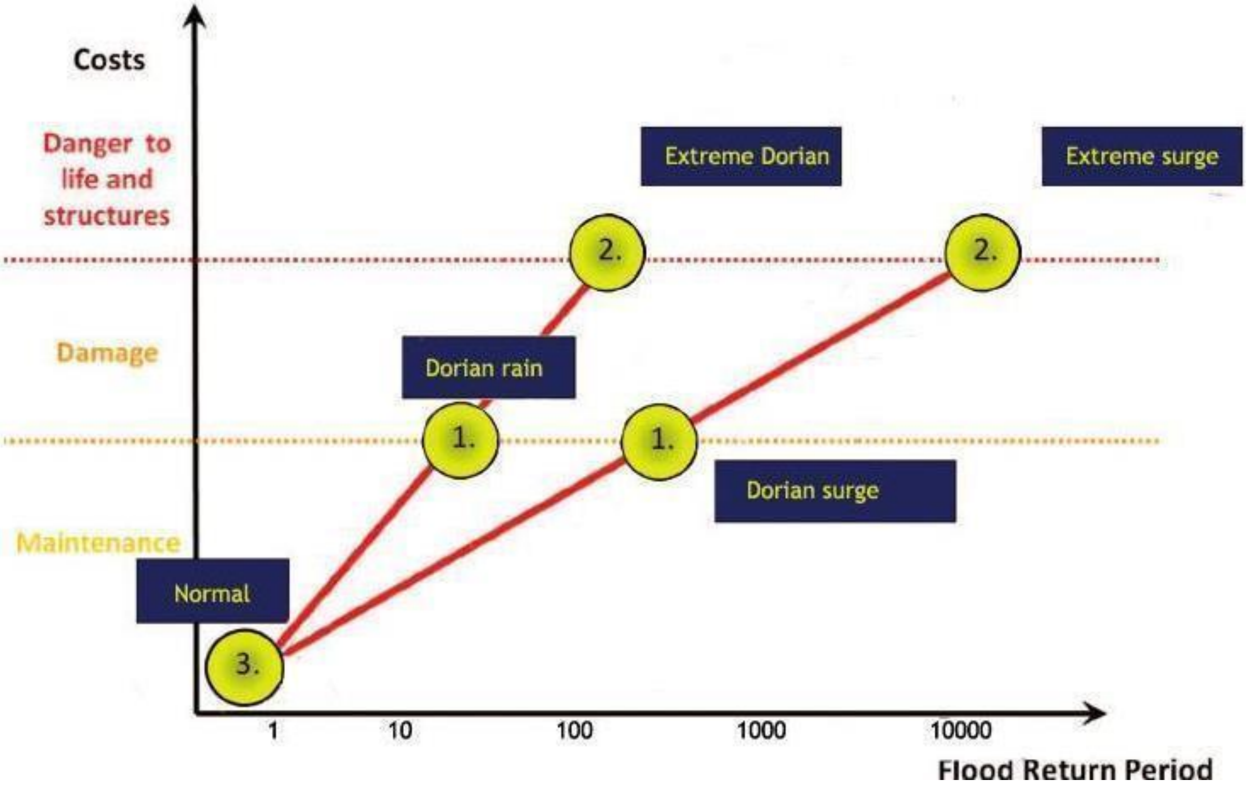


Fig 14: Three-point approach for the independent storm surge and the extreme rainfall

2. As can be seen in Fig 08, the total accumulation of rainfall during Dorian over parts of Grand Bahama exceeded 36 inches or over 910 mm. For this study the values of the Dorian protection level will be simplified to 91 mm/48h and an intensity of 19mm/h over 48h. This event is assumed to have an occurrence of once every 15 years, consequently T=15 yr.

3. For the Extreme Dorian design storm a doubled intensity of Dorian is used. 182cm/48h and a constant rainfall of 38mm/h over 48h. This hypothetical extreme is based on the fact that the increase in temperature can fuel stronger storms in the future (Goudzari, 2006). Considering the missing detailed data for Freeport and the changing boundary conditions such as climate change it is hardly possible to estimate the return period to this scenario compared to the first two. But it seems safe to consider this Extreme Dorian scenario to have a rate of occurrence of less than once every 100 years, thus T≥100 yr. Hopefully a storm of this magnitude will never exist, but this amount of rainfall will give a look into the behaviour of a failing drainage system .

As seen in an earlier explanation, The rain is, in contrast to the storm surge, independent of the wind direction, meaning there is no correlation between the extreme rain and the extreme storm surge. So, two distinct three-points approaches are used, as illustrated in Fig 14.

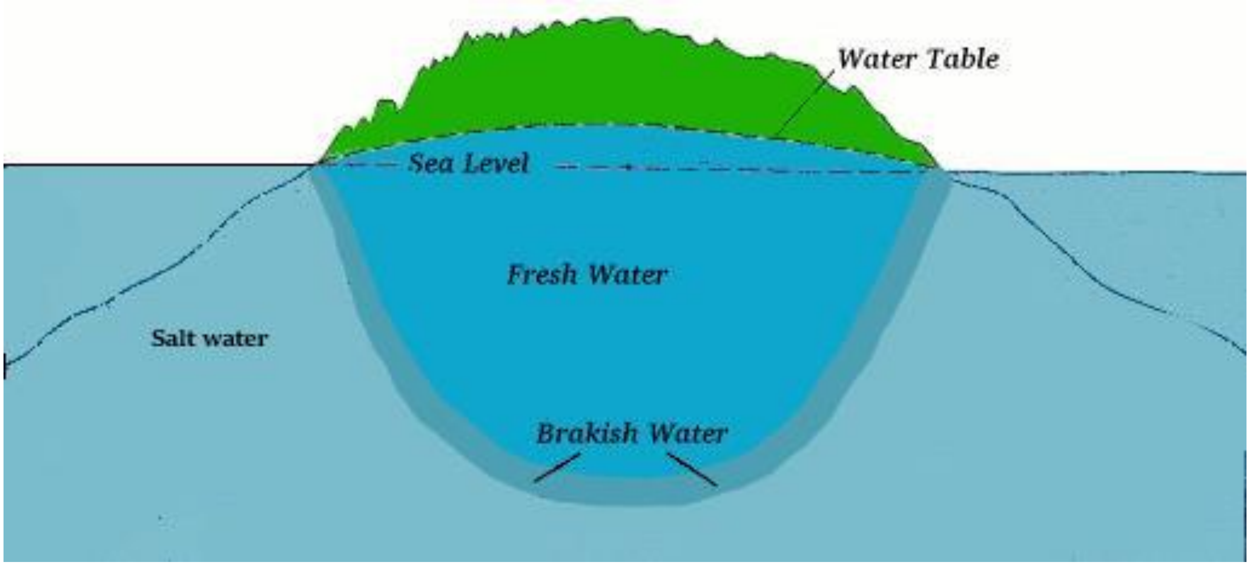


Fig 15: Depiction of a fresh ground water bubble on an island (Geo101, 2007). For more information see the Badon-Ghyben-Herzberg principle.

Salt intrusion and freshwater supply.

The lithology Grand Bahama consists mainly of Limestone as stated earlier. This is a very porous material and thus is easily eroded by rainfall and runoff from the surface, resulting in a large potential to form caves (Lytle, 2006). Some of these caves are filled with freshwater basins and are used by the population as a freshwater resource. Fresh water is lighter than the heavier saltwater and hence floats on the salt water with only a thin mixing zone, as can be seen in Fig 15. The area of the island Grand Bahama is large enough to form such a freshwater bubble.

Water supply of Freeport makes use of this fresh-groundwater reservoir. Wells are installed to capture this water in the area as shown in Fig 16 and Fig 17. However, if a sea water surge flows over the ground level and the saltwater infiltrates into the ground, mixing of fresh and salt water occurs, making the basin brackish and unusable as a freshwater resource for drinking water production. The salt intrusion following hurricane Dorian's storm surge flooding has made the basin out of use for a long time. Saltwater is heavier than fresh water and will move through the whole basin before reaching the saltwater layer, contaminating the whole basin.

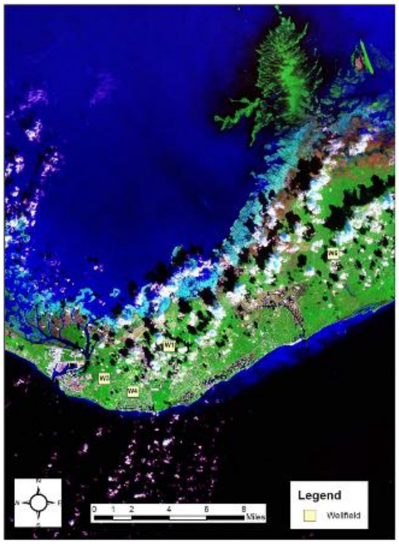


Fig 16: Location of fresh water wells around Freeport (GBUC, 2008)

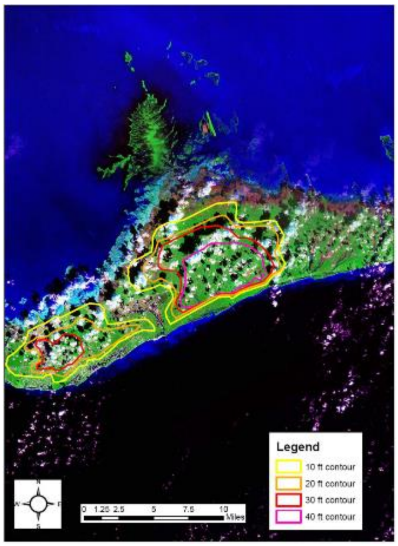


Fig 17: Map of thickness of the groundwater lens (GBUC, 2008)

Fig 18: Extent of storm surge impacting the GBUC wellfields in 2004 (GBUC, 2008)

3.1.4 Ecosystems

The island of Grand Bahama hosts five terrestrial ecosystems and natural habitats. They are shown in Fig 20. Three of them are particularly relevant for our project: the pine forest, coral reef and sparse mangrove ecosystem. They are further analysed in this chapter.

The shallow coral ecosystem is particularly important when it comes to its effects during a storm. The coral reef performs as a natural breakwater. It can provide a higher protection of the coastal areas during storms and hurricanes (The Bahamas National Trust, 2008d). Furthermore, these are important areas for the economy of the Bahamas. First of all, they are the food source for many species that constitute the commercial and sport finishing industry. Second, they are a big attraction for the tourism industry. The drawing in Fig 19, depicts the characteristic species of the coral reef ecosystem on the island of Grand Bahama.

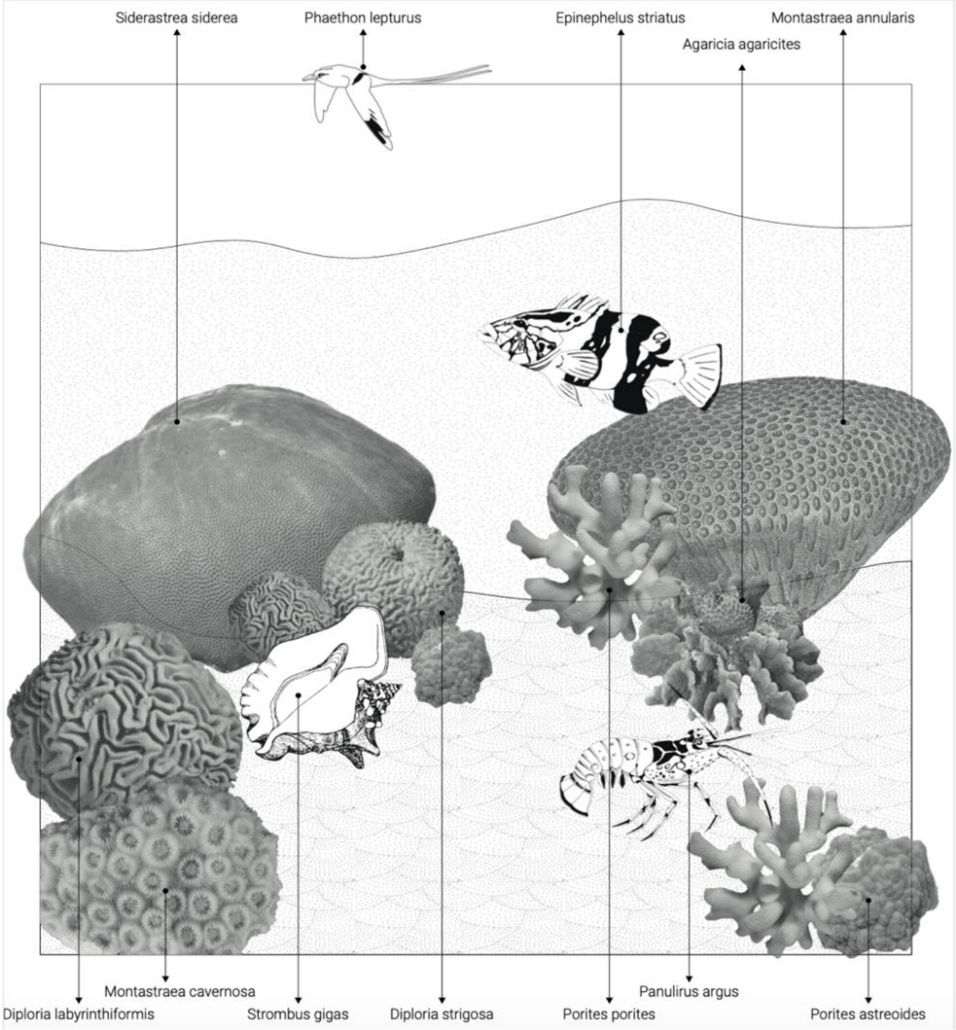


Fig 19: The coral reef ecosystem in Grand Bahama; based on: (“Corals of the World”), (The Bahamas National Trust, 2003), (The Bahamas National Trust, 2008e), (The Bahamas National Trust, 2008f), (The Bahamas National Trust, 2010d).

The ecosystem of the pine forest is the one that is present on the majority of the island's area. The Bahamian forest hosts an incredibly rich and diverse flora and fauna, especially in terms of birds. That is why, Grand Bahama is also a destination for birdwatchers arriving from all over the world. This ecosystem is important for the project as it is located in the central areas of the island, not so close to the sea, where the majority of the urban area is positioned as well. Fig 20 shows the most important inhabitants of this natural ecosystem.

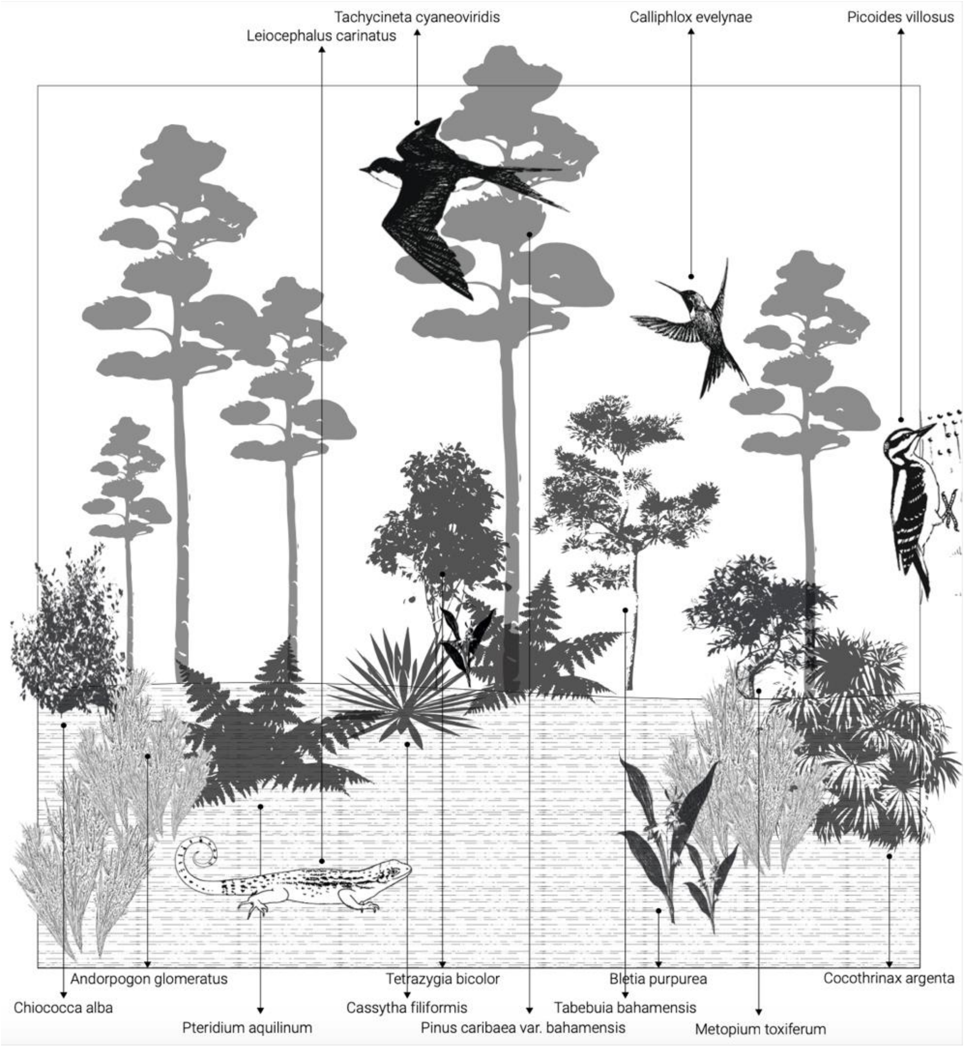


Fig 20: The pine forest ecosystem in Grand Bahama; based on: ("Plants of the World Online | Kew Science," n.d.), ("University and Jepson Herbaria Home Page," n.d.), (The Bahamas National Trust, 2010a), (The Bahamas National Trust, 2005b), (The Bahamas National Trust, 2005a), (The Bahamas National Trust, 2005c), (The Bahamas National Trust, 2008b).

Mangrove wetlands can be found mainly along the northern coast of Grand Bahama. Similar to the coral reef, they can provide a natural barrier during storms and hurricane events. Mangroves host various animal species and plants, creating a rich ecosystem. Fig 21 shows just some of them, that can be found mainly in the Bahamas and in Grand Bahama particularly.

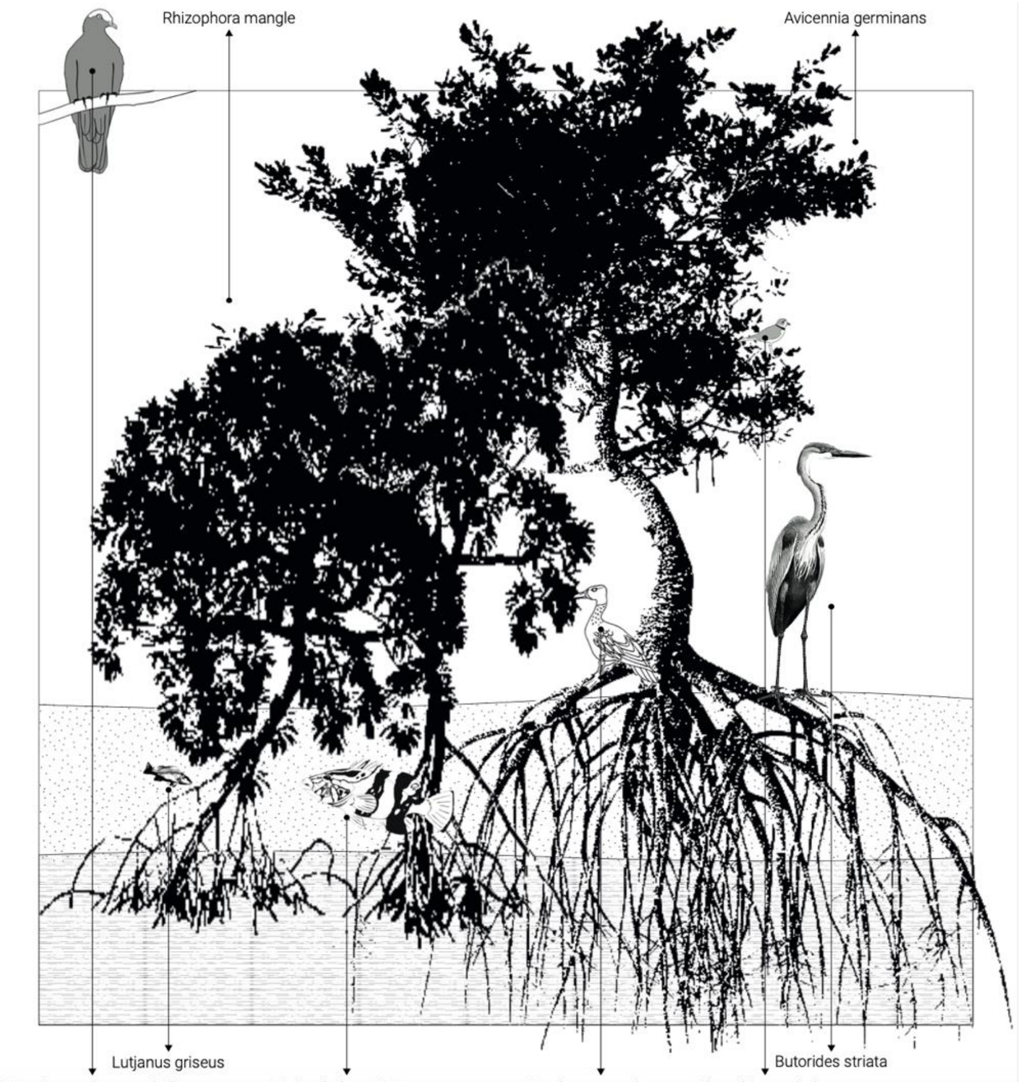


Fig 21: The mangrove ecosystem in Grand Bahama; based on: (The Bahamas National Trust, 2008a), ("Plants of the World Online | Kew Science," n.d.), ("University and Jepson Herbaria Home Page," n.d.), (The Bahamas National Trust, 2010c)(The Bahamas National Trust, 2008g)(The Bahamas National Trust, 2010b).

Coastal ecosystems

The island is also rich in terms of coastal diversity. The next map depicts the three diverse ecosystems present on the shore of the island. There are three main types of coast found in Grand Bahama: sandy, rocky and muddy. The muddy seashore is mainly covered with the mangrove ecosystem, described in the previous part of the chapter. The sandy seashore presents a surface without bigger rocks and stones, no algae or tidal pools. It can be divided in four zones, as shown in Fig 24.

Fig 22: The shore typologies of Grand Bahama. Note, data from Grand Bahama Port Authority and Office of Coast Survey.

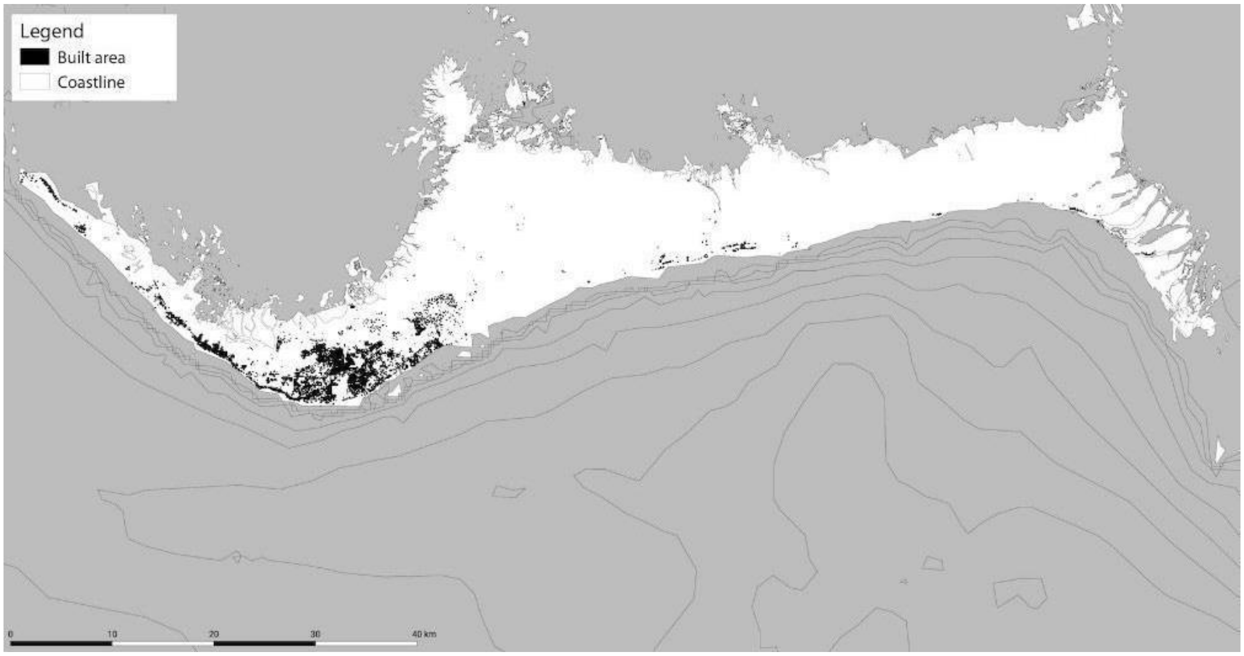


Fig 23: location of the built volumes. Note, data from Grand Bahama Port Authority and Office of Coast Survey.

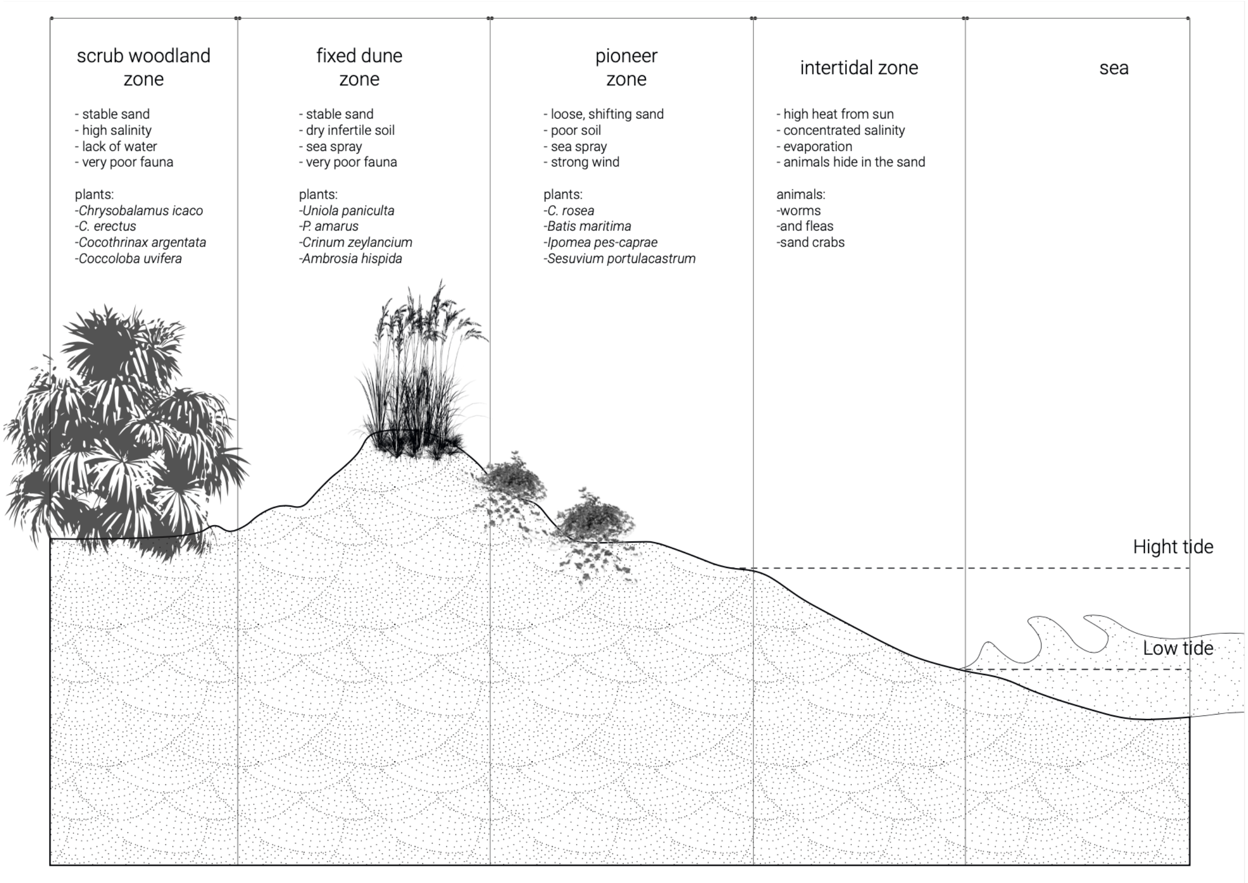


Fig 24: Section of a sandy seashore. Retrieved from: (Bahamas National Trust, 2008c), (Bahamas National Trust, 2011)

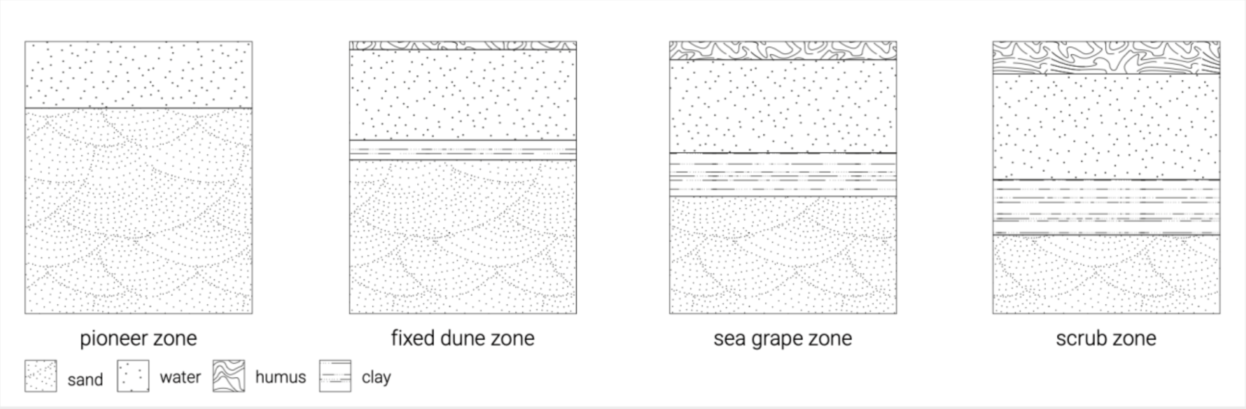


Fig 25: Sections of the different zones of the sandy coast. Retrieved from (Bahamas National Trust, 2011)

Other than by their position, they are also characterized by the different proportion of the soil types. They are visible in the Fig 25.

The rocky seashore in the Bahamas is made of limestone rock. It presents similar living conditions for the flora and fauna as the sandy coast: high salinity, strong wind, sea spray. Furthermore, the organisms living here are vulnerable in the timeframe between a high and low tide, since they can remain stuck in rock pools that they create. A typical rocky coast is depicted in Fig 26.

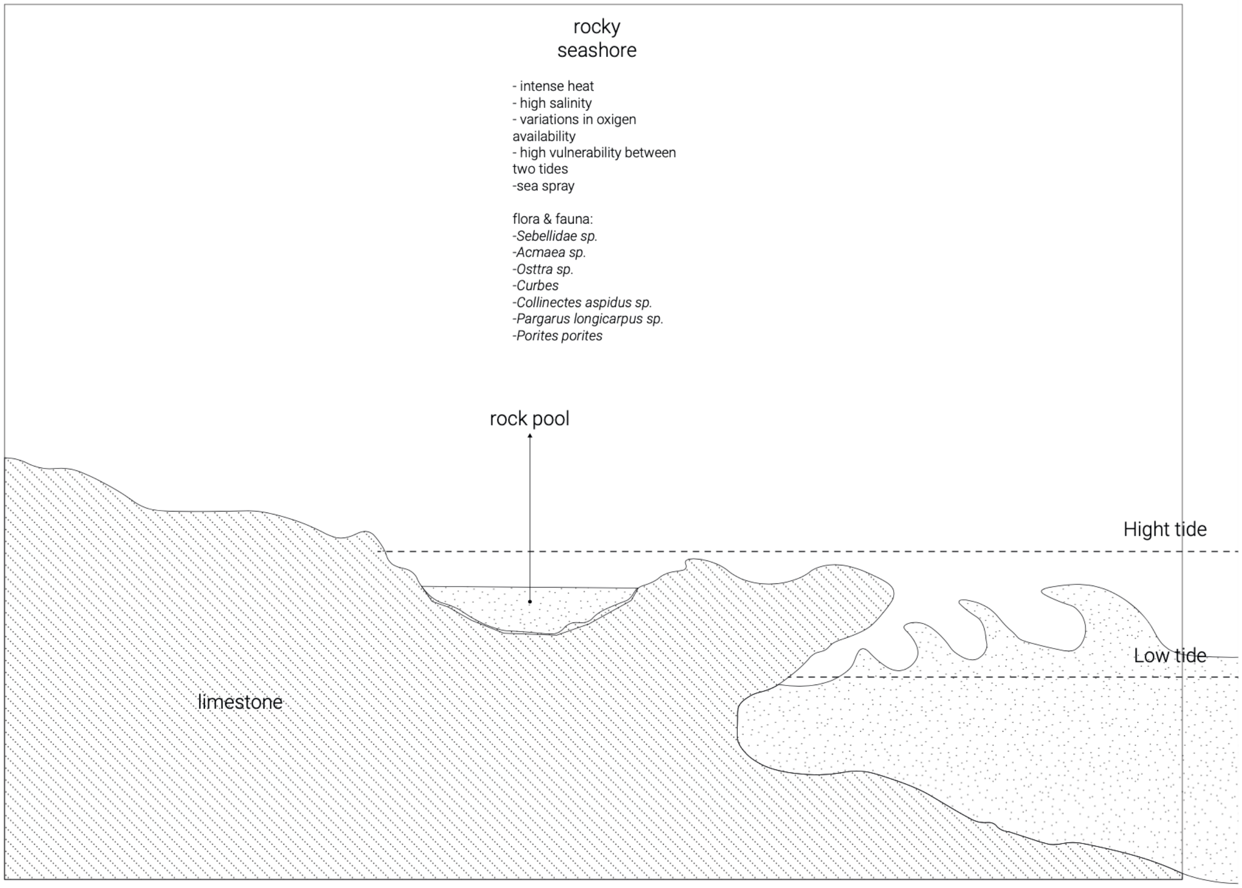


Fig 26: Section of a rocky seashore. Retrieved from: (Bahamas National Trust, 2008c), (Bahamas National Trust, 2011).

3.2 Urban scale

3.2.1 Built environment

The density of the existing built environment in Grand Bahama is very low. The lack of data about the buildings' surface and height does not allow a precise calculation of the actual density, data retrieved from the Office of Coast Survey (n.d.). The maps and drawings in this chapter, Fig 27 till 32 show the density that was calculated only for the residential function and for the area of Freeport, where most of the buildings are located.

Every building registered in the datasets as "residential" was, therefore, counted a "traditional" Bahamian household, better described in the chapter about the architectural scale. This analysis considers each of these buildings as a dwelling (that usually hosts one family unit). In this way, it is possible to indicate a rough density analysis expressed in dwelling per hectare: dividing the perimeter of Grand Bahama into polygons with a dimension of 100x100m, i.e., one hectare. Afterward, the analysis counts the number of dwellings in each polygon. The map in Fig 27 shows the results.

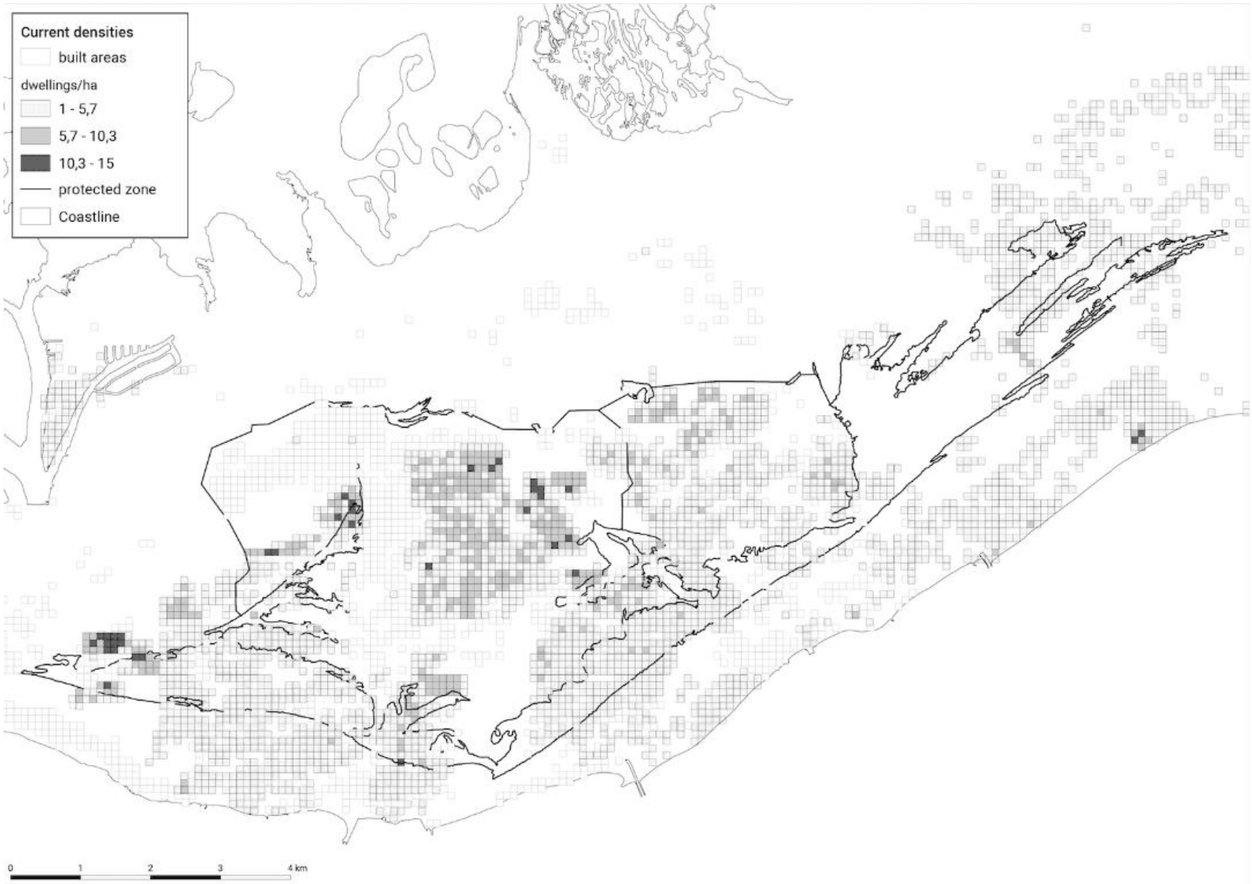


Fig 27: Existing densities in Grand Bahama. Note, data from Grand Bahama Port Authority and Office of Coast Survey

The different densities characterize different urban forms. The main differences between them are mainly in terms of the ground use: although there is no available data about the exact amount of the ratio between built and green area, we can see these differences with satellite images. The three density classes shown in Fig 27 can therefore be visualized in the Fig 28, retrieved from Google Maps.

3.2.2 Functions and activities

As shown in Fig 29, together with the highest residential densities, Freeport hosts most of the other activities. The maps show activities present on the island of Grand Bahama, divided into four categories.

First one, the social functions, including all the activities that make the social and cultural of the inhabitants richer, such as the art centres, churches, libraries, parks, public buildings, sports facilities, and other social facilities.

The second one depicts the critical functions. These are all the activities and functions that are fundamentally important during an extreme hurricane scenario and for the recovery of the urban environment after an extreme event. These are the health facilities, governmental offices, clinics, courthouses, fire stations, hospitals, airports, education facilities, police stations, and post offices.

The third map shows the functions and activities crucial for the island's economy, both in the daily scenario and after a storm event. These are and in general tourism facilities, offices, companies, commercial activities, fast foods, hotels, marketplaces, nightclubs, retails, restaurants, and other shops.

The fourth and last map shows the industrial facilities, which are the most difficult to integrate with the residential function, because of managerial and technical reasons. These are farms, hangars, car rentals, construction sites, industrial facilities, parking plots, storage, rentals, and warehouses.

Fig 28: Visualization of existing densities in Grand Bahama, retrieved from Google Maps, from left: 15dw/ha, 11dw/ha, 4dw/ha.

Fig 29: location of functions and activities. Note, data from Grand Bahama Port Authority and Office of Coast Survey.

The photos below, taken from the Google Maps Street View, show examples of spaces that these functions create in the urban environment.

Fig 30: The spatial qualities of the public space, retrieved from Google Maps Street View

3.2.3 Transportation

The following map analyses the mobility infrastructures of the Grand Bahama island. It uses a space syntax analysis to understand where the traffic concentrates. To understand this, the space syntax analysis shows the option of the choice, therefore measuring how likely a street will be passed through on all shortest routes from all spaces to all other spaces in the entire system or within a predetermined distance from each segment (Hillier, B. et al., 1987). The distance that was taken into account in this case was 25000m, which corresponds to the distance that is usually covered by car.

The map shows that the most important in this sense are some route lines crossing the island from west to east. Although, the majority of them are focused in the area of Freeport. It is possible to draw the conclusion that all the roads indicated here as the darkest one, are mainly used by car traffic and therefore also designed for it.

Fig 31: The space syntax analysis showing streets with the highest traffic (the darkest) of the island. Note, data retrieved from Grand Bahama Port Authority (2017) and Office of Coast Survey (n.d).

3.3 Building scale

The Bahamian architecture responds to cultural and climatic aspects. This chapter will analyse the typical Bahamian house, due to it being the most common building typology, and especially because it is the main space people inhabit on a daily basis. The simplicity of a typical Bahamian house layout suggests a conventional and repeated construction process and use of materials, where the social areas are the main core of the house, while rooms and other facilities follow in hierarchy.

The following paragraph analyses the damages that water and wind hazards have on the buildings and physical infrastructure of Grand Bahama during Hurricane Dorian.

3.3.1 Water hazards

Coastal hazards are the greatest threat to life and physical infrastructure during hurricane events. In the case of Dorian, Grand Bahama suffered intense sea surge, where winds of 295 km/h pushed the water from the shallow northern coast inland, creating great flooding and damage in several locations. The storm surge, waves, and tides are the main contributors to coastal flooding, carrying with it secondary – but equally damaging – hazards, as debris.

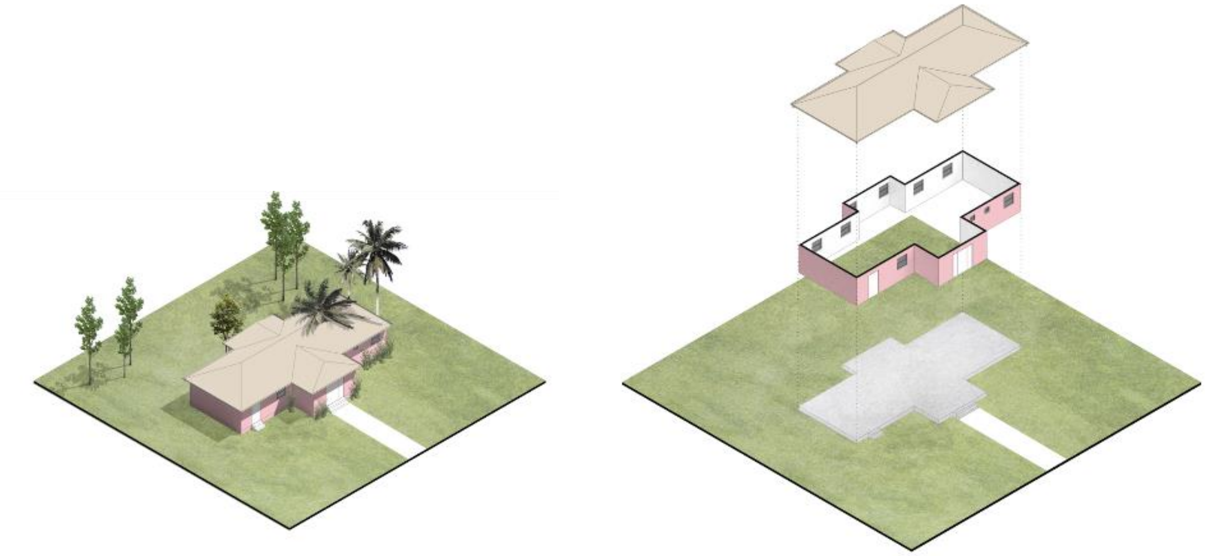


Fig 32: Analysis of the typical Bahamian architecture

Coastal areas are subject to flood risks, especially those associated with tropical cyclones. As storms surge and waves propagate onto the coastal area, they can inundate the beaches, buildings, and vegetation. In the V Zone, shown in Fig 33, hurricane-induced waves and currents can generate significant hydrodynamic forces to destroy flooded buildings. In Zone A, wave forces are less significant, but buildings can still be flooded. For further information about storm surge hazards see chapter 3.1.3 .

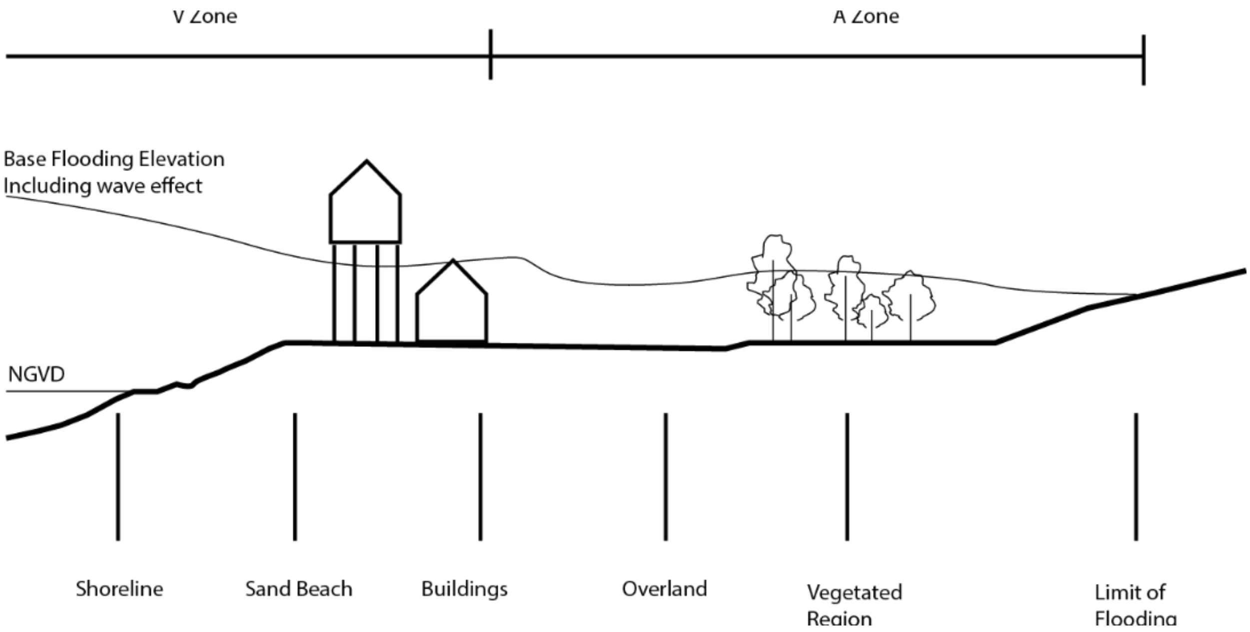


Fig 33: Coastal Zoning. Hurricanes: Science and Society

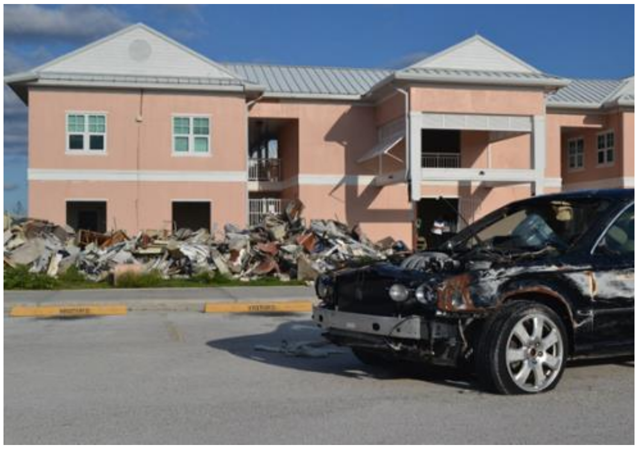


Fig 34: Destroyed school building of the university campus.

Fig 35: Destroyed dorm of the university campus.

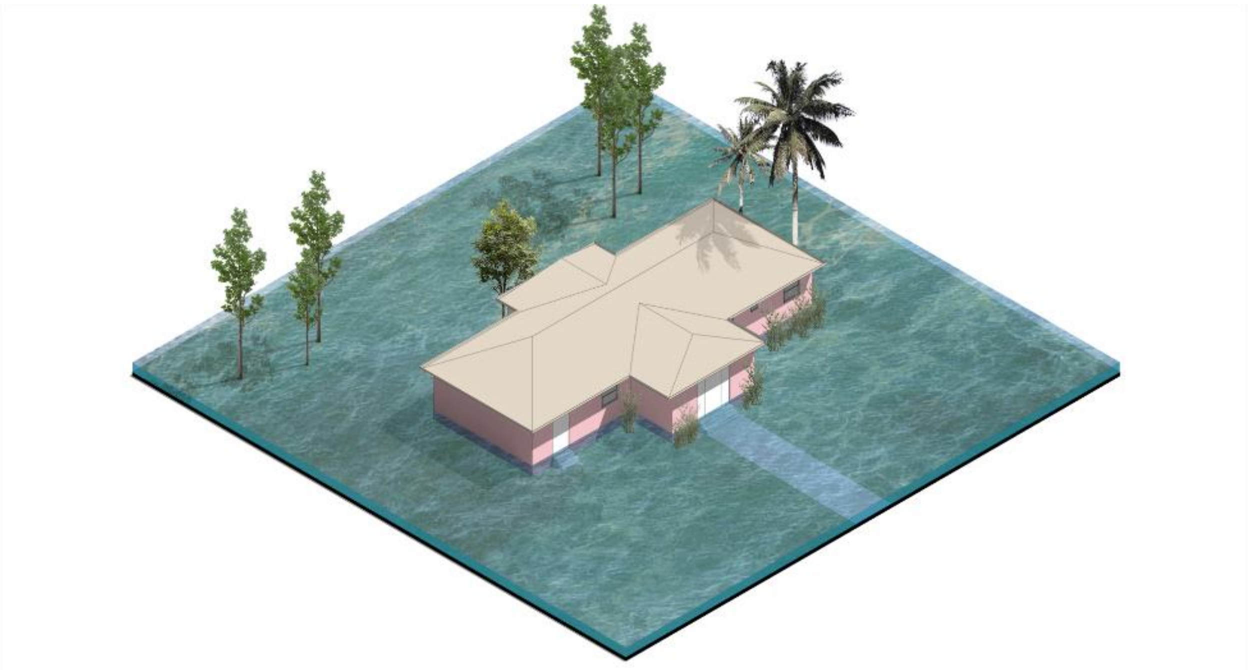


Fig 36: Sea surge of the hurricane Dorian in A zone, shown in Fig 33

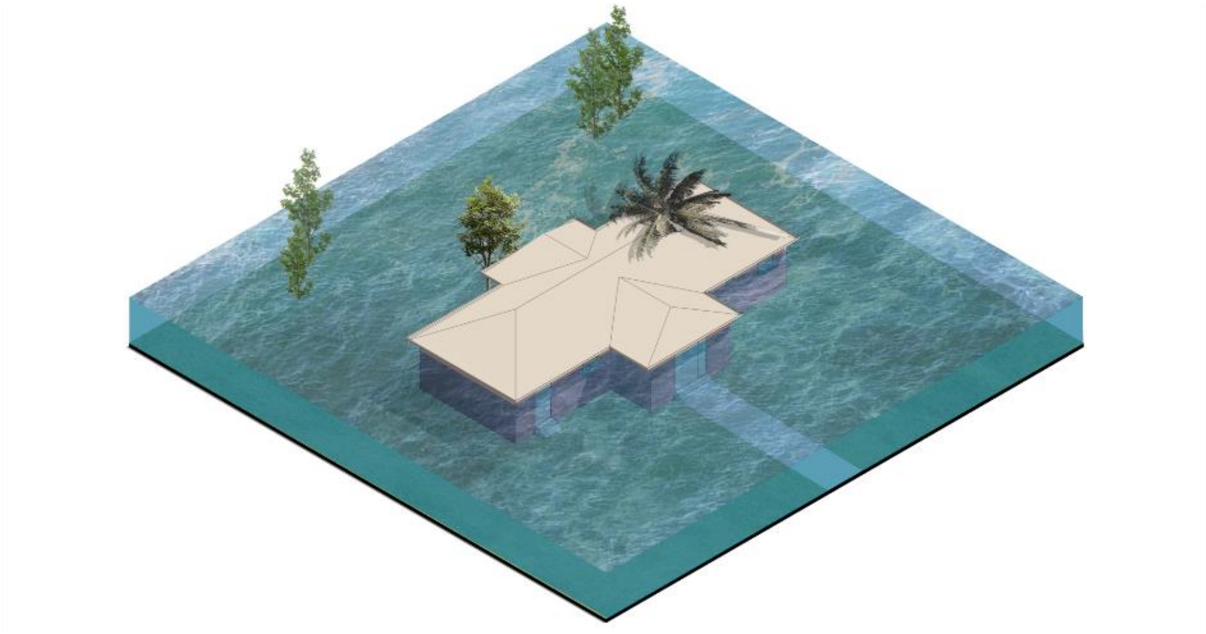


Fig 37: sea surge during Dorian in the V-zone, shown in Fig 33.

The combination of a surge, waves, and high winds is deadly. In addition to past hazards, hurricanes threaten coastal areas with heavy rains. All tropical cyclones can produce widespread torrential rains, which cause massive flooding and trigger debris flow. Human interaction and land use can also affect how rainfall may impact a region. Areas lacking a naturally occurring base layer of sediment, plants, trees, etc. will be more apt to erode or washout with large volumes of rainfall or flowing water. For further information about precipitation hazards see chapter 3.1.3 .

In terms of the affectation on buildings, the housing units of Grand Bahama are highly vulnerable to waterborne and windborne hazards. In the case of debris, the building envelope – facades and roofs – are the main issue to tackle. The importance of protecting the envelope from windborne debris, which could also affect the building through debris floating on the water, will be explored in the project.

Direct loss of human life and damage to property are caused by physical contact with floodwater and the corresponding forces. The location of the flood will also indirectly affect networks and social activities, resulting in indirect losses, such as traffic disruptions, the loss of public services and the reduction of trade. Urban flooding can cause permanently damp houses, leading to the growth of indoor mould and resulting in adverse health effects, particularly respiratory symptoms.

Fig 38: The outside of a house destroyed by Hurricane Dorian, damaged by water and wind *picture taken 4 months after Dorian.*

Fig 39: The inside of a house destroyed by Hurricane Dorian, damaged by water and wind *picture taken 4 months after Dorian.*

3.3.2 Wind hazards

Uplifting force is the upward pressure applied to a structure with the potential to lift it. All roofs are subject to wind elevation which varies by location, terrain, height, size, shape, exposure, etc. Wind uplift occurs when the air pressure is greater under the roof than the air pressure above it. This may be exacerbated during high wind speed, as air infiltration into the building may increase pressure below the roof, while wind speed above the roof surface will decrease air pressure above it. This will cause roof damage if the pressure difference is too high. If the fasteners are nails, they are more susceptible to pull-out caused by dynamic loading of the panels, than screws. The attachment should be sufficient to resist current uplift loads. On the roof add-ons like gutters, the uplift and rotational wind load exerted on the gutter will be transferred to the wall or deck, depending on the bracket design and attachment.

Wind pressure

Winds with sufficient speed to damaged houses can damage even a well-designed, -constructed, and -maintained facility in an event that exceeds the facility's design criteria. Fortunately, except in the case of tornado damage, it is rare for buildings to experience winds that exceed design levels. Most damage occurs because various building elements have limited wind resistance, resulting from inadequate design, poor installation, or material deterioration.

Wind-Driven Rain

Rain or wind-driven rain, and hail damage are not assessed in the same classification as flood damage. Wind-driven interior water damage is a significant loss factor impacting coastal and inland property during hurricanes, severe thunderstorms and other high wind incidents followed by rain .

Many building owners overestimate their buildings' wind and storm-driven rain tolerance and underestimate how much time it will take to restore a destroyed building or build a new one. They also tend to underestimate the impact of disturbances from wind and water on the viability of the construction operations. This lack of awareness may prevent building owners from minimizing the weaknesses of their buildings.

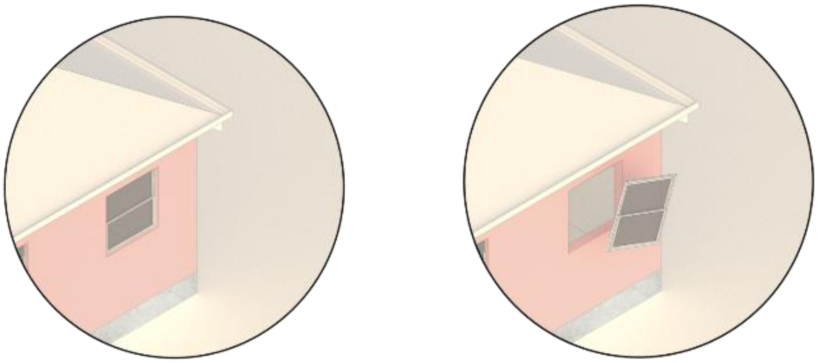


Fig 40: The change of the wind pressure during a hurricane affects the windows.

4 Synthesis & Design

4.1 Scoping

In order to establish the design relation between the involved disciplines, it is necessary to go through the understanding of each of their scopes and scales. For every discipline, the authors tried to envision scenarios that could represent the solution to rebuild the reconstruction. The scenarios listed below are often extreme and establishing them completely is unrealistic. Although, when combined together, they define a common ground where disciplines range and work together.

The scenarios need to take into account four main factors:

1	People:	The impact on the inhabitants and their role in the scenario.
2	Planet:	The impact or the role of the ecologic layer in the scenario
3	Prosperity:	Whether the scenario is economically and financially feasible.
4	Preference:	Indicating the (sometimes non completely objective) preference of the exponents of the discipline.

4.1.1 Urbanism scope

The discipline of Urbanism envisioned four possible scenarios and put them in a matrix. The first line (horizontal), runs from the option of a diluted urban environment, meaning all the resources are scattered across the island, towards a denser scenario. In this case the urban environment is concentrated on a smaller area, which allows a more efficient use of resources and a lower use of the ground. The second line (vertical) starts from a vision of ecology, where nature plays a major role and arrives at a scenario where the urban system is more important.

To describe the four scenarios, the discipline of urbanism looked at three main elements: the infrastructure (mobility, connectivity, energy), the urban fabrics (density), and the urban metabolism (energy production).

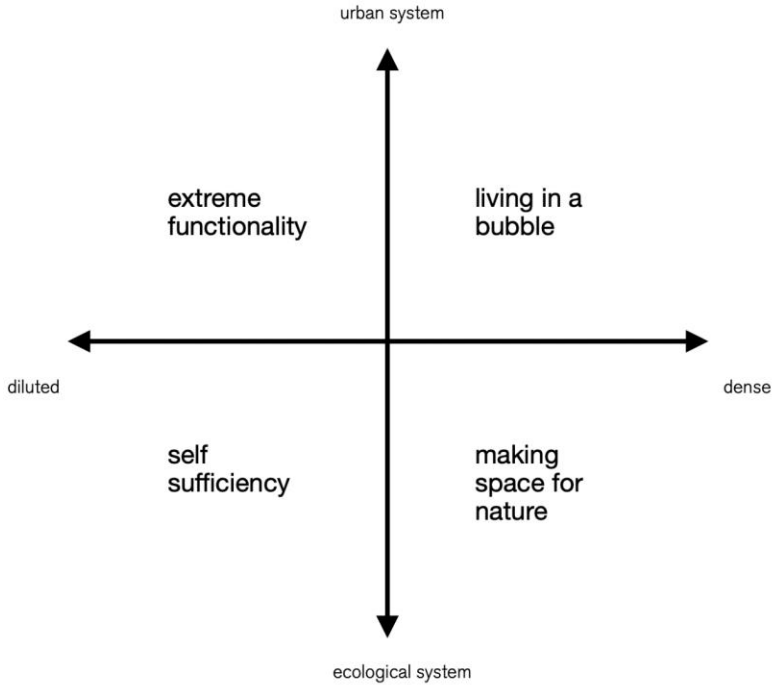


Fig 41: the matrix depicting extremes of urban scenarios

Scenario 1: extreme functionality (enhancing mass tourism and functionality of the free-port and airport, urban form not regulated)

- Urban and ecological system interact on the urban (regional) scale.
- Heavy infrastructure to accommodate the needs of the harbour, airport, population, mass tourism.
- Ecological systems are only considered as a means to enhance mass tourism, fishing activities and agriculture.

Scenario 2: extreme density, living in a bubble, the city does not need the surroundings, but is connected globally

- Very dense urban area
- Urban fabrics centralized in one place
- Isolated from the outside
- Technologically advanced so that it achieves complete self sufficiency
- No cars, only bikes
- High diversity of functions and activities

Scenario 3: extreme sprawl and self sufficiency

- Individualistic society
- Circular economy on the dwelling scale
- Agriculture on the small scale
- Urban and ecological system interact and have effect on the scale of the dwelling (or propriety)

Scenario 4: making space for nature

- Barrier of mangroves around the island
- More coral gardens, coral regrowth
- Rehabilitating damaged areas
- Having more seagrass
- Humans as ecosystem

4.1.2 Hydraulic engineering scope

The hydraulic engineering discipline mainly focuses on protecting the island against coastal flooding. These interventions can be on different scales and are explained below.

Core protected area

Protect the city against a storm surge by high levees that (fully) blocks the water. It protects all the structures in the area and the people up to a certain level that is rarely exceeded and it prevents large-scale salt intrusion in the area that is protected in this way. Large scale intervention can have a large impact on the society and can consequently have secondary effects, like separating and disconnecting certain areas.

Local protection measures

The interventions which can protect the core area can be used only on a small scale. It will hereby only protect individual buildings and/or a small group of buildings, as visible on Fig 42. The surrounding infrastructure and thereby the emergency activities are still affected by the flooding.

Mangrove forest

A mangrove forest cannot prevent the area from getting flooded. The water will go through the trees, as visible on Fig 43. These trees reduce the height and therefore the impact of the waves. However, it is only a local solution since the waves start to grow outside the mangrove forest. Furthermore, mangroves mainly live in a muddy coast with barely any waves. Other more suitable trees can also be used if trees are desirable for wave breaking.

Coastal flood wall

An extreme solution is to prevent flooding completely by placing a flood wall at the shore. However, these structures are very expensive and will have a huge impact on the society. So is, for example, the view on the ocean completely blocked. This is visible on Fig 44 and 45

Do (almost) nothing

The other extreme, compared to the coastal structures, is to do no hydraulic interventions. This solution focuses on relocating the important buildings, which are needed to facilitate emergency services, to the higher ground. This is combined with (re)organizing and coordinating the services. The solution therefore lies mainly to the other disciplines. Small scale, ‘individual’ hydraulic interventions can be used at certain locations if this is needed.

Fig 42: Individual protection measure

Fig 43: flooded mangrove forest

Fig 44: Coastal structure

Fig 45: No view on the ocean due to the structure separating and disconnecting certain areas.

4.1.3 Architecture scope

The architecture scope addresses two scenarios: the protected area, and the non-protected area. Both scenarios consider two lenses, the lens of the daily conditions of life in Grand Bahama, and the extreme conditions under hurricane events; the combination of these two will lead into a design proposal for future developments, protecting the lives of their residents and the longevity of the spatial infrastructure.

The architectural scope on the protected area acknowledges that the ground floors will not suffer from large surges, therefore, we propose to create an active public layer where neighbours and residents of the suggested housing typology can meet, increasing the levels of social cohesion and improving the social network within the island. Social cohesion can be defined as “the extent of connectedness and solidarity among groups in society. It identifies two main dimensions: the sense of belonging of a community and the relationships among members within the community itself.” (Manca, 2014). This will improve the community reaction on extreme scenarios, as communication and response could be faster. On the other hand, the non-protected area has a similar layout but a different approach on its ground floor. The lower level should remain empty from valuable spaces, and water storage tanks could occupy this space. Therefore, the architectural scope was founded to protect the vital housing infrastructure and lives of its residents. Therefore, the design ideas will try to provide the right spatial conditions to achieve so. Besides this, architecture will respond to daily and extreme conditions, where the protection of the spatial infrastructure should interfere with the right functioning and unfolding of activities on the daily basis for the inhabitants.

We acknowledge that architecture itself cannot provide the ultimate solution for a problem of such magnitude as the hazards caused by hurricanes. Nonetheless, the interdisciplinary approach of this project shows how the agency of architecture, as the smallest scale of intervention, can provide the right spatial conditions for people to live their lives in a suitable space, to properly develop their daily activities, and be safe from the hurricane hazards.

4.1.4 Water management scope

The discipline of water management is to reduce the risk of pluvial flooding and other water related hazards while offering maximum additional benefit through the rest of the year. Water management is a solution-focused study. Flood protection solutions can be categorized as individual and collective protection. The differentiation of individual and collective is based on the risk equation which is optimized with respect to population density.

Individual protection describes a personal and separate flood protection structure for every building, object or local activity. This case-by-case approach can be more cost- effective, despite very high costs per individual. Furthermore, the surrounding area stays as vulnerable as it was before the implementation of the protection. In some cases, individual protection can increase the exposure of the surrounding area and can have a negative influence on the emergency response.

Collective protection is seen more favourable for the more densely populated areas, due to the lower cost and the broader benefits of protecting collectively. Collective protection protects an area against flooding and is not focused on a single structure. This protected area doesn't pertain only to buildings, but also to critical infrastructure, economic structures and ecological significant areas.

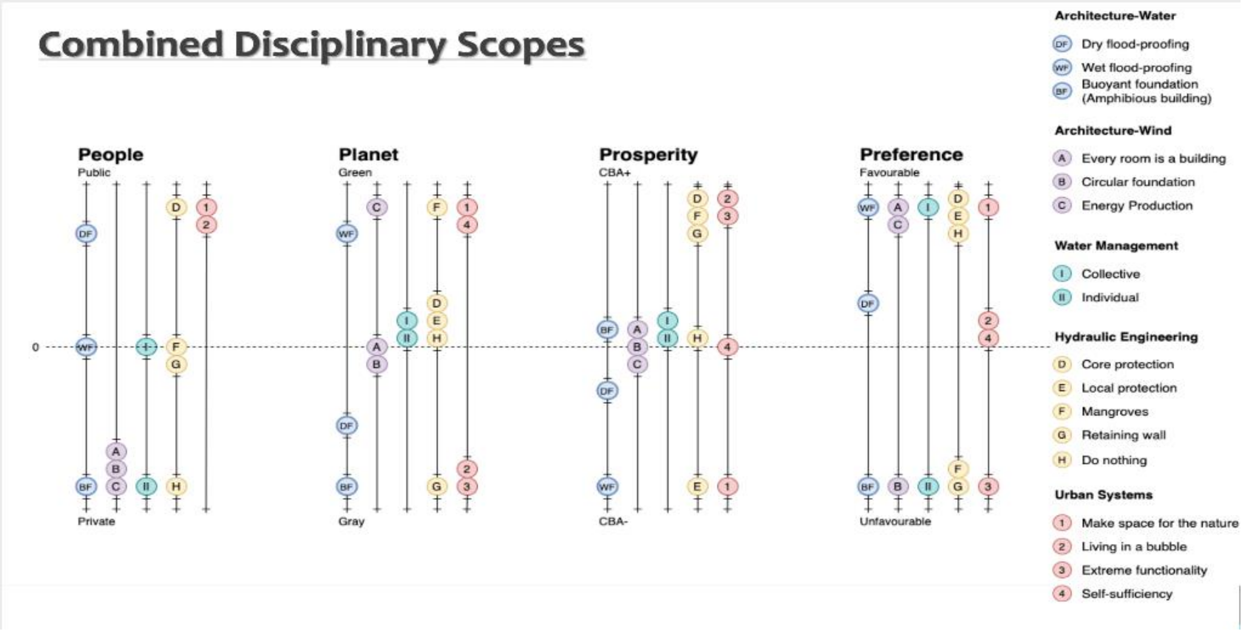


Fig 46: Diagram of Combined disciplinary scopes

4.2 A comprehensive protection strategy

From the interdisciplinary perspective the overall strategy for Building Back Better of Grand Bahama should aim at balancing out risks and opportunities. There is the need to enhance social and economic structures that are less vulnerable to the hurricane's hazards. At the same time the quality of living on the island is about the natural areas and spaciousness. Due to the surge from the north during a hurricane, large parts of the island and its society will be impacted. To increase resilience, the main proposition of the interdisciplinary strategy is to collectively protect the most densely populated part of the island. This core with critical infrastructure will serve as safe ground for the rest of the island, where individual protection measures and improvement of evacuation must reduce vulnerability.

The two distinct flood protection methods, collective protection and individual protection, are applied both, to deal with the fact that the flood risk is not equally distributed over the island. The vulnerability of the island is a function of involved economic losses which is closely linked to population density. Taking these aspects into account the resulting macro areas have been determined. The individual protection area and the naturally elevated, industrial and densely populated collective protection area of the city of Freeport are visible in Fig 47, shown with the black colour.

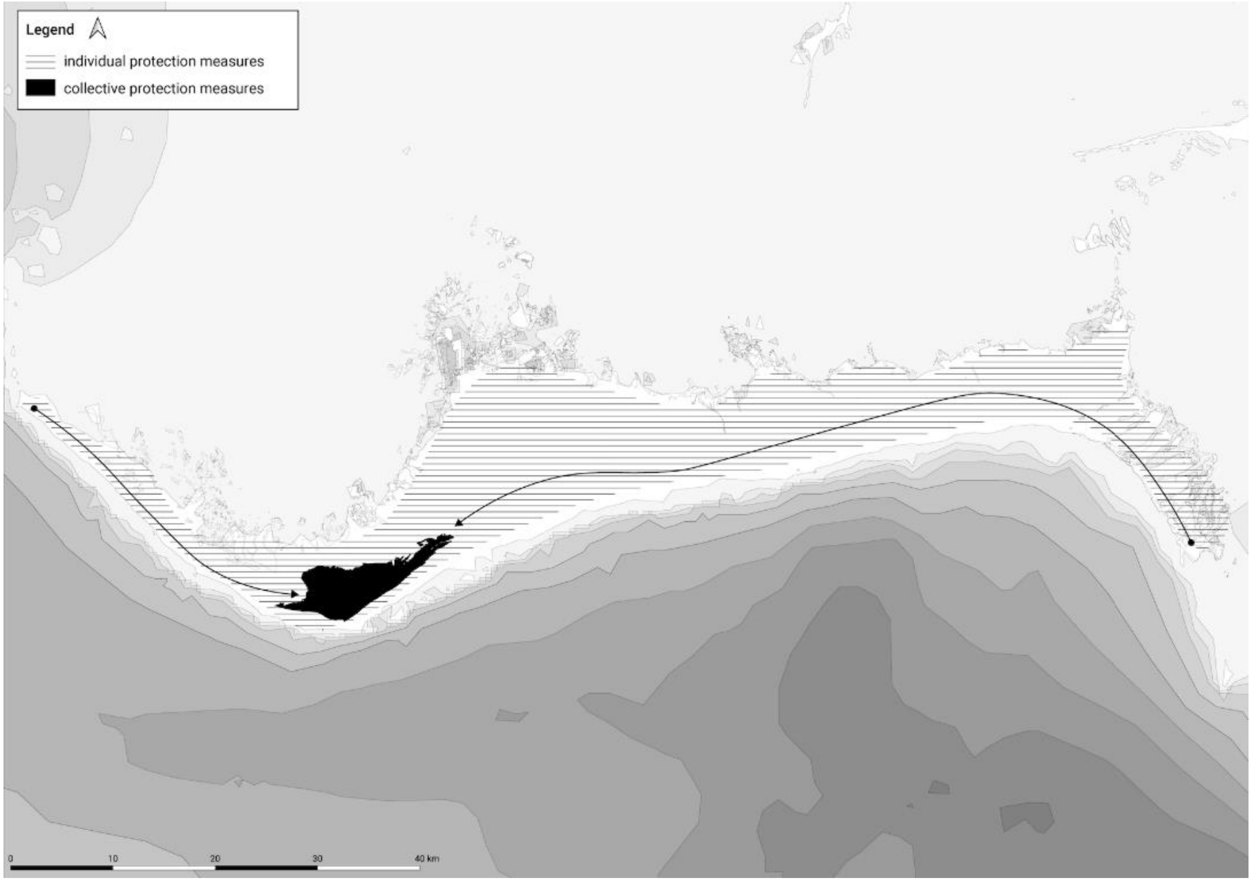


Fig 47: Location of the two macro areas of intervention; individual protection area and collective protection area. With black arrows the connection between the area and evacuation routes are depicted.

Collective protection protects an area against flooding and is not focused on a single structure. This protected area doesn't pertain only to buildings, but also to critical infrastructure, economic structures, and ecological significant areas. Collective protection tends to have a bigger impact on the surrounding areas. If the cost of this implementation is divided by the protected population it can be less costly than individual protection.

Collective protection is not suitable for all situations and landscapes. If the number of individuals in an area is sparse, collective protection can be too high of an investment. This is the same if the landscape is not suitable for a collective protection, the cost will be higher than that of individual protection
Individual protection describes a personal and separate flood protection structure for every building, object or local activity. This case-by-case approach can be more cost- effective, despite very high costs per individual. Furthermore, the surrounding area stays as vulnerable as it was before the implementation of the protection. In some cases, individual protection can increase the exposure of the surrounding area and can have a negative influence on the emergency response.

4.3 Collective protection

To protect the densely populated area, Freeport, a system is designed that protects this area against flood hazards. This system consists of dikes, that protects this area for a storm surge, and interventions that manage the flow of water that still enters the protected area. This water is mainly due to excessive rainfall, waves overtopping the dikes, and piping of the dike. These hydraulic loads will be explained in chapter 4.3.1. The system is visualized in Fig 48.

A smart way to design a protective solution is by using the topographic features, the natural scale, of the island to the advantage. If the storm surge level of Dorian is used as a starting point, it becomes visible that during flooding of Freeport the high parts are not flooded, which resulted in a series of "natural islands". If the islands would be connected by dikes to form a large "ring", they would prevent direct coastal flooding of the relatively lower hinterland area as long as the water level of the surge is lower than the height of the "ring" protection.

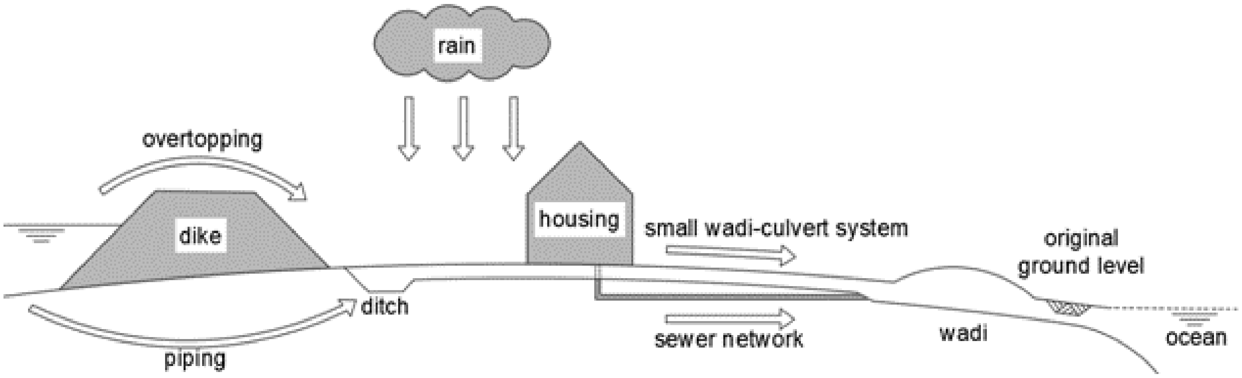


Fig 48: Flood forcing and interventions in the collective protected area. Explanation on the definitions can be found in chapter 4.3

Freeport is chosen to become protected with a collective protection system. Freeport is a densely populated area that lies on top of a ridge; this central site hosts the majority of economic and social functions, and public facilities in general. Hence the area can sustain significant economic damage during a hurricane. Protecting the residents of this area and their surrounding by a collective protection system ensures safe and stable living in the area.

4.3.1 Natural scale; Coastal flood protection

As the main collective protection for Freeport, a "ring" was designed as an assembly of natural heights and dikes. The goal of these dikes is to protect the core of the city from flooding and salt intrusion due to a storm surge from a Dorian-like hurricane and smaller storms. However, the precipitation can still cause flooding, since the water cannot leave the area due to these dikes, other interventions are focussing on this rain/pluvial hazard. It is important to notice that excessive precipitation will fall independent of the wind direction. Dorian-like storm surge only can happen if the position of the hurricane is such that it will result in extreme winds towards the south for a longer period, as derived in chapter 3.1.3.

Fig 49: Levees with their corresponding number and the 20 feet contours, surrounding the proposed collective protected area of Freeport which is divided in the industrial and urban area.

With a height of 20 ft applied for the levees, storm surge water can no longer enter the inner-city area and eastern area if a Dorian storm surge occurs. The assessment of the necessity of 20ft can be found in the chapter “Flood hazard with levees”. Increasing the height of the dike will reduce the overtopping but will increase the construction cost and the effects on society, as seen in Fig 45. The height of the dike is not only a hydraulic adjustment but also an urban planning and water management.

Levee/dike positioning

If the proposed levees fit into the natural landscape construction can be more cost effective. Following the natural topographic features of the landscape will result in less construction material. The social impact of positioning of levee structures shouldn’t be neglected. A dike must preferably be placed in such a way that the toe of the structure does not interfere with existing buildings. By raising the wide non-critical roads, the interference between this new dike and the currently built environment is minimized.

Local topography and the built environment are used to minimize the impacts of the levees while protecting the important buildings in Freeport. See Fig 49 for the recommended locations of the dikes. Due to the difference in ground surface level the height of the dikes is different if they are made up to 20 feet of elevation. An overview of the lengths of these dikes are added in appendix 9.2. The coming paragraphs elaborate further on the positioning of the levees.

Levee 1

The elevation around the Ruby Golf course is above the needed 20 feet. This created a natural barrier on the west side of Freeport. This protection is not watertight, so small levees need to be placed in the natural barrier to prevent leaks. These are the levee location 1a and 1b. On the placement of levee 1a is a road, so the levee needs to be constructed in a way that will protect the area from flooding from the north but still make it possible to cross in the day-to-day situation. An example of such a combination of a levee

Fig 50: visualisation of a road crossing a levee and the small visual impact it can have

with a road can be seen in Fig 50. The levee 1c connects the elevation around the Ruby Golf course with the elevation south of the airport. This levee goes through an industrial area. This levee protects the “central area”.

If levee 4 is placed, the outer slope of levee 1 can be steeper, since levee 4 breaks the incoming waves. This will reduce width and thereby the impact of the levee on its surroundings. This concept will be explained in more detail in this chapter below under “flood hazard with levees”.

Levee 2

Levee 2 follows the natural dry islands which are formed by the elevation of the island. The levees 2a, 2b and 2c connect the natural island on the north side of the freeport protecting it from the northern storm surge. Levee 2d goes further to the north, this to include necessary functions during and after a hurricane. Building levee 2d more to the south would reduce the construction cost but would put outside the protection zone important structures like; Settlers Way Grand Bahama Fire Station, Jack Hayward Junior School, St. John's Jubilee Cathedral and Bahamas Telecommunications Company with its towers.

For this study it's assumed that these structures are not moved and the levee will go around them. The placement of the levee in this way will also protect the Rand nature centre. In this nature centre the ecological unique pine forest grows, which exclusively grows in the Bahamas and needs fresh ground water to survive. Consequently, making the placement of this levee have an ecological significant value.

Levee 3

Levee 3 finishes the protection “ring” in combination with levee 1 and 2. Levee 3a directly connects to levee 2 and goes through residential areas to the elevation in the south. It follows a low-density path in the area and includes Jack Hayward Senior High in the protected area.
Levee 3b completes the natural barrier on the east side of Freeport, just like 1a and 1b did in the west.

Levee 4

Around the Queens highway there is significant industrial activity. If a surge occurs in this area, economic damage will be substantial. To reduce damage a levee can be built on the proposed location of levee 4. The elevation of industrial areas is minimal compared to the natural seawater level. Levee 4 mitigates flooding from the surge, but wouldn’t be able to prevent overtopping of water over the levees. This phenomenon will be explained later under thechapter overtopping. Therefore levee 1 will still be needed even if levee 4 is created, to ensure that no water flows into the central area. Though levee 4 doesn’t prevent flooding in a Dorian-like storm surge, it will significantly reduce the frequency of flooding and corresponding rebuilding. The placement of levee 4 also secures growth of industrial possibilities on the island.

Levee 5

Levee 5 is similar to levee 2. Levee 5 is focused on protecting the growing residential area in the east. It also will help connect the protected area of Freeport with the unprotected area in the east, ensuring a safe route for after and possibly just before a hurricane to and from the east. This levee will not be the focus in this study, but will be recommended as an option for expansion of the proposal.

Flood hazard with levees

Overtopping

As mentioned in the wave analysis in chapter 3.1.3 , during the hurricane large waves will propagate towards the shore. If they propagate towards the “natural islands'' the water depth becomes very small. As a consequence, the waves will break and the water will not go over these “islands”.

This is in contrast to the dikes. Here the water depth (h) on the seaside of the dike can become very large. As a result, the wave height, and thus the significant wave height (H_s), are also larger. As visible on Fig 51, The wave will propagate towards and over the side of the dike towards the top, the run-up. If the waves are large enough, they will go over the dike, which is called overtopping (Schiereck & Verhagen, 2019).

There are multiple empirical formulations that describe the overtopping. The situation of a dike next to the sea seems to be the most appropriate, which was included in the Dutch guidelines of 1989 (Popescu, 1997). In the case of Dorian, the storm surge is up to the dike and the flooded land is represented by the sea. The important parameters to determine the amount of overtopping are independent of the location and can thereby be applied in this case. The parameters are illustrated on Fig 52.

In this empirical formulation the amount of overtopping is related to the significant wave height (H_s), the run-up height (R_c) and the iribarren number (ε), which is explained in chapter 3.1.3. The run-up height is the vertical distance between the water level (z_w) and the top of the dike (z_d). In the empirical formulation some factors are added; friction, the wave angle and an optional horizontal plateau. The optional horizontal plateau is on the seaside of the levee, also called a berm (Popescu, 1997; Schiereck & Verhagen, 2019). The positive effect of the wave approaching under one angle is for this first conceptual design neglected.

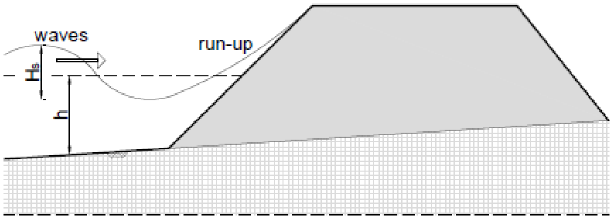


Fig 51: wave run-up

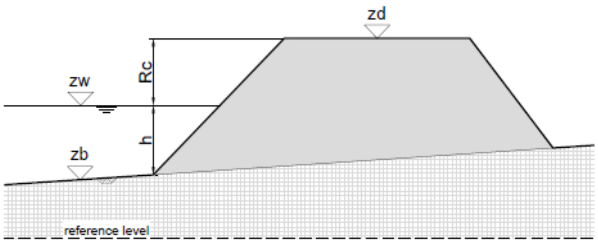


Fig 52: parameters overtop calculation

For all the locations the shallow water condition, as described in the wave analysis chapter 3.1.3 , can be used. This means that significant wave height (H_s) is half the water depth (h). So, with the bed level (z_b), the water level (z_w) and the top of the dike (z_d) known and a chosen outer slope, the overtopping can be calculated. The outer seaside slope of all the levees is set to 1:8. This slope of 1:8 is chosen because the waves generated by the hurricane will break which result in approximately 3 times less overtopping. The inner slope is set to 1:2, a flatter slope will increase the robustness of the dike but will also have more impact on the direct surroundings.

For the calculation 3 scenarios were used, of which the result is visible on Fig 53 and Fig 54:

1. The normal condition, without storm surge and thus no overtopping,
2. The Dorian situation, with a storm surge to the 16 ft contours.
3. “Dorian+” scenario, where the storm surge equals the 20 ft contours of the “natural islands”.

To illustrate the consequences of overtopping; the maximum allowed overtopping is approximately 1 l/s per meter of dike to not damage a normal quality grass slope and buildings at the edge of the dike. For a safe passage over or along the dike for pedestrians the overtopping should not exceed 0.1 l/s per meter of dike and for cars this only 0.01 l/s per meter of dike. (Schiereck & Verhagen, 2019).

In figure 53 it is visible that for the Dorian situation dike 1, 2 and 3 with height of 20 ft results in almost no overtopping, which is 0.5 l/s per meter of dike. Increasing the height of the dike further will barely result in less overtopping. While for dike 4, as seen in Fig 54, there is still a significant discharge of 12 l/s per meter of dike increasing the dike to 27 ft will be needed to decrease overtopping to 0.7 l/s per meter of dike. The advantage of the location of this dike is that, at most locations, it can reach this large height without interfering with the population. However, the cost of these dikes is significantly increased compared to the other levees.

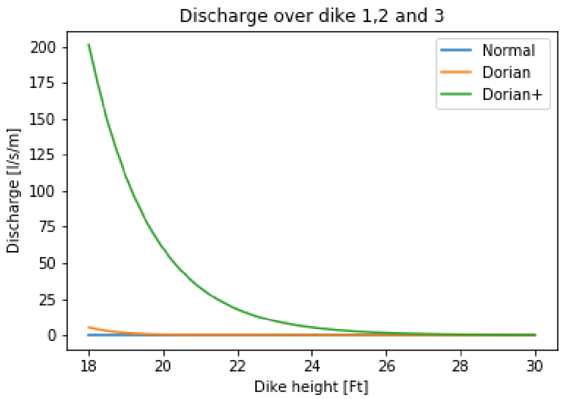


Fig 53: Illustrated overtopping at dike 1, 2 and 3 at different storm surges height

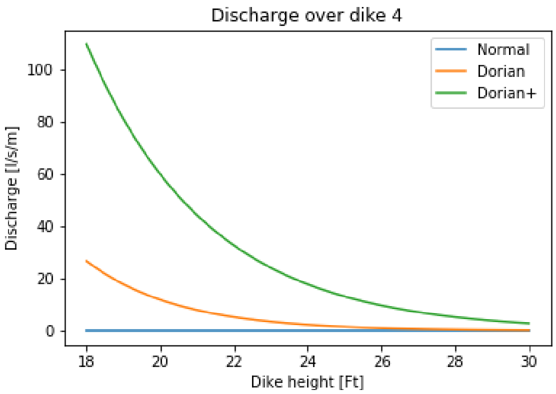


Fig 54: Illustrated overtopping at dike 4 at different storm surges height

Based on the above numbers, it can be concluded that the maximum allowable amount of overtopping is stricter for preventing flooding of the area and the corresponding salt intrusion than that for the stability of the dike during a Dorian storm surge event, if the dike is in a good condition.

There is always a chance that a bigger hurricane comes by. This bigger hurricane can, under unfavourable conditions, have a storm surge that is larger than that of Dorian. To analyse the effects of such a condition a storm surge of a 20 ft contour is used, Dorian+. In Fig 53 and 54 it is clearly visible that a storm surge up to 20 ft will result in a relatively large increase in overtopping or needed height of dikes to prevent flooding. From this it can be concluded that a trade-off must be made between reducing the chances of flooding and for example the impact on daily life and costs.

Levels of safety and failure

The impact of a storm surge is larger for dike 4, and thus the industrial area as seen in Fig 49. To give this area the same level of protection a higher dike would be required. A choice can be made to give this area a lower level of safety compared to the other areas that are illustrated in Fig 49. Which means that the industrial area is protected with the same dike height as the other areas. Making this area be protected for hurricanes with a high frequency and a lower surge, but not a low frequent Dorian-like scenario. This will decrease the frequency of damage and the corresponding recovery inside this area.

Trying to prevent flooding in the industrial area for a Dorian-like scenario is not as achievable as in the other areas. To have the same safety level in the industrial area dike 4 needs to be 23 ft high to elevate it to a level of 27 ft. This is technically simple to accomplish but has a high cost and it will have a big impact on the society. The other dikes only require a height increase of 8 ft to protect against storm surges comparable to Dorian. For this project the possibility of a lower safety level in the industrial area is used.

A lower level of safety for the industrial area means that dike 4 will reduce the frequency of flooding and corresponding recovery. The visible intervention will also give the residents a sense of security. It will also give time to evacuate the area in the case of a Dorian-like scenario. In the case a major Dorian-like storm surge occurs, the dike 4 will not be able to prevent the industrial area from getting flooded. It should be mentioned that overtopping can cause a lot of damage to the levee, which should be repaired after the hurricane.

Dikes can support each other's safety level. If dikes 1, 2 and 3 are at a height of 20 ft. The overtopping in a Dorian situation would be respectively 1 m^3/s, 1 m^3/s and 0.75 m^3/s. However, if dike 4 is placed, there is no overtopping over dike 1, since dike 4 still works as a wave breaker in case the industrial area gets flooded. Dike 5, would even keep the hinterland dry, so there is no overtopping at dike 3. Even without dike 5, if the direction of the waves is considered, the overtopping on dike 3 would reduce significantly. Therefore, about 1 m^3/s of water will enter the inner city due to a Dorian-like storm surge if a dike height up to 20 ft is applied.

This design, if dike 5 is included, has some aspects that improve the acceptance of the plan by the local residents. So is the majority of the buildings protected by the dikes. Which means that barely any buildings fall outside the protected area of Freeport. As a result, there are no groups of residents who are excluded and feel left out, increasing social cohesion. Another important aspect is that the levees have the same height. For example, if dike 2 is lower than the other dikes, the people can think that they purposely got a lower level of safety and could possibly blame the lower dike height in case of flooding.

Piping

A higher water level on the outside of the dike will result in a horizontal pressure difference which drives a flow, seepage, through the soil. The amount of water that is going through the soil and underneath the dike depends on the permeability of the soil. The permeability of the limestone is highly variable on Grand Bahama and potentially very permeable. This makes it hard to determine the amount of water that enters the protected area and assess the hazard due to piping. As mentioned earlier, between 15 to 20 ft above mean sea level there is most likely a low permeable layer, which reduces the seepage underneath the dike. The flow of water can also lead to erosion and thereby undermine the structure. To prevent erosion a protection must be placed at the inner toe of the dike, as seen in Fig 55. This can consist of a granular filter or a geotextile (Schiereck & Verhagen, 2019).

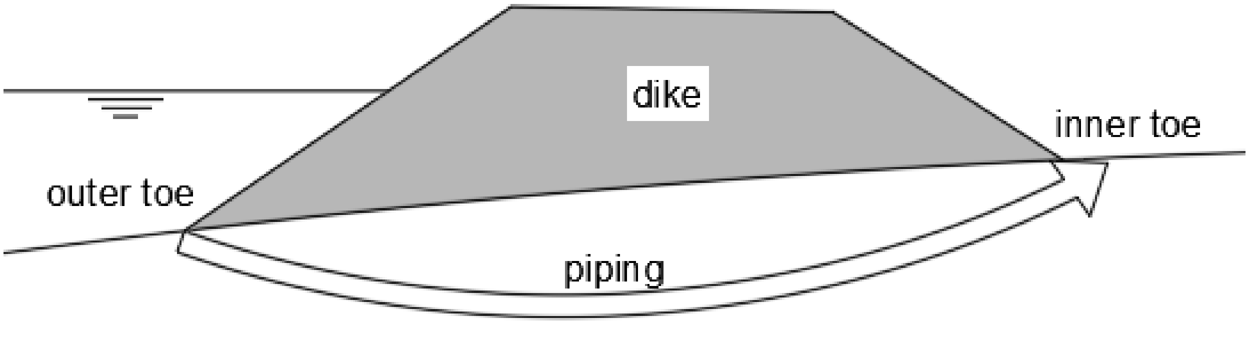


Fig 55: Visualisation of piping, water that is going through the soil and underneath the dike

4.3.2 The natural and urban scale: Pluvial flood protection

Not only the seawater is a hazard during a hurricane, but rainfall can cause flooding as well, pluvial flooding. Pluvial flooding occurs when an extremely heavy downpour of rain saturates drainage systems and the excess water cannot be absorbed creating a flood on the ground level.

Need for pluvial drainage system

When levees are placed in the landscape, they do not only prevent water from entering the protected land, but they also prevent water from leaving the system. During a hazardous event the area will fill up with stormwater, due to excessive rainwater, similar to filling up a bathtub with a plug. A model simulation has been made to illustrate this filling of the area with a constant downpour. In Fig 56 the areas of accumulating water are illustrated. These regions are equivalent to the areas where the bathtub effect is occurring. As can be seen in Fig 57, there is minimal flow velocity in the area, which is related to the small height difference in the area. If only the dikes would be installed without future intervention water wouldn't be able to leave the area and would cause flooding in the protected area.

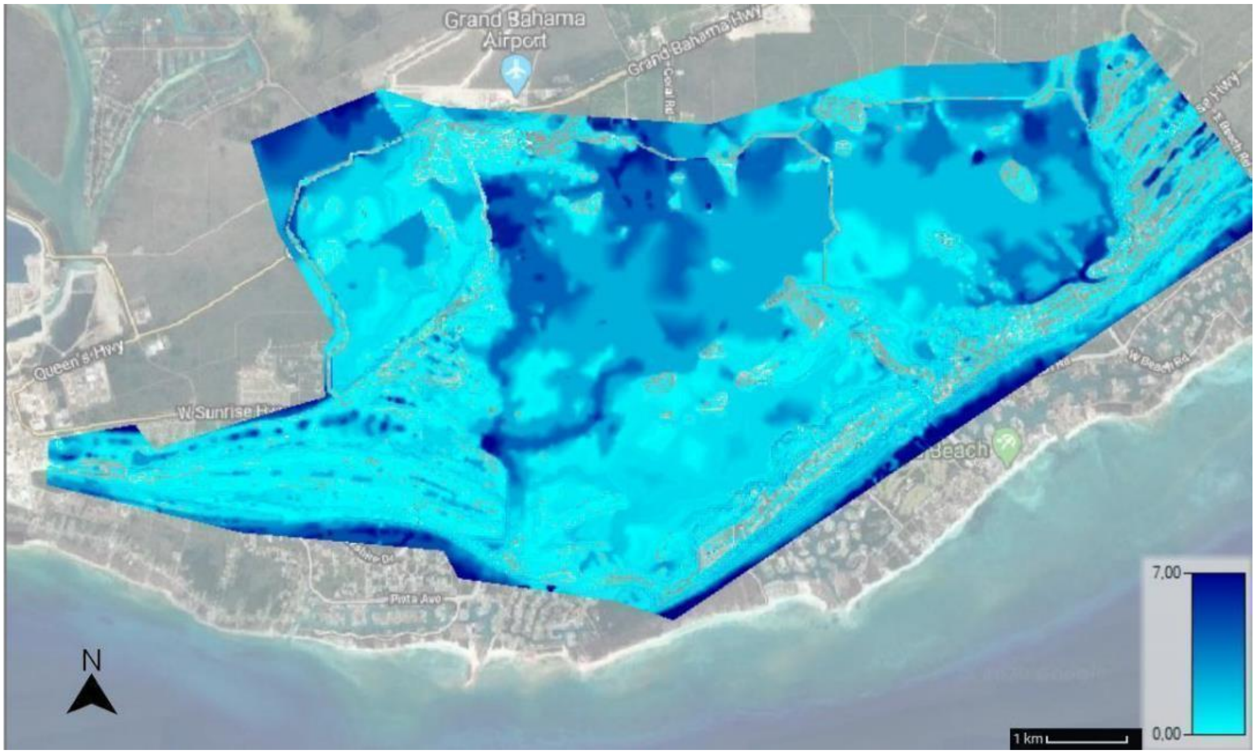


Fig 56: Maximum depth (feet) Calculation of pluvial flooding in a Dorian event with levees. Made with Hec-RAS. background(www.google.nl/maps) There are flow errors on the boundary.

To cope with the hazards originating from placing the levees a multiple facet combined solution is proposed. In this design a balance has been made between the disposal of water and storing of water. This design is starting with a stormwater drainage system. The drainage system majorly consists of a characteristic discharge capacity, which will determine the corresponding storage capacity. The proposed solution is expected to offer sufficient discharge capacity for a dorian-like senario. With respect to pluvial flooding this involves the design of storage facilities and a stormwater sewage network that are together capable of carrying discharge that occur during the peak intensity of a hurricane event like Dorian.

In Fig 56 and Fig 57 the rainfall of Dorian is used which intensity is comparable to a return period of 15 years. Rain is assumed to fall homogeneously in the catchment at an average rate of 19 mm/h over 48 hours. This study focuses on Dorian peak intensities which will be further used as a Design scenario.

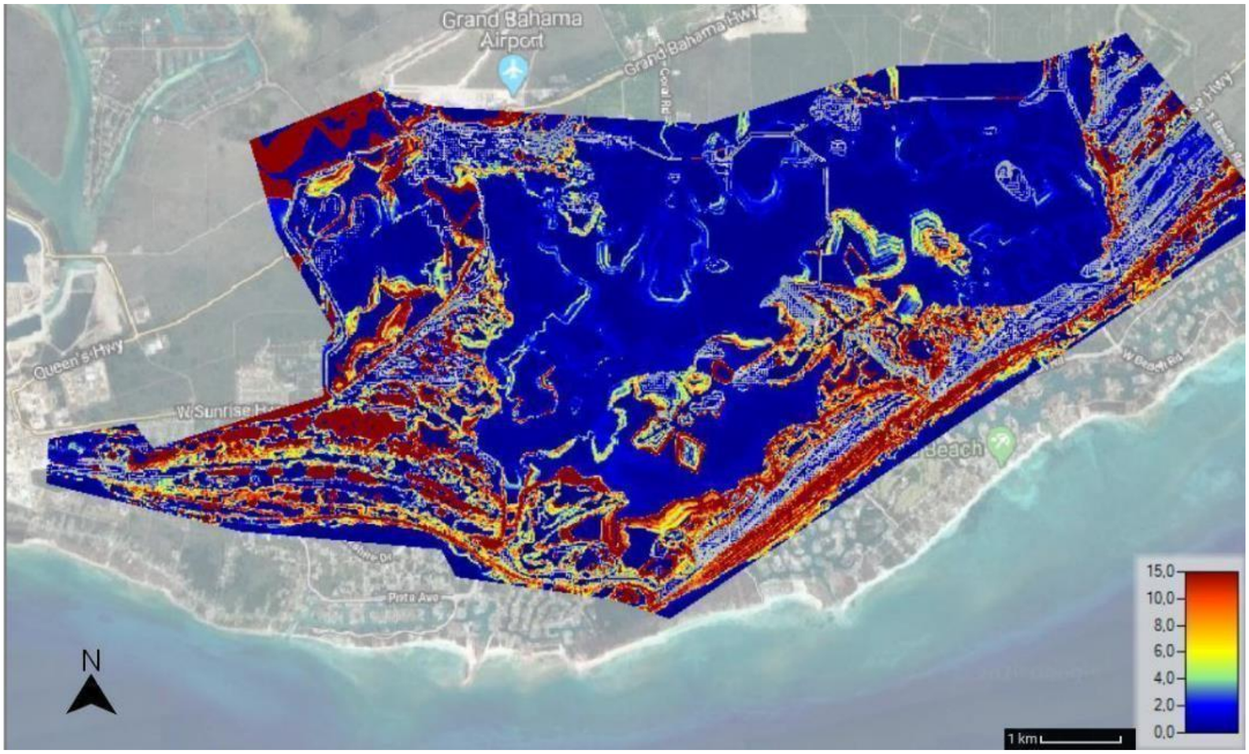


Fig 57: Maximum velocity (feet/sec) calculation of pluvial flooding in a Dorian event with levees. Made with Hec-RAS. background(www.google.nl/maps) There are flow errors on the boundary.

Main drainage system

In order to avoid pluvial flooding in the area enclosed by dikes and high grounds a stormwater drainage system is to be implemented in the city of Freeport. This system is composed of a closed underground conduit-system, stormwater drains, and open drainage canals. In this section the design discharge capacity is determined. Consequently, the resulting storage requirements are determined as well. This does not just involve pluvial flooding but the overall water stresses that the collective protected area is experiencing. Since the system is supposed to serve more functions than just draining the area, storage solutions have to be implemented in such a way that residential areas have sufficient water access during the aftermath of a hurricane. This will be explored in chapter “Multi-functionality of the presented measures”.

The stormwater drainage network serves to drain the inner city of Freeport. As rainfall amounts such as for Dorian are occurring the incoming water exceeds the storage capacity of the network. Consequently, not all the runoff water can enter the network. This includes the water stress caused by storm surges, which is primarily occurring at the levees and thus in the north of Freeport. Hence more water is accumulating in the north than in the south. Hence it has been decided to drain the network towards the south.

Fig 58: Elevation(feet) north of the Rum Cay village, starting location of the wadi, source background (www.google.nl/maps)

During a storm event the southern sea water level stays stable or decreases. This is because the southern sea doesn't suffer from surges during a storm, as explained in 2.1.3. Because the southern sea's water level is stable and lower than the island it offers the possibility to drain the system to the south in hurricane situations.

This allows a special combination of a regular system of underground stormwater sewers and an open canal that drains the collected stormwater of this system to the coastline by gravity. Such an open canal is also called a wadi. This system will carry water only in times of extreme rainfall and storm surge. A dry river was found during the simulation, depicted in Fig 56. This natural dry river is situated in the south of Freeport, with the lowest point near the village Bahamia and Freeport Resort and Club, just north of Rum Cay Villas as seen in Fig 58. This dry river and the fact that there is no sea level rise in the south make it possible to drain the area of the excess water towards the south.

The wadi has to cut through the high ridge at the south in order to be able to drain to the south coast, as can be seen from the elevation map. If a riverbed is dug out of the high ridge the stormwater surplus from the levee-protected area can be drained by gravity only, without the need for pumps.

Wadi

In the decision making it was of highest importance to keep the maintenance costs as low as possible even if it meant a high initial cost. This is accomplished by aiming for gravity induced flow where no pumps are required. In order to reach this goal, it has been decided to construct a wadi. A wadi is a water channel that does not carry water for most parts of the year. During a storm event the wadi fills up with water and carries it to a designated outlet.

As can be seen in Fig 56 it has been decided to make use of the indentations of the southern dunes to construct a wadi towards the south of the city. Excavation will be required in order to offer sufficient channel gradients so gravitational runoff can be accomplished.

The requirements for the design of the wadi are to keep interventions minimal and costs low. Impacts that also have to be considered during the design phase are: protecting of the freshwater resources and impact on social cohesion.

The starting location of the wadi is set to start in the North-east of the Rum Cay Village, on the place where the road splits, from now called the wadi-start-location (wsl) of Rum Cay. The elevation map shows that wsl of Rum Cay is the lowest point found in the southern part of the protected area, with low elevation paths reaching to the south and north-east of the island, as shown in Fig 58. Wsl of Rum Cay itself has an elevation of 3,05m+MSL or 10 ft+MSL and is directly surrounded by a lower elevation of 2,44m+MSL or 8ft+MSL, as seen in Fig 58. This area of 2,44m+MSL or 8ft+MSL is limited in size, but will help with storage as a flood retention zone by providing and helping with a constant drainage of the system; decreasing peak flow with temporary storage.

The outflow of the stormwater sewage system is connected to the wadi by overland flow in a natural dry river bed. The proposed outflow location of the wadi is Xanadu beach channel. This location is approximately 2 km from the wsl of Rum Cay.

Size of the wadi

To design a wadi and determine the amount of space that is required depends on the amount of water that needs to be drained, its cross section and its slope. There is a relation between water depth, flow velocity and channel width. If the water depth increases, the average flow velocity will decrease. And if the flow velocity or the channel width increases, the water depth will reduce. In the following calculation a design discharge of 12,2m^3/s is applied. This is the design discharge from the storm sewerage network, according to Tab 4, plus 1 m^3/s entering from the levees, as stated in chapter 4.3.1 .

In case the flow is steady there is an equilibrium state where the depth of the water and the friction due to the bed are in balance. If the water depth increases the water at the surface is less impacted by the bottom friction. The friction is described using an empirical equation, the Strickler equation. For the surface roughness a Strickler coefficient (k) of 35 is used, which value corresponds with a short grass cover of the wadi bed.

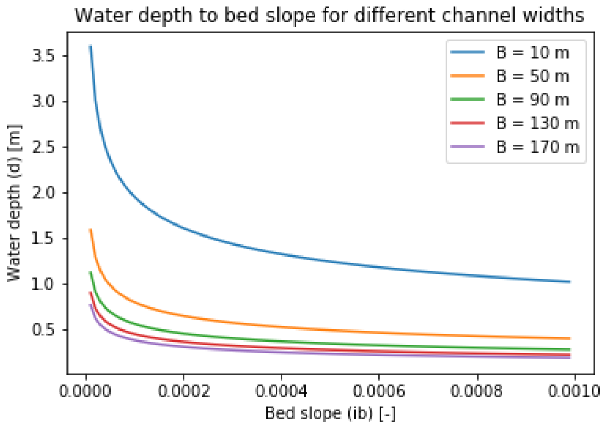


Fig 59: water depth for wadi

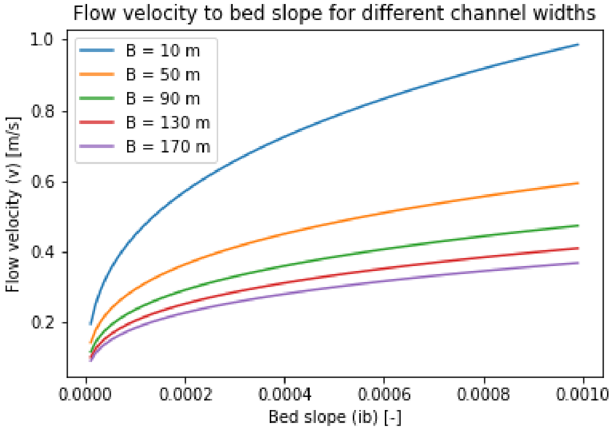


Fig 60: Flow velocity for wadi

It is recommended to have the flow velocity below 1.0 m/s. In this situation a grass field can prevent erosion of the bed. The bed of the wadi needs to be below ground surface level. A slope of 1:2 of the hillsides on both sides of the channel are taken into account, as illustrated in Fig 66.

The results for a combination of different bed slopes and channel widths, are visible on Fig 59 and Fig 60. On these graphs it is visible that increasing the bed slope to more than 0.0002 will have a minimal effect on decreasing the water depth. Increasing this slope will therefore mainly result in unnecessary lowering of the bed of the channel, which will result in a deeper excavation and more alterations on the natural state.

The sensitivity to changes of the bed width of this wadi is visible on Fig 61 and Fig 62. The relation between the flow velocity, discharge and width can be used in the spatial integration of the wadi. This wadi drops 0.45 m (1.5 ft) over 2 km which results in a bed slope of 0.000225. With a bed slope of about 0.0002 the outflow water level at 2 km needs to be below 8.5 ft to fulfil the most effective result. The surface elevation at Xanadu beach channel is approximately at 8 ft, which is below the 8.5 ft needed for the wadi and therefore does not interfere with the proposed solution.

The connection of the sea with the Xanadu beach channel is poorly maintained. Currently this connection is too small to handle the influx of water, making flooding in the area surrounding this channel likely in a hurricane scenario. If this outflow location is used the connection channel should be widened and better maintained. This adjustment also has benefits for the residents. Larger boats could enter the bay increasing the value of the houses.

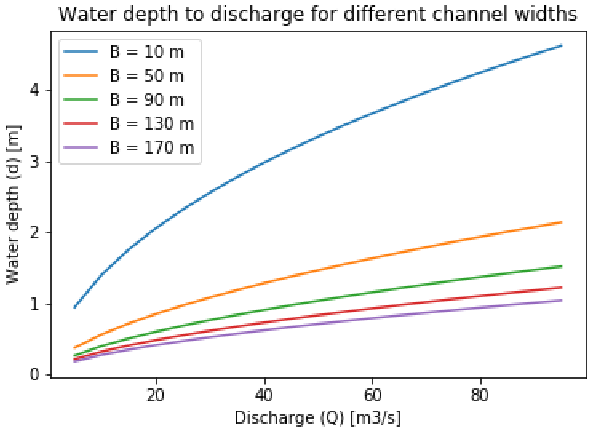


Fig 61 water depth for designed wadi calculated with a bed slope of 0.000225

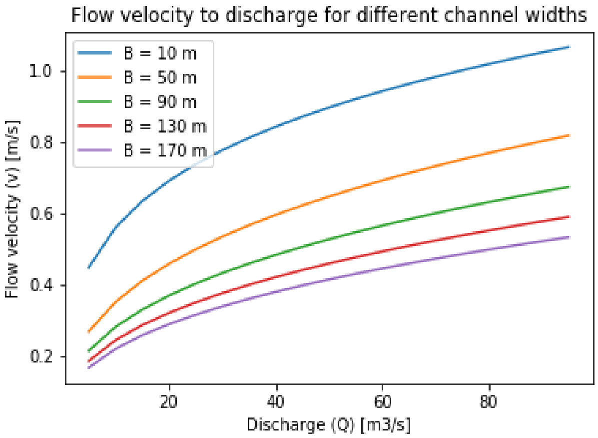


Fig 62 Flow velocity designed wadi calculated with a bed slope of 0.000225

Design of the wadi

Three design alternatives are suggested for the wadi, as shown in Fig. 63. All the designs are based on possibilities in the landscape and the fundamental needs of a wadi. The designs are based on aerial observations.

- Following the road
- Following the natural elevation and width
- Following the road and following elevation.

The first design alternative is to keep the design constructed to the location of a road. This design has less interference with the existing buildings in the area. Though it also has its downsides. If the wadi is constructed only on the location of the road the wadi will be deep, due to the narrow width, creating a barrier. Banks will still have a 1:2 slope, but this will be less integrated in the landscape compared to the other designs. This barrier can have an impact on social cohesion, because it might make difficult to traverse it from one side to the other. This also can make it difficult to enter and exit the road, due to the depth. Entrance and exits need to be created to ensure accessibility. The depth of the design will have consequences for the groundwater table. As stated before, the groundwater freshwater lens is 1 meter below ground surface. If the wadi reaches deeper than the groundwater level, the wadi results in drainage of the island's freshwater resources by lowering the groundwater freshwater lens throughout the year in that area, which is unwanted. This design has the deepest vertical excavation and consequently the biggest groundwater withdrawal.

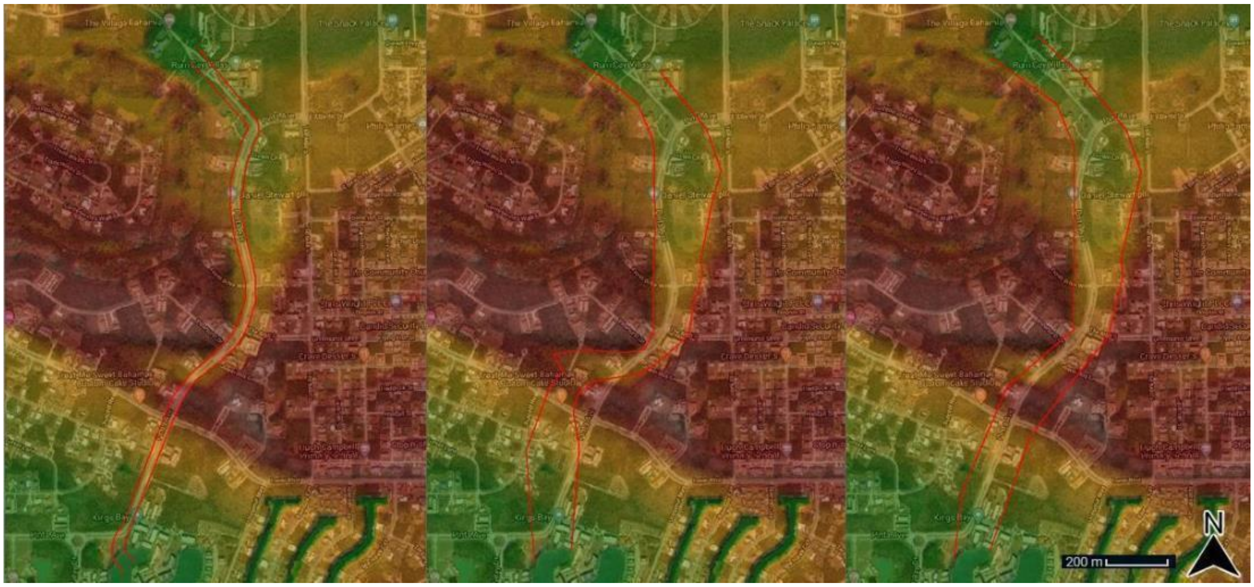


Fig 63: Placement boundaries of the wadi made with the program Hec-RAS: left "Following the road", middle "Following the natural elevation and width", right "Combination of following the road and following elevation".

The second design alternative highlighted the possibility of keeping the natural elevation and the freshwater aquifer. The depth of the wadi shouldn't reach the groundwater freshwater lens, by making the cross section wider than for the first design. Furthermore, if the goal is to keep the natural elevation and water system, the natural state of the island shouldn't be touched. So, this design follows the natural elevation of the island to ensure the impact on the surrounding is minimal. This natural elevation is illustrated by the yellow band between the red boundaries of the wadi on Fig 63. In the south, while the wadi crosses the natural higher elevation, this design makes a bend to follow the natural elevation, as seen in Fig 63. This design does not take into account the human structures in the area.

The third design alternative is a combination of the two designs. Combining the impact reduction on existing buildings and keeping the natural elevation and the extension of the freshwater lens in the area. The design follows the natural elevation in the north, but then follows the road towards the south. This design is wider while following the road than the first design, ensuring the freshwater aquifer stays intact.

Using the three designs and the calculation made in the chapter Size of the wadi, the dimensions of each design can be made.

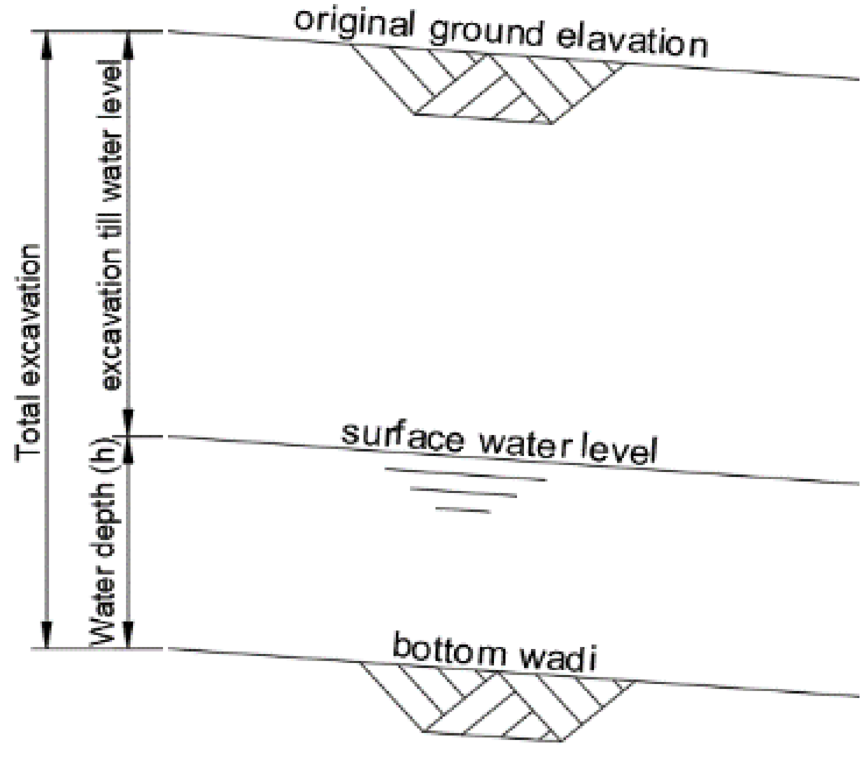


Fig 65: Overview of the excavation to get the suitable elevation for the wadi including the water depth while carrying the anticipated discharge of maximum 12,2m3/s

Design 1: Following the road, the wadi would be constructed as wide as the existing road, making the channel have a width of 12 m, see also Fig 63. Combining this set of parameters in the strickler equation would result in a water depth of 1.42 m. The elevation difference in the northern part between the wadi and the surrounding area of Rum Cay is 0.6m, to which the depth 1.42m needs to be added, resulting in a total vertical excavation of 2.02m. The resulting bottom of the wadi, which equals the level of the road 3.66 m minus 2.02 m = 1.64 m +MSL. The construction shouldn't interfere with the width of 12 m. In order to reach sea level elevation an excavation of 5.10m is required combined with the requested water depth of 1.42m gives a total excavation of 6.52m. This can be difficult to construct, but working with the surrounding and the construction slope possibilities can make this possible. As a consequence of the excavation the groundwater level will decrease. If the bottom level of the wadi is lower than the groundwater level which is expected to be in the magnitude of 1m + MSL this will lower the average ground water table. If the bottom of the channel comes below the ground water level, the groundwater will flow into the wadi and then through this wadi towards the sea. This will lead to lowering of the ground water level, possibly decreasing the fresh groundwater reserves.

Design 2: Following the natural elevation and width will result in a channel width of 100 m, see also Fig 63. Applying the strickler equation again results in an equilibrium water depth of 0.42 m. In the northern part the additional height difference results in 1.5 m of excavation. Infrastructure is able to enter the wadi easily, 1.5 meter can easily be crossed by a bridge, but requires some structures to exit and enter the wadi. The excavation in the southern ridge elevation, in the middle of the wadi, adding the water level (5.10m) and the water depth of 0.42m results in a total excavation of only 5.52 m, but with a width of 100 meter this results in a significant amount of soil that needs to be moved. In Design 2 the wadi will cross multiple houses which need to move or need to be constructed on poles, as depicted in Fig 66. This means that there will be less disturbance to the natural landscape, but this design will force the residents in the area of the wadi to move to another location.

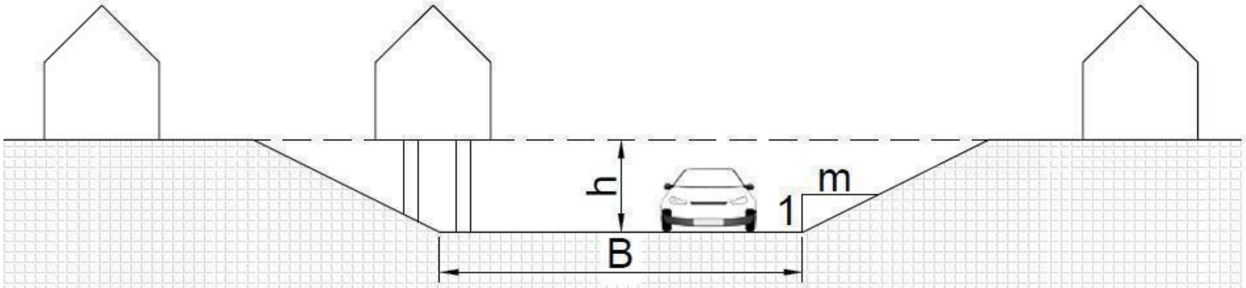


Fig 66: Possible implementation of a wadi in a neighbourhood, with a house on poles.

Design 3: Following the road and following elevation combines the previous designs, see also Fig 63. The minimum channel width is set to 120 m. Taking the explained calculation above the depth of the water to the bottom of the wadi will result in 0.37 m equilibrium water depth. In this alternative the wadi will still cross some houses, which need to move or, need to be constructed on poles. If the natural elevation and width is followed the connection to the Xanadu beach channel will have a significant impact on the building around the beach. So, for this suggestion the south of the wadi is shaped in a way to reduce the impact between the elevation and the beach. This also has the benefit that the wadi becomes wider and decreases in water height. In Design 3: Following the road and following elevation, Combines the strengths of Design 1 and Design 2, but at a price of having to move much more soil for the wider excavation.

Tab. 2: Overview of wadi dimensions including vertical elevation at different locations along the wadi

location	Length from start wadi (m)	Elevation Surface water level wadi (m+MSL)	Original ground elevation before excavation (m+MSL)	Elevation difference between original elevation and surface water level (m)
Rum cay Village	10	3.05	3.66	0.60
Ridge Elevation	1000	2.82	7.62	5.10
Xanadu beach channel	2000	2,44	2,44	0

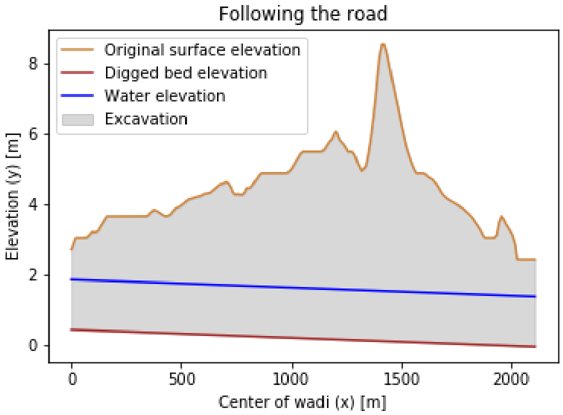


Fig 67: Depth of the wadi following the road

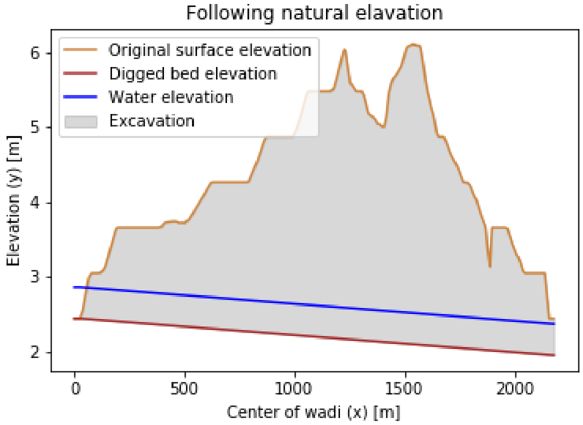


Fig 68: Depth of the wadi Following the natural elevation

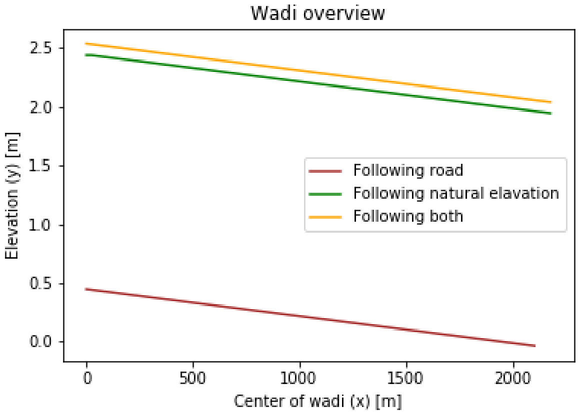


Fig 69: Bed levels of all the wadi designs

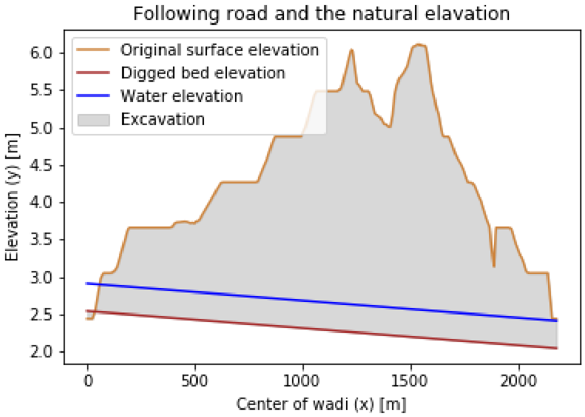


Fig 70: Depth of the wadi Following the road and following elevation

Estimated excavation cost of the wadi

In the Tab 3 is shown how much there would need to be excavated to construct the wadi for each proposed design. Tab 3 is based on the calculation of the difference between the elevation line in the centre of wadi design and the bed slope needed for the wadi design with a 10 cm between calculation points along the wadi.

Following the road will be the cheapest option, if you purely look at the relocation of residence and excavation needed. Stability of the wadi bank and the material needed for that will however be more significant than that of lower banks. Ground water drainage, subsequently lowering of the groundwater level and subsequent loss of fresh groundwater is a hazard of this alternative 1.

Below is a graphical presentation of the estimated earth work of the three designs; Following the road (Fig 67), Following the natural elevation (Fig 68) and width and Following the road and following elevation (Fig 69). Also shown below is an overview of all the wadi bottom combined (Fig 70)

The original surface elevation is based on the elevation of the centre of the design wadi. Because of this Fig 68 and Fig 70 look similar, because they follow a similar path as seen in Fig 63. Though the calculated excavation in Tab 3 is different because of the height difference of the east and west bank of the design wadi.

Recommended is to look at the option given and plan the most efficient and inexpensive option for the location. The combination of “Following the road and following elevation” seems to be preferred. This design protects the freshwater aquifer and tries to minimize the social impact, protecting social cohesion, but at a price of having to move much more soil for the wider excavation.

Tab. 3: Total estimated excavation of the wadi designs

Design wadi	Excavation trace line of wadi to wadi-bottom (m^2)	Width of the wadi (m)	Total excavation (m^3)
Following the road	5735	12	68820
Following the natural elevation and width	4115	100	411500
Following the road and following elevation	3997	120	479640

Storm sewage network

To drain stormwater and incoming surge water from the collective protected urban area to the wadi a piped stormwater drainage system is suggested in this design. Since a major requirement was to drain the network by gravity the first step was to determine the required pipe diameters which lead to satisfying discharges.

Runoff conditions were determined with respect to the amount of impermeable area since detailed data with respect to local runoff coefficients is missing and was therefore based on on-site observations. The assumed impermeable coverage for which a runoff coefficient of c=0.8 is assumed is indicated in Fig 71. For permeable surfaces a runoff coefficient of c=0.1 is assumed. In order to receive the runoff coefficient for each manhole catchment the sealed and unsealed areas got combined to a representative average. This ended up at approximately 0.3 immediate runoff in the entire catchment, which means that it is assumed that 70% of the incoming water is infiltrating and not entering the sewage network. So, the 70% is not considered for the peak runoff calculations. The assumed peak rain intensity of 19 mm/h was applied on the catchment. Additionally, the pipe diameters were estimated by storing 570mm of rain for the Dorian block rain event and leaving the additionally required parameters as for the resulting design condition. This includes that approximately only 30% of the rain is entering the system, while the rest has the potential to seep into the ground.

Fig 71: Impermeable area, areas that can't absorb waters, in the collective protection area

For the location of the stormwater drainage system the current road network is used. The network is positioned underneath roads in order to reduce construction costs. At each junction a manhole gets placed, which functions as a water entrance and as a representation for the required storage in that area. In the catchment each junction got determined by assigning the closest neighbour in a 5m*5m grid that got layered on top of the collective protected area. The resulting network is stated in Fig 72.

Water that is now entering a manhole in freeport will be guided via pipes towards the outlet which is indicated in Fig 72. Since the network is split in four subnetworks there are 4 pipes that are joining at that point. The four pipes merging at the outlet of the network have the design discharges stated in Tab. 4. As can be seen in the table the overall design discharge of the sewage network is 11.2m^3/s. This means that this discharge is the maximum the system is able to carry. The overall water that is now accumulating is resulting from stormwater runoff and from incoming surge water. For Dorian conditions the expected water entering from the levees is 1m^3/s, as stated in chapter 4.3.1. Consequently, for a Dorian scenario 12.2 m^3/s is the resulting overall design discharge capacity from which further storage requirements are determined. Equally distributed on the catchment area of 2925 ha this means 0.004 m^3/s/ha.

Taking into account that pipe diameter normally ranges in the magnitude of 1 to 3 meters in an urban environment led to the decision to limit the diameters to 2 meters and set the wished velocity to 1.5 m/s. The final pipe diameters are stated in the appendix 9.3.2 .

Tab. 4: Discharge of outgoing pipe segments based on rainfall

Pipe segment	Discharge (m^3/s)
62	1
69	1.7
75	3.8
137	4.7
Total	11.2

Design of the Stormwater drainage system

It was assumed that in order to drain the system by gravity a reasonable flow velocity was 1.5 m/s. With the final pipe diameter and the expected velocity, the resulting gradient of the individual pipes was determined.

The resulting peak velocities got determined by calculations according to Manning assuming a surface roughness (n) of 0.0013. The corresponding local hydrostatic pressure levels were calculated using Darcy Weißbach and assuming surface friction (λ) of 0.02 according to the average surface roughness of concrete (k) of 0.5 mm and the desired flow velocity of 1.5 m/s. These two roughness terms are based on the assumption that the pipes are made of concrete of average concrete characteristics. The system parameters were optimized by making use of NOMAD non-linear solver in excel. The overall outcome of pipe network characteristics can be looked up in Appendix 4.3.2 The resulting pipe network is indicated in Fig 72. The network consists of 4 pipe connections which are joining at the inlet of the wadi. After applying the optimization, it was apparent that the resulting pipe level at the outflow location lies 7 meters below mean sea level. Even though the local gradients that are asked to support the required velocities are generally able to be realized. In the Netherlands the corresponding standard is at 5 meters below mean sea level, making this a very deep laying pipe. To reach equal discharges with a lower gradient can be either accomplished by adding a second pipe or by increasing the maximum allowed pipe diameter. Resulting in potentially lower construction and maintenance costs since it requires less digging.

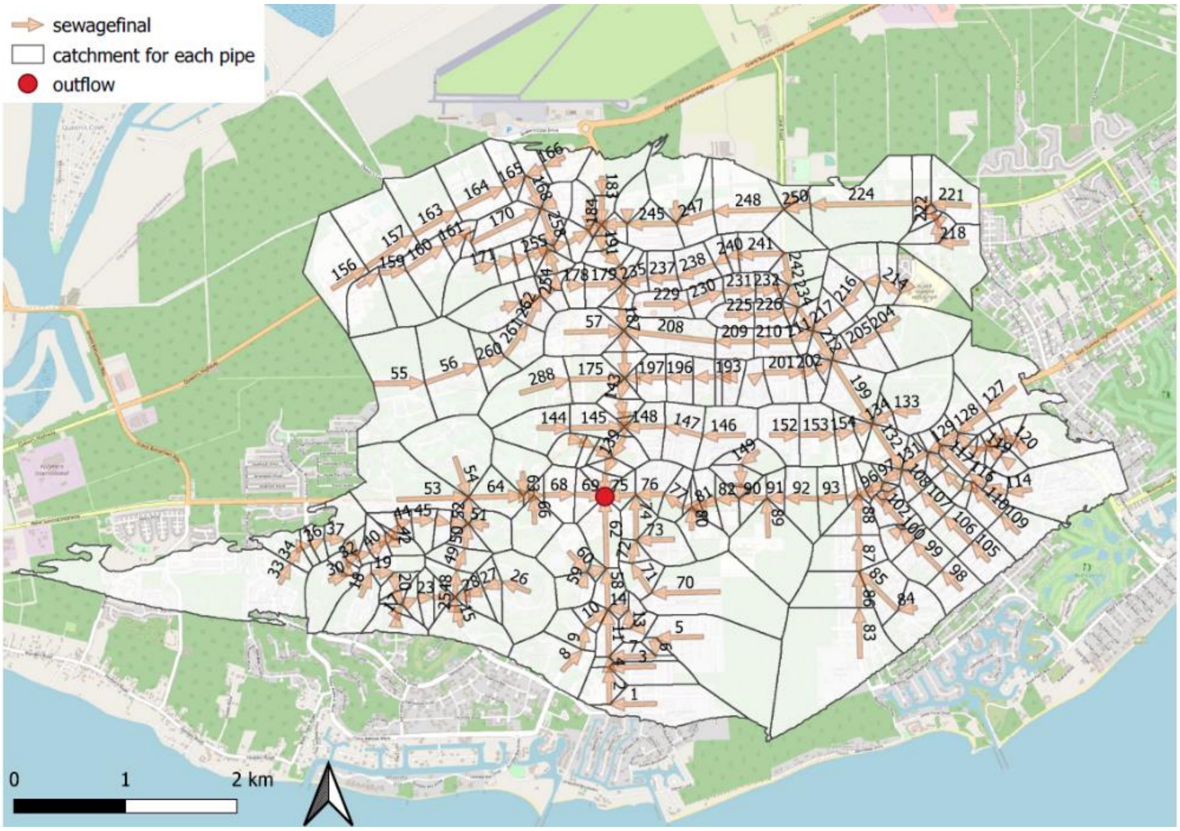


Fig 72: Resulting Sewage network including pipe ID, cumulative flow direction and catchment of each manhole

Connection Sewage network and wadi

In order to prevent the mentioned filling up of the protected area it is important that the presented solutions are functioning well and that the individual discharge capacities are aligning so outgoing water and overall storage capacity can handle the incoming water. As indicated in Fig 72 does the sewage network end up with four pipes with discharge capacities as expressed in Tab. 4. These discharges require a cost-effective construction to guide the water from the outlet of the sewage network towards the Wadi. The simplest way to do so is by constructing one pipe that is leading from the outlet towards the wadi. A pipe was used because it has an expected higher flow velocity than an open channel. At design capacity this could be accomplished with a pipe diameter of 3.1 m. Assuming a maximum length of 400 m towards the wadi results in pressure losses according to Darcy Weißbach of ΔH=0.3 m which does not lead to flooding.

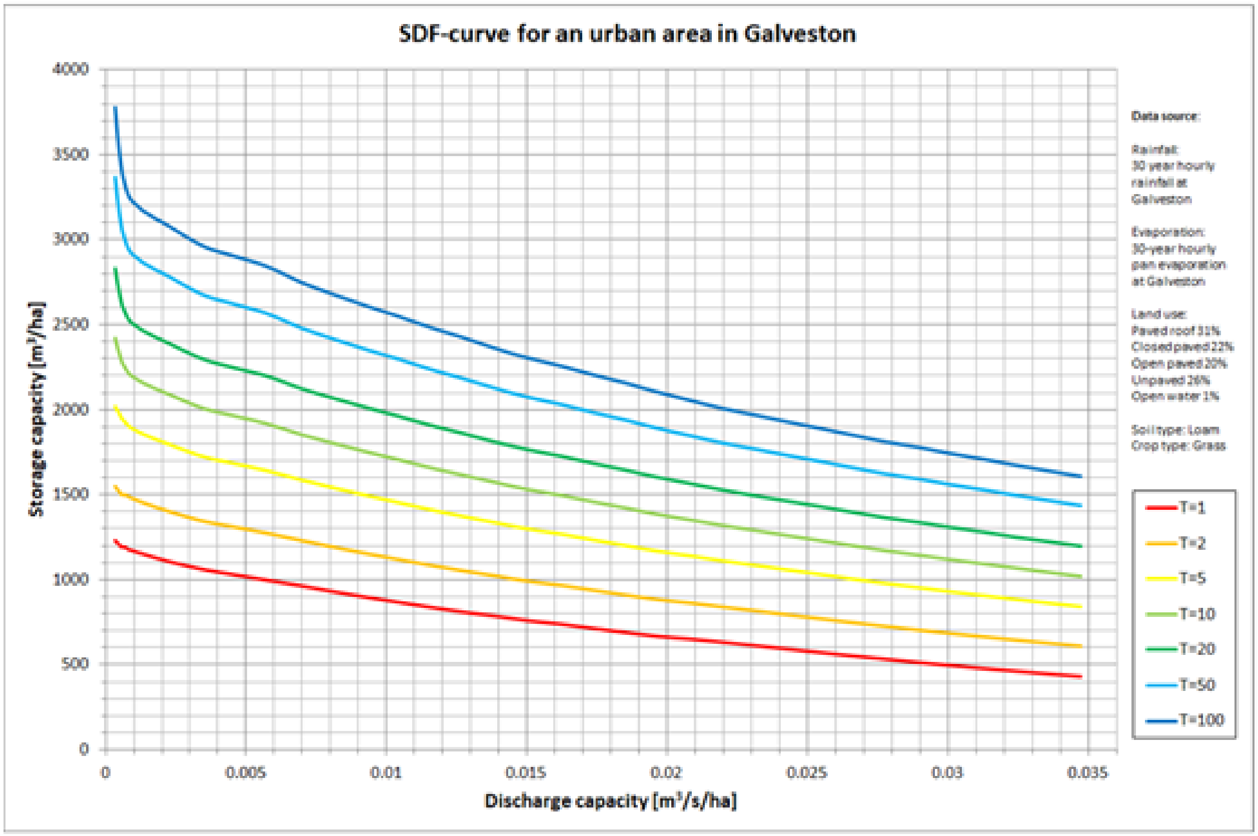


Fig 73: Representation of storage discharge frequency requirements for an urban area in Galveston Texas.

Required detention/storage capacity

After the design condition was set for the system, the storage that is required in the system can be approximated by the outcomes of the Galveston field study due to its climatic and setup related similarities. The overall runoff characteristics in Galveston are indicated in the SDF curve in Fig 73. The SDF curve states the storage capacity to discharge capacity relation for an urban area in Galveston. Extrapolating the given return periods to T=0.5, T=15, T=100 gives an indication for the discharge to storage capacity relation for the taken scenarios. For the designed sewage system not just the resulting discharge at the outlet but in each pipe segment was calculated. Applying the local discharge capacity on the extrapolated SDF relationship states the required storage capacity for each pipe segment in Freeport. The outcomes are stated in Fig 74. For the overall discharge capacity of 0,004 m^3/s/ha the corresponding overall storage capacity for a Dorian scenario is approximately 2150 m^3/ha or 215 mm. Applied on the overall area of 2925 ha the overall required storage is 6,3 10^6 m^3.

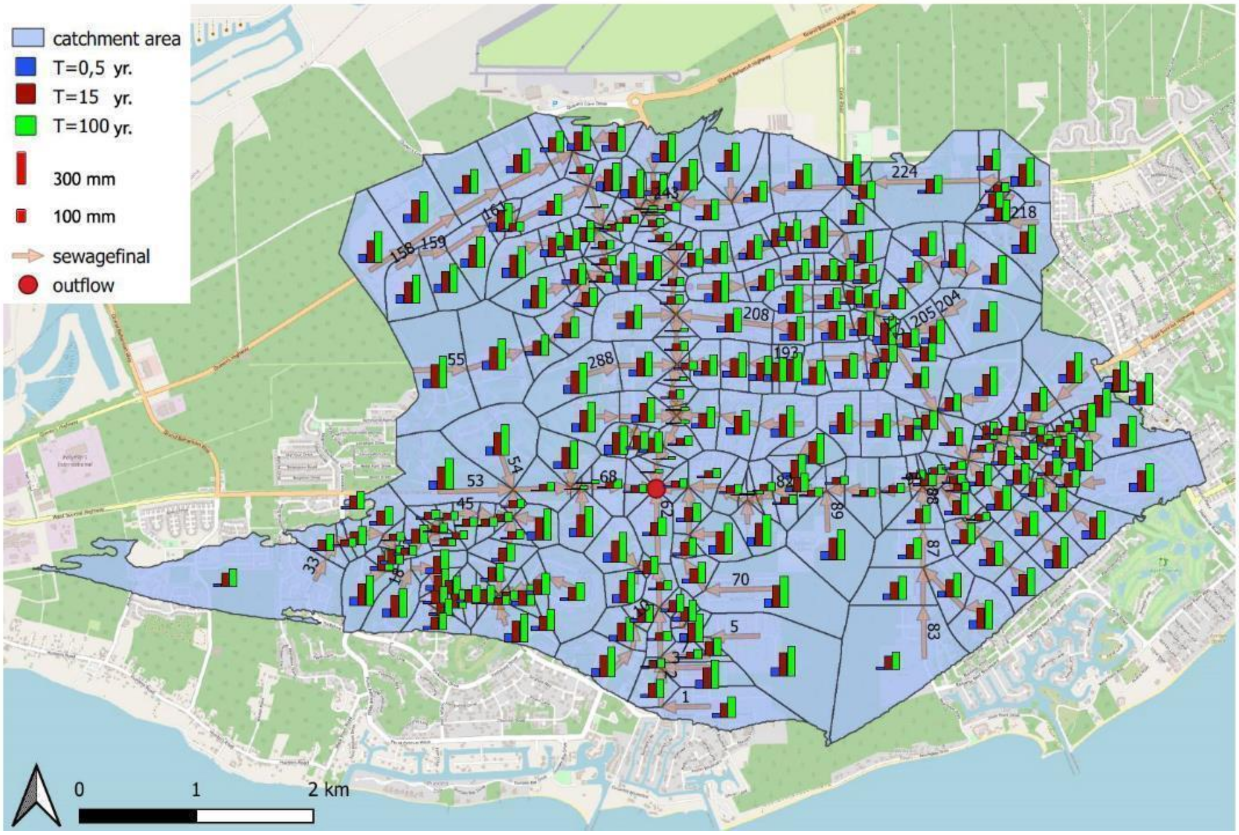


Fig 74: Anticipated required storage in mm (ranging from 50 mm to 350 mm) for three rain scenarios of return period T=0.5 yr, T=15 yr and T=100 yr. The storage was obtained by determining resulting discharge conditions with respect to pipe diameter and local pipe slope. Corresponding storage requirements were transferred from storage requirements in an urban area in Galveston Texas

Local stormwater storage infrastructure

As shown in Fig 66, stormwater retention capacity is to be installed to avoid pluvial flooding. Besides offering water for periods of droughts and therefore offering added value to the daily life its main function is to reduce peak flows and to drain as steadily as possible. The characteristic that is determining a storage tank is the retention time. Every storage solution is accompanied by its individual retention time. In case of a hurricane event the peak intensities are quite severe and generally retention time in the order of 24 to 48 hours is required.

Multi-functionality of the presented measures

Significant volumes of storage are required to avoid pluvial flooding, on average about 215 mm or 2150 m3/ha. This retention capacity can however serve multiple functions. Rainwater can be harvested for household water use. This rainwater can also be infiltrated to recharge the fresh groundwater resources of the island and /or to be used for irrigation and to lower local temperatures over the year. In addition, the fact that the island is one of the few on which a fresh water aquifer is located offers the possibility to increase the infiltration capacity across the board in order to have more drinking water available in times of water scarcity. Since there is insufficient data with respect to the currently available infiltration infrastructure and the overall geological conditions the increased infiltration potential has been neglected in this analysis. To upgrade the living standard for the aftermath and during the reconstruction of a hurricane event the primary focus was set on the potential to store household water. Since the water that will enter the storage tanks is not necessarily rain water, sea water can lead to salt intrusion which lowers the quality and useability of the stored water. In order to make the highest possible use of the tanks it would be reasonable to have several sub tanks, so stored water of different qualities does not contaminate each other. Besides the issue of offering sufficient drinking water, intruding salt water can also lead to corrosion, therefore the tanks should be sufficiently protected. Besides salt intrusion the storage tanks should not result in additional cross-sectional areas for the housing facilities and thus increase the effective wind force. Therefore, it is reasonable to construct the tanks subsurface. This results in increased construction costs but the tanks are expected to withstand the accepted damages on the buildings and do not have to be rebuilt after a storm event. A potential solution is stated in Fig 75.

Household water storage

The simplest way to answer the individual storage requirements for fresh water before, during and after a hurricane is by constructing storage tanks underneath the housing space. Since the proposed network leaves space to implement storage at each pipe junction, the actual required storage can be determined with consideration of local water demand by adjacent buildings. Particularly during the aftermath of a hurricane, the required self-sufficiency leads to water stress. Whether big or small, storage tanks are constructed to serve this demand. A potential storage solution is indicated in Fig 75. The retained water can help reduce that stress by offering the stored water to daily life purposes such as showering. The so-called household water, contrary to drinking water, makes a majority of the average daily water requirements. Approximately 90 percent of daily water requirements could be offered that way.

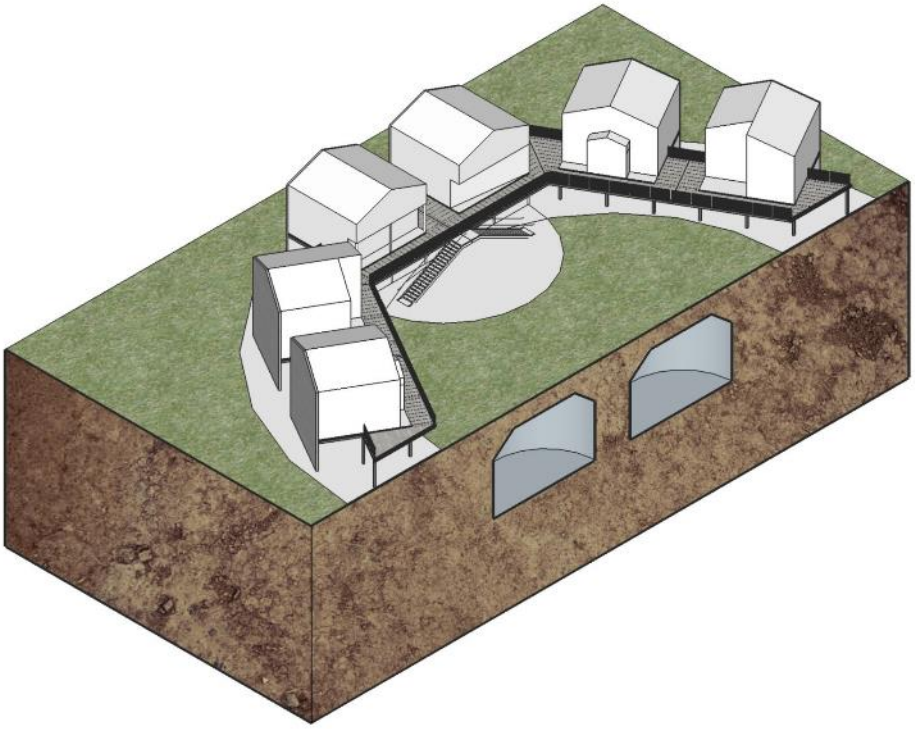


Fig 75: Example of potential storage solution for residential complex excluding sewage network and pipe connection towards water demanding facilities such as kitchen and plumbing

Infiltration

Another way stored water can improve life quality is by feeding infiltration facilities. Infiltration will feed the groundwater and add to the groundwater resources of the island as indicated in Fig 77.
Local infiltration facilities can also have a significant effect on local temperatures as long as there is sufficient groundwater access for the vegetation (Deltares, 2019).

Ditch or infiltration-strip

A ditch is a small channel and facilitates temporary rainwater retention, transportation, and infiltration. A ditch can contain water or can stand dry. Ditches can be integrated into green verges or the roadside. They look natural but they do need extra space and maintenance. A potential outcome is indicated in Fig 78 and 79 (Deltares, 2019).

Infiltration field

Adding fields next to paved surfaces to temporarily store runoff is a simple way to allow water to infiltrate from impermeable surfaces such as roofs and roads. Besides the volume of precipitation that needs buffering, the permeability of the ground is a factor that determines the minimum dimensions. A potential outcome is indicated in Fig 80 (Deltares, 2019).

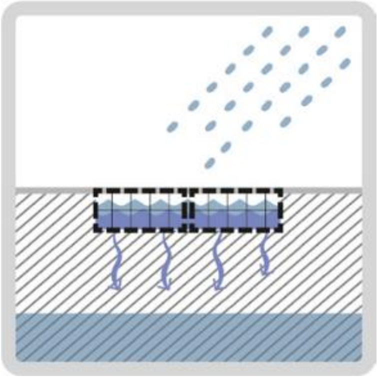


Fig 77: Example of water storage in subsurface boxes including potential of increased infiltration (Deltares, 2019)

Fig 78: Example Bio-swale; additional to normal infiltration ditches it has the advantage of lowering local pollution (Deltares, 2019)

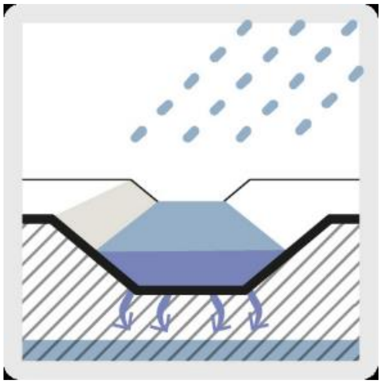


Fig 79: example infiltration ditch (Deltares, 2019)

Gravel layers

A gravel layer is a subsurface facility packed with gravel for infiltration of stormwater as can be seen in Fig 81. Runoff is carried above or below the surface and led into the layer or shaft. Such systems are used next to paved surfaces or next to unpaved surfaces that do not offer sufficient room for infiltration ditches or where the ground has an insufficient permeability factor (Deltares, 2019).

Co-benefits of local stormwater infrastructure

Besides offering the determining discharge capacity for a storm event the sewage is expected to serve additional purposes through the rest of the year. Since in the case of Dorian approximately ⅔ of the annual rain has fallen there is a decisive advantage in keeping this water for periods in which no rainfall occurs. This water can then have an impact on the external water consumption and on the general living quality. As the water is preferably extracted from the storage facilities the water extraction of the public fresh water wells is reduced. As a result, the freshwater body of Grand Bahama might increase again (Deltares, 2019).

Multifunctionality of the Wadi

The Wadi is used for discharge but can be used as storage too. Storing water in the system prevents it from flooding into vulnerable areas while decreasing peak flows due to its limited discharge capacity. The wadi is designed in combination with the levees and answers to the circumstances during the extreme point of the storm surge of the three points approach. To accomplish Flood Risk reduction, it makes the water flow differently by improving drainage and creating storage in the system (Deltares, 2019).

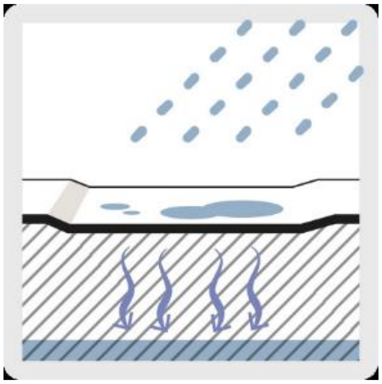


Fig 80: example infiltration field (Deltares, 2019)

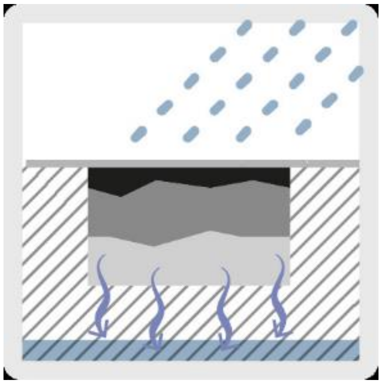


Fig 81: example gravel layer (Deltares, 2019)

Damage reduction for overloaded system

Handling the extreme scenario of the three-point approach, representing an overload of the system. The discharge capacity of the sewage network is derived for a scenario of an occurrence rate of T=15 year. If the incoming precipitation exceeds the design discharge the system can only be drained by adding additional storage. Once the storage capacity is completed the system will fail. In this situation the sewage network will completely fill up with water and flooding in the surrounding areas cannot be prevented. In such a case it is reasonable to disconnect selected pipe segments and to accept flooding in these areas, while other areas can still be drained properly. A reasonable area for such a scenario is the industrial area, which got surrounded by a separate safety level dike system exactly for this reason, as described in the chapter 4.3.1 . Even though part of the stormwater sewage network has failed in such an occasion, water is still guided towards the wadi so that a major part of the collective protected area of Freeport is drained and protected from flooding.

Conclusion of the overall drainage network

A new stormwater drainage strategy has been presented for the collective protected area. It primarily consists of a wadi that is guiding water out of the collective protected zone. By doing so the primarily northern water stress is directed into regions of lower water stress namely the south of the island. The low elevation area there is a natural dry pond where water would have accumulated anyway, see Fig 56 and Fig 58. By creating a wadi there that cuts through the high ridge a natural stormwater outlet can be created to the south of the island, where no storm surge is expected to increase the sea level. Additional to the overall drainage strategy of the wadi the pluvial water stress is addressed by constructing a stormwater drainage network in combination with a substantial stormwater retention (storage; sponge) capacity. This retention capacity includes rainwater harvesting facilities as well as stormwater infiltration facilities that feed the resources of fresh groundwater. During the aftermath of a storm event this harvested and stored water can be of vital importance for the water supply. This strategy can only succeed if the members are functioning and communicating properly with each other. In a scenario in which the future wadi is insufficiently maintained and the overall drainage is blocked by clogging of the upstream sewage network this attractive overall strategy is condemned to fail.

4.3.3 The urban and building scale: Governance of future urban growth

As a result of the construction of the collective protection around Freeport, this area becomes less exposed to the hazard of flooding originating from storm surges. Therefore, policies that regulate future urban developments should strongly encourage urban growth to focus on Freeport.

The expansion scenario that the project looks at envisions the long-term future. It considers four layers of the urban and natural landscape to describe a solution that arises in the context and enhances its singularities by respecting the natural heritage and offering a framework to encourage social interaction in a shared, public and open space. These layers are visible in the map depicted in Fig 83.

During the first phase, the project introduces more density in the areas that allow the inhabitants to leave the transportation by car, so to choose a more sustainable means of transportation, such as walking or cycling. The space syntax analysis employment identifies the areas in which the existing transportation structure and transportation networks allow slow traffic. Using the 800m segments is possible to individuate the walkable areas among the already built areas. Walkability also intrinsically leads to more interaction in the public spaces: roads, small squares and similar. The map of phase 1, Fig 82, shows the areas that will first host more density and diversity, thanks to architectural interventions.

Fig 82: Areas of intervention during the phase 1 of urban expansion


Layer 4: sewage system
Layer 3: collective protection
Layer 2: urban
Layer 1: mobility
Layer 0: nature

Fig 83: urban and natural layers that inform the future governance of urban development

In the second phase of urban expansion, the project should introduce more residential buildings in the area running throughout the collective protected site from north to south. At the moment, this place hosts mainly commercial functions. However, there are many spaces of low spatial quality, such as parking lots. Densifying in these areas could represent a great opportunity, since most of them are not permeable due to asphalt surfaces, so no permeable areas would be employed to accommodate new housing. Furthermore, looking again at the space syntax analysis, the area allows the movement again by sustainable transportation means.

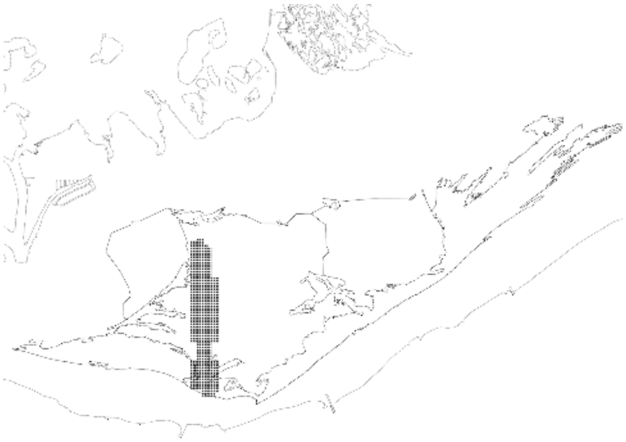


Fig 84: Areas of intervention during the phase 2 of urban expansion

Fig 85: Areas of intervention during the phase 3 of urban expansion

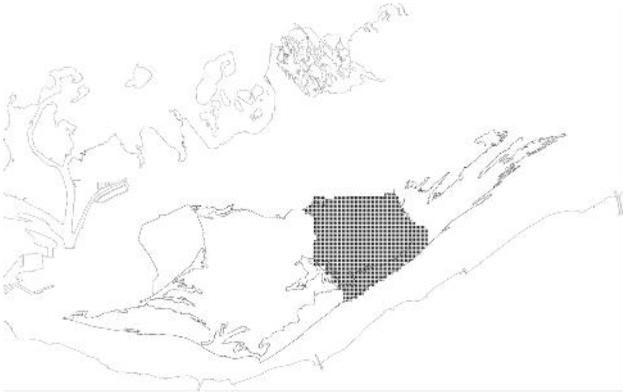


Fig 86: Areas of intervention during the phase 4 of urban expansion

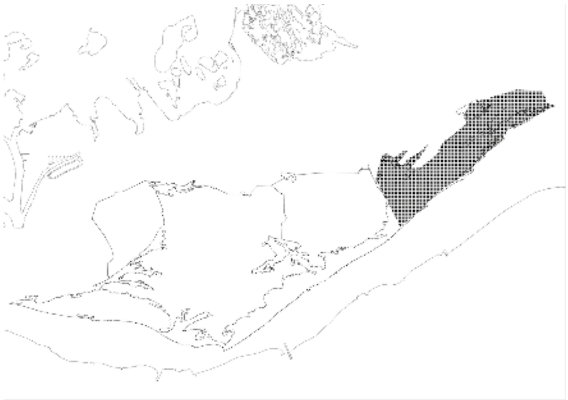


Fig 87: Areas of intervention during the phase 5 of urban expansion

The third step envisions the urban expansion to continue in the area protected by the levee number 4, the industrial area. This area has a lower level of safety than the area in the earlier phases. To finalize expansion this step, additional safety measures need to be taken into account, because of the storm surge entering the area on the northern part of this site. Furthermore, some of the heavy industries now operating there would have to be well integrated with the new residential functions. As for phase two, the densification in this area should be encouraged to avoid the loss of permeable ground, since there are many paved and impermeable surfaces here as well.

In the fourth phase, the density will occur in the area protected by the levee number 5. This protection infrastructure has not been fully addressed in this report. Therefore, the same calculation and design principles need to be applied to this area to be able to expand to this region. By densification in this area, we would encounter an already built environment, with the transportation infrastructure that already exists. Furthermore, because the area is already populated, there will not be a huge loss of permeable surfaces.

The fifth and last phase that this project envisions is the densification of the highlands on the eastern part of the protected area. The densification here would be more difficult, since the road structure is not as developed as in the other places. However, the biggest concern is about the use of land: the area is not poorly populated, meaning that the practice of densification here would lead to the loss of important permeable surfaces that perform towards a fast recovery after a storm event.

The quantities of the new density that this project wants to propose would almost double the current density, arriving at around 30 dwelling per hectare. The following images show three examples of similar densities, so that it is easier to imagine the possible solutions. They are all examples of urban fabrics and forms which belong to the city of London. Therefore, the social and urban environment they create is not similar to the context of the Bahamas. Although, they show well what is the ratio between built and area and open areas that is possible to achieve.

Fig 88: Existing urban environments in London with the new proposed density (cca. 30dw/ha). Retrieved from the density Atlas (Density Atlas, n.d.)

4.3.4 Building scale: architectural concepts for density and diversity

The chosen concepts are found for specific locations in Grand Bahama, in order to support the general strategy on site. This intervention illustrates how the concepts take shape and reflect on the urban scale and urban context. Considering the creation of public spaces and public functions, which will improve the social interaction -and cohesion- between neighbours. Improving not only the new developments, but the neighbouring blocks as well. The location of the site can be seen in the aerial view and the map in Fig 89 with the initial site plan.

For the design a series of adjacent empty plots in a residential area was chosen. This allows the project to interact with the existing and improve the spatial conditions around. Following the concepts presented in the previous chapters, nine courtyard modules on the plot were placed, composing the urban plot in a way that public space and architecture work together.

Activating the urban layer

The ground floors of these units are filled with public functions, creating activities and pedestrian flows within the urban block, and attracting the neighbouring inhabitants to make use of the public space as well. Accessibility will play a major role, where the welcoming public space will attract neighbours and residents to use the ground floor areas. The distribution of public functions attracts people from the neighbouring places, making this intervention a livelier space. Therefore, the idea of social cohesion from the larger scale starts taking shape, as the ground floor and main public layer is active. On a smaller scale, the platform becomes the main meeting and collective space for the residents of the housing units. A diagram of the relationship between the platform construction and the possible public volumes can be seen in Fig 90 and the public layer flows can be observed in Fig 91.

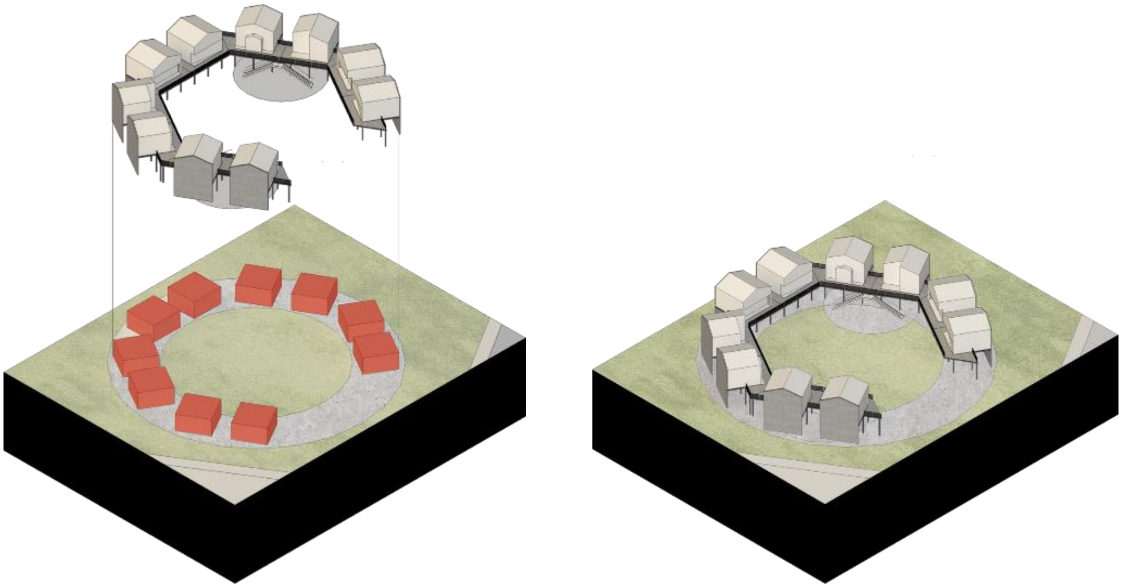


Fig 90: Close up diagram on the composition of a typical courtyard structure, with ten housing units, platform, and commercial areas in the ground floor.

Fig 89: The site on which the architectural concepts were applied and the initial site plan.

Fig 91: Diagram of the public layer flows.

As stated before, the commercial areas on the ground floor host the public space, strengthening the social cohesion between residents and neighbours, while protecting the housing units on the upper levels. With further research on the structural aspects, these clusters can offer safe environments in case of a hurricane by protecting the insides from flying debris. Architectural impression of the public level can be observed in Fig 92.

In this design proposal, the Flood Risk Reduction is also addressed by installing a levee for the protection of the central Freeport area. Using the building structure that was already mentioned in the previous chapter, the buildings are adapted as well, in order to be prepared for possible floods that could arise in the future. Although, the height of the houses in the collective protection area does not need to be as high as in the area where individual protection measures are applied.

Fig 92: Architectural impression from the ground floor of the protected area.

4.3.5 The natural and building scale: new urban environments

The new protection infrastructure will have an important effect on the urban and natural environments of the island. This paragraph focuses on the description of a site in the collective protected area where the levee meets the urban fabrics and the ecosystem of the pine forest. The map below shows the site.

On the site there is an overlapping of many concepts and strategies introduced by this project. First of all, the levee interacts with and divides a natural landscape. In cases that the levee interacts with bigger plants, for instance in the case of a pine forest ecosystem, special attention must be put in the maintenance of the structure of the levee. When plants' roots penetrate the structure, they make it more porous and therefore less effective to keep the water outside the area. The Fig 93 below shows the integration of the levee with the ecosystem of the pine forest. Only smaller sized plants with a less penetrative root structure can grow there, to prevent the damage of the levee.

The levees also need to be integrated in the built environment. In the case of this specific site, a road will run on the levee, until it finally crosses it. Fig 94 shows how the two systems coexist on the site. The ground is in this case at the height of 14 ft. Consequently, the levee is 6ft tall, to reach the requested elevation of 20ft.

In Fig 95 drawing it is also possible to see the sewage network that allows to get rid of the water coming from the rain during hurricanes and storms in general (the red pipe).

Fig 93: The location of the site, In this design proposal, the Flood Risk Reduction is addressed by the realisation of the levee for the wider Freeport area. second map retrieved from Google Maps, 2020

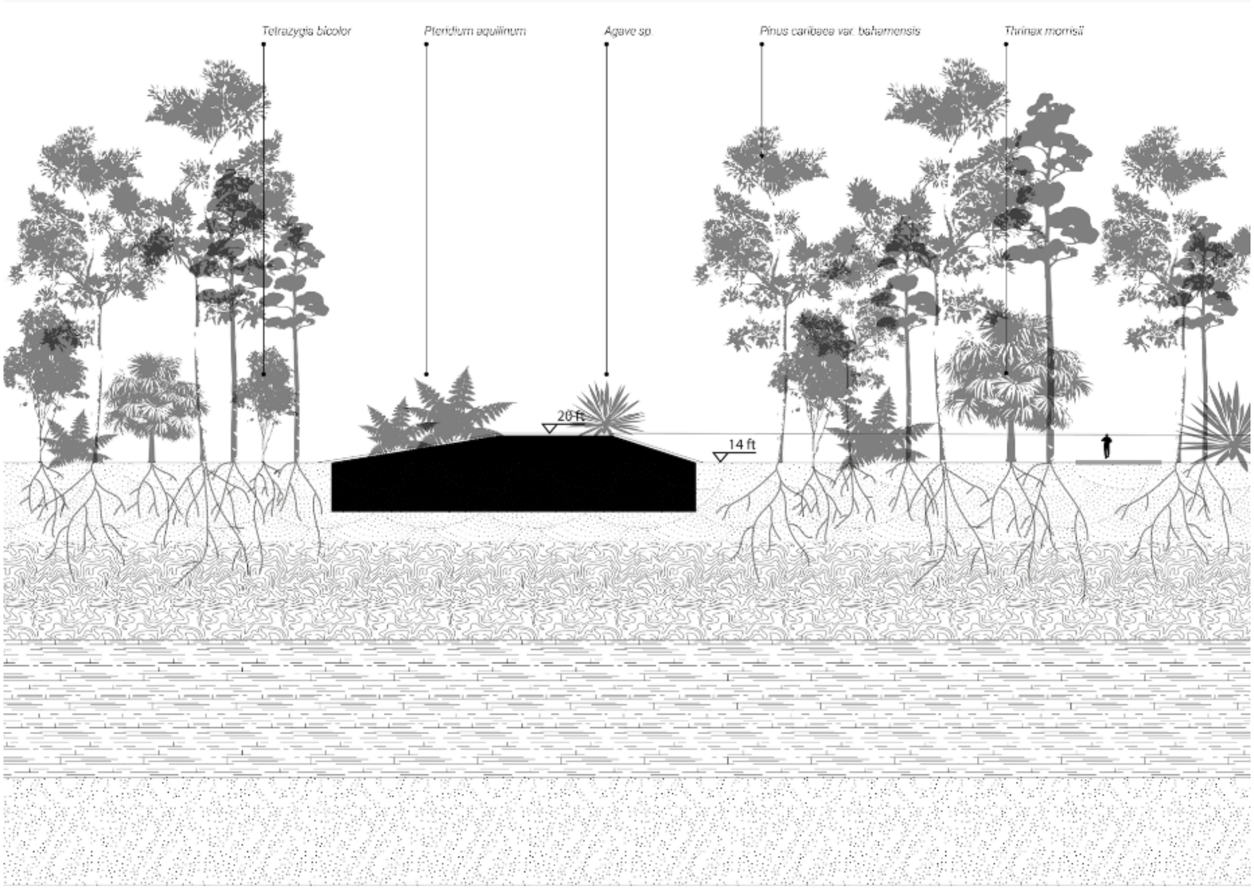


Fig 94: The integration of the levee in the pine forest ecosystem

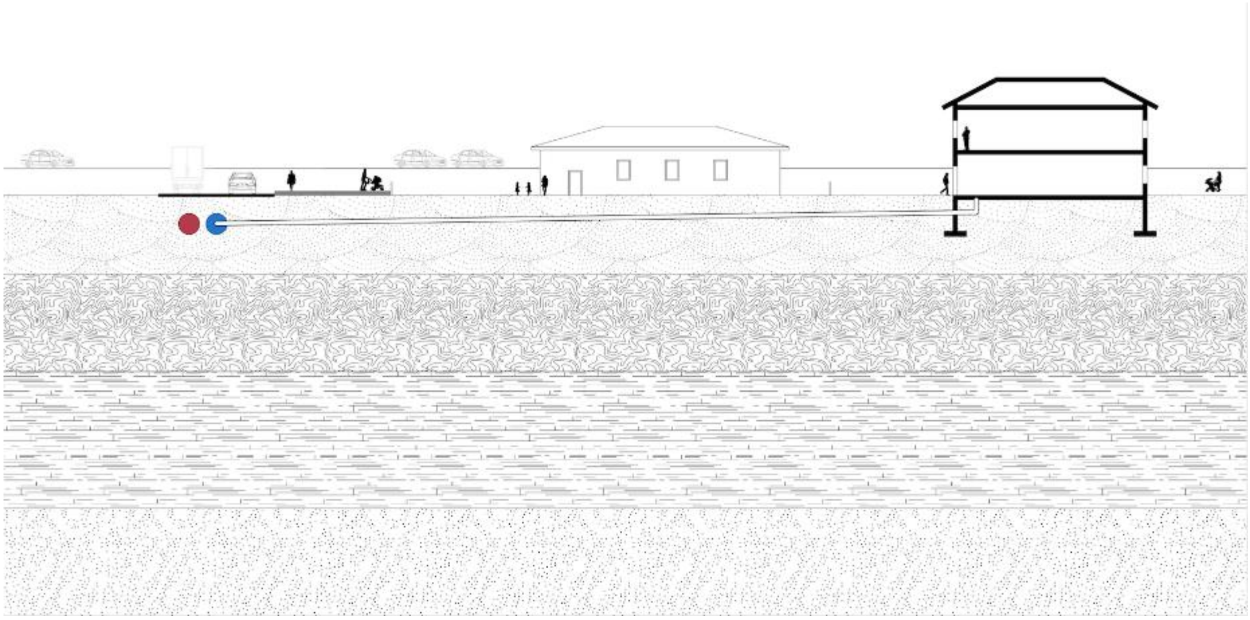


Fig 95: Side view of a levee in the built environment.

Connecting scales: Case study Central Campus

The main vision for the design of the campus in the central area of Grand Bahama was of a space that performs as a heart of the city, both in everyday life and in extreme weather conditions. To do so, we propose to "join forces with nature". Meaning that we stop building and designing to completely resist and oppose natural forces. The building will perform as a shelter for the wider community in hurricane scenarios. In daily life, it will work as a figure that provides knowledge about technological advancement and conscience about the contemporary environmental question, both for the social and the economic urban layer.

The site we are developing has a particularly strategic position. It is situated in the central area that will be protected with the collective infrastructure against flooding. In the surroundings there are numerous other elements of the critical infrastructure, such as the hospitals, schools, police stations, and a power plant. Furthermore, different land use and functions intersect in the area, creating a diversity that we cannot find anywhere else on the island. A business district connects the airport area on the North and the touristic functions on the South of the island. Western and Eastern of the site there are mainly residential functions areas.

Fig 96: the location of the Campus (yellow dot)

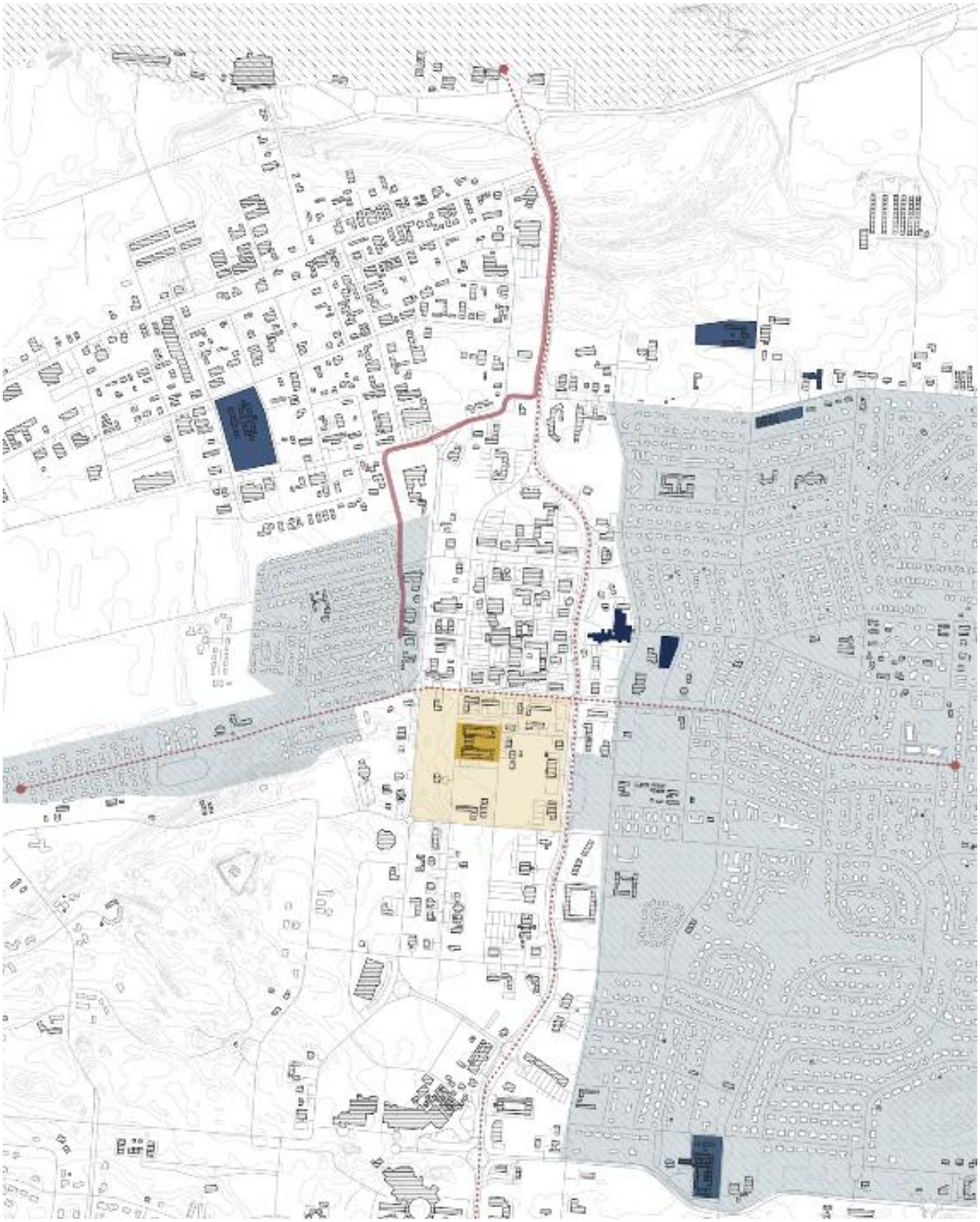


Fig 97: The site of the central campus

The context naturally allows the development of a project that brings together the need for protection in extreme weather scenarios, the need for increased social cohesion, and economic growth.
During Dorian the site did not experience severe damage. Although, there is a need for a project that goes beyond the mere reconstruction of the structural elements that were damaged. The new proposal brings together multiple disciplines, from water management, to architecture, to urbanism.

The project addresses two situations. First the extreme conditions that the city faces during hurricanes. As mentioned earlier, the building becomes a shelter for the wider community when extreme weather conditions occur. To do so, the ground floor of the whole building will be designed in a way that it can be flooded. In this sense, there is a need of further development of function and activity organization on this level. Furthermore, the interiors will need to be designed so that they can be easily moved or replaced after the flooding.

The project also wants to address a second scenario, that of the daily-life urban experience. Therefore, the project proposes spatial interventions and strategies to achieve more spatial and social cohesion with the surroundings. To do so, the area without current use surrounding the university building, should be developed as well. In the area, two main axes will be developed. The first one is obtained from the axis of symmetry of the building. It connects the campus area with the surrounding urban fabrics on the East and on the West

Fig 98: sections of the buildings in two scenarios

The second one crosses the campus area from North to South, bordering the western façade of the building. In the campus area the car traffic should not be allowed. A smaller parking area will be placed in the North-Eastern part of the site. At the same time, water management technologies will be developed for more permeability and water detainment. To achieve a higher permeability, green surfaces are preferred to grey surfaces such as asphalt that is now widely used in the whole urban area. The technology will have two beneficial consequences. First of all, the increased permeability allows the water to leave the area faster in case of flooding. Second, green surfaces allow the implementation of possible sub-surface storages.

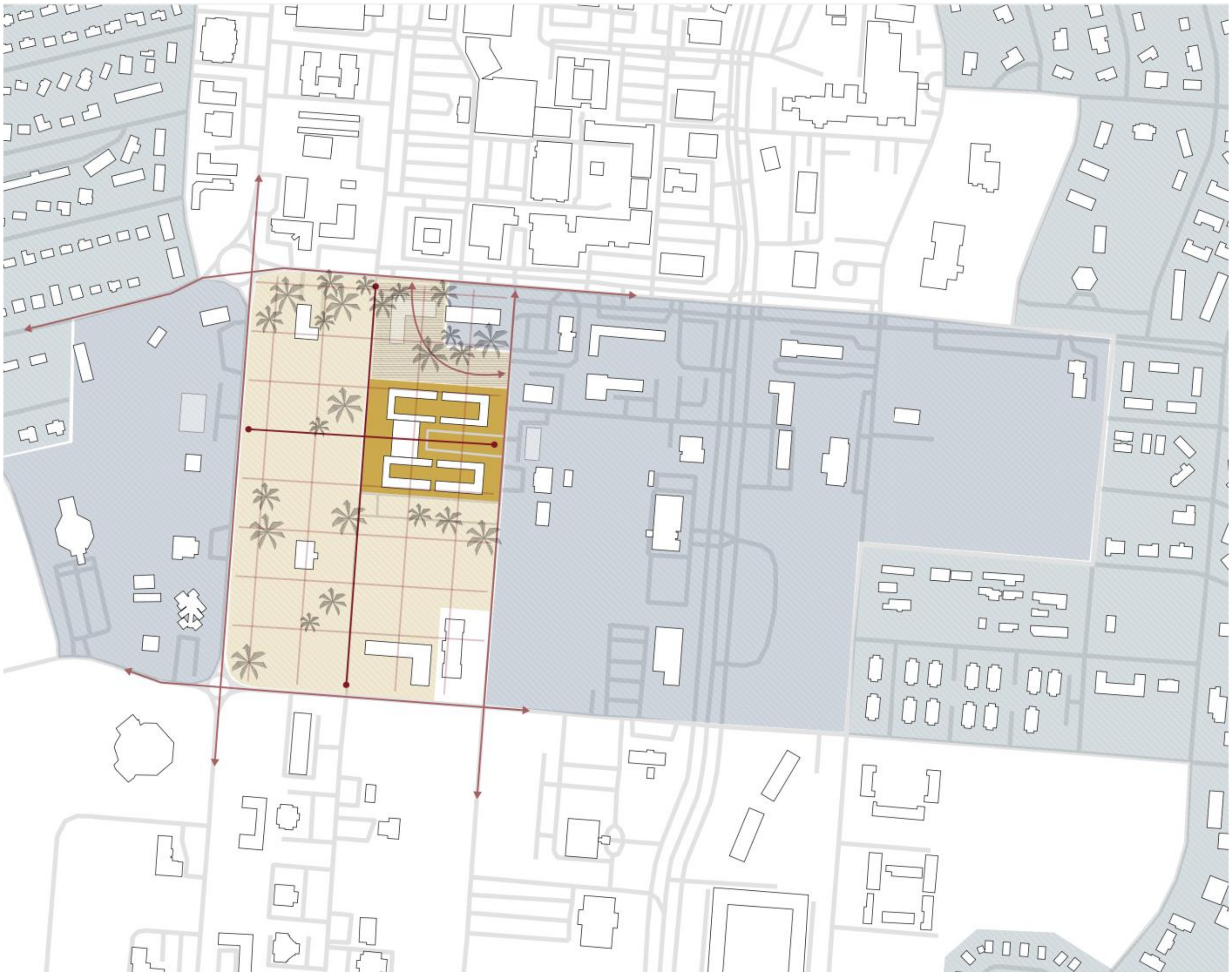


Fig 99: The surroundings of the campus and the mobility

Water storage is an important element that we can develop, and the area can benefit from it both in everyday life and extreme weather conditions. Therefore, the project also foresees water detainment strategies on roofs. In the Bahamas all the rainwater falls off the roofs as quickly as possible. This water blocks paths and increases flood damage. Storing it on the roof will slow runoff from large areas and decrease flooding in lower areas. The water will eventually reach the ground, but over a longer period of time. We depicted a few examples, but we highly encourage looking for other possibilities to store water above the surface, to decrease damage and flooding on the ground. A second beneficial outcome of such technologies is the water weight on the roof, which might help against the loss of roof material due to the hurricane winds.

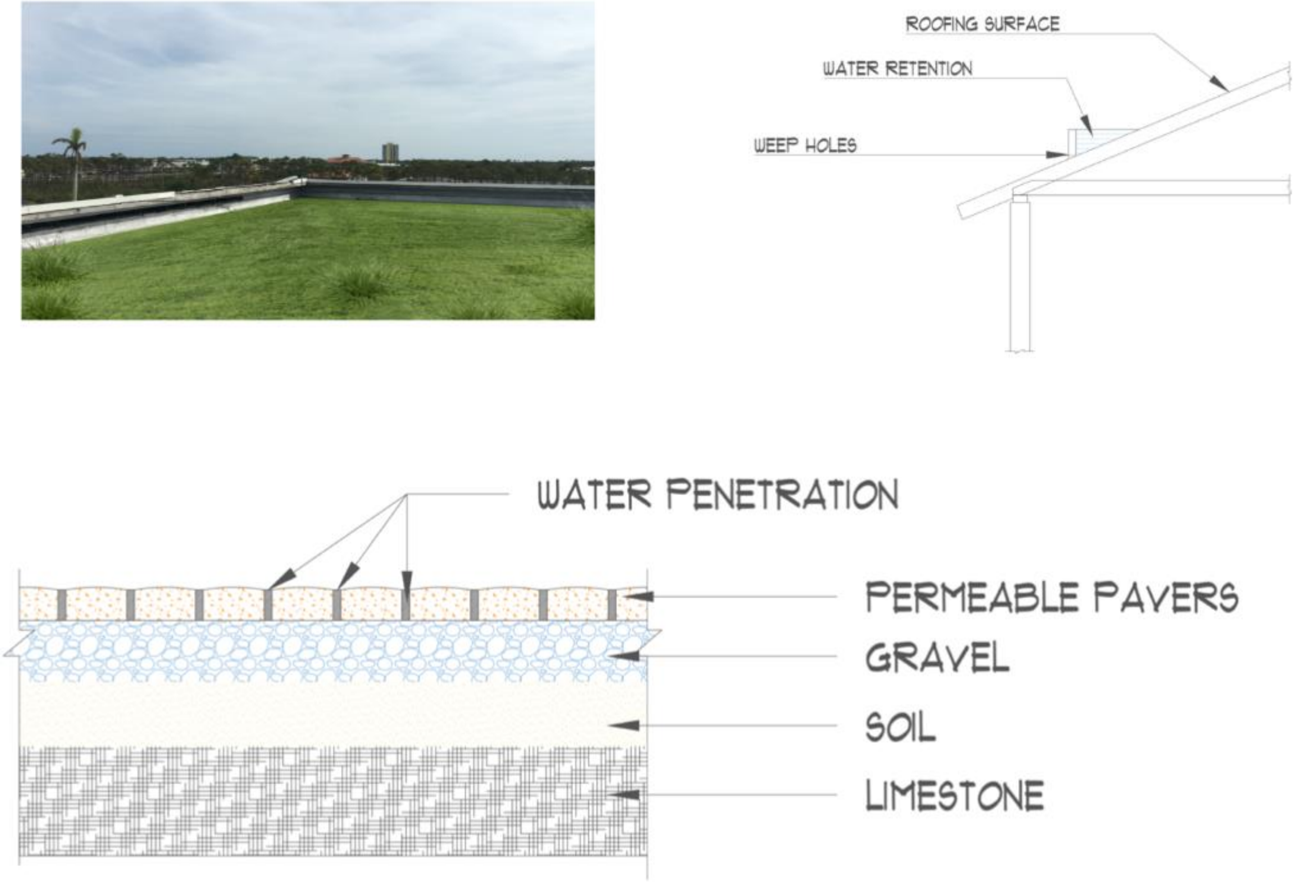


Fig 100: technological solutions for water retention

4.4 Individual protection

To connect the individually protected sites with the area that is collectively protected against hazards, there is need for mobility infrastructure that performs as evacuation routes in case of extreme weather conditions and hurricanes. The Fig 101 shows the possible placement of such routes. The same map also shows the possible placement of vertical evacuation sites, i.e., shelters. Two of them are the University campuses. More shelters need to be decided along these routes. Buildings with more than two floors, meant for public use in daily life can perform well in this case. For example, secondary airports or similar can be designed to shelter function. These infrastructure lines perform as the layer that answers to the need of the "preparedness" layer envisioned in the concept of multi-layer safety.

Not everything can be protected by dikes. The parts that lie on the outer region of the dikes are still prone to flooding. Therefore, these buildings require another type of solution. These areas will have to respond to daily conditions, where, on the one hand, the everyday life of the island should unfold, mixed with cultural, climatic and spatial conditions. On the other hand, the intervention will have to deal with extreme scenarios in response, protecting the physical infrastructure and lives of the inhabitants.

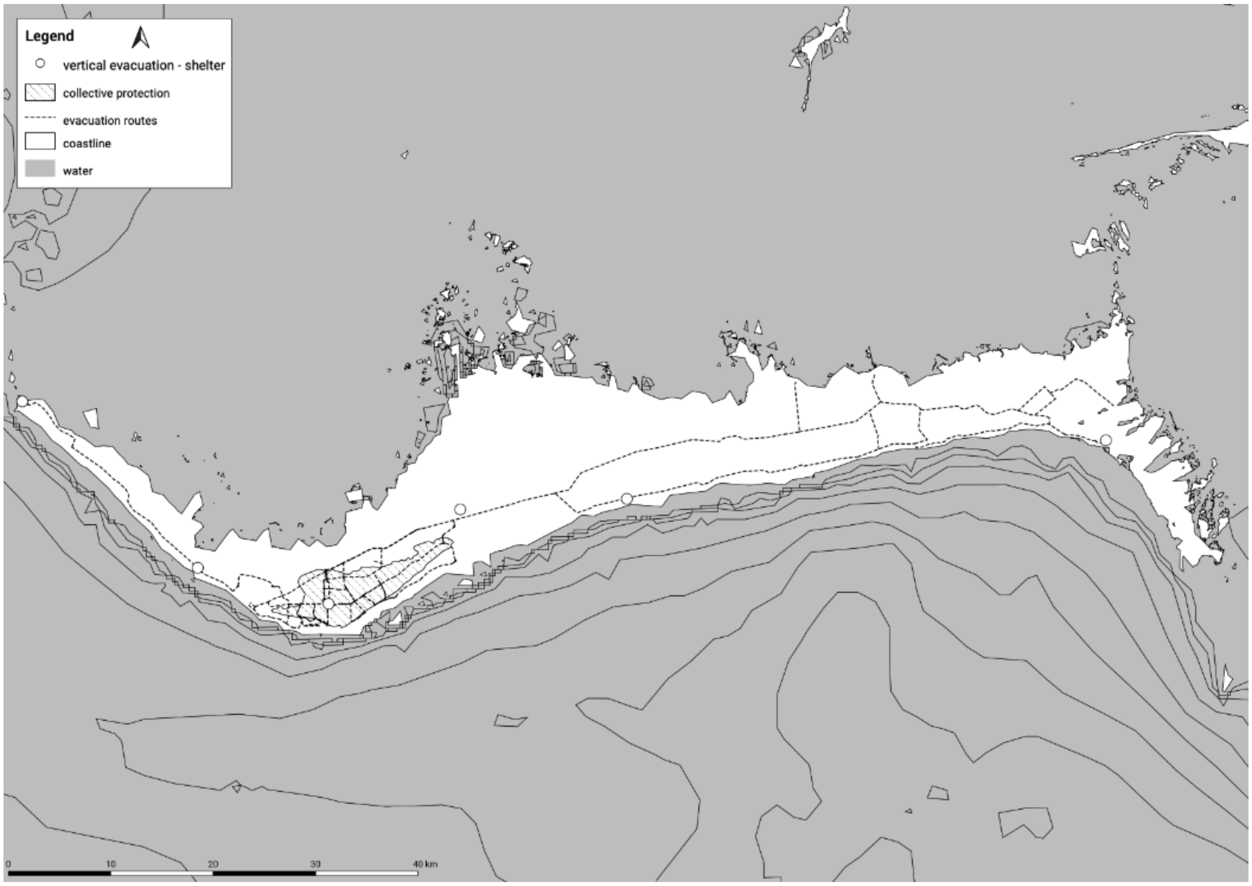


Fig 101: Evacuation routes and vertical evacuation sites

4.4.1 The natural, urban and building scale: Elevating residential buildings

The current relation between buildings and the plots becomes an issue to face: the flooding hazard. One very basic concept then is to elevate the housing units, reducing the chances of floods, and mostly, being destroyed by the storm surge.

Nonetheless, this can generate more questions:

- What happens at the street level?
- What is the relationship between pedestrians and buildings?

In order to respond to this, we applied some basic principles. The ground floor can become a space for retail and commerce, services and other facilities. In the case of storm surge and flooding, these spaces would face the main damage, but the lives of the residents would be safe. This would be very unlikely to happen within the protected area, as the surrounding levees would contain most of the water coming into the system.

The non-protected area is solved with a similar approach. Even though the wooden houses are elevated, not many public spaces are created beneath, avoiding a great damage on the infrastructure and in people’s business. Therefore, these empty spaces are suggested to become water storage tanks for most of the houses.

Fig 102: Concept diagram: lifting the houses.

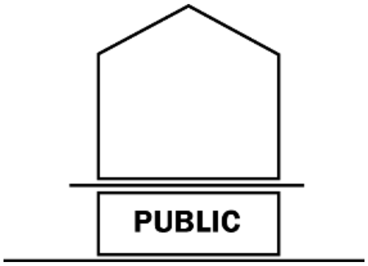


Fig 103: Concept diagram: creating a public ground floor to improve the spatial conditions of the neighbourhood.

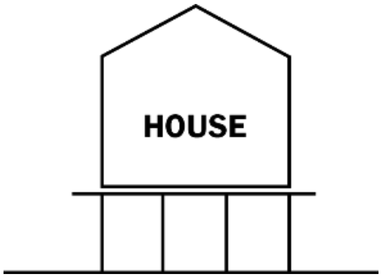


Fig 104: Concept diagram: lack of program in the ground floor for the non-protected zones.

The layout of the basic housing unit shows a space of 8 m by 8 m, with social spaces on the ground floor and private spaces, namely rooms, on the upper levels. As a first design approach, the staircase and services (kitchen and bathrooms) structure the layout of the interior. The distribution of rooms can change depending on the preference of the resident.

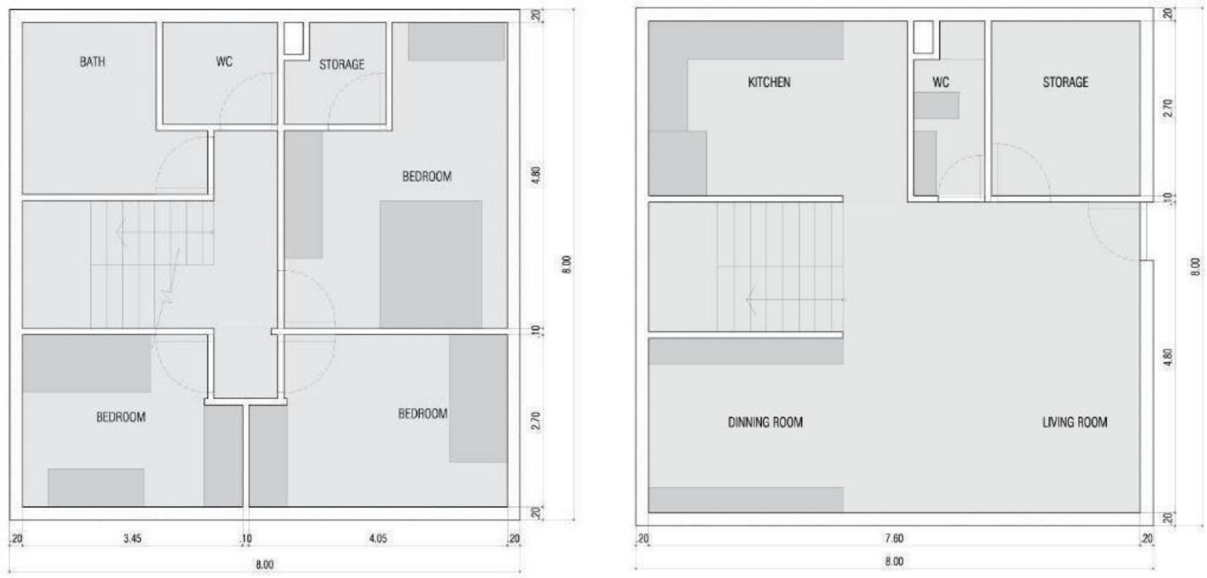


Fig 105: Example of a House layout, with the elevated ground floor and first floor.

In this sense, we find a square floor plant that contains the main housing spaces, and a platform that protects such spaces from surge hazards. The basic layout of the house responds to adaptability to various urban contexts and site conditions, where the orientation and wind direction don't compromise the functioning of the space. This design makes it possible to have small variations on the layout of the house, with a distribution of spaces that can adapt to specific needs and conditions that the residents of the housing units may have.

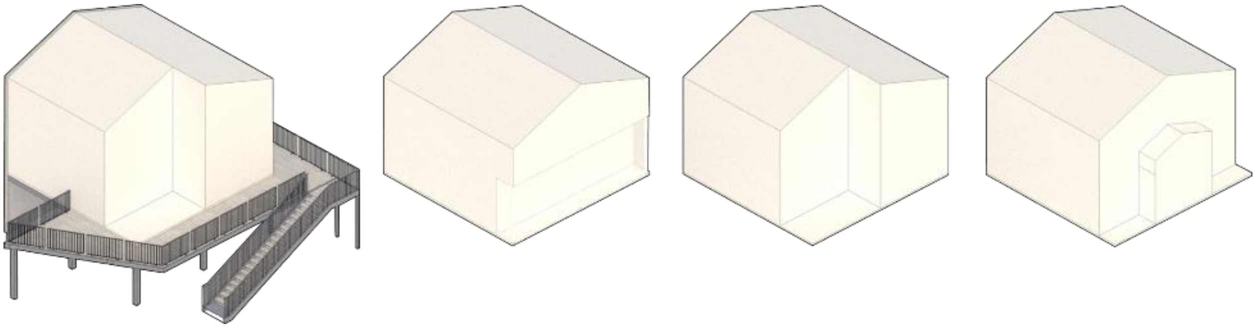


Fig 106: Module: housing unit and different elevated varieties.

Protective System

The assembly of houses is conceived as part of one system, a main courtyard that works as the core of activities and spatial response to hazards and daily life. The layout of this system performs as a “fortress” where the courtyard and the main spaces of the house will be protected.

As stated before, the idea of lifting the houses is the main design concept in order to protect them from the storm surge. Therefore, the platform as a second layer is introduced, within the urban fabric.

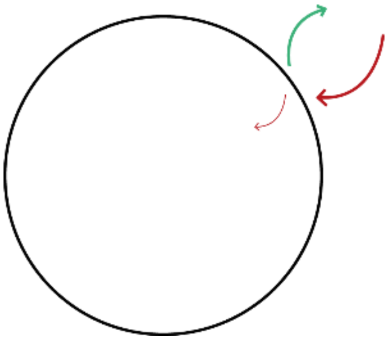


Fig 107: System protection: the protective walls and the layout of the urban block conform to a system, which protects the vital infrastructure and life of its residents.

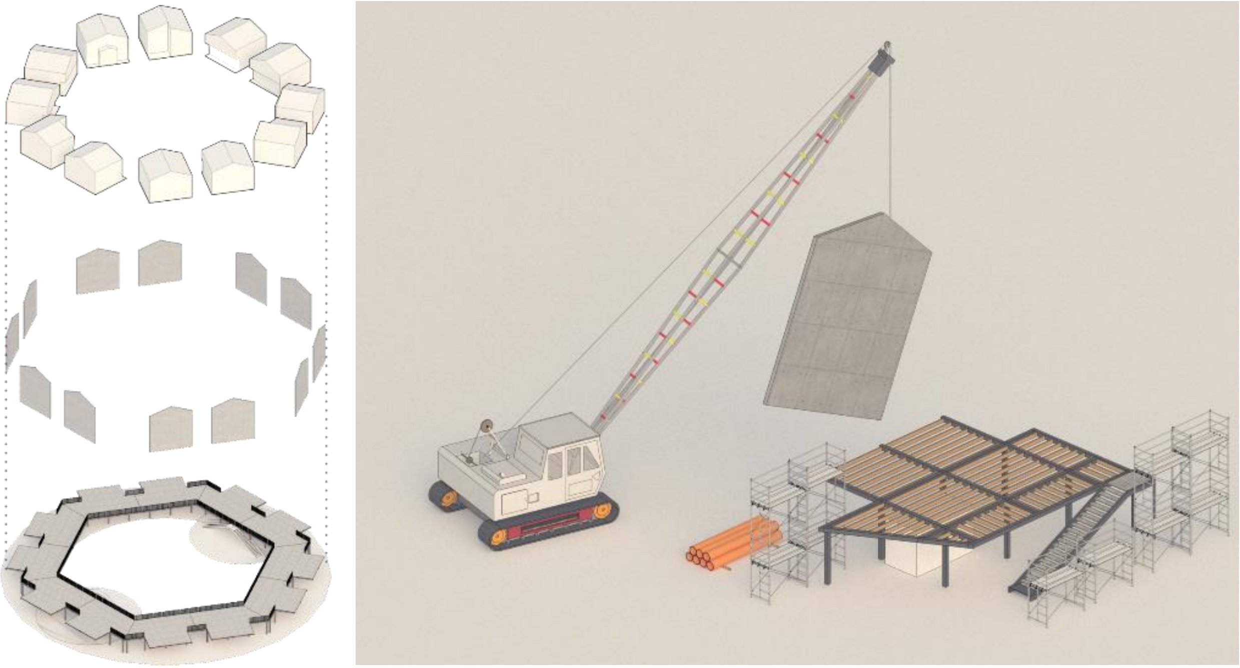


Fig 108: System components: platform, walls, and houses.

4.4.2 Building scale: flood-resilience strategies

Wet floodproofing

Wet floodproofing is a series of measures taken to protect a structure or its substances from flood damage while allowing the storm water to enter the site or even the house. Such interventions, according to FEMA (2008), include " properly anchoring the structure, using flood-resistant materials below the Base Flood Elevation (BFE), protection of mechanical and utility equipment, and use of openings or breakaway walls". Wet floodproofing is particularly beneficial for residential buildings in flood plains where part of the building falls below the base flood elevation (BFE)— the elevation at which flooding happens during a 100-year storm event. Building codes sometimes define a flood elevation requirement (DFE) as the base flood elevation plus some additional level climb, such as one foot.

Anchoring the structure

A key aspect of wet floodproofing is to adequately secure a house to its foundation but allow floodwaters to penetrate a building and equalize pressures on base walls or lower-level walls. By contrast, if floodwaters are kept out of a building, there are very large hydrostatic forces with which to cope. When a proposed building site is in a flood-prone area, all new construction and major modifications shall be built or modified and properly protected to prevent floatation, collapse or lateral movement.

Flood resistant materials

All structures below the BFE are susceptible to flooding and must consist of flood-resistant building materials. Products not resistant to moisture and water damage are unacceptable for applications below BFE (FEMA, 2008). For example, the materials contain products of wood or paper, or other materials which dissolve or weaken, lose mechanical integrity or are negatively affected by water. Sheet floor coverings such as linoleum, rubber tile, or wall coverings limit the fabrics they cover to dry out. Materials are unstable in dimensions. During submergence, the materials absorb or keep excess water.

Elevating mechanical equipment

The mechanical and electrical components below the BFE must be engineered or placed in such a way that floodwater does not penetrate or collect within them. The preferred method of satisfying this requirement is to find elements at risk of flooding within the expected flood level. The solutions for the electrical systems which cannot be raised, include emergency operation and maintenance measures, like unplugging and raising or relocating electrically controlled appliances, installing elevated electricity-cutting control panels, or containing service equipment in sealed utility enclosure places (FEMA, 2008).

Safety and Access

Safe access to a wet floodproof design may be a critical factor in determining if wet-floodproofing is a suitable alternative method. Most wet-flood proof structures are expected not to have to be broken during flooding. Safe access shall be considered in cases where there is a need to reach the network under flooding conditions. Many sites are only suitable for wet-flood proof buildings if changes are made to the site to reduce flood hazard, and there is sufficient alert time available to leave the site safely.

Dry floodproofing

Dry floodproofing is defined as "combinations of structural and non-structural additions, changes, or adjustments to structures which reduce or eliminate flood damage to real estate or improved real property, water and sanitary facilities, structures and their contents" by FEMA (2008).

The objective of dry floodproofing a building is to keep it watertight for a few hours and the depth usually under 3 ft of flooding with limited duration. Dry floodproofing lowers the flood damage potential by reducing the likelihood that the interior of the structure will be flooded. It can be an appropriate alternative for flood mitigation when relocating or elevating buildings is not cost-effective or technically feasible. A residential building's lowest floor must be raised at or above the base flood level (BFE) or dry flood-proofed to the BFE.

These are the key aspects that FEMA points out considering:

Materials

"Incorporating flood damage-resistant materials into the dry floodproofing design up to the height of the dry floodproofing measure is recommended. Additionally, building systems such as walls and foundations may need to be strengthened to withstand direct flood forces and the loads imposed by floodproofing measures like shields and watertight doors, which are used to temporarily seal openings." (FEMA, 2008)

Shields for openings

"Dry floodproofing of wall systems is a complex undertaking because openings such as doors, windows, and utility connections are rarely designed to be watertight or to resist flood loads. When openings that must be maintained below the flood protection level are evaluated, a primary consideration should be the wall or foundation system's ability to resist the loads. Any system of flood doors, panels, or shields will depend on the transfer of the flood loads from the shields to the wall such that the load path is maintained. If the walls or foundation are structurally insufficient to carry these loads, they must be reinforced to maintain the load path." (FEMA, 2008)

Interior drainage

“Even with sealants, a dry floodproofed building still requires a well-developed internal drainage system to collect the inevitable leaks and seepage that will develop. Many dry floodproofing systems still experience some water infiltration, and the owner will need a dewatering system capable of removing the water. Such a system may require drains to be built along footings and slabs to guide inlet to a central collection point where a sump pump may extract it. Additionally, dry-floodproofed buildings usually need backflow devices and other measures designed to eliminate backwater flooding through waste and wastewater system components.” (FEMA, 2008)

Amphibious buildings

Amphibious architecture is an alternative strategy for flood mitigation which enables an otherwise ordinary structure to float on the surface of growing flood water rather than to surrender to flood. The Buoyant Foundation led by Elisabeth English proposed the following definitions:

Amphibious foundation

“An amphibious foundation retains a home's connection to the ground by resting firmly on the earth under usual circumstances, yet it allows a house to float as high as necessary when flooding occurs. Beneath the building, a buoyancy device displaces water to provide flotation if required, and a vertically guiding system allows the house to return to exactly the same place. Amphibious construction is a flood mitigation strategy that works in synchrony with a flood-prone region's natural cycles of flooding, rather than attempting to obstruct them. Amphibious foundations make homes resilient; resilient homes are the bases for resilient communities.” (Sumanth & English, 2015).

Buoyant foundation

“A buoyant foundation is a particular type of amphibious foundation that is specifically designed to be retrofitted to a house that is already slightly elevated off the ground and supported on short piers. The system consists of three basic elements: buoyancy blocks underneath the house that provide flotation, vertical guideposts that prevent the house from going anywhere except straight up and down, and a structural sub-frame that ties everything together. The posts that provide vertical guidance are installed not far from the corners of the house. When flooding occurs, the flotation blocks lift the house and the vertical guideposts resist any lateral forces from wind or flowing water.” (Sumanth & English, 2015).

Conditions for the buoyant foundation

- "The use of buoyant foundations is an approach to flood mitigation that disperses risk rather than concentrating it. They are a low impact solution that improves community resilience. They promote restoration rather than demolition, which is a much more sustainable response to local housing needs. They preserve a form of traditional vernacular housing that is particularly appropriate for the local climate and made of a particularly appropriate local material (native cypress is termite-, mould- and rot- resistant) that is no longer available and thus irreplaceable." (English, 2009)
- "The visual and spatial relationship between the building and the ground is preserved by placing the buoyancy elements either above or just below ground level, as called for depending on the specific site and context. The vertical guidance posts may be configured to telescope out of the ground and/or placed in visually unobtrusive locations to minimize their visual impact. A buoyant foundation retrofit offers a strategy for sitting lightly on the land, where permanent static elevation would significantly compromise the appearance of a historic structure and may also produce unacceptable voids at street level." (English, 2016)

Concluding, the buoyancy and stability of amphibious building is dependable on the force's waves can have on the structure. When amphibious architecture is implemented the impacts of wind and waves can be as important as the lift the building can have due to flooding. Wave mitigating tactics can be implemented to reduce this risk externally, but can be difficult to implement on a large scale, except in the cause of a dike and levee.

4.4.3 Natural and building scale: responsive architecture

Structural aspects

The aim of the structural investigation on the building scale is to supply safe residential environments protecting its users from flying debris or debris dragged by flood streams as shown in the impression in Fig 109. The concepts introduced in this chapter are the initial ideas of the architectural team and need further research and design.

Wood is a material available on the island. Most of the existing housing units use such material as part of their structures and frames for the walls. As we have evidenced throughout this research and site visit, all these buildings suffered great damage or complete destruction. We propose to continue building with wood, since it is a sustainable and local resource, and there is already an existing industry working with this material.


Fig 109: Impression of the outside environment after a hurricane.


Fig 110: Wooden structure: a light wooden system to build the houses.

Now we have a platform and a wooden structure. We think that the platform itself will not fully protect the housing unit, therefore, we propose to have a concrete wall that protects one of the sides of the house. The concrete wall will be located on the outer facade of the house, protecting the unit from exterior hazards that might affect the functioning of the system. This wall can be casted on site, but we suggest having a prefabricated module that can be easily put in place. This is not only relevant for the construction of the houses in the very beginning, but for the re-construction and reparation after hurricane events.

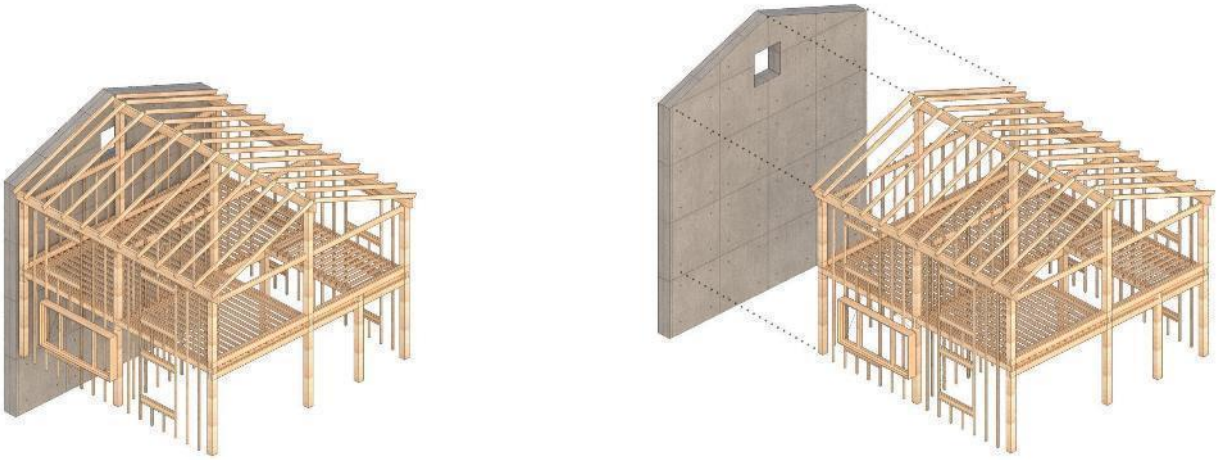


Fig 111: Protective wall: a concrete wall on the outer facade.

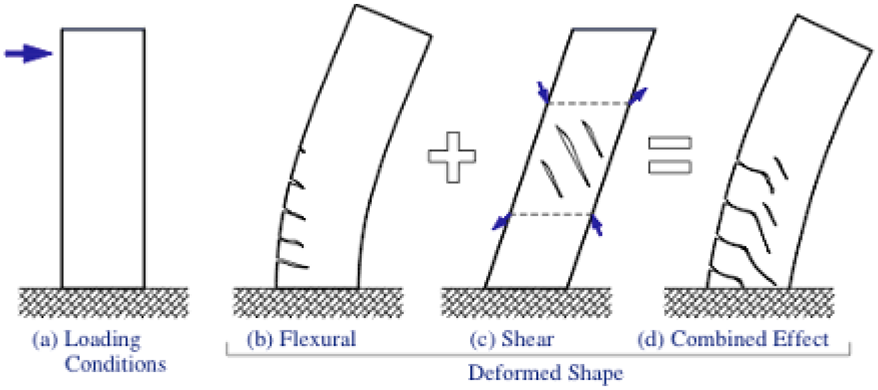


Fig 112: How flexural and shear deformations can be seen in a structural element (Roselli, 2011).

In further research, realistic damage cases can be modelled. Flexural damage of the structural elements and shear failures (Pitilaki, 2019) can be investigated. In Fig 112, how these effects can be encountered in a building.

One approach may be increasing the momentum area of inertia of individual elements, to increase lateral load bearing capacity. This can be done by adding flanges to the sides of the walls in the impact direction.

This would strengthen the weaker section of the wall and make the cluster safer, by distributing the diagonal forces in two perpendicular directions, as can be seen in Fig 113.

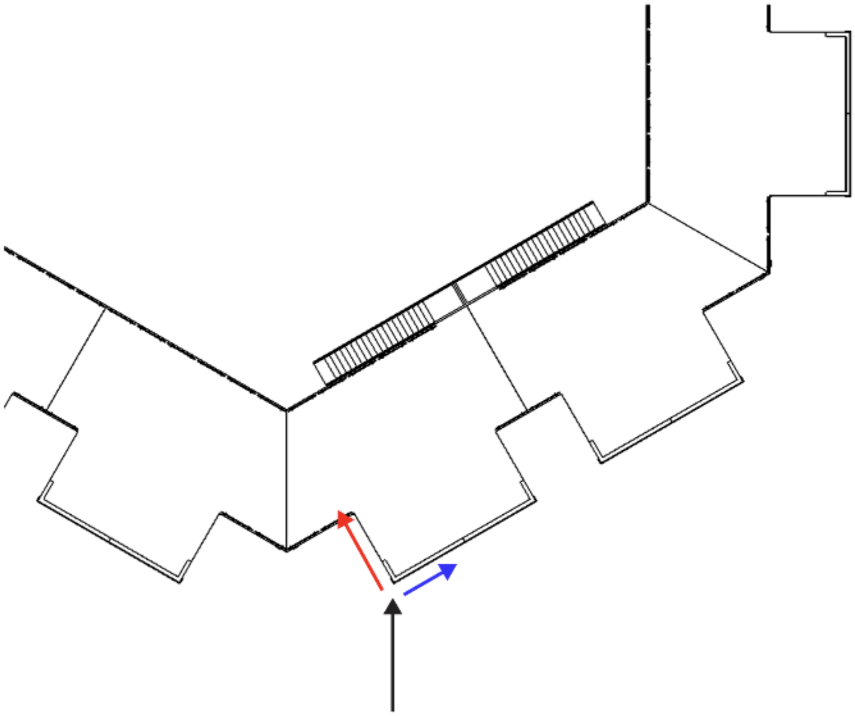


Fig 113: The clusters can be made safer by increasing the lateral load bearing capacity of the protective walls.

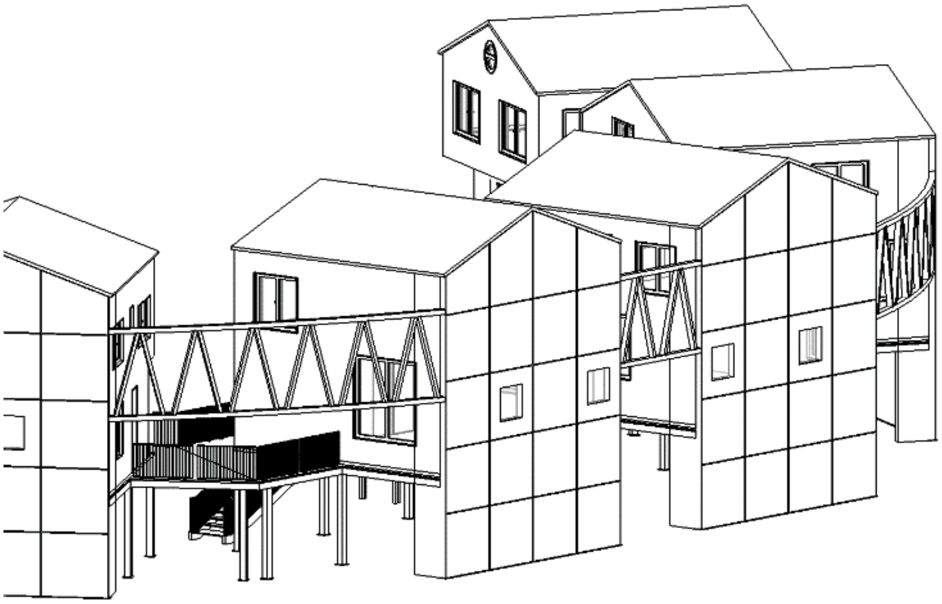


Fig 114: Walls can support each other if they are connected by braces.

Another approach may be connecting the walls together with braces to make them act as complete ring. By doing this, the forces which a wall takes in its weaker direction can be transferred to the other walls, as can be observed in Fig 114. However, the rings are difficult to close in the joint clusters. In such a case, the walls themselves can be strengthened by complementarity, as in the previous example Fig 113.

Thermal comfort aspects

Thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment (ISO 7730:2005). Freeport is a city which needs cooling around nine months a year. From March to November, the temperature of the air exceeds 31°C, while the comfort level is 26°C as seen in Fig 115 (Meteo Blue, n.d.), and this situation necessitates solar protection both in the site-scale and the building-scale.

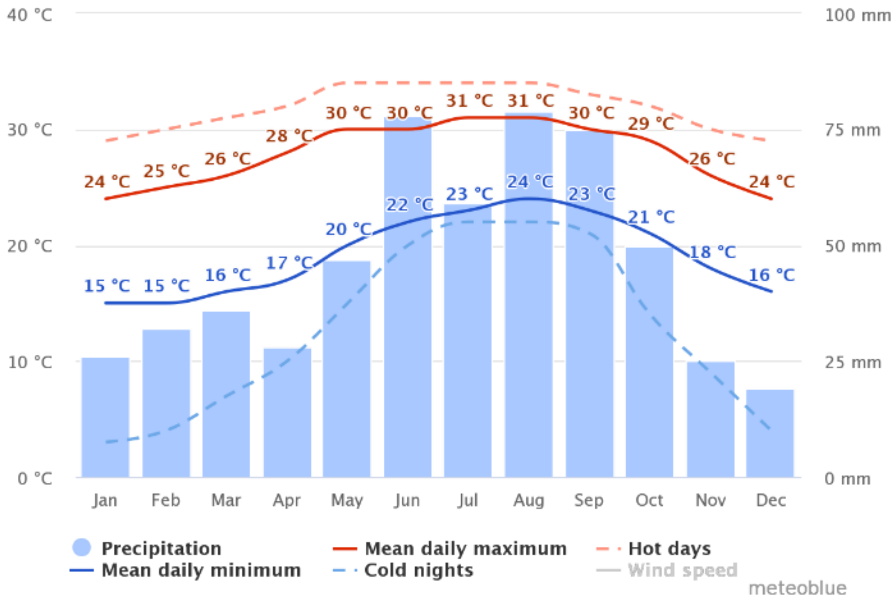


Fig 115: Freeport modelled climate graph (meteoblue.com, nd.).

Fig 116: Courtyard cross-ventilation diagram.

Cross-ventilation in the courtyards

In fluid dynamics, the velocity of an incompressible fluid must increase as it passes through a constraint in accordance with the principle of continuity of mass, whereas its static pressure must decrease in accordance with the principle of mechanical energy conservation. Thus, restricted longitudinal sections tend to create a wind tunnel effect. This is called the Venturi effect (Felföldi, 2019).

This effect can be beneficial in summer by increasing the human skin surface heat transfer coefficient and increasing the thermal comfort levels. A simulation was made using the Autodesk Flow Design software to explore the benefit of different accumulation styles. As a benchmark, an accumulation with 4 courtyards was tested as Option 0, as can be observed in Fig 117, this option would not let wind inside the courtyards, thus neither assist the ventilation of the courtyard, nor the houses.

To overcome this issue, the houses in the predominant wind direction can be cancelled out, which blows from the East, South-East and North-East in Freeport. Several options were tried to explore the cross-ventilation opportunity. These options can be observed in Fig 118. Option 1 is a simply edited version of Option 0. However, the solution is quite effective. For the sites which require different architectural massing due to roads, trees etc. Examples such as Option 2 and Option 3 can be used. However, if a clear escape for the air flux is not placed in the leeward side, as Option 4, cross-ventilation opportunities may be lost.

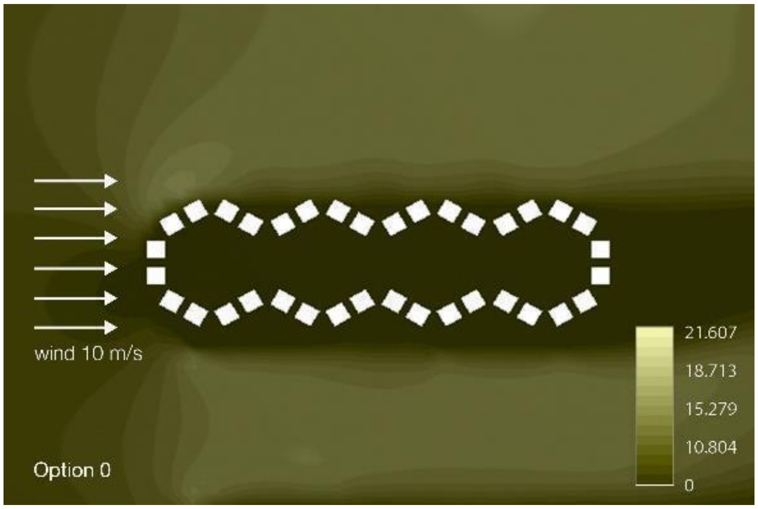


Fig 117: Option 0; Wind flow diagram of closed clusters.

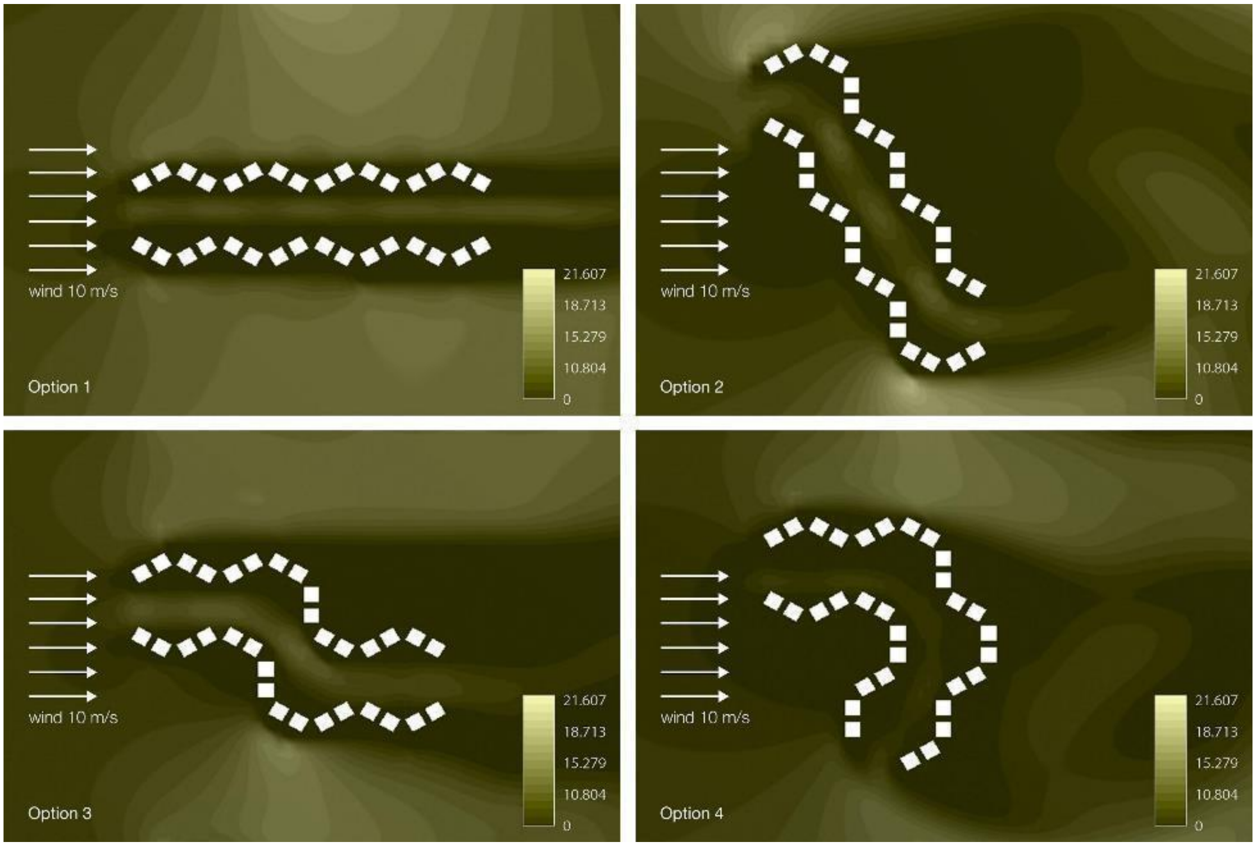


Fig 118: Option 1,2,3, and 4 Windflow diagrams of different cluster configuration trials.

Ventilation in the buildings

As well as the outdoor thermal comfort, indoor thermal conditions should be considered to achieve a holistic climate approach. Since the indoor air temperature can be in an uncomfortable range in summer on the Grand Bahama Island, ventilation and air conditioning is necessary to obtain a comfortable living environment.

Cross ventilation is a method for naturally cooling the building. It is also called wind effect ventilation. This is a wind-driven effect where air is drawn into the building on the windward side with high pressure and is dragged out on the low-pressure leeward side (Designing Buildings Wiki, 2018). The cooler outdoor air is let into the building through an opening such as a wall hatch or a window. The outlets let warmer indoor air outside through a roof vent or a higher window. An illustration showing the air movement in buildings with window openings and roof vents can be observed in Fig 119.

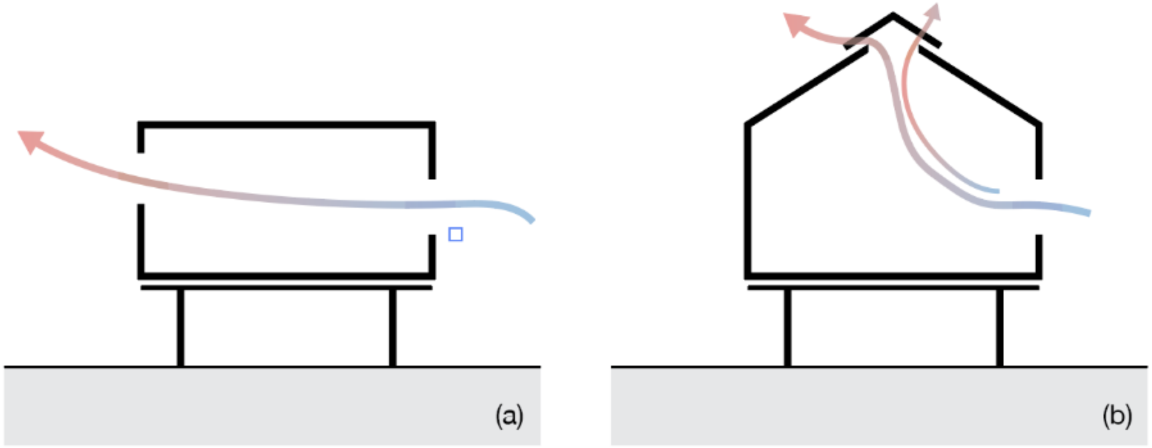


Fig 119: Cross ventilation in buildings with window openings (a) and roof vents (b).

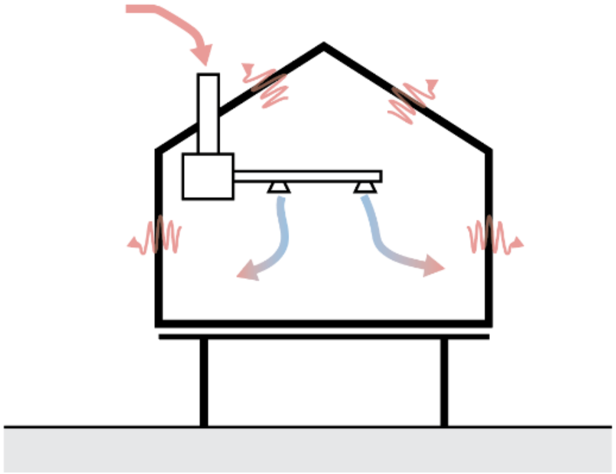


Fig 120: Supply ventilation systems in the housing units have the ability to filter, dry, heat or cool outside air before it is introduced

Mechanical ventilation strategies can be classified as exhaust, supply and balanced ventilation. Exhaust ventilation is forcing the indoor air out and so drawing outdoor air in. This is the most affordable mechanical ventilation strategy. However, exhaust ventilation is not recommended for hot and humid climates. Humid air entering the building cools off as it works through the wall, potentially resulting in condensation inside the construction. Furthermore, there is no way to filter or pre-condition the outside air before it is introduced into the home.

Supply ventilation systems have the ability to filter, dry, heat or cool outside air before it is introduced. These systems can be preferred in the housing units within the project. The illustration of this system can be observed in Fig 120. The main drawback with fresh air ventilation is that the hot and humid air drawn into the building increases cooling loads. Thus, dehumidification systems work well as a supplement.

Most of the balanced systems use a heat recovery ventilator (HRV) or an energy recovery ventilator (ERV). These systems push air out of and into the building simultaneously. The two airstreams are put through an exchange for heat (HRV) or heat and moisture (ERV) exchange. Tempering the outdoor air with the conditioned indoor air reduces operating costs. However, these are expensive units and lack the ability to mechanically remove moisture (Therma-Stor, 2020).

Solar energy generation

The world energy consumption rate which was calculated as 13,5 TW is projected to more than double, 27.6 TW by 2050, and 43.0 TW by 2100 (Tsao et. al., 2006). To obtain this much power by using fossil fuels is challenging in terms of carbon neutrality and the remaining resources (Tsai & Lee, 2019). According to the MIT physics professor Washington Taylor, "A total of 173,000 terawatts of solar energy strikes the Earth continuously, which is more than 10,000 times the world's total energy use" (Chandler, 2011). Considering these facts, employing solar energy generation methods in the BBB concept is sensible.

Photovoltaic energy

Photovoltaics (PV) is a technology that utilizes semiconductors to convert solar radiation into direct current (DC) electricity. When the sun reaches the semiconductor inside the PV cell, electrons are released and formed into DC (Isabella et al., 2016).

PV is normally used on a panel. Typically, PV cells are found interconnected and mounted in a frame called a module. Many modules can be connected together to create an array that can be scaled to deliver the appropriate level of power. The benefit of PV is the power generation varying from large consolidated arrays into smaller, localised production sites, such as residential rooftops. This transforms former energy consumers into prosumers, people who can produce their own electric power and consume it.

Concerns over solar photovoltaics have historically been about cost, intermittency and performance, but large-scale installation and rapid decline in costs have exposed more complex matters such as grid integration, lack of experience in the solar industry and the use of rare and precious metals in cell manufacture (Lehner, n.d.).

Solar thermal energy

Solar thermal systems (STS) gather thermal energy from the sun to increase a heat transfer fluid 's temperature. This fluid, such as water, air or a specially designed fluid can be used straight for hot water or space heating and cooling needs. The generated heat may also be stored in a storage tank for when there is no sun available. Solar thermal systems are also used to heat swimming pools and supply the commercial buildings and manufacturing facilities with hot water. In the case of STS cooling, a thermally driven chiller uses the warmed fluid to cool the air (Solar Heat Europe, 2017).

Water storage

An average person requires approximately 130 litres of water per day. Only 3 litres are used for drinking. Therefore, the remaining 127 litres have lower quality requirements. In case of self-sufficiency after a hurricane event the storage of salt contaminated water can make a decisive difference in the required infrastructure in order to sufficiently build back better. We propose to place a storage tank beneath each housing unit, which will provide enough water to supply the household during an extreme scenario until the public service of water supply can be re-established.

The water tank received the water coming for the gutters, meaning that most of the water storage here will be rainwater. Therefore, the tank will require a water treatment system per household. The ground floor is big enough to cover the needs of both elements.

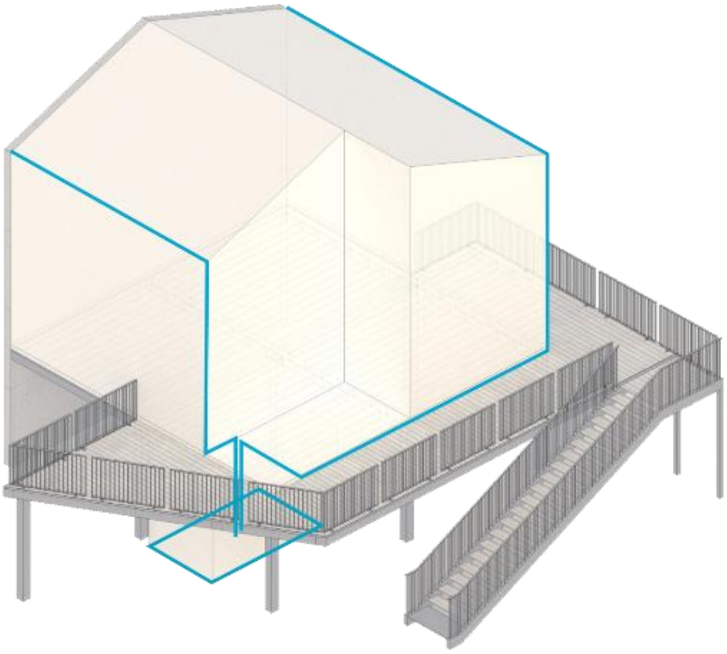


Fig 121: Water storage system on the ground floor.

4.4.4 Connecting scales: Case study airport, outer campus and harbour

Airport

Grand Bahama International Airport is a privately-owned international airport in Freeport, Bahamas. It has 4 terminal buildings and a single 11,000 ft or 3.35 km runway capable of handling the large aircrafts. This report believes that one of the strongest links of the chain of services in daily life and extreme situations is this airport. Different establishments located in the airport area should act as a whole in case of an emergency. In the larger scale, it must always be connected to the hospitals, fire-fighter stations and the defence forces.

The airport is outside the area that is protected by dikes which means that that airport should have his own flood protection against storm surges. There are several ways of protecting the buildings and the airstrip. One possibility is to build a dike ring around the facility. This dike prevents the whole area from getting flooded. Another solution will be lifting the whole area and creating a so-called mound.
When designing any of these solutions, a decision has to be made about the height of the dike or the mound. If the airport has to be protected for only small storms, then a low dike or mound is sufficient. But if the airport has to be protected against medium or large size storms then the dike or mound should be higher. The height of the dike or mound is related to the design storm. Here it must be taken into account that there is always a chance that there will be an even larger storm, which will result in flooding of the airport. With this in mind, it can be concluded that if the dikes fail to prevent flooding, the system will act as a bathtub and the water can't get away from the airport. However, if the mound gets flooded, the water can easily withdraw if the storm gets less intense. From this it can be concluded that a mound is preferred over a dike to protect the airport from flooding.

Fig 122: Conceptual design solutions of levee protection

Fig 123: Conceptual design solutions of raising the whole area

Fig 124: Conceptual recommended solution for the airport

Fig 125: Conceptual recommended solution for the airport

However, the airstrip does not need to be raised. In the current situation the airstrip is at a height of 6 ft above mean sea level. This means that if the airstrip gets flooded the storm surge is at least 6 ft. This only occurs if there is a strong wind. Which means that if the airstrip is raised to prevent it from flooding, the airplanes still cannot fly due to the strong wind. At the moment that the wind is weakening, also the storm surge will decrease. Recent floods have shown that the water is withdrawn within approximately 48 hours. So, it is recommended to only build the buildings on top of a mound and leave the airstrip at the same height. An additional advantage of this solution is that the airstrip can remain in use since it has to be closed if this is lifted.

Another important aspect is the design of the buildings. The buildings can be made wet flood-proof, which means that the building does not collapse and can maintain functionality even if the building gets flooded. For example, if the building has a second floor, people can shelter here and sit out the storm. Also, some medical provision can be stored here so injured people can be helped. An important aspect of these wet-proof buildings is that in case of flooding, the non-structural walls on the first floor can and will collapse. With as a result that the load and damage to the main structure is minimized. Of course, after the storm, these walls can easily be replaced.

Multiple Flood Risk Reduction solutions are combined in this solution. The buildings are placed on mounds. Which reduces the frequency of flooding and thus the exposure to hazards and is therefore a combination of strategy 2 and 3 of Flood Risk Reduction. Furthermore, the design of the building, including the organisation of facilities in the building, are optimized for daily-situation but hereby also supports evacuation and emergency operations in case a hurricane strikes. This is part of strategy 4 of the Flood Risk Reduction strategies.

Outer campus

The UB North Outside Campus is an important investment for education in Grand Bahama. The aftermath of hurricane Dorian creates a bigger challenge, considering the design of a masterplan for its growth and its protection from the threat of future hurricanes. This campus was one of the most destroyed infrastructures on the island during hurricane Dorian. This caused severe traumas to all inflicted parties. Supported by the long-term plan of increasing the national importance of the Campus side, the following reconstruction proposal has been designed to respond to the daily conditions of its operation while having adequate endurance for the extreme scenarios.

The strategy is resolved in four scales of intervention: Island, Neighbourhood, Campus, and Building. Due to the distance from the city centre and the low elevation terrain, it has been decided that the campus is located in a less vulnerable region and consequently has to protect itself rather than protecting its entire vicinity as one unit. Consequently, the hazard of hurricanes needs to be tackled separately. The threat caused by hurricanes has been split in wind and water.

Firstly, the wind is one of the main two hazards a hurricane carries, where high speeds create great damages in physical infrastructure. Dorian registered a speed of 185 mph (BCC News, 2019), pushing the water from the northern bay of Grand Bahama, creating a strong storm surge, while impacting buildings in two different ways: differential pressure on facades and roofs, and different kinds of debris that impact the different surfaces. The Outside Campus was affected by the phenomena mentioned before, and the two buildings are in poor condition, therefore, the strategy adopted works with the remaining administrative building and disregards the residence building.

Secondly, water hazard - flooding, water refining, water storage - is expressed as a flooding hazard specifically for hurricanes with surge heights comparable to hurricane Dorian. Besides flooding hazards, the system needs to sustain water stresses during extreme and day to day scenarios. Therefore, the system is equipped with water storage and water refining facilities involving reverse osmosis and rainwater harvesting to offer sufficient water access. The general quality standards are split in drinking water and household water causing separate storage facilities.

For the island scale, we conceive the university as the meeting space for East Grand Bahama, becoming a demonstrator of the most appropriate intervention to respond to daily and extreme scenarios, creating a stronger sense of community and increased social cohesion between neighbours, and working as a shelter during hurricane extreme conditions. The measures of natural hazard reduction from the sea towards the campus are stated in Fig 126 and Fig 127.

The neighbourhood scale defines a protection area towards the northern bay - the shallowest and therefore the largest threat - with the implementation of mangroves, reducing the possible wave formation.

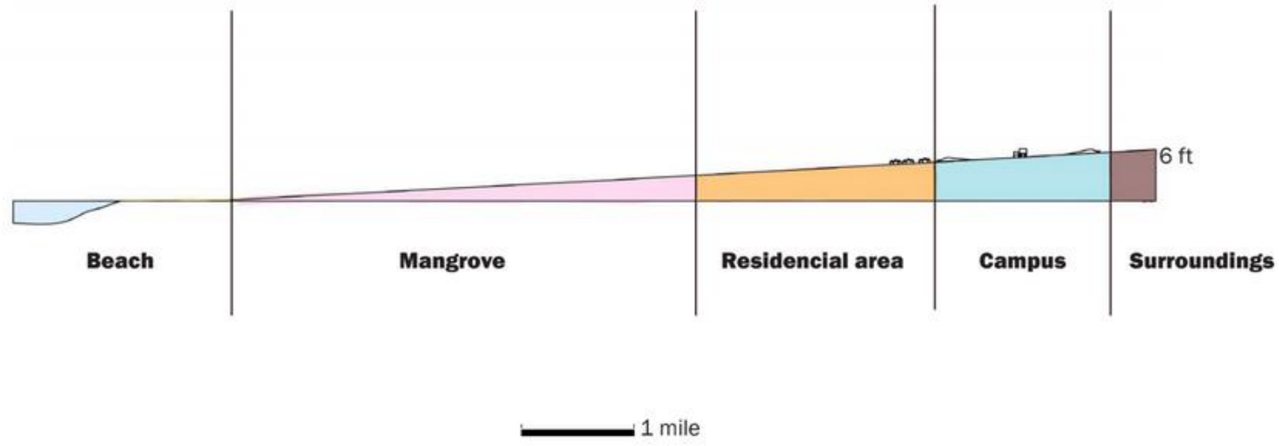


Fig 126: Indication of natural risk reduction measures, crosssection

The campus scale is defined as a masterplan, which will be developed in four main stages, as the academic community grows over time, see also Fig 128. The first - and main - intervention in the existing campus is a ring levee, a structure that provides complete protection to the inner infrastructure. Secondly, the introduction of a forest of a native species, Pinus caribaea var. Bahamensis aims to reduce the waves that surpassed the ring levee.

Thirdly, the campus infrastructure is conceived as a modular growth of spaces over time, with a hexagonal building that allows different configurations and adaptations as the campus grows.

Consequently, this takes us to the fourth scale or design, the building scale. The hexagonal module reduces the extension of facade surfaces, compared to the existing buildings with orthogonal shapes. These buildings are lifted from the ground floor level, allowing water to flow in case of surge.

The applied strategies in this case are quite apparent. The change in flow by construction of a ring levee responds to requirements determined in strategy 2 of Flood Risk Reduction namely to change the land level. Strategy 3, the improvement of building exposure is obtained by lifting the campus on pillars. Strategy 4 was realized by determining vital infrastructure and sufficient shelter during and after a hurricane event. This was supported by improving the social cohesion and consequently the ability to adapt as a community.

Fig 127: Indication of natural risk reduction measures, aerial view

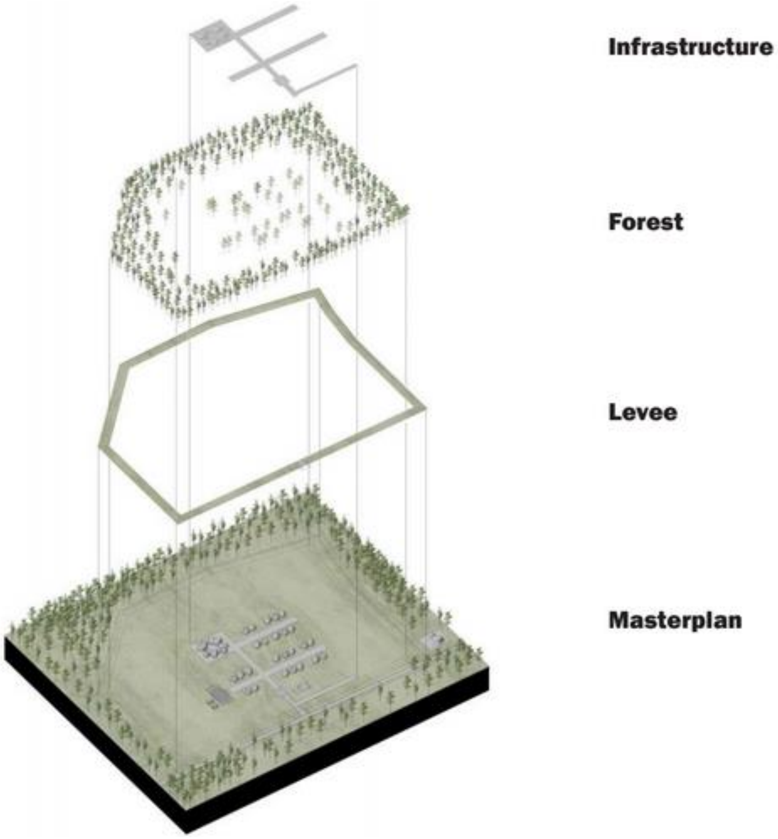


Fig 128: Indication of different layers on campus scale

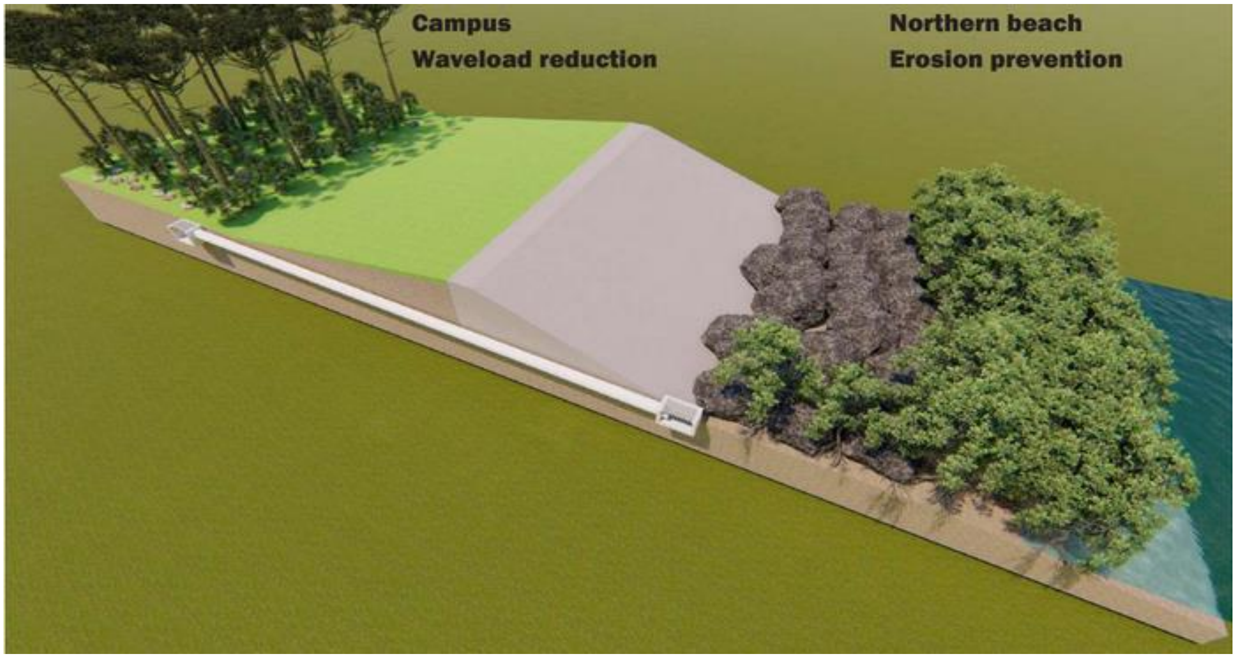


Fig: 129: Proposed ring levee for the outer campus

Preliminary proposal for the Harbour

The harbour is one of the most important economic actors on the Grand Bahama island. It needs to be protected with individual protection measures, because of its proximity to other actors. Fig 130 shows a preliminary design of a solution imagined for the harbour. In that area there is already some highland, protecting the harbour from the north. With this intervention, the holes between them are closed, so that the harbour area is fully protected. The canal that starts in the northern part of the island and meets the harbour waters is closed, but the bridge that is built above it allows the water to flow underneath, through the existing canal. Therefore, it is recommended to build a storm surge barrier that closes during a flood.

The harbour plays a major role in the recovery phase after a hurricane event. In fact, basic needs such as food and water arrive through the harbour into the city. Therefore, this project envisions some critical infrastructure starting from here and leading towards the western and eastern part of the island.

Another important aspect of this design is the bridge crossing the canal on the northern part of the site. Looking again at the space syntax analysis, it can be seen that the areas in the western part of the island are poorly connected because the bridge is the only connecting point. This can be visible in Fig 131 and 132.

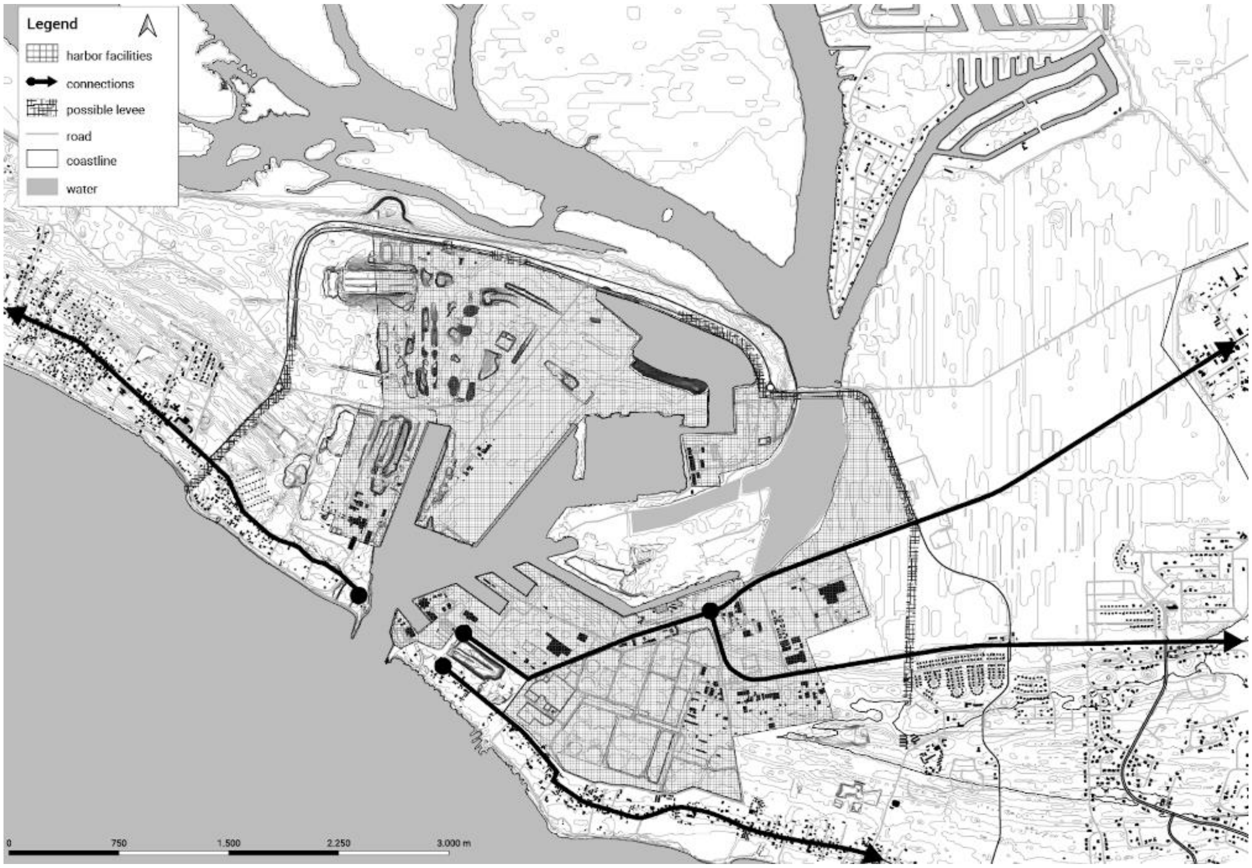


Fig 130: Key interventions for the harbour area

Fig 131: The poor connection towards the west, zoomin depicted in Fig 132

In the space syntax analysis, the western part of the island seems very poorly connected to the central area because the bridge is the only connecting element.

Fig 132: Existing bridge on the northern harbor area, zoom in on figure 131.(source Googlemaps 2020)

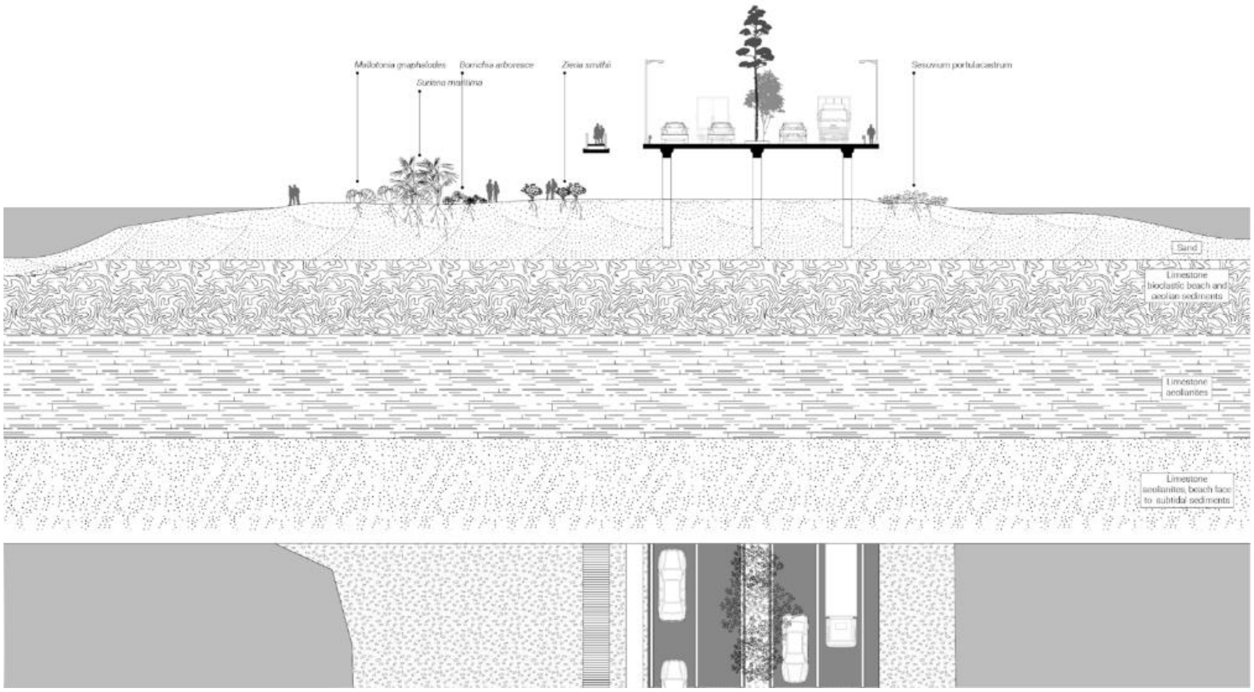


Fig 133: A preliminary design proposal for the bridge, crosssection and aerial view

The previous drawing, Fig 133, depicts a conceptual proposal of the new bridge. This project needs to be further developed and the precise characteristics and hazards of the area need to be defined.

The dimension of the height of the bridge is very important here. In this case it is designed to endure events such as hurricane Dorian. The height has to be at least 1.5 times the water depth, due to the storm surge. Next to this height also a safety margin of at least several feet is highly recommended. For this site, the exact storm surge levels are not available.

In this solution of the harbour, the Flood Risk Reduction is addressed by installing a levee on the northern part of the area. Furthermore, adaptation is addressed as well with the introduction of evacuation plans and plans and for the fast recovery of the area and of the critical routes that connect it with the main urban area.

5 Evaluation

The results presented in this report show how different disciplines interact with each other on their own scales. By consciously taking steps to integrate goals and products of the separate disciplines the design conditions were created to optimize the solutions.

The exchange between the disciplines is prominent in the construction of the strategy that consists of a collective and an individual scheme. By creating a collective area with a dike system, the basis for urban development was laid out and unique opportunities on the building scale became possible. The collective area has different design conditions than the individual area outside the levee system since the risk is reduced.

An example of an interdisciplinary in the collective system was the dike height. A lower height of the dike will reduce the environmental and daily-life impact and will reduce the cost of the dike. On the other hand, it will result in more overtopping water and thus more water in the protected area when there is a large storm surge. This additional water has to be considered in the management of emergency services and the design of critical infrastructure and buildings. So, there is a balance between the size of the wadi and the height of the levee. If the height of the levee increases then there is less overtopping and the size of the wadi can be smaller. Due to environmental considerations, it is chosen to minimize the salt intrusion and thus the overtopping by lifting the levee to the 20 ft elevation. The interaction of the disciplines made it possible to name these potential critical aspects and to optimize the design.

In the individual area outside of the collective zone, the protection is based on coping with flooding rather than preventing it. Which results in increased small scale and individual solutions, shifting the focus more towards the urban and building scale. For the buildings this resulted into clustering of the buildings and creating a raised platform. Individual roads will be lifted, these roads are required for the evacuation of areas which are very prone to flooding. At some point the interventions are not practical on a daily-basis or not feasible. For example, there is a limited height of the platform at the buildings which people will use in daily life. With this kind of scoping, urbanism and architecture are prominent compared to hydraulic and water management, but still combining the different approaches resulted in new and more optimized solutions.

In conclusion, changes in aspects of one specialisation can affect the outcome of other solutions. By varying and implementing different kinds of solutions it is visible how the different disciplines affect each other. With this insight the solution can be optimized.

6 Discussion

In this section the reflection and discussion of the proposal and its limits are presented. On the larger scale, the constructability of the levees, the connection of the pipe network with the wadi, the variant of dikes, and the usage of mangroves and trees plantations is elaborated on; on the architectural level the constructability of the proposed module, and the uncertainty on the social conditions generated by the space created is reflected on.

6.1 Change in culture

This project is part of an academic explorative research in which the learning aspects are considered most valuable. Not only for the students and staff involved, but also for the case that is in a recovering phase and eager to explore how to change their way to make the storm events part of strengthening the community.

With the start of the project, when every discipline had to indicate what extreme outcomes it could bring, this projected an extreme result and outcome. The use of an extreme scenario is done for the sake of the research and testing of the interdisciplinary approach, has been useful to investigate boundaries. It is a road of change in planning, design and engineering accompanied by other financial models. Therefore, it is diverting from current reality in the context of Grand Bahama but contains applicable solutions that endorse change towards Build Back Better.

The protection structures of the levees have an important impact on both the natural environment and on the urban fabrics and life. Protection on the smaller scale, the individual protection measures could be applied to this context as well, which is a scenario that is close to the current reality of this island. Although, this moves the financial responsibility from the government to the private part. The most vulnerable communities of the island, both in economic and social terms, would in this case also become the most exposed to the hazards arising from hurricane events and floods.

Therefore, the strategy for Building Back Better in which the collective and individual approaches are made cooperative and depended, is an important foundation for resiliency.

Furthermore, the project beholds the proposition for a transition towards more socially and environmentally sustainable communities, mainly by promoting the use of modes of transportation that are different to the exclusive use of cars that exist at present. In this sense, the urban plan proposed directs future urbanisation towards a higher density in the proposed protected area. By doing so, it also takes into consideration the transportation of these areas. It is expected that a higher density and smaller distances between the communities, functions and activities will lead to a different use of the transportation space: by bike or walking.

6.2 Constructability of the levees

Dikes can and have a large impact on their surroundings. They may divide the communities and function as a border, which is not difficult to cross but still divides the land socially and visually. In the Netherlands there have been studies conducted on the impact of dikes on their surroundings, the social fabric (Feddes, 1988). It is recommended to look at the placement of a dike not only in its function as a protection, but also with respect to its impact during the rest of the year. We tried to minimise the negative impact of the dike or levee with integration of other functions, like using them as foundation for roads.

Levees require long term commitment, not only for the construction, but also for maintenance by the local authority. Support of the inhabitants is also important. In the Netherlands it is common practice to pay for safety directly, which depends on location. It is not clear whether this is a viable financial model on Grand Bahama, or whether the commitment and the impact of dikes on the society is fully comparable, thus further investigation is needed. Nevertheless, it would be helpful to find a financial model in which the individual advantages of the measures would be supported by society as a whole.

For the Island of Grand Bahama this does not represent an unwinnable issue. The island in fact, has an urban environment with a very low density. As a consequence, only a few buildings would have to move to other locations. During construction of the dikes, the inner area is unprotected. Therefore, it is recommendable to shift the construction period to the non-hurricane period of the year. This also means that if the dike isn't finished before the hurricane season, it is possible that the collective protected area is unprotected. Stressing again the importance of the commitment. As the levee system is failing when there is a gap during the construction phase the area gets flooded as if there was no dike at all.

6.3 Connecting the pipe network with the wadi

The connection between the wadi and the sewage network is designed as an open overland flow, which is effectively an open sewage. This can have negative consequences and might be difficult to implement. Although, it can be argued that this drain only stores stormwater and non-contaminated (black & yellow) water. When the wadi is in use for its designed function, it can be assumed that the area is already polluted due to the hurricane.

6.3.1 Variant to dikes

The focus of the project is on the placement of dikes as a flood protection. However other interventions can also be placed on the same location. This can for example be a concrete wall. Since the dikes can be made of soil that is locally available, not a lot of material has to be imported from outside the island, which will reduce the investment. If the wadi has to be dug, the released soil can be used for the construction of the dikes. An important point of attention is that the core of the levee has to be impermeable Since limestone is permeable, perhaps cementation of limestone may be a solution. The solution may lie in alternation of different structures. Which can even be temporarily installed if a hurricane is predicted. The choice of the solution can be based on the spatial possibilities, the effect on the environment, the constructability and aesthetic considerations.

The solution may lie in alternation of different structures. Which can even be temporarily installed if a hurricane is predicted. The choice of the solution can be based on the spatial possibilities, the effect on the environment, the constructability and aesthetic considerations.

6.3.2 Usage of mangrove and trees in levee related flood protection

This study didn’t include a full analysis of the usage of mangrove or other trees in flood protection. Trees reduce the waves, but they don’t stop the volume of water and debris from the storm surge. A low dike stops the volume of water from the storm surge (to a specific level), but doesn’t stop the largest waves, which overtop and thereby cause flooding behind the dike. A combination of the two interventions mitigates the risks but can have unwanted side effects which have to be taken into account. So, does the trees increase the roughness, which may enhance the set-up. Next to this, the waves are reflected from the dike back to the forest. The incoming and outgoing waves interact with each other. As a result, the flow velocities increase. Since the mangrove forest lives on a muddy soil, the bed can erode easily and this negatively affects the health of this forest. So, a mangrove forest is probably not the most convenient protection with respect to wave height reduction in front of a levee-system.

Other trees, like the native pine trees, can potentially be used. These can live outside the mud coast, which is also needed since the area in front of the dikes is generally not under water and therefore cannot offer living space for a mangrove forest. Trees growing near a dike also result in additional maintenance of the dike. Saplings growing on top of the dike must be prevented since the tree's roots can undermine the stability of the dike. For example, the uprooting of large trees during an event can create a point of weakness that may eventually lead to failure of the dike during strong wind. Next to this, trees may change the biodiversity which could lead to animal burrows inside the dike, which thereby reduces the strength of the levee.

6.3.3 Limitations of conceptual design

The sewage network designed in this study was done in order to estimate the impact of rain during a hurricane event. Since no information was available with respect to the current infrastructure such as current sewage network or the available infiltration capacity, calculations could only be considered at a very conceptual level. In order to execute more detailed calculations, additional information is needed. Additionally, the proposed network and the wadi drainage solution were evaluated independently from each other. Consequently, drainage directions in the network are not adjusted to the preferential flow path of the wadi. The harbour plays an important role in Grand Bahama. The conceptual interventions to protect the harbour and the critical infrastructure are not optimized. This is a study in itself, in which the hazards that threaten the harbour must be precisely analysed. The impact on the harbour and society due to a failure of the interventions could be larger than in the situation with no intervention. Therefore, further improvements in the design of the interventions are needed. Also, the feasibility of the different aspects, like the flood defence near the bridge, need to be examined.

The proposed module complies with the main spatial requirements that the current situation demands, namely the response for emergency scenarios of flooding, sea surge, and debris during a hurricane, while performing adequately on the daily life of its residents. Nonetheless, we acknowledge that a thorough analysis of the structural conditions and the construction process are required. Firstly, the outer concrete wall aims to protect the housing units from the surge and debris, but the specific thickness and specification for its construction is not developed further, as the main goal of this stage of the document is to speculate and provide possible solutions and open the floor for further discussions on the field of architecture and its responsibility within these scenarios, rather than providing an ultimate solution for Grand Bahama.

The model should be put into experimentation, to evaluate its real performance with wind and water hazards. Furthermore, the selection of wood for the main skeleton of the house responds to a fast system, besides being a common construction material of the island. We acknowledge that another aspect to take into account will be the economic feasibility of the units, therefore, some materials will be changed.

6.4 Looking back on the BBB framework

The report has analysed the external or internal factors that provoke or amplify the damages of the urban and natural environment on a building scale, urban scale & natural scale. The project then proposed a design solution of the elements which have the power to lead the physical and governmental dimensions of the island towards a resilient reality, allowing eventually the mitigation of negative impacts of extreme natural phenomena. In the chapter methodology Table 1 depicted the concepts and scales mentioned of these methodologies, and the relation between them. These relations gave life to the framework of Building Back Better that this research proposes. This all came together in an Interdisciplinary design composed of vulnerability, multi-layer safety approach, flood risk reduction tactics and resiliency values.

The key aspects of BBB addressed in the report are:
Damage of buildings, prevention of damage and casualties in case of flooding, raised buildings, damage on the built environment, higher population density and exposure to flood risk, collective and individual scale protection, evacuation routes & all the four flood risk reduction tactics. These aspects together gave the points of contact and conflicts among the involved disciplines. These aspects also gave an overview of the relationship between scales and involved disciplines. The concluding design was a systemic and holistic attitude towards the problem and a balance between tactics

This report couldn't detail all the aspects mentioned in the framework. The preparedness for future flooding and the required communication with the residents is an important aspect which could not fully be exploited. Providing information can help people to understand the situation and could improve the willingness and preparedness to evacuate in case this is required. This evacuation should be planned and documented to improve the emergency activities.

Aspects to improve fast recovery of economic and social systems are also not elaborated in depth. To optimize this for Grand Bahama it would require the corresponding specialization and a longer stay on the island. This is now partially realized due to the concrete wall in the proposed design of the individual buildings, however not all buildings are provided with robust elements.

Damages to the island ecosystem due to flooding are not thoroughly researched in this report. It is suspected and suggested by this report that the ecosystem can support flood mitigation, though salt intrusion and the ground water level might make it difficult for the ecosystem to sustain itself and be supportive. Thus further research is needed on how to resiliently implement a supportive ecosystem.

The report focuses on the mitigation phase and doesn't focus on the preparedness phase in the case of a hazard. It is recommended that if this plan gets implemented further attention will be given to the aspect of preparedness, meaning possibility of evacuation and usage of portable resources.

7 Conclusion

The island Grand Bahama lies in an active hurricane region, and the island is not fully recovering from recent hurricanes, especially Dorian, which resulted in a decline in population and loss of social and economic opportunities. Through Building Back Better, this decline can be addressed by laying the foundation for a more resilient society that can have an improved future prosperity by being prepared for the effects of natural hazards. By reducing the frequency of flooding and damage that must be repeatedly rebuilt while also acknowledging the needs for daily life, the interdisciplinary design focuses on the wind and water hazards produced by hurricanes. Due to the local bathymetry, a storm surge can (only) occur from the north. The position of the hurricane has to be such that it will result into a wind towards the south. The south of the island is threatened by large waves which hit the coast, but will not result in severe flooding. Other hazards are high amounts of rain and a high decline in air pressure.

The Building Back Better strategy consists of a main shift in approach, to a new paradigm in which creating a collective protection in the core of the island to secure the social and economic base of society and for a safe haven for the areas that have to use the individual protection measures. The shift in approach is characterised that a clear choice is made for a core stability where government intervenes in balance and relation with the zones outside.

This Build Back Better strategy is the result of the interdisciplinary approach where the different disciplines interact with - and affect each other on their corresponding scales. Due to this interaction the different disciplines can integrate goals and complement each other in such a way that conditions are optimal and boundary conditions stretched. As the disciplines work together, the proposed strategies and designs allow to prevent potential damage and argue for a strategy in which collective and individual protection measures applied to the key actors of the economic system of the island (airport, harbour, industrial areas), allow a fast recovery of the community after a hurricane event.

When adopting the Building Back Better concept and use the three-point approach, the collective area was determined and three differing rain and storm surge scenarios were applied to measure the performance of the current and the improved infrastructure. The locally differing measures to reduce the flooding threshold and corresponding levee requirements can be summarized by construction of dikes up to 20 ft above mean sea level. Multiple zones can be made: the inner-city zone, which can be protected for a storm surge and a large amount of precipitation; the west-zone: industrial area that has a very low ground level, here a storm surge will result in very large waves that go over the dike and will flood but people can evacuate towards the safer inner-city area.

The levee system protects the inner city and the proposed expansion area in the east for a Dorian-like storm surge. A larger storm surge is unlikely since a larger rarer hurricane also has to be in an unfavourable location for a long period. However, this can, and probably will, happen but less frequent. Increasing the height of the dike will protect against larger storm surges and reduces thereby the frequency of damages and the corresponding recovering. However, a trade-off must be made between reducing the chances of flooding and for example the impact on daily life and costs.

The levees also prevent the water from flowing out of the areas. To be able to drain the system measures can be taken like a pipe network to deal with rain events and a wadi system to deal with excess water that cannot be stored. This wadi system drains the inner-city area by connecting the low grounds south of the inner-city area, which will form a dry river, to the ocean.

Additional to collective water storage it is required to offer residential water storage facilities. This individually stored water is of high importance to sustain the required self-sufficiency of two days after a hurricane event. By doing so the failure of critical infrastructure is less severe and the overall strategy to let the system fail is not circumvented.

The inner city and the area in the east can be protected for Dorian storm surges, giving thereby also space for future developments and secure investments and social structures. To increase the acceptance of the local residents it is recommended to exclude as few people as possible and to raise the dikes to the same elevation.

Consequently, the architectural proposals respond to the two scenarios, where the protected area has a public ground floor occupied with public services and commerce, activating the urban layer of the project and increasing the levels of social cohesion while bringing economic profit. The non-protected area has a different ground floor, where water storage tanks occupy the space and store rainwater, in order to be used during the hurricane season in case of emergency. The height of the platforms will be dictated by the location of the module and is related to the desired level of protection against storm surge.

As a result of the adopted Build Back Better approach, every house in the zones outside the inner city should be built with a certain level of individual protection. If no collective measure is taken, individual protection should at least offer debris protection of the houses, and local area planning for a scenario where the communication with outside would be blocked for some time. For such a case, platforms are designed that are to be built by the government and offered to the citizens as raised plots for residential construction. The height of the platforms can be arranged depending on the designed flood level and the temporary ground floor functions.

Furthermore, these platforms can form clusters with protective reinforced concrete walls to preserve the community inside. Structural aspects of this concept should be studied further.

To contribute to the microclimate and the thermal comfort inside the clusters, wind direction was considered. In Freeport, the prevailing wind blows from the East, so wind entrances and exits were placed accordingly in the case study.

The context of Grand Bahama is significant in which the concept of Build Back Better can be further defined. The concept presents a significant importance of an overall vision for the future of the island, relevant for the normal state, but especially for the hazardous state that arises during hurricane events. The importance of a unified and coordinated system and systemic governance is crucial to approach the problems of the area in a holistic way. To do so, an interdisciplinary approach is necessary in which goals and measures are integrated and can serve for a strategic approach in which the exchange and interaction between levels of intervention can be balanced out. To Build Back Better means to oversee these levels and make strategic choices for a future in which the hazard will lead to strengthen the community.

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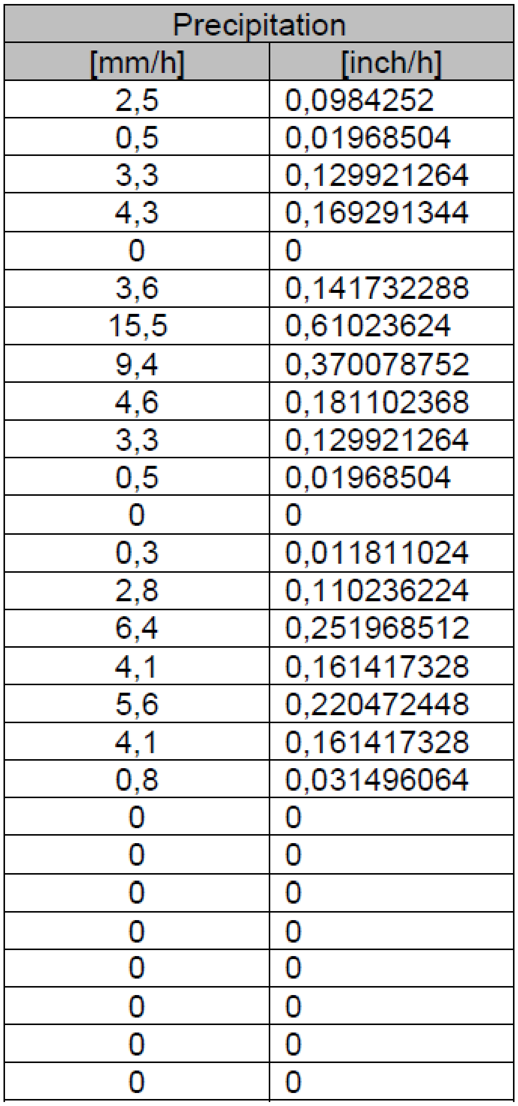
9 Appendix

9.1 The used normal rain event

To have a potent overview of a normal storm event, this study used a storm that has been abstracted from the hourly precipitation data from New Orleans and Galveston. This detailed data was used as the climate and latitude are similar to that of Grand Bahama.

Tab. 6: hourly precipitation event in New Orleans and Galveston



Precipitation	
[mm/h]	[inch/h]
2,5	0,0984252
0,5	0,01968504
3,3	0,129921264
4,3	0,169291344
0	0
3,6	0,141732288
15,5	0,61023624
9,4	0,370078752
4,6	0,181102368
3,3	0,129921264
0,5	0,01968504
0	0
0,3	0,011811024
2,8	0,110236224
6,4	0,251968512
4,1	0,161417328
5,6	0,220472448
4,1	0,161417328
0,8	0,031496064
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0

9.2 Overview of the Levees

Tab. 7: Forcing’s applied on the particular levees

Levee	Length (m)	Forcings Dorian (l/m/s)	Forcings Double Dorian (l/m/s)
1a	64	-	-
1b	67	-	-
1c	1353	-	-
2a	190	0,5	60
2b	942	0,5	60
2c	65	0,5	60
2d	784	0,5	60
3a	1987	0,5	60
3b	141	0,5	60
4	4583	11,9	60
5a	481	-	-
5b	1972	-	-
5c	221	-	-
5d	42	-	-
5e	252	-	-

9.3 Outcomes Sewage Network

9.3.1 Setup Sewage Network visualisation

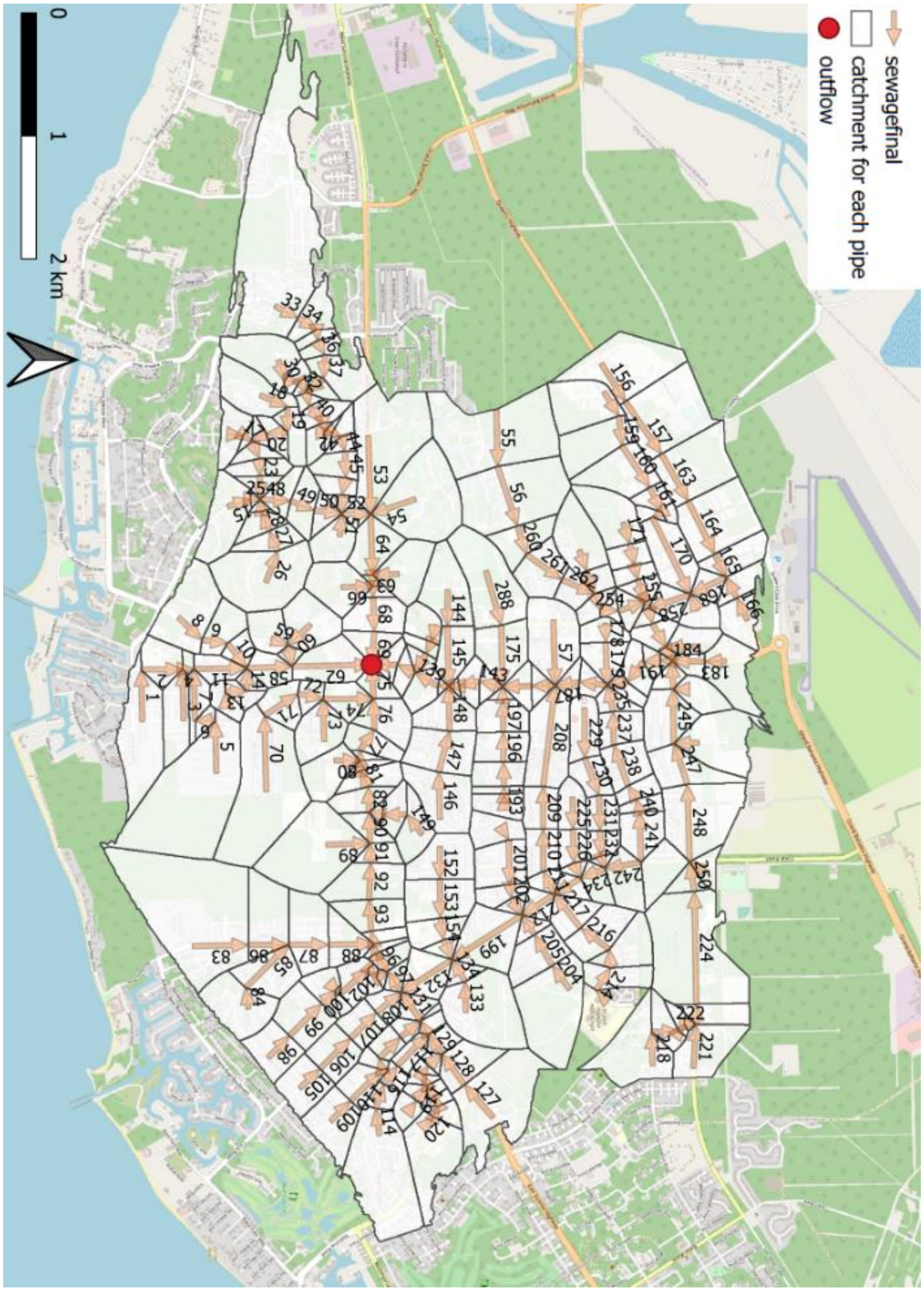


Fig 125: Setup Sewage Network

9.3.2 Sewage Network table

FID	connect FID	elev	length	pipestartlvl	surfslope	slope network	Pipe Diameter	velocity	deltaH	S: T=0,5	S: T=15	S: T=100
		m	m	m	-	-	m	m/s	m	m^3/ ha	m^3/ ha	m^3/ ha
1	2	8,54816892	424,2225476	8,548168927	0,00290642	0,001244317	0,8	1,473088452	1,172984833	400	1400	2000
2	4	7,3152	255,6900459	7,3152	0,002384137	0,001258974	0,8	1,481739112	0,715316614	300	1300	1700
3	4	7,17410338	159,7263264	7,17410338	0,002933163	0,004563467	0,3	1,467005245	1,168017944	800	2000	2700
4	11	6,7056	49,80678008	6,445197507	-0,008349035	0,002395631	0,5	1,494146806	0,226691897	150	650	850
5	6	5,44085278	310,9920244	5,44085278	-0,005404712	0,002944884	0,4	1,427613739	1,615257217	800	2200	2800
6	7	7,12167518	103,9398439	4,525017438	0,013673315	0,003186279	0,4	1,484972934	0,584103942	300	1300	1700
7	11	5,70047298	105,1558929	4,193836107	-0,013512943	0,000948838	1	1,492677984	0,238834391	150	650	850
8	9	5,37640380	228,6577892	5,376403807	-0,000481052	0,004326019	0,3	1,428329399	1,585084751	800	2100	2900
9	10	5,4864	350,0079219	4,387225822	0,001741675	0,002900748	0,4	1,41687529	1,790655856	600	1700	2300
10	58	4,8768	298,0084972	3,371941134	-0,003004599	0,002918796	0,4	1,421276235	1,534110481	300	1200	1600
11	58	7,12143857	262,7604986	4,09406015	0,005134876	0,001257087	0,8	1,48062777	0,733994598	150	650	850
12	13	5,96207387	232,6543559	5,962073872	-0,000575644	0,007060166	0,2	1,392507164	2,299360459	800	1800	2700
13	14	6,096	427,5721795	4,319495506	0	0,003948368	0,3	1,364560974	2,705235442	400	1400	2000
14	58	6,096	357,2536347	2,631283351	0,00090637	0,004110763	0,3	1,392340177	2,353298962	300	1100	1600
15	25	7,88809177	96,79629196	7,888091776	-0,001721534	0,00466353	0,3	1,483001278	0,723355036	800	2000	2700
16	17	6,92659813	241,3777537	6,926598138	-0,001609932	0,007207736	0,2	1,406984859	2,435438033	800	2000	2700
17	22	7,3152	213,2196663	5,186810967	-0,001506946	0,007401871	0,2	1,425806982	2,209274747	300	1200	1600
18	19	7,61563863	221,4429403	7,615638638	0,001356732	0,004488655	0,3	1,454930574	1,592781187	800	2000	2700
19	20	7,3152	208,5235575	6,621657664	-0,001410393	0,004495137	0,3	1,455980779	1,502021491	600	1700	2300
20	21	7,60930007	186,5342454	5,684315612	0,000731986	0,004539353	0,3	1,463124063	1,356846186	400	1400	2000
21	22	7,47275956	359,7835496	4,837570745	-0,000455138	0,00425296	0,3	1,416216974	2,451944465	300	1300	1700
22	23	7,63651062	91,35626657	3,307425758	-0,003155661	0,003198626	0,4	1,487847351	0,515378262	300	1300	1700
23	24	7,9248	151,3202219	3,015211229	0	0,003164476	0,4	1,479883508	0,84454546	300	1200	1600
24	48	7,9248	91,59617816	2,536362057	0,00515159	0,002384708	0,5	1,49073664	0,414992448	300	1300	1700
25	48	8,05472986	94,68697325	7,436679397	0,006355635	0,004668383	0,3	1,48377282	0,708328628	150	650	850
26	27	6,7056	97,84239153	6,7056	-0,001153262	0,004641322	0,3	1,479466011	0,727690627	300	1300	1700
27	28	6,81843788	88,42301055	6,25148198	0,001276114	0,003193945	0,4	1,486758289	0,498100566	400	1400	2000
28	29	6,7056	105,4873335	5,969063738	-0,005778893	0,003180855	0,4	1,483708537	0,591791205	400	1400	2000
29	48	7,3152	97,37248073	5,633523804	-0,001414507	0,003192339	0,4	1,486384518	0,548238565	150	650	850
30	31	7,3152	83,64087423	7,3152	0,00311898	0,004671394	0,3	1,484251191	0,626099149	800	2100	2900
31	32	7,05432580	147,4142085	6,924480517	-0,005904954	0,004577839	0,3	1,469313319	1,081378954	400	1400	2000
32	39	7,9248	353,9651114	6,249641992	0,000180241	0,004298561	0,3	1,423789189	2,438156492	300	1300	1700
33	34	7,3152	309,6048601	7,3152	-0,001968961	0,001815619	0,6	1,468869449	1,134890362	300	1300	1700
34	35	7,9248	197,1126107	6,753075479	0,006185297	0,001850103	0,6	1,482752984	0,736260948	300	1100	1600

FID	connect FID	elev	length	pipestartlvl	surfslope	slope network	Pipe Diameter	velocity	deltaH	S: T=0,5	S: T=15	S: T=100
		m	m	m	-	-	m	m/s	m	m^3/ ha	m^3/ ha	m^3/ ha
35	36	6,7056	176,3077694	6,388396787	0	0,001847427	0,6	1,481680067	0,657597373	150	650	850
36	37	6,7056	123,4217434	6,062681087	0,007772816	0,001862007	0,6	1,48751533	0,463974721	300	1300	1700
37	38	5,74626553	296,8570159	5,746265533	-0,003231638	0,001474972	0,7	1,467215636	0,93061096	300	1300	1700
38	39	6,7056	488,7246972	5,308409651	-0,002364114	0,001442363	0,7	1,45090611	1,498220923	150	650	850
39	40	7,86100098	251,428871	4,60349119	0,000645601	0,001502462	0,7	1,480825087	0,802889215	150	650	850
40	41	7,69867833	209,6384449	4,225728858	0,007644964	0,001508708	0,7	1,483899811	0,672222494	300	1300	1700
41	42	6,096	143,2725622	3,9094457	0,001574655	0,001513499	0,7	1,486254123	0,460873912	150	650	850
42	43	5,87039516	104,060094	3,692602827	-0,001391257	0,001520742	0,7	1,489806143	0,336338581	150	650	850
43	44	6,01516946	207,5364458	3,534354287	0,002971026	0,001499091	0,7	1,479163126	0,661240538	150	650	850
44	45	5,39857338	158,9387576	3,223238179	-0,000552581	0,001505822	0,7	1,482479889	0,508674993	150	650	850
45	46	5,4864	214,354972	2,983904722	0,002566597	0,001254956	0,8	1,479372653	0,597763977	150	650	850
46	47	4,93623707	187,5664205	2,714898629	-0,002933163	0,00125601	0,8	1,479993432	0,523498778	150	650	850
47	52	5,4864	87,2506585	2,479313404	7,01958E-05	0,001276619	0,8	1,492086423	0,247512807	150	650	850
48	49	7,45293403	82,97418717	2,317931917	0,001659962	0,001874842	0,6	1,492633497	0,314071925	300	1300	1700
49	50	7,3152	171,4918912	2,162368405	0,007109374	0,001513575	0,7	1,486291453	0,551676523	300	1300	1700
50	52	6,096	190,6789837	1,90280257	0,003229116	0,001503397	0,7	1,481285908	0,609275288	150	650	850
51	52	4,8768	294,9532446	4,8768	-0,002046004	0,006283713	0,2	1,313705926	2,59448096	800	2100	2900
52	64	5,48027537	489,5442143	1,616136304	-0,001420684	0,000906599	1	1,459075226	1,062376075	150	650	850
53	64	6,04146146	383,6380477	6,041461469	-0,000350074	0,002902738	0,4	1,41736136	1,96405593	800	2100	2900
54	64	6,7056	345,5204566	6,7056	0,001533446	0,002981139	0,4	1,436374804	1,816687896	800	2100	2900
55	56	2,48396117	369,7494295	2,483961172	-0,001525462	0,002307763	0,4	1,263782332	1,504953466	800	2200	3000
56	260	3,048	205,3989634	1,630666999	-0,002967883	0,002202662	0,5	1,432706578	0,859555148	800	2100	2900
57	186	5,13158851	195,074367	5,131588518	0,007556034	0,002306459	0,5	1,466075074	0,854817914	600	1700	2300
58	62	5,77219592	199,7350627	1,162698454	0,005492156	0,001259312	0,8	1,481938017	0,558927393	150	650	850
59	61	3,99859343	112,9491803	3,99859343	0,001378741	0,007431561	0,2	1,428663672	1,175016816	800	2100	2900
60	61	3,22248004	265,4542693	3,222480048	-0,002337072	0,003775283	0,3	1,334316714	1,605895579	900	2000	2800
61	62	3,84286572	317,0649687	2,220314989	-0,002625185	0,003773439	0,3	1,333990703	1,917183149	300	1300	1700
62	289	4,67521986	179,4357724	0,911169623	-0,007977697	0,001076693	0,9	1,482214296	0,446497989	300	1300	1700
63	65	5,52827011	176,3958255	5,528270119	0,003693229	0,004456024	0,3	1,449632571	1,259545664	700	2000	2600
64	65	6,17576315	363,1182847	1,172315842	0,003577245	0,00081838	1,1	1,477210954	0,73429651	150	650	850
65	67	4,8768	518,112218	0,875147225	-0,001176579	0,000711369	1,2	1,459502639	0,937526062	50	100	300
66	67	4,2672	231,3323102	4,2672	-0,00527034	0,006507949	0,2	1,336940456	2,107470083	800	2100	2900
67	68	5,4864	242,7946412	0,506578365	0,000507367	0,000736242	1,2	1,484799484	0,454699482	50	100	300
68	69	5,36321391	121,1424745	5,363213914	0,009047313	0,000743921	1,2	1,49252289	0,229238833	150	650	850
69	289	4,2672	408,7215634	4,2672	-0,004500629	0,000715871	1,2	1,464113673	0,74426379	150	650	850
70	71	4,8768	223,0414057	4,8768	-0,002733125	0,003017158	0,4	1,445025981	1,186882716	800	2100	2900
71	72	5,4864	88,22953604	5,4864	0,006909251	0,002372354	0,5	1,486870243	0,397668438	400	1400	2000
72	74	4,8768	441,7549349	4,8768	0,002450426	0,002109973	0,5	1,402238031	1,77086674	300	1300	1700
73	74	4,8768	482,2410296	4,8768	0,002244703	0,003549693	0,3	1,293836884	2,743045102	800	2100	2900
74	75	3,79431200	209,390798	3,164992589	-0,005169702	0,00178797	0,6	1,457642137	0,75585617	300	1300	1700
75	289	4,8768	201,5693155	-6,582158679	-0,006101643	0,000432251	1,8	1,490800969	0,253701036	150	650	850

FID	connect FID	elev	length	pipestartlvl	surfslope	slope network	Pipe Diameter	velocity	deltaH	S: T=0,5	S: T=15	S: T=100
		m	m	m	-	-	m	m/s	m	m^3/ ha	m^3/ ha	m^3/ ha
76	75	4,83198209	193,4716931	-6,491937792	-0,000231651	0,000466326	1,7	1,490553012	0,257747438	150	650	850
77	76	4,8768	324,4740499	-6,341996363	0,000138125	0,000462106	1,7	1,483793404	0,428360003	150	650	850
78	77	3,6576	144,4595662	-6,274618961	-0,008439732	0,00046641	1,7	1,490687386	0,192487056	50	100	300
79	78	3,048	84,75537136	-6,234937023	-0,007192465	0,000468194	1,7	1,493535052	0,1133653	50	100	300
80	78	4,37758512	701,7963784	4,377585123	0,001025917	0,002877498	0,3	1,164908212	3,235968378	800	2100	2900
81	79	3,88509512	183,7133594	-6,149474373	0,004556528	0,000465196	1,7	1,488745312	0,244153876	150	650	850
82	81	4,73200825	180,4144916	-6,065289092	0,004694263	0,000466621	1,7	1,491025153	0,240504624	150	650	850
83	86	13,4112	119,6984267	13,4112	0,060946621	0,002391711	0,5	1,492923855	0,543907122	300	1300	1700
84	85	14,6767332	500,5216431	14,67673322	0,007031869	0,004430138	0,3	1,4454158	3,55318806	800	2000	2700
85	87	11,1571306	180,670689	11,15713061	0,034761204	0,003178637	0,4	1,48319107	1,012868129	600	1700	2300
86	87	6,11598540	196,5449026	6,115985408	0,006304846	0,002325109	0,5	1,471990459	0,868225952	600	1700	2300
87	88	4,8768	155,0785203	4,8768	0	0,001502707	0,7	1,480945828	0,495293863	400	1400	2000
88	94	4,8768	350,2745709	4,8768	-0,001405383	0,00144406	0,7	1,451759148	1,075055053	300	1300	1700
89	90	5,31853640	241,150922	5,318536409	0,001831784	0,003019558	0,4	1,445600529	1,284270553	800	2100	2900
90	82	4,8768	215,9155008	-5,956380842	0,000670594	0,000504402	1,6	1,488807173	0,304910048	150	650	850
91	90	4,8768	262,5726094	-5,824398374	0	0,000502651	1,6	1,486220967	0,369510852	150	650	850
92	91	5,4864	122,0588224	-5,762357255	0,004994313	0,000508289	1,6	1,494531926	0,173696305	150	650	850
93	92	5,21411080	173,4154265	-5,674544757	-0,001570156	0,000506371	1,6	1,491709566	0,245848344	150	650	850
94	93	5,36906995	263,2142643	-5,542006449	0,000588719	0,000503538	1,6	1,487530821	0,371067037	150	650	850
95	94	4,8768	237,3204997	-5,399563672	-0,002074283	0,000600213	1,4	1,48573469	0,381435173	50	100	300
96	95	4,8768	190,6383003	-5,284682952	0	0,000602611	1,4	1,488699934	0,307629126	150	650	850
97	96	4,8768	196,7087368	-5,154067895	0	0,000664002	1,3	1,487363146	0,34122852	150	650	850
98	99	10,0401464	228,5529831	10,04014646	-0,005732741	0,004558168	0,3	1,466153044	1,669380147	800	2000	2600
99	100	11,3503816	167,8246872	8,998363624	0,030078509	0,003185374	0,4	1,484762037	0,942845553	600	1700	2300
100	101	6,30246530	211,3945161	6,302465305	0,006744098	0,003088442	0,4	1,461996605	1,151482776	400	1400	2000
101	102	4,8768	211,7947373	4,8768	0	0,003031123	0,4	1,44836637	1,132251827	150	650	850
102	103	4,8768	135,6355182	4,8768	0	0,003119698	0,4	1,469375861	0,746294488	400	1400	2000
103	104	4,8768	99,10644772	4,453658187	0	0,002360395	0,5	1,483117806	0,444441082	150	650	850
104	96	4,8768	117,919596	4,219727838	0	0,002349193	0,5	1,479594489	0,526298801	150	650	850
105	106	11,3467364	60,89596973	11,34673648	0,015358978	0,004726043	0,3	1,492907728	0,461173369	800	2100	2900
106	107	10,4114365	198,8760068	10,41143659	0,02926453	0,003164442	0,4	1,479875657	1,109951097	600	1700	2300
107	108	4,59142381	242,7640363	4,591423814	0,000883003	0,002972576	0,4	1,434310299	1,27274554	600	1700	2300
108	97	4,37706248	264,0183786	3,869789306	-0,001892813	0,002924047	0,4	1,422554249	1,361578969	400	1400	2000
109	110	12,192	107,6506301	12,192	0,030178168	0,004695354	0,3	1,488052779	0,809958905	800	2000	2700
110	111	8,94330120	673,4824958	8,943301204	0,004219568	0,003875076	0,3	1,351836858	4,182005651	600	1700	2300
111	112	6,10149617	335,6763713	6,101496176	0,003664442	0,002958819	0,4	1,430987497	1,751715008	300	1300	1700
112	113	4,87142968	176,6313959	4,871429688	-3,04041E-05	0,003073111	0,4	1,458363349	0,957349213	400	1400	2000
113	131	4,8768	132,4313502	4,328621871	-0,009206279	0,003123189	0,4	1,470197934	0,729480058	300	1300	1700
114	115	9,02170746	365,4296659	9,021707465	0,003396552	0,00229834	0,5	1,46349227	1,595679461	800	2000	2700
115	116	7,78050648	113,0778071	7,780506482	0,011667375	0,002376629	0,5	1,488209309	0,510583057	300	1300	1700
116	117	6,46118526	163,8124169	6,461185268	0,009671949	0,002345725	0,5	1,478501888	0,730048265	300	1300	1700

FID	connect FID	elev	length	pipestartlvl	surfslope	slope network	Pipe Diameter	velocity	deltaH	S: T=0,5	S: T=15	S: T=100
		m	m	m	-	-	m	m/s	m	m^3/ ha	m^3/ ha	m^3/ ha
117	130	4,8768	239,9639529	4,8768	-0,005080763	0,002268954	0,5	1,454106369	1,034425812	300	1300	1700
118	119	5,4864	290,2853586	5,4864	-0,000639915	0,006555173	0,2	1,34178232	2,663730321	800	2100	2900
119	124	5,67215784	188,6483652	3,583529235	0,004216087	0,007262819	0,2	1,412350798	1,917958474	600	1700	2300
120	121	5,57341387	489,0923952	5,573413875	0,000177909	0,002732231	0,4	1,375103366	2,356853569	800	2100	2900
121	122	5,4864	347,3437995	4,237100517	-0,001755033	0,002904025	0,4	1,417675376	1,779033572	800	2000	2700
122	123	6,096	131,8117885	3,228405553	0,001158655	0,003151835	0,4	1,476924857	0,732726761	150	650	850
123	124	5,94327560	343,3824521	2,81295651	0,003105795	0,002940837	0,4	1,426632559	1,78103872	150	650	850
124	125	4,8768	207,5131063	1,803124647	0	0,002291569	0,5	1,461335018	0,90345412	150	650	850
125	126	4,8768	313,742731	1,327594041	-4,09713E-05	0,002214236	0,5	1,436465812	1,319852044	150	650	850
126	129	4,88965444	124,9858578	0,632893526	-0,009651856	0,002345106	0,5	1,478306888	0,556866464	150	650	850
127	128	5,46293747	216,7583391	5,462937479	-0,000108243	0,003053363	0,4	1,453670194	1,167289523	800	2100	2900
128	129	5,4864	153,3973378	4,80109552	-0,003973993	0,003118914	0,4	1,469191205	0,843811545	600	1700	2300
129	130	6,096	289,9668203	0,339788386	0	0,001804576	0,6	1,464395562	1,056440048	300	1300	1700
130	131	6,096	349,2193055	-0,183478774	0	0,00123629	0,8	1,468329407	0,959370242	150	650	850
131	97	6,096	275,9149133	-0,615215129	0,004418754	0,001071588	0,9	1,478696193	0,683315965	150	650	850
132	97	4,8768	223,3115786	-4,914858835	0	0,00107119	0,9	1,4784212	0,552835709	300	1300	1700
133	134	4,2672	153,839165	4,2672	-0,001636183	0,004406685	0,3	1,441584683	1,086317984	800	2000	2700
134	132	4,51890905	75,33511695	3,589279255	-0,004750652	0,003176326	0,4	1,482651823	0,422033397	300	1300	1700
135	136	4,02105659	358,8225542	4,021056594	-0,001048137	0,005378183	0,2	1,215367891	2,701445674	800	2000	2700
136	252	4,39715166	93,72114415	2,091243378	-0,005117824	0,007650041	0,2	1,44951216	1,003650033	300	1300	1700
137	289	4,8768	165,5169189	-3,804725419	-0,007430684	0,000376853	2	1,493284535	0,188117208	50	100	300
138	137	4,8768	917,8350872	-3,475675461	0	0,000358507	2	1,456482395	0,992375725	50	100	300
139	138	4,8768	262,458304	-3,377316548	0	0,00037476	2	1,489132525	0,29663884	150	650	850
140	139	4,79577849	274,9472338	-3,274381207	-0,00029468	0,000374382	2	1,488381362	0,310440803	50	100	300
141	140	4,47692382	136,2928434	-3,219354716	-0,002339482	0,000403737	1,9	1,493671533	0,163140073	50	100	300
142	141	4,2672	250,7861301	-3,118950901	-0,000836266	0,000400356	1,9	1,487404422	0,297672724	150	650	850
143	142	4,19912770	407,7303603	-2,957702404	-0,000166954	0,000395478	1,9	1,478315157	0,478062306	50	100	300
144	145	4,2672	140,2637196	4,2672	0,004346099	0,004444729	0,3	1,447794116	0,999007397	800	2100	2900
145	140	3,6576	325,9614097	3,643765749	-0,003491758	0,002722367	0,4	1,372618853	1,565082038	600	1700	2300
146	147	4,09459454	289,7048772	4,094594547	-0,001880194	0,00393966	0,3	1,363055489	1,82891118	800	2100	2900
147	148	4,63929589	205,6528997	2,95325578	0,001809339	0,002285618	0,5	1,459436238	0,893030057	600	1700	2300
148	140	4,2672	108,2790436	2,483211851	-0,004881632	0,00234566	0,5	1,478481438	0,482544258	400	1400	2000
149	150	4,2672	214,1208452	4,2672	-0,003155453	0,006654692	0,2	1,351929221	1,994655286	800	2100	2900
150	151	4,94284829	91,83949114	2,842291779	0,000719171	0,004601693	0,3	1,473136389	0,677212743	600	1700	2300
151	82	4,8768	271,9500581	2,419674669	0,00053242	0,004150025	0,3	1,398973647	1,808497696	300	1300	1700
152	153	4,2672	352,4366301	4,2672	0	0,003772254	0,3	1,333781285	2,130394414	800	2000	2700
153	154	4,2672	127,5950495	2,937719509	-0,004852971	0,003108468	0,4	1,466728923	0,699527091	600	1700	2300
154	155	4,88641511	190,8921598	2,541094362	-1,58609E-05	0,002303046	0,5	1,464990003	0,835253689	400	1400	2000
155	132	4,88944283	106,7504927	2,101460866	0,000118433	0,002356045	0,5	1,48175049	0,477838387	300	1300	1700
156	157	2,4384	414,3451312	2,4384	0	0,002796795	0,3	1,148456287	1,856952996	800	2100	2900
157	163	2,4384	293,9758408	1,279561638	-0,000389598	0,001982326	0,5	1,359161014	1,107170349	800	2100	2900

FID	connect FID	elev	length	pipestartlvl	surfslope	slope network	Pipe Diameter	velocity	deltaH	S: T=0,5	S: T=15	S: T=100
		m	m	m	-	-	m	m/s	m	m^3/ ha	m^3/ ha	m^3/ ha
158	159	2,83334943	231,4779612	2,833349439	0,001163546	0,003784801	0,3	1,335997519	1,403882265	800	2000	2700
159	160	2,56401413	133,5900738	1,957251534	-0,002597074	0,004199979	0,3	1,407368216	0,899082209	800	2000	2700
160	161	2,91095749	443,5580815	1,396175966	-0,000146983	0,002285784	0,4	1,257749857	1,788175124	800	2100	2900
161	162	2,97615293	206,0060927	0,382297831	-0,000348762	0,002195647	0,5	1,430423271	0,859350208	800	2000	2700
162	170	3,048	349,0848268	-0,070018802	0	0,002008313	0,5	1,368040667	1,331956296	150	650	850
163	164	2,55293225	630,7647629	0,696805553	-0,001102161	0,001288023	0,6	1,237179242	1,640258943	600	1700	2300
164	165	3,24813662	394,7476197	-0,11563396	-0,004058393	0,001357176	0,7	1,407408065	1,13865601	600	1700	2300
165	168	4,85017778	79,16689918	-0,651375805	-0,014638013	0,001522469	0,7	1,490651776	0,256170426	400	1400	2000
166	167	6,77208489	246,3204604	6,772084895	0,002744737	0,004402789	0,3	1,440947224	1,737826333	600	1700	2300
167	168	6,096	162,2180585	5,687587962	0,000536168	0,004516352	0,3	1,459412521	1,173991825	600	1700	2300
168	258	6,00902391	182,7382015	-0,771904933	0,011736777	0,001263322	0,8	1,48429533	0,512992474	150	650	850
169	258	4,88742725	139,7595901	4,887427258	0,007320863	0,007420099	0,2	1,427561521	1,451684634	800	2000	2700
170	258	3,048	149,2733534	-0,771090356	-0,005468266	0,001801556	0,6	1,463169741	0,542939519	400	1400	2000
171	172	1,8288	188,420008	1,8288	-0,009705976	0,003495481	0,3	1,283919013	1,055387663	800	2100	2900
172	173	3,6576	231,6540791	1,170181437	0,00526302	0,004044591	0,3	1,381088345	1,501386855	600	1700	2300
173	255	2,4384	62,41357129	0,233235433	-0,00429674	0,004527536	0,3	1,461218399	0,452813154	400	1400	2000
175	143	6,01725829	355,906489	4,593317345	0,00510845	0,002931811	0,4	1,424441419	1,840331644	600	1700	2300
176	177	3,48410216	129,7841968	3,48410216	-0,006033846	0,004392071	0,3	1,439192242	0,913417167	800	2100	2900
177	253	4,2672	273,209388	2,914080808	6,00321E-05	0,004034872	0,3	1,379428039	1,766458562	400	1400	2000
178	179	3,048	242,8913128	3,048	0	0,005652389	0,2	1,245965501	1,921874422	800	2100	2900
179	188	3,048	353,0005394	1,67508375	-0,00172691	0,002529931	0,4	1,323216682	1,575100626	600	1700	2300
180	182	3,6576	289,3804722	-1,499238735	4,09029E-06	0,000722788	1,2	1,471170675	0,532040982	150	650	850
181	182	4,26103148	177,6108916	4,261031481	0,003404156	0,006964431	0,2	1,383033849	1,731554666	800	2000	2700
182	192	3,65641635	171,6765485	-1,708399575	-6,89464E-06	0,000662015	1,3	1,485136151	0,296914326	50	100	300
183	184	5,58267203	460,6673418	5,582672031	0,000731958	0,003773305	0,3	1,333966988	2,785398422	800	2000	2700
184	192	5,24548279	99,47168087	3,844433874	0,015963164	0,004597792	0,3	1,472511841	0,732869733	400	1400	2000
185	143	3,6576	421,3993928	-2,780088302	-0,00128507	0,000421486	1,8	1,472120714	0,517177045	150	650	850
186	185	3,6576	177,04253	-2,703731921	0	0,000431288	1,8	1,489139963	0,22233464	50	100	300
187	186	3,51999648	128,0129108	-2,643963719	-0,001074919	0,000466892	1,7	1,491457248	0,170748722	150	650	850
188	187	3,6576	109,8673254	-2,592561536	0,001252452	0,000467857	1,7	1,492997568	0,146848266	150	650	850
189	188	4,2672	210,7106827	-2,486474472	0,002893066	0,000503473	1,6	1,487434707	0,297011583	150	650	850
190	189	3,40786001	179,7456637	-2,38809404	-0,004780866	0,000547331	1,5	1,485556962	0,269573237	150	650	850
191	190	3,6576	94,70421474	-2,335727179	0,002637053	0,000552952	1,5	1,4931649	0,143490975	150	650	850
192	191	3,6576	131,1756515	-2,263461461	0	0,000550908	1,5	1,490402955	0,198016039	50	100	300
193	194	4,2672	194,4337513	4,2672	0	0,006823271	0,2	1,368945959	1,857142622	800	2000	2700
194	195	4,2672	180,0704691	2,940525758	0	0,006945746	0,2	1,381177256	1,750823336	600	1700	2300
195	196	4,2672	113,3351683	1,689802096	0	0,004516914	0,3	1,459503238	0,820322374	600	1700	2300
196	197	4,2672	92,0712906	1,177876892	0,001448824	0,003152067	0,4	1,47697915	0,511851477	600	1700	2300
197	198	4,13380494	176,2627358	0,887662016	0,000714353	0,002291274	0,5	1,461241059	0,767300053	400	1400	2000
198	143	4,00789111	78,18452241	0,483795731	-0,002445965	0,00236272	0,5	1,483848038	0,350962431	150	650	850
199	132	4,8768	67,68359548	-4,81161125	0	0,001525445	0,7	1,49210798	0,219440548	400	1400	2000

FID	connect FID	elev	length	pipestartlvl	surfslope	slope network	Pipe Diameter	velocity	deltaH	S: T=0,5	S: T=15	S: T=100
		m	m	m	-	-	m	m/s	m	m^3/ ha	m^3/ ha	m^3/ ha
200	201	4,2672	78,80467771	4,2672	0,00103992	0,004602837	0,3	1,473319519	0,581240169	600	1700	2300
201	202	4,18524947	120,7731976	3,904474929	-0,000678549	0,003114107	0,4	1,468058598	0,663328028	600	1700	2300
202	203	4,2672	216,0371968	3,528374302	0	0,002986818	0,4	1,437742098	1,138050445	400	1400	2000
203	199	4,2672	142,6033891	2,88311062	-0,004274793	0,003089126	0,4	1,462158521	0,77694409	300	1300	1700
204	205	4,2672	156,3318756	4,2672	0	0,004399583	0,3	1,440422621	1,102140957	800	2100	2900
205	206	4,2672	246,1875317	3,579404871	0	0,002941383	0,4	1,42676487	1,277149888	600	1700	2300
206	199	4,2672	207,476945	2,855273139	-0,002938158	0,002999373	0,4	1,440760909	1,097550921	300	1300	1700
208	186	4,2672	430,5672495	0,751196388	0,001415807	0,002636969	0,4	1,350918409	2,002489433	600	1700	2300
209	208	4,2672	226,856336	1,425124393	0	0,002970726	0,4	1,433863931	1,188605662	600	1700	2300
210	209	4,10337162	183,6225393	2,214235947	-0,000892202	0,004297466	0,3	1,423607807	1,264493054	600	1700	2300
211	210	3,6576	234,3812523	3,6576	-0,001901908	0,006158189	0,2	1,300518373	2,020490653	600	1700	2300
212	199	4,2672	642,1091747	-2,138081579	-0,000949371	0,004163668	0,2	1,069370177	3,742535923	800	2000	2700
213	214	4,2672	385,2026965	4,2672	0	0,003665724	0,3	1,31481309	2,262700605	800	2000	2700
214	215	4,2672	461,0376506	2,855153343	0	0,002585421	0,4	1,337649435	2,102287047	600	1700	2300
215	216	4,2672	512,241315	1,663176761	0	0,002500135	0,4	1,315401717	2,258720081	600	1700	2300
216	217	4,2672	535,4123394	0,38250415	0	0,001961176	0,5	1,351890899	1,994952927	400	1400	2000
217	212	4,2672	368,7313499	-0,667533868	0	0,002127191	0,5	1,407947823	1,490198674	400	1400	2000
218	219	4,2672	147,7235968	4,2672	0	0,004423957	0,3	1,444407019	1,047222081	800	2000	2700
219	220	4,2672	158,4286488	3,613677198	0	0,003068142	0,4	1,457183965	0,857301309	400	1400	2000
220	222	4,2672	253,3152109	3,127595582	0	0,002930381	0,4	1,424094135	1,30921106	300	1300	1700
221	223	4,2672	173,9170902	4,2672	0	0,004348503	0,3	1,432036298	1,211881205	800	2000	2700
222	223	4,2672	644,999593	2,385285474	0	0,002293377	0,4	1,259837119	2,608910859	150	650	850
223	224	4,2672	216,3792001	0,906058053	0,001435566	0,002263722	0,5	1,452428769	0,93060672	400	1400	2000
224	250	3,95657332	493,0783215	0,41623575	0,00060634	0,001610807	0,6	1,383542578	1,603543363	800	2100	2900
225	226	3,94720383	93,76696017	3,947203835	-0,002291318	0,007575292	0,2	1,442413165	0,994329187	800	2000	2700
226	227	4,16205380	257,3576192	3,23689171	0,001883994	0,004065671	0,3	1,384682722	1,676668916	400	1400	2000
227	228	3,67719357	90,63735651	2,190560289	-0,006509528	0,004537886	0,3	1,462887514	0,659081064	300	1300	1700
228	212	4,2672	277,3451734	-1,648391706	0	0,001765633	0,6	1,448508582	0,988649839	300	1300	1700
229	230	4,17289587	271,0358222	4,172895872	-0,00034794	0,004021815	0,3	1,377194179	1,746734055	800	2100	2900
230	231	4,2672	421,9835061	3,082840043	0,001444606	0,002651545	0,4	1,354647032	1,973416597	400	1400	2000
231	232	3,6576	618,9665255	1,96393177	-0,000984867	0,002185658	0,4	1,229894104	2,38601737	400	1400	2000
232	233	4,2672	324,3634716	0,611082818	0,001489384	0,002816209	0,4	1,396075975	1,611094619	400	1400	2000
233	234	3,78409838	211,0534497	-0,302392371	0,000502181	0,002953903	0,4	1,429798287	1,099544982	400	1400	2000
234	228	3,67811124	344,5603193	-0,925823825	-0,001709683	0,002097072	0,5	1,397944778	1,372796874	300	1300	1700
236	188	4,2672	409,8335011	0,685657971	0,001487433	0,002087159	0,5	1,3946368	1,625139647	300	1300	1700
237	236	4,2672	277,2640303	1,29891538	0	0,002211817	0,5	1,435681011	1,165119397	400	1400	2000
238	237	4,65532369	256,0296285	2,056490217	0,001515933	0,002958934	0,4	1,431015384	1,336133436	600	1700	2300
239	238	3,6576	203,8423617	2,902532538	-0,004894585	0,004150474	0,3	1,399049168	1,355720409	600	1700	2300
240	239	3,6576	79,32597249	3,265016231	0	0,004569546	0,3	1,467981856	0,580853377	400	1400	2000
241	240	3,6576	86,29573226	3,6576	0	0,004549284	0,3	1,464723553	0,62908653	800	2100	2900
242	234	3,6576	264,2198989	3,6576	-7,76295E-05	0,005885325	0,2	1,271379552	2,176792122	800	2100	2900

FID	connect FID	elev	length	pipestartlvl	surfslope	slope network	Pipe Diameter	velocity	deltaH	S: T=0,5	S: T=15	S: T=100
		m	m	m	-	-	m	m/s	m	m^3/ ha	m^3/ ha	m^3/ ha
243	192	3,6576	210,0493895	-2,040342953	0	0,001062219	0,9	1,472217844	0,515648859	150	650	850
244	243	4,2672	146,5224996	4,2672	0,004160453	0,00722551	0,2	1,408718533	1,482018994	800	2100	2900
245	243	4,2672	208,5861455	-1,78063582	0,002922534	0,001245083	0,8	1,473541997	0,577100566	400	1400	2000
246	245	4,93504935	456,8298313	4,935049352	0,001461921	0,003634367	0,3	1,309177521	2,660487793	800	2000	2700
247	245	3,6576	175,130761	-1,562403871	-0,003480828	0,001246109	0,8	1,474148574	0,484937706	400	1400	2000
248	247	3,048	496,2371976	-0,928476361	-0,001228445	0,001277469	0,7	1,365454247	1,347338044	600	1700	2300
249	241	3,6576	324,8996026	3,6576	0	0,005389321	0,2	1,216625751	2,451117761	400	1400	2000
250	248	3,6576	322,0640945	-0,378018104	0,001892791	0,001709157	0,6	1,425154203	1,111336985	300	1300	1700
251	248	4,90589241	367,222389	4,90589241	0,005059311	0,005801723	0,2	1,2623171	2,982408119	800	2100	2900
252	138	4,8768	357,0684445	1,374272783	0	0,003904681	0,3	1,356990914	2,234164195	400	1400	2000
253	254	4,25079867	210,4844441	-0,031411991	0,003237535	0,001478096	0,7	1,468768562	0,661240877	150	650	850
254	256	3,56934782	252,6202775	-0,342528258	0,002063761	0,001445735	0,7	1,452601269	0,776236391	150	650	850
255	257	2,70657491	157,7683435	-0,049344287	-0,003135988	0,002937453	0,4	1,425811586	0,817363321	400	1400	2000
256	257	3,048	298,3982204	-0,707750338	-0,000513859	0,001400181	0,7	1,429532514	0,888008773	150	650	850
257	259	3,20133453	260,1363515	-1,125561735	-0,001753947	0,001209511	0,8	1,452339547	0,699162903	50	100	300
258	259	3,86426645	107,4243099	-1,040014675	0,001923833	0,000943854	1	1,488752282	0,242704845	150	650	850
259	180	3,6576	79,32950485	-1,440199432	0	0,000744229	1,2	1,492831267	0,150177868	150	650	850
260	261	3,6576	174,7738556	1,178242497	-0,00209113	0,002273861	0,5	1,455677707	0,755036449	400	1400	2000
261	262	4,02307478	202,7539803	0,780831127	-0,003492658	0,001798481	0,6	1,461920663	0,736201571	400	1400	2000
262	253	4,73122516	249,5862196	0,416181845	0,001924892	0,001793344	0,6	1,459830942	0,903660864	300	1300	1700
288	175	6,10670399	370,8152734	6,106703998	0,000241214	0,004081241	0,3	1,38733166	2,425090471	800	2100	2900