Government of the Netherlands

DRR Team Final Report – Climate Change Adaptation of the City of Recife, Brazil

Mission dates: 6 – 10 February, 2023

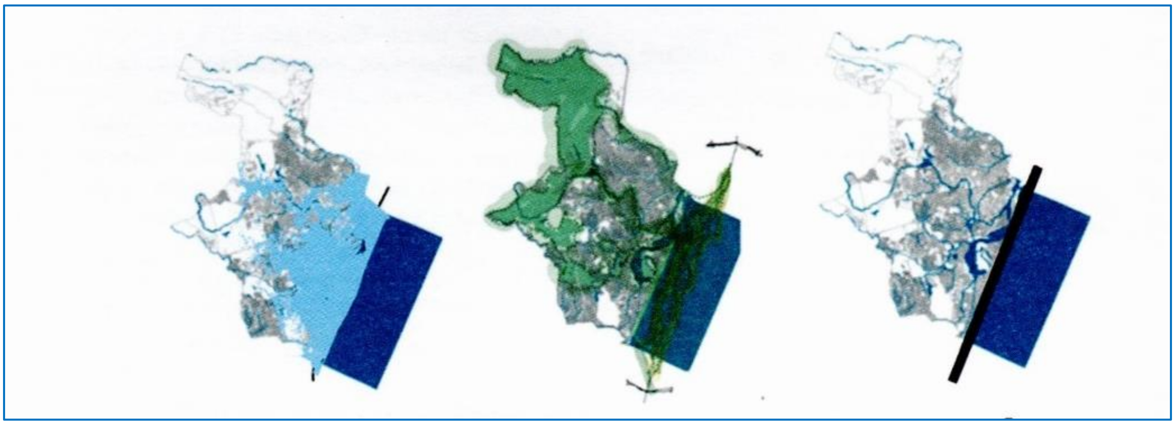


Table of Contents

Document title	Recife DRR EN - Final Report 31-March-2023
Status	Final draft
Date	29 March 2023
Project name	DRR Team Final Report – Climate Change Adaptation of the City of Recife, Brazil
Reference	DRR222BR2A
Front page graphic	From: Recife Exchanges Amsterdam | Holland | Netherlands International Exchanges for the Reinvention of Recife Pernambuco State Government, 2022

Drafted by	DRR Team: Ben Lamoree, Adri Verwey, Frederico Vilhena, Marjolijn Haasnoot
Checked by	DRR-Team leader: Ben Lamoree
Date/initials check	29 March 2023 | BL
Approved by	RVO

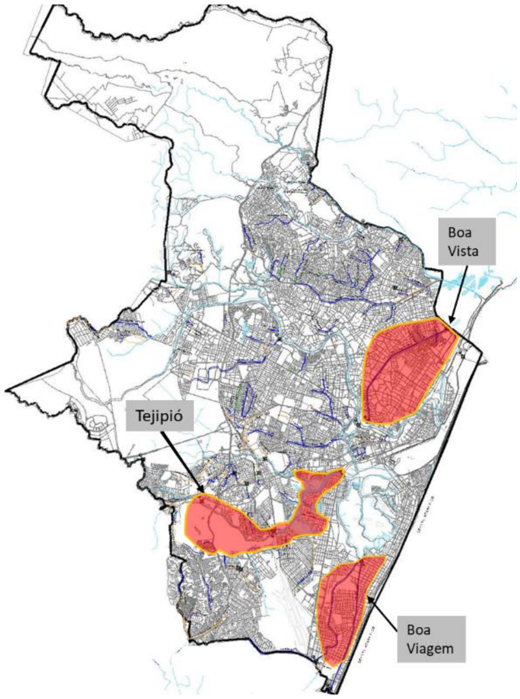
Readers Guide

This is the report of the visit of the DRR-Team to Recife from 6 to 10 February 2023. The mission took place after a request of the Recife Mayor to the Netherlands' Embassy in Brazil, in 2022, to support Recife in assessing the impact of climate change, in particular sea level rise, on the drainage system of the city.

The mission program – as implemented – can be found in annex 1.

Chapter 1 presents the **background** of the mission and general information about Recife that is relevant for the analysis.

Chapter 2 presents the **current problems** with the drainage system as found by the mission. The focus is on the Boa Vista area, the Teijipió basin, and the Boa Viagem areas of the city, see adjacent map.



Chapter 3 presents the forecasted **effects of sea level rise and rainfall intensification**, using the most recent IPCC data and analysis. The graphically presented forecasts show that sea level rise in the magnitude of 20 centimeters is expected to become a reality well before 2050, making it necessary to start planning measures immediately. The forecasts also show that extreme rainfall events are expected to be a reality in the very near future.

Chapter 4 presents the principal **adaptation strategy options**: accommodate, protect, advance, retreat. These strategies are not fixed. Adaptive pathway analysis becomes possible with reliable data. The identification of tipping points, in combination with hydrodynamic modelling of the river systems and drainage canals, will allow for the quantification of impacts and a time line that will facilitate decision making on timely investments, and their preparation. It is recommended to follow up with a policy hackathon to prepare a quantified adaptation strategy, as well as to facilitate short term decision making about investments in the river and drainage system.

Chapter 5 presents details of **drainage system measures** should be taken to improve and sustain the functioning of the drainage system in the period until 2030, until 2050 and until 2080, under a 'protect – pump' strategy. These measures are urgent for the period until 2030, while later measures need to be studied in more detail prior to decision making and in the light of potential alternative adaptation pathways.

Chapter 6 focuses on the need for **data collection**, development **of hydrodynamic models** and their use in studies and projects. The DRR mission was followed up immediately in February 2023 with a three-day master class in hydrodynamic model development. Annex 2 has the report of the master class and its recommendations. The proposed hackathon will build upon that event. Annex 3 presents a full concept note for the hackathon as a basis for the organization of the event.

Chapter 7 presents **recommended follow up actions**. These are:

Summary of Recommended Actions

- **There is an urgent need to develop an integrated hydrological-hydrodynamic Recife Drainage Master Model (RDMM)** as specified in this report, covering the whole area of Recife and its upstream river basins. This model will provide much improved understanding of Recife's drainage and flooding problems and provide quantitative support to the cost-effective design of flood risk reduction measures.
- The development of this tool will have to be followed by **studies on specific flood prone areas based on local refinements of this model**, sensitivity analyses of the impacts of possible interventions and the impacts of climate change, in order to avoid maladaptation and destruction of invested capital.
- **There is an urgent need to start with the collection of data** supporting Recife's flooding and drainage studies. Most urgent is the installation of a hydrological monitoring network across Recife, including a robust tidal station, as specified in this report. In addition, bathymetric surveys of rivers and drainage canals will have to be taken up.
- **There is an urgent need to develop a better insight into the impacts of storm surges from the ocean and perceived soil subsidence processes** in the coastal zone of Recife, to support the decision making in the design and implementation of flood reduction measures in Recife. Given these uncertainties it is strongly recommended to install a robust tidal gauge at the Port of Rectify, for the analysis of SLR and its guidance on flood risk protection needs in Recife the coming decades.
- **The updating of the Recife Drainage Master Plan**, which is due the coming years and shall be supported by the RDMM, shall focus more on pro-active measures to be taken as a result of city densification and the impact of climate changes, in particular sea level rise. Within the coming two decades, significant investments will be required, starting with the implementation of no-regret measures the coming years to more complex and costly interventions, subsequently.
- The built-up area of **Recife has a severe lack of retention space for water**. Such retention is badly needed for slowing down the runoff of storm water into the primary drains and, even more so, to secure the robust functioning of tidal sluices and pumps. Such retention space is difficult to find and it has to be considered to maximize usable space in the city by giving terrains a double function, e.g. the construction of buildings on foundation piles above retention basins.

Follow-up on Master Class

It is recommended that the team, composed of staff of the Municipality of Recife, State of Pernambuco, consulting firms and academics, that participated in the **Master Class, continues to meet** on a monthly basis to exchange experience with the development and application of their models. Focus initially should be on the development of the hydrological-hydrodynamic Pilot Model for Recife and the selection of the most appropriate modelling system. For the coming months the DRR Team Senior Drainage Expert can connect to part of these meetings online for further guidance.

Hackathon

It is recommended that a hackathon can be held to explore the **impact of rainfall intensification and sea level rise** on the performance of the current drainage system of Recife, as well as evaluate the potential **impact of measures** such as linear parks and other green areas, small dikes and levees, or tidal gates. This way, qualitative insight into the impacts of short term decisions can be achieved, while the more detailed full Drainage Master Model is being developed in the coming years. The Hackathon should also evaluate potential **alternative adaptation pathways**.

1. Introduction

1.1. Background of the mission

The city of Recife is one of the most vulnerable in the world to climate change, according to IPCC (2014) due to its physical characteristics. In May of 2022, torrential rains caused widespread flooding and landslides, leading to multiple casualties. In response, the Recife Municipality rapidly developed the ProMorar project[1] with funding of the Inter-American Development Bank that became operational in January of 2023.

At the same time, in July of 2022, Mayor João Campos requested assistance of the Netherlands' DRR Team[2] to assess the impact of climate change, in particular sea level rise, on the drainage system of the city. The Netherlands' Embassy in Brasília together with the Netherlands Enterprise Agency RVO in the Hague, decided to respond positively to the request of Recife.

A team of four experts was put together: an institutional expert and process manager on urban climate change adaptation, a senior international drainage expert, a Brazilian drainage expert and a climate change impact and adaptation expert. **The objective of the mission: to analyze the impact of sea level rise on the drainage of the city and propose adaptation solutions and strategies to the city of Recife with short term and long-term options based on various climate change scenarios.**

In February of 2023 the team visited Recife. A kickoff meeting on 6 February was attended by Mayor João Campos and his team, Netherlands' Ambassador André Driessen and his team, and the DRR Team members. The mission consisted of field visits, meetings with stakeholders and discussions with Recife municipality counterparts. The full mission program in annex 1.

1.2. Partners and Stakeholders

The Municipality of Recife was the key partner of the DRR Team, notably the EMLURB, municipal company for maintenance of the drainage system, next to the departments of infrastructure, environment and urban planning and their institutions.

Key stakeholders that were part of the meeting program also included the Federal University of Pernambuco (UfPE), notably the Oceanography Department and the Drainage Department, Pernambuco State hydrological monitoring agency APAC, and the NGO ARIES.

1.3. Short Characteristics of Recife

Recife, capital of the State of Pernambuco, is a coastal city located in the Northeast Region of Brazil. With a surface area of 218 km², strongly urbanized and a population of about 1,660,000 inhabitants, Recife is bordered to the north by the cities of Olinda and Paulista, to the south by Jaboatão dos Guararapes and to the west by São Lourenço da Mata and Camaragibe.

The climate is predominantly hot, with an average temperature of 25°C, average annual precipitation of 2,300 mm, with the rainy season concentrated between the months of March and August.

---

[1] See: https://www.iadb.org/en/news/brazil-improve-urban-management-and-housing-vulnerable-areas-recife and also: https://www.iadb.org/en/project/BR-L1609

[2] for more on DRRTeam: https://english.rvo.nl/actueel/videos/drr-team-practice

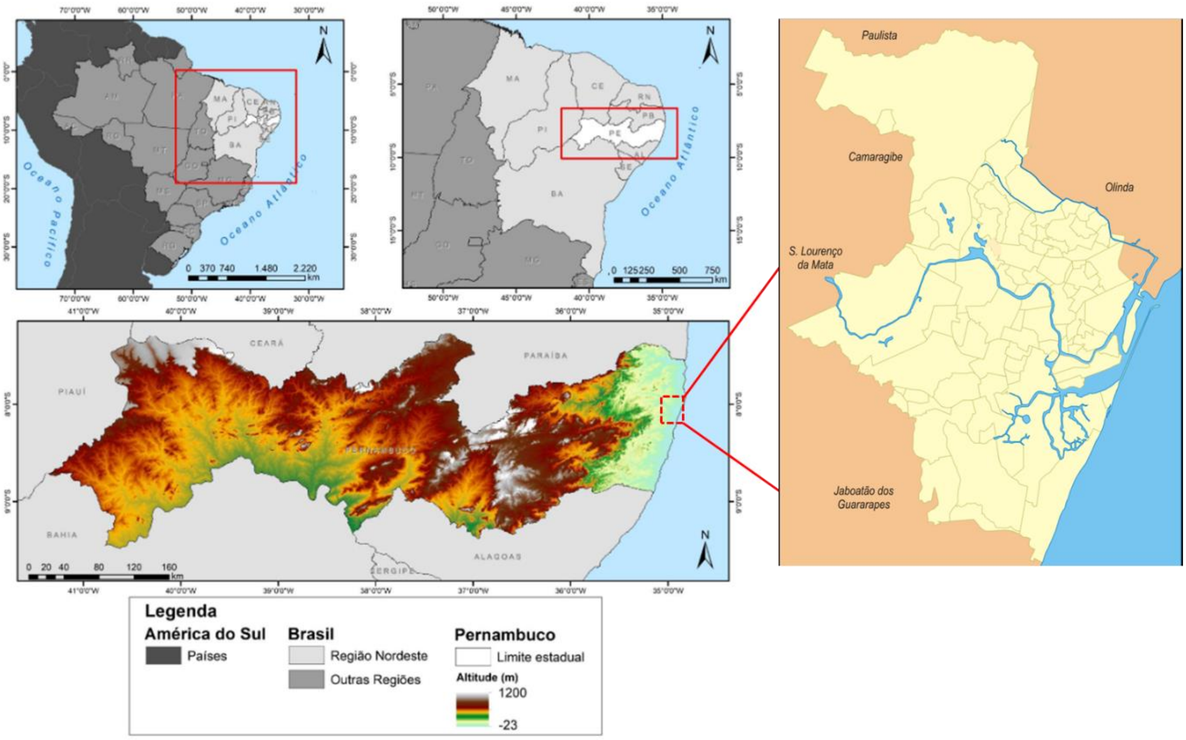


Figure 1: Location of the city of Recife

Water Resources

The city of Recife has five hydrographic basins, three of which (rivers Capibaribe, Beberibe and Tijipió) flow into the same estuary, which includes the Pina Basin and the Evolution basin of the port. Thus, the hydrodynamic conditions in this estuary, which depend both on the maritime regime and on the precipitation in the basins tributary to it, condition the efficiency of the drainage systems in most of the city.

The relief of Recife is predominantly formed by plains that extend along the coastal region, with elevations varying from sea level to +10 meters. The low elevations of the coastal plain, which in some regions is even below mean sea level (MSL), makes Recife subject to flooding by tides, even without the presence of rainfall and sea level rise resulting from climate change. The tides are semidiurnal, with an average period of 12.42 hours. The average tidal amplitude is 2.50 m, while neap and spring tide amplitudes are 1.60 and 2.90 m, respectively.

Currently there are two altimetric references considered in studies and tide assessments in Recife: the Navy and IBGE references, being attributed a difference of 1.14 m in the forecast data.

According to tide data forecast provided by the Navy in Recife Port area, the maximum astronomical spring tides can reach an elevation of 2.70 m. This corresponds to an elevation of 1.56 m in the IBGE reference, which defines levels with reference to approximately MSL. However, it has been noticed that observed maximum spring tides are sometimes higher than astronomical spring tides and, which points at the effect of storm surges. As no data on storm surges appear to be available, such difference and corresponding frequency needs to be investigated.

Figure 2 below illustrates the hydrographic basins pertinent to the city of Recife, indicating that a significant part of the city is already below high tide.

In addition to the influence of the tide on natural waterways, a large portion of the macro drainage channels, as well as associated micro drainage systems, are also currently affected by the partial loss of their hydraulic efficiency, leaving the city very vulnerable to rainfall events, even if of low intensity.

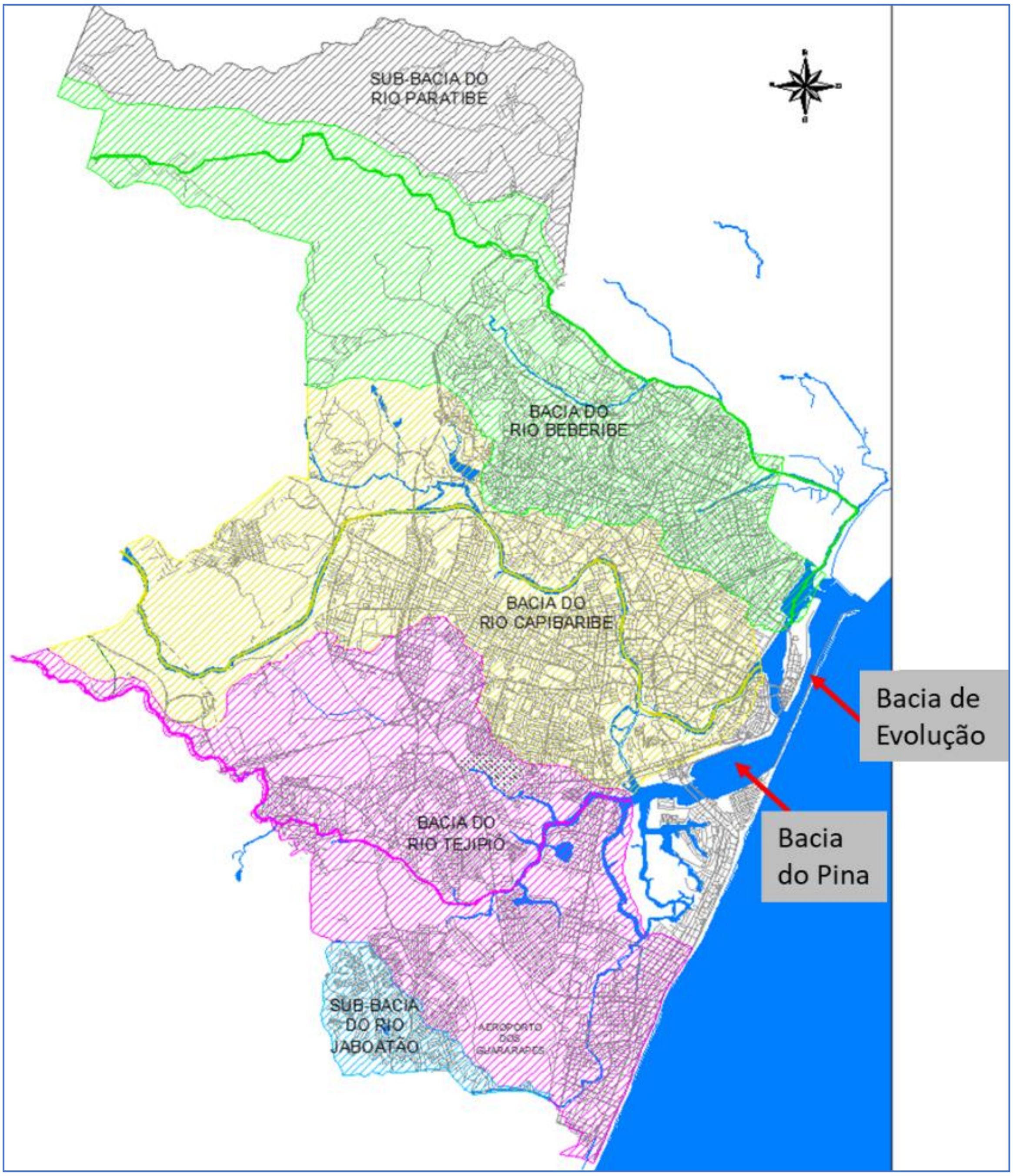


Figure 2: Recife river basins

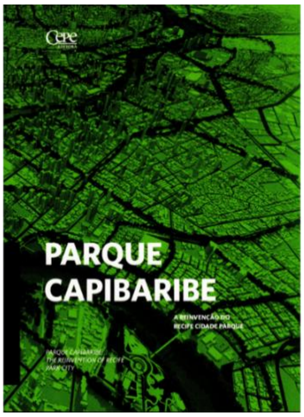
It is also worth noting that the large occurrence of untreated sanitary effluent discharges into rivers and channels, in addition to the high presence of silting in them, increase the problems of flooding., reducing the hydraulic capacity of the rivers.

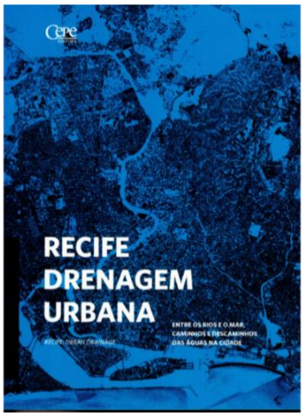
The main **institutional entities** involved in the management of the city's water resources are:

- Emlurb (Empresa de Manutenção e Limpeza Urbana), linked to the Secretariat of Public Services of the Recife Municipality, whose objective is, among others, to provide maintenance and conservation services for the drainage systems, road systems and green areas of the capital city of Pernambuco.

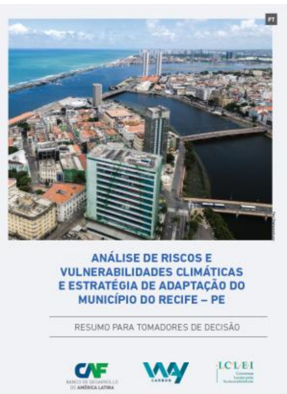
- Autarquia de Urbanização do Recife (URB) (Recife's Urbanization Authority) is in charge of executing structuring works and engineering services with the aim of improving the quality of life of Recife's citizens.
- Secretariat for Environment and Sustainability of Recife, which is responsible, among others, for licensing, norm setting and monitoring; planning of activities and actions, as well as acting in the most diverse spaces for discussion of the environmental agenda, sustainability, environmental education and climate change.
- Secretariat of Development and Urban Planning of Recife, through the integration of several dimensions of the city's organization, and consolidating the planning of the city's use and occupation.
- Agência Pernambucana de Águas e Clima (APAC) - responsible, among others, for the climatological and pluviometric monitoring of the whole state of Pernambuco, alerting the municipality to the rain forecast in the Recife region.
- National Center for Monitoring and Alerts of Natural Disasters (CEMADEN) - which compiles and publishes real-time measurements of rain gauges in the region, providing information on total rainfall in the region.
- University Centers, especially the Federal University of Pernambuco (UFPE), which, through academic programs, conducts studies and evaluations on the drainage system in its current condition, as well as in relation to future scenarios.

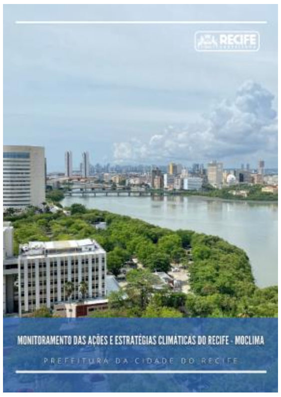
Key documents were made available during our mission that provided valuable information on which this report has been based, and on which it builds for further insight and action. Particular mention should be made of the superb four Volume ‘Recife 500 Years’ collection.





Mention should also be made of the studies performed by the Municipality to design its current climate change adaptation strategy.





See also section 3.3 with a wider list of documentation.

2. Current Problems of the Drainage System

The drainage system of the municipality of Recife includes an important estuarine area (Pina Basin and Evolution Basin), basins of the rivers Capibaribe, Beberibe and Tejipió, sub-basins of the creeks Jiquiá, Curado, Morno, Camaragibe, Dondon and Moxotó. Moreover, the municipality has implemented macro draining channels and micro draining systems. According to the Recife Macro Drainage Plan (2016), 99 macro drainage channels are mapped in the municipality (totaling about 115 km in length), and a network of galleries and micro drainage channels with an approximate length of 1,580 km. Furthermore, the municipality has some sluice gates and pumping systems, although in inefficient operation.

As presented above, the drainage system is strongly influenced by the tides (without the occurrence of rainfall), causing flooding points throughout the city (figure 3 - condition I), but mainly, reducing the efficiency of the city's macro and micro drainage, making the city susceptible to flooding even with small rainfall intensities if the tide is high (figure 3 - condition II).

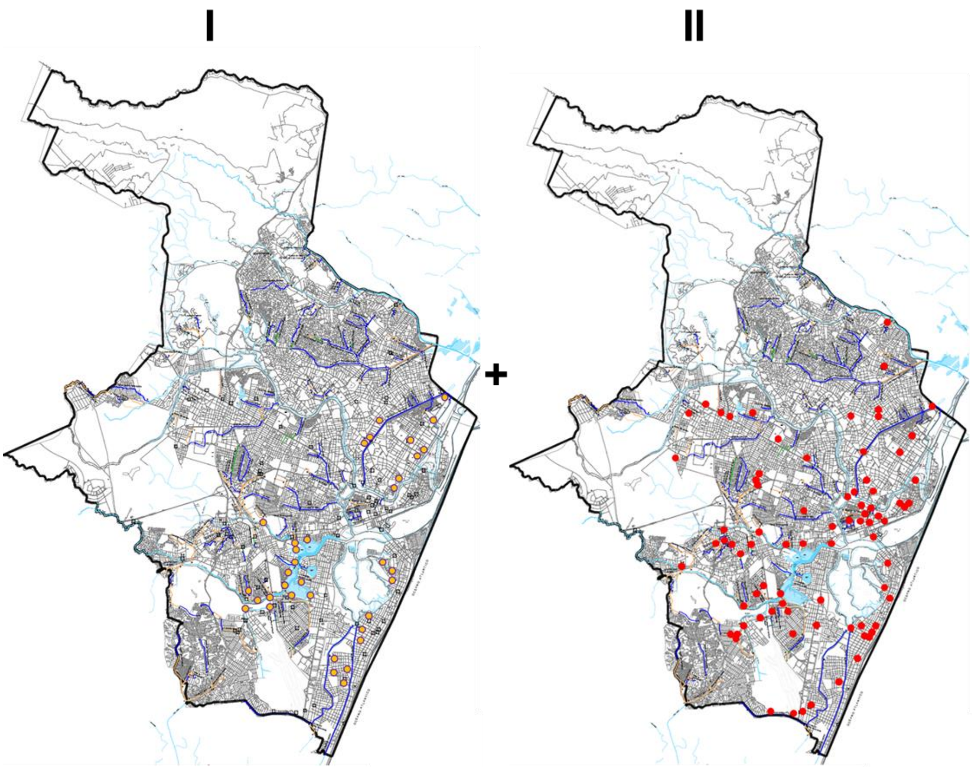


Figure 3: Current susceptibility to flooding. Left (I) for high tide with no additional rainfall. Right (II) for high tide and additional rainfall. Circles indicate flooding points

In the following photos you can see occurrences of flooding and inundation, associated with the two scenarios in question.

Figure 4: Street floods at high tide

Figure 5: Street floods at high tide + intensive rainfall

Parts of the drainage systems that are critical to flooding, both due to tides and rainfall, were visited during the February 6 – 10 Recife DRR mission and discussed below:

Boa Vista area

The region presents, among others, the following critical conditions:

Aurora Street and surroundings is constantly vulnerable to flooding once the micro drainage system is partially submersed during high tides. Consequently, during rainfall events, flooding is more intense. A gate and pump system were implemented in order to close a specific micro-drainage discharge on Capibaribe river, and the retained volume is pumped into Capibaribe river. However, this system has not been working properly due to the following aspects:

- The current gate system is very robust and difficult to maintain.
- The pumping system is apparently undersized.
- As only one of the micro-drainage networks discharge in the region has gate closure control, and floods hydraulically connect several drainage networks in the surroundings, pumped water returns to the network itself during floods.
- Lack of larger areas for significant rainfall storage.

Regarding the Tacaúnas – Derby Canal, parallel to Av Agamenon Magalhães, the following issues were verified:

- The flood control system for this Canal was not fully implemented according to its original design, so it cannot attend the initially designed conditions.
- Currently there is not a sufficient technical understanding of the Canal regarding its efficiency and hydraulic capacity, due to the lack of an integrated hydrodynamic model that

considers the Canal conditions itself, as well as its two discharge points, on Capiberibe and Beberibe rivers. Thus, it is not possible to make solid robust decisions.

- At the north limit of the Canal (Tacaúnas) there is a closure system, equipped with gates, to prevent the backwater of the tide and backwater Capibaribe and Beberibe rivers. Moreover, this enclosure is equipped with a pumping system, which consists of 3 pumps with 1 m³/s capacity each. However, only one of the pumps is currently operational. The municipality technicians have mentioned that the volume of the pump sump runs out very quickly, causing suction problems, and once the Canal slope is very low, the intake flow is also too low. The gate system has relevant structural pathologies.

Figure 6 Identified problems Tacaunas region

Agamenon Av. and surroundings have been subject to soil subsidence (on the order of 1.0 m over the last 40 years), and in some areas the road level are lower than the crest of the channel and present lower points, increasing susceptibility to flooding. Furthermore, many of these low points do not have micro drainage devices, without the possibility to drain the retained volumes.
Due to the effects of subsidence, several stretches of the Canal do not have enough free board, and several culverts discharges are currently submersed. The following figure illustrate the flooding effects in some areas of the Canal and surroundings due to Capibaribe and Beberibe rivers rising levels, and without an effective system of gates.

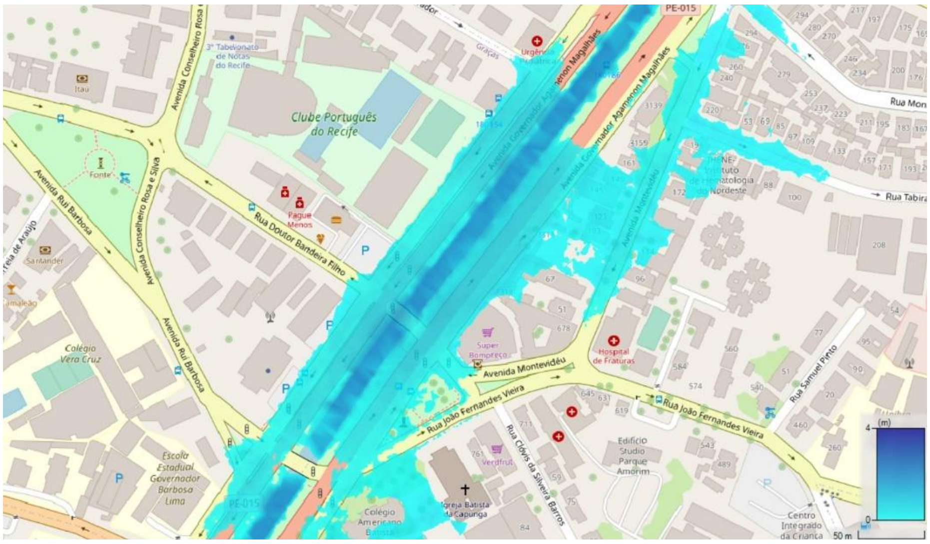


Figure 7: Flood problems Tacaunas Derby canal caused by spring tides and rainfall

- The Canal has a high drainage point in its longitudinal center, with slopes towards both ends. The slope of this channel is very low, tending to zero, reducing its flow capacity.
- At the southern end of the channel (Derby region), close to Capiberibe river confluence, there is also a gate system to avoid / mitigate the influence of the Capiberibe river inside the Canal. However, currently it has sealing problems, and it has been verified water leakage into the Canal even with the gates locked. Furthermore, at this point there is no pumping system to help deplete the volume retained in the Canal.

The following figure illustrates the location of the main critical points:

Figure 8: Identified problems in the Boa Vista area

Tejipió River Basin

Tejipió Basin has generalized deficiencies regarding to macro and micro drainage systems, with emphasis on:

- The runoff generated upstream and along Tejipió Basin is already high enough to produce significantly effects of flooding in the Basin.
- Almost the entire extension of the Tejipió River within Recife municipality is influenced by tidal effects, therefore, many drainage systems already operate flooded and inefficiently during rainfall events. According to municipality technicians, during spring tides (without rainfall events) many areas are flooded with water depths of up to 0.3 m. When precipitation events occur at low tide periods, the water depths reach the order of 0.75 m. However, when there are intense heavy rainfall events in concordance with high tides, water depths can reach 1.5 m in certain places. These effects will be even greater considering sea water level rise effects.
  Thus, although the effects of high tides are significant, their main influence is to prevent the flow of rainwater into the Basin, increasing the effects of flooding.
- The absence of an effective and integrated water management of Tejipió River Basin considering neighboring municipalities, limits the municipality actions, considering that the upstream of the river basin is located in Jaboatão dos Guararapes municipality. There are currently no flood control reservoirs before the river reaches Recife.
- In several areas there are low drainage points in, without micro-drainage systems, and so the runoff volumes stay retained without being able to drain.
- The IPSEP region has a flood control system, consisted of a sump and pumps, in order to mitigate flooding on local roads. However, this system has not been operating properly, because during Tejipió river floods, the pumped volumes end up returning to the pumping basin, as well as increasing the contribution of surface flows.
- Absence of other flood detention reservoirs.
- A significant portion of Tejipió River banks presents irregular occupations, reducing locally the hydraulic section / capacity of the river and increasing the risks of social impacts. The Drainage Master Plan foresees the implementation of some linear parks in the basin, however, these impact on high efforts in expropriations and relocations of communities.
- The municipality has contracted some Engineering and Consultancy Studies for Tejipió River Basin, for a better evaluation of the solutions in relation to those foreseen in the Drainage Master Plan. However, as they do not cover the other river basins in Recife, as well as the estuarine area, these studies may not adequately predict the real hydrodynamic effects of Pina Basin on Tejipió River.
- Currently there is not a sufficient technical understanding of the Tejipió river regarding its hydraulic efficiency and capacity, as well as the tide effects on the local fauna and flora, to guide future decision-making. There are no integrated hydrodynamic models that consider the conditions of the river and other rivers in the region, as well as the estuarine and maritime conditions in the Port of Recife. Thus, it is not possible to make solid robust decisions.

The following figure illustrates the location of the main critical points:

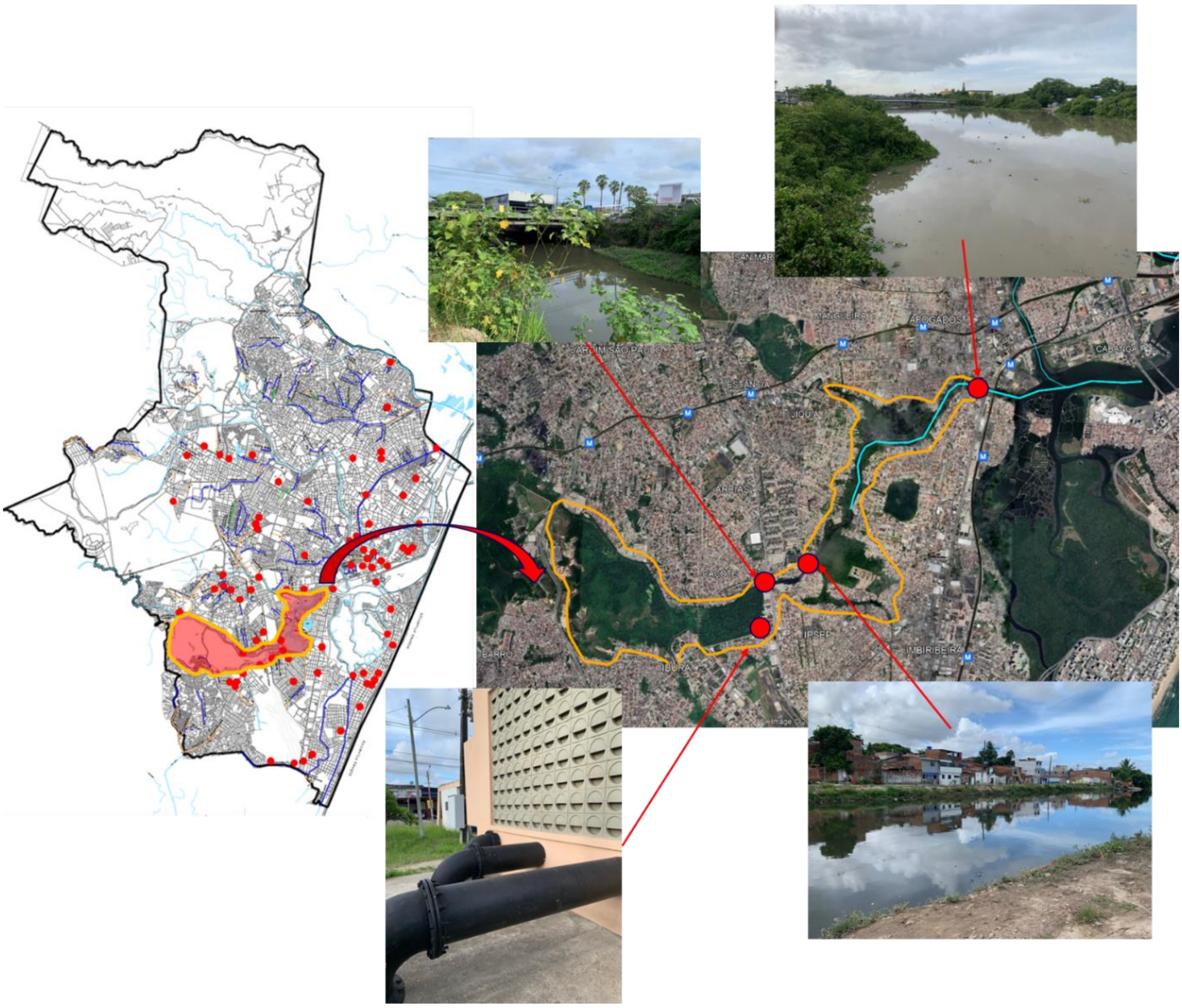


Figure 9: Identified problems in the Tejipió area

Jordão River Basin (Setúbal / Jordão / Boa Viagem channels)

Setúbal and Jordão rivers consist of two natural watercourses currently channeled, belonging to the Pina Basin. Both rivers mouth are in Parque dos Mangueizais area.

Practically the entire length of these two rivers, within the municipality of Recife, is influenced by the tides, so that many drainage systems are already flooded and almost inefficient when during rain events.

As reported by the municipality, during spring tides (and without rainfall events) some areas of the basin experience flooding with a water depth of up to 0.2 m. However, during heavy rainfall events in concordance with high tides, water depths can reach 0.5 m in certain places. These effects will be even greater considering sea water level rise effects. Thus, although the effects of high tides are significant, their main influence is reducing the macro e micro drainage efficiency, increasing the effects of flooding.

In addition, significant effects of tidal flooding are also verified in Bode and Encanta Moça communities, in Rio Mar shopping mall surroundings.

Due to subsidence effects on the region, many of roads stretches in Boa Viagem area have low drainage points without micro-drainage systems, where rainwater accumulates over the course of a day. It is estimated that continued subsidence effects over time, concurrent with rising sea levels, will lead to critical conditions around 2040, considering the IPCC forecasts added to the subsidence estimate of up to 0.5m in 20 years verified in other areas of the city.

It should be noted that these canals extend beyond the limits of Recife, covering areas of Jaboatão dos Guararapes. An example is Setubal canal, which is connected to Lagoa do Olho d'Água, which exerts hydraulic influence on the canal. Thus, it can be concluded that: i) In order to better understand of the current hydraulic capacity of these canals, a better technical understanding of these hydraulic interconnections should be developed, as well as the effects of the tide at both ends of the channel, to guide future decision-making. Furthermore, the lack of an effective integrated water management of these channels, considering neighboring municipalities, reduce the effectivity of the decision-making.

The following figure illustrates the location of the main critical points:

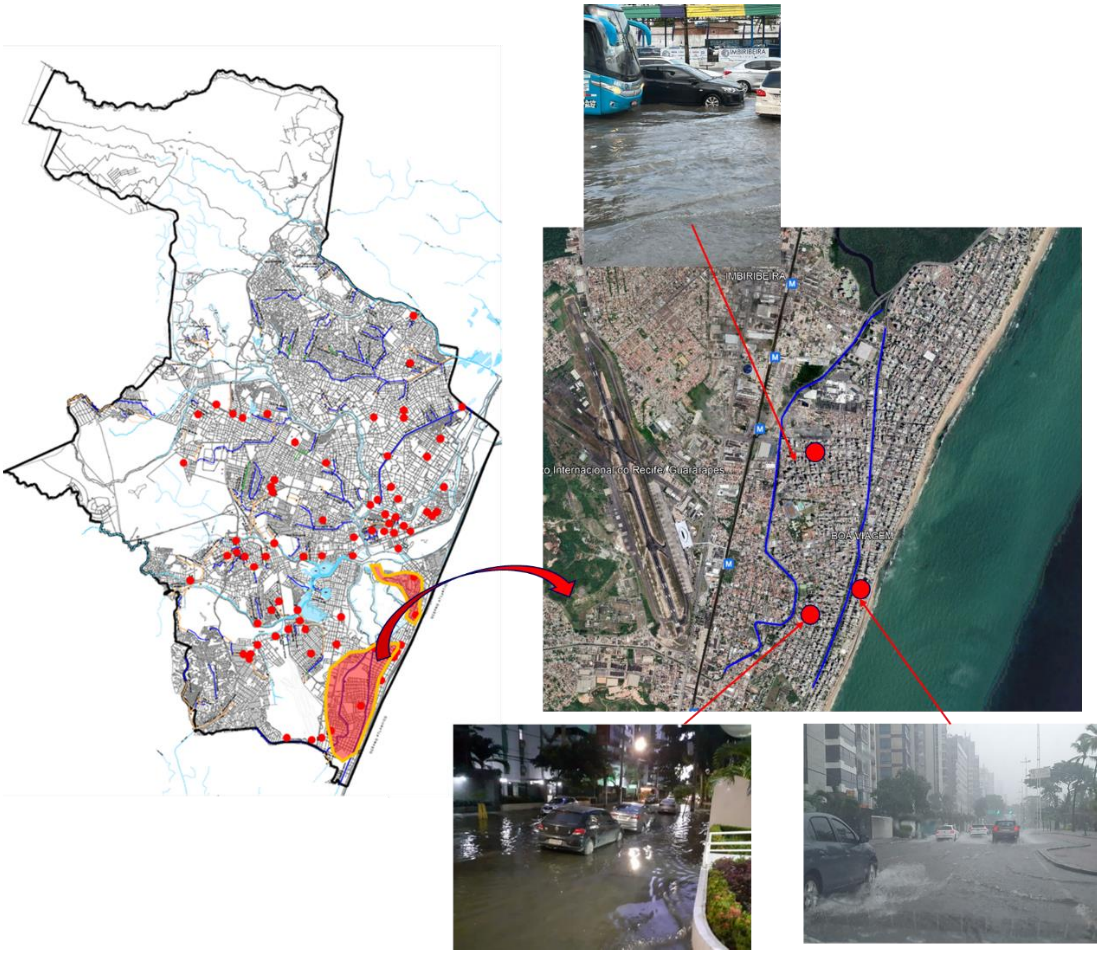


Figure 10: : Identified problems in the Jordão - Boa Viagem area

3. Recife – Forecasted Effects and Impacts of Climate Change

3.1. Short Description of the Projected Climate Change Effects of Rainfall and Sea Level Rise

According to scenarios predicted by the Intergovernmental Panel on Climate Change (IPCC) for the South Atlantic, the Recife region will be subject to the following effects:

- Intensification of winds in the North East of Brazil due to climate change in the South Atlantic.
- Sea level rise, resulting in increase of the mean, high tides and the extreme sea levels during storms. Under all warming scenarios the IPCC projects an increase of 0.18-0.24 meters in the 27 years (median values for 2050) at the coast of Recife. By 2100, sea levels could rise 0.39 m (median value with a likely range of 0.23-0.59m under a low climate change scenario (SSP1-2.6), and could rise 0,77 m (0.58-1.06) under a high warming (SSP5-8.5). A sea level rise of 1.7 m by 2100 cannot be ruled out due to uncertain ice-sheet dynamics. Beyond 2100 sea levels will continue to rise, with the rate and amount largely depended on global warming.

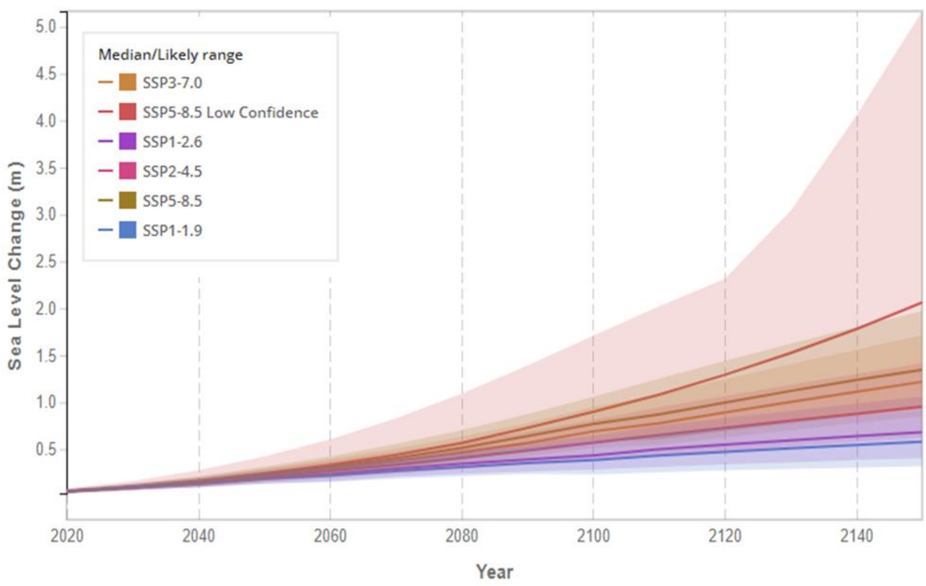


Figure 11: Sea Level Rise Scenarios for Recife (IPCC, 2021)

Table: Sea level rise scenarios

	Sea level rise						
	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5	SSP1-2.6 Low Confidence	SSP5-8.5 Low Confidence
2050	0.18 (0.13–0.25)	0.19 (0.13–0.27)	0.21 (0.15–0.28)	0.22 (0.16–0.29)	0.23 (0.17–0.31)	0.20 (0.13–0.33)	0.24 (0.17–0.42)
2100	0.39 (0.23–0.59)	0.43 (0.28–0.64)	0.57 (0.40–0.81)	0.69 (0.51–0.95)	0.77 (0.58–1.06)	0.45 (0.28–0.84)	0.90 (0.58–1.71)
2150	0.58 (0.32–0.92)	0.68 (0.41–1.06)	0.95 (0.62–1.42)	1.22 (0.85–1.71)	1.35 (0.93–1.97)	0.74 (0.41–1.42)	2.06 (0.93–5.17)

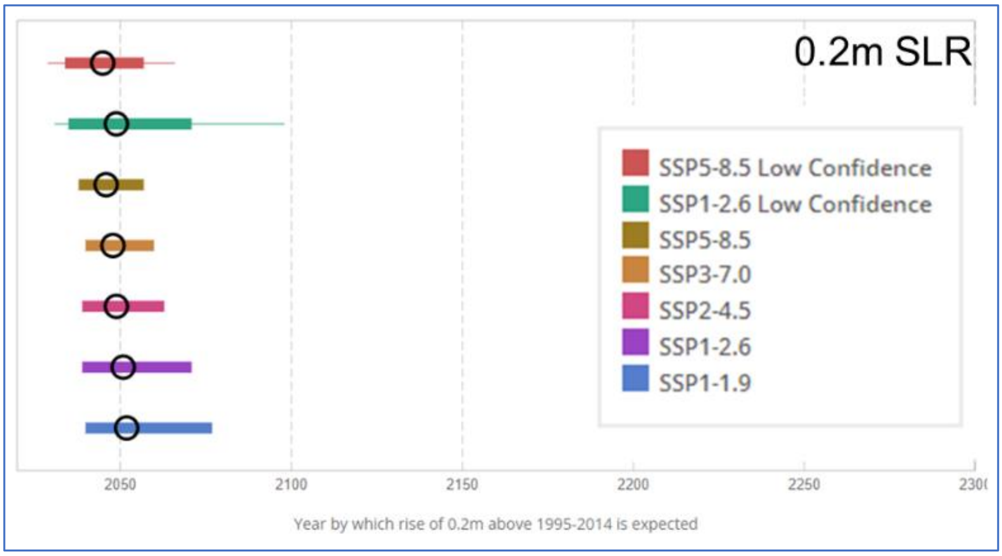


Figure 12: sea level rise under different IPCC scenarios. Timing of exceedance of 0.2 m (IPCC, 2021)

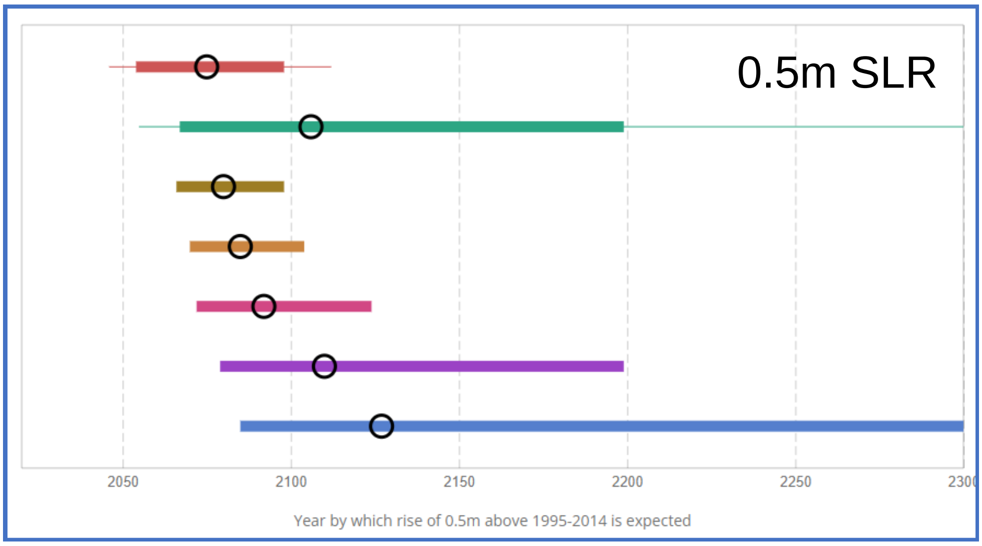


Figure 13: sea level rise under different IPCC scenarios. Timing of exceedance of 0.5 m (IPCC, 2021). Source: https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool

Source: [IPCC projections derived from Sea Level Projection Tool – NASA Sea Level Change Portal]

An increase in precipitation volume and rainfall intensities in extreme events is also projected for the Recife region, as presented in the following figure.

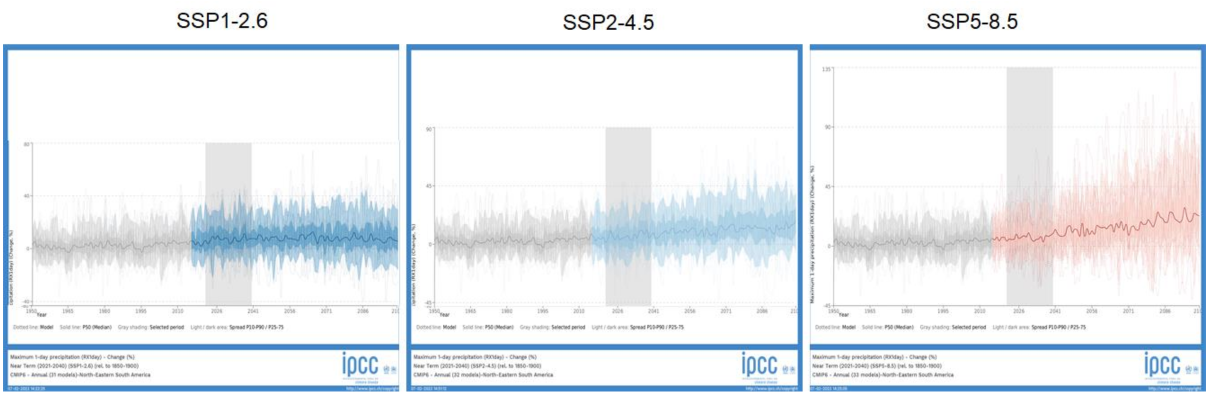


Figure 14: Projected change (%) daily maximum Precipitation under a low (SSP1-2.6), medium (SSP2-4.5) and high global warming (SSP5-8.5) (IPCC, 2021)

A tendency of intensification of erosive processes both in the coastal region and in the rivers and estuary region, also increasing siltation processes.

Because of these and other potential consequences, the IPCC considered Recife as the 16th most vulnerable city in the world to climate change.

3.2. The Potential Impact of Extreme Rainfall and Sea Level Rise on Recife

The above mentioned effects of sea level rise and intensified rainfall will impact Recife in many ways. Coastal cities are disproportionally affected by interacting and compounding impacts from heavy rain, sea level rise, erosion, and salinization. Climate change impacts are strongly determined by other developments, such as urbanization, deforestation, exhaustion of natural resources, poverty and inequality.

Sea level is going to continue to rise for many centuries to come, creating an escalating hazard for coastal communities. For any amount of sea level rise it is a matter of when it will occur. (e.g. 1 m of rise will occur at date X under a low warming or at date Y under a high warming scenario). Understanding these scenarios in a quantitative manner is of key importance in order to be able to devise a sound climate change adaptation strategy.

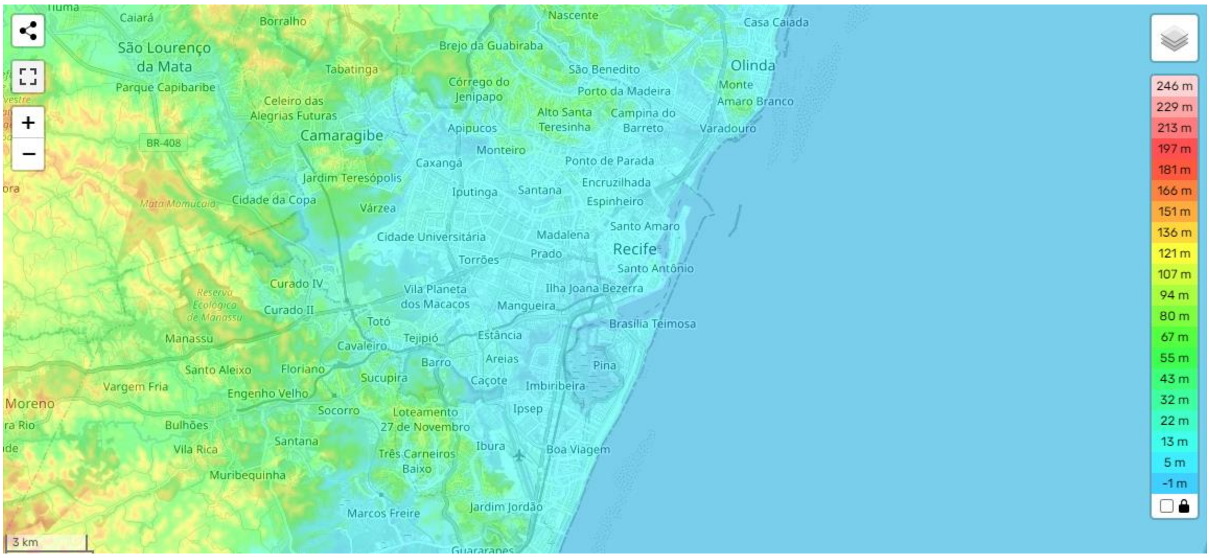


Figure 15: Recife topographic height map

Recife, due to its low lying topography, is highly vulnerable to climate change impacts, in particular sea level rise, as the map shows.

Impact quantification requires a suite of scientific model approaches. More about these in the next chapters.

3.3. Recife Current Efforts Towards Climate Change Adaptation

Currently the Municipality's efforts made towards climate adaptation include:

- The ProMorar project, financed by the Inter American Development Bank and Recife Municipality to a total of USD 260 million, aiming to reduce the impact of increased rainfall on the city (flooding, landslides).

- Strategic Plans developed by Recife Municipality to assist future decision making, such as the document: "Analysis of Climate Risks and Vulnerabilities and Adaptation Strategies of the Municipality of Recife - PE, 2019", which presents an Action Plan and adaptation measures.
- Recife Drainage Master Plan, prepared by the Recife Municipality and Company of Maintenance and Urban Cleaning (EMLURB), 2016, aimed at designing and sizing macro drainage solutions to solve / mitigate the city's current flooding problems.
- Law projects, some subsidized in the Recife Master Plan, aiming to establish new sustainable guidelines for the municipality, such as limiting the land occupation rate (coefficient of utilization), delimitation of Sustainable Development Zones, need for runoff retention systems in the lots and expansion of green areas.
- The highly strategic ProUrbano project, implemented by the Recife Municipality with ICLEI and funded by German bank KfW, aiming to propose an insurance policy against climate change impacts for public infrastructure in the city.
- Complementary studies to the Master Plan, such as the one being developed by TPF for EMLURB, aiming to complement and consolidate Recife's Drainage Master Plan.
- Scientific studies and papers developed by the Federal University of Pernambuco (UFPE), through master's and doctoral programs, aiming at evaluating the extent of the impacts of the sea level rise on the city's water systems.
- Studies and scientific papers developed by other University Institutions (UNIT) related to the evaluation of the extent of the impacts of the effects of the rising tide level on the city's drainage systems.
- Studies and workshops promoted by other non-governmental entities, such as the NGO ARIES, among others, aiming to foster management strategies in face of climate change in the city.

4. Climate Change Adaptation Strategies

4.1. Types of strategies

Risks

A mix of adaptation measures is available and necessary to manage coastal risk and build resilience over time. These include infrastructural, nature-based, institutional, and socio-cultural measures. Adaptation measures can address the hazard (current and future climate events, such as sea level rise), the exposure (presence of people in places that could be affected by climate change, being located in low-lying regions or in the floodplain), and the vulnerability (determined by the sensitivity to climate change and the adaptive capacity). Together, hazard, exposure and vulnerability determine climate risks. Risks can also be influenced by unintended consequences of human responses (e.g. adaptation measures). The feasibility to implement these measures and their effectiveness to reduce risk can be increased through governance with disaster risk management and long-term inclusive adaptation planning (adaptation plans, finance, law and regulations) and climate services (e.g. data on risks).

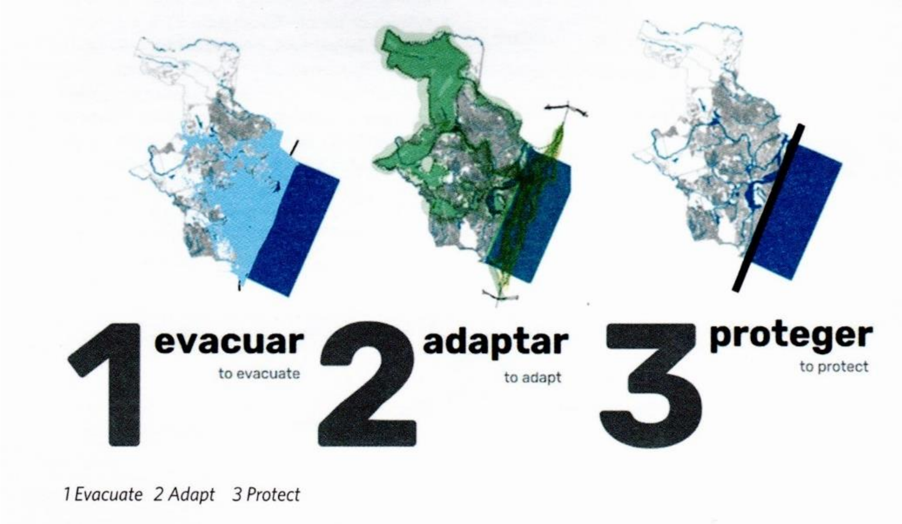
About Adaptation Strategies

Adaptation strategies to sea level rise can be categorized into:

1. Accommodate: reduce vulnerability to climate risk, e.g. flood proofing of buildings and roads);
2. Protect against flooding through hard engineering measures (e.g. levees or barriers) or soft/nature based measures such as dunes and vegetation. Two main alternatives exist for this strategy in case of deltaic situation: open with connection between rivers and sea, or permanently closed. In case of a closed situation rivers would need to be stored and discharged to sea with pumps),
3. Advance through building a new higher coastline and
4. Retreat from risky areas through planned relocation.

Combining these strategies with early warning systems, disaster responses and spatial planning can further reduce risk. Early warning systems have relatively low-cost and have been successful in reducing fatalities. In addition, an Avoidance strategy can reduce risk through disincentivizing developments in high-risk areas and making no/low-risk areas attractive. Improving urban drainage through nature-based solutions within urban areas (e.g. linear parks) and managing upstream land to reduce run-off from the hinterland can reduce local flooding and compound flood events, where extreme rainfall and storms happen at the same time. However, in extreme rainfall events (which high intensity and duration) even a sophistication drainage-storage system may not be able to prevent all flooding.

Across the world cities have adapted to sea level rise, but future options are challenged due the rate of sea level rise and socio-economic changes. Some of these strategies have been described for Recife in the Volume 'Recife Exchanges' (part of the collection 'Recife 500 Years) that documents knowledge exchange with partners in the Netherlands. The Netherlands has mapped these strategies of the Rhine-Meuse delta, identifying different alternatives based on a generic set of building blocks (measures), that can be sequenced over time.



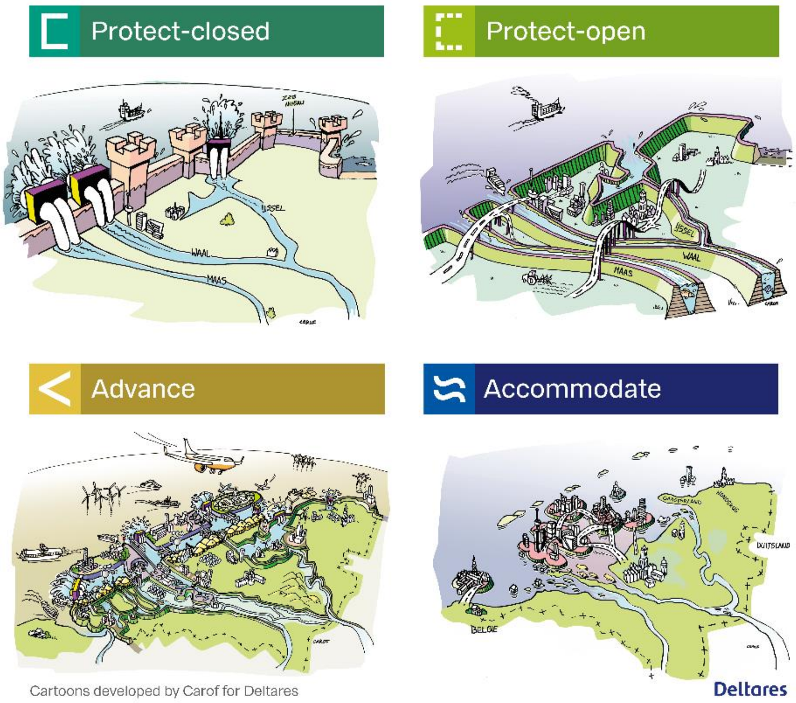


Figure 16: Potential Adaptation Strategies for Recife (upper): 1) planned relocation from high-risk areas; 2) accommodate through reducing vulnerabilities; 3) protect the regions from flooding from sea and increase drainage of excessive rainfall (Source: International Exchanges for the Reinvention of Recife, Pernambuco State Government, 2022); and for the Netherlands (Haasnoot et al. 2022; van Alphen et al. 2022)

Combining and sequencing adaptation measures can help to reduce risk over time, spread coasts and minimize lock-in. Exploring alternative adaptation pathways with the Dynamic Adaptive Policy Pathways approach provides a stepwise analytical framework to prioritize near term actions and identify long-term options, while managing uncertainty about the future through monitoring and learning (see figure 17). As the future unfolds the adaptation strategy can be implemented and/or updated (e.g. depending on rate of sea level rise, extreme rainfall and socio-economic developments).

Recife Adaptation Strategy Options

Current plans have made important steps towards addressing the need for climate change adaptation of the city, in various thematic areas, including water. At present the most concrete plans mainly aim at addressing current problems, based on recent events, with some anticipation about the future as evidenced in the Recife Climate Change Adaptation Strategy reports.

The current strategy is to a certain extent qualitative in its design. This is mostly due to the absence of hydrodynamic models for forecasting of the impacts of sea level rise and rainfall intensification that would allow for the quantification of the combined impacts. Such forecasting and scenario development would be required for an improved adaptation plan.

If well planned and well designed, short term adaptation measures are a meaningful step towards longer term adaptation.

As part of one of the current projects, the closing of rivers with tidal gates is being considered. This will strongly affect the hydrodynamics of the basin and its ecosystems. With increasing sea-level rise this solution will eventually become difficult to maintain, requiring pumps and upstream storage space in case of extreme events.

An alternative option would be to construct embankments along the river and keep the open connection to the sea.

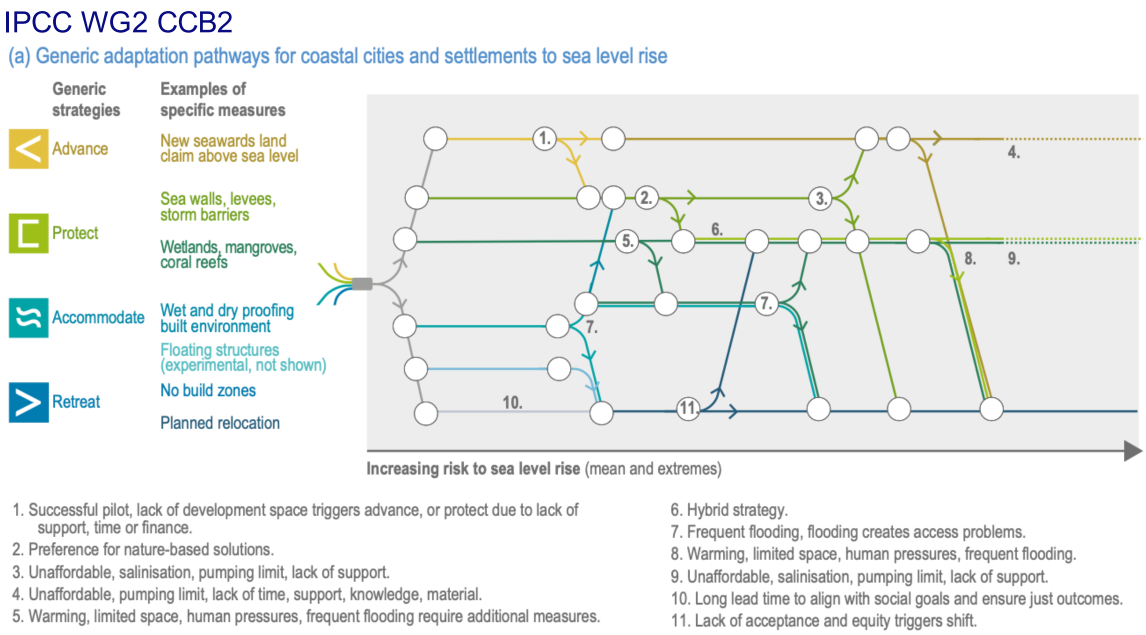


Figure 17: Generic Adaptation Pathways for Coastal Cities (IPCC, 2022)

Guidance for policy makers can be found in the summaries of the IPCC report nr. 6, 2022.

4.2. Assessing Tipping Points and Quantifying Adaptation Pathways

To assess when and under what conditions adaptation is needed, the approach of adaptation tipping points has been used (Kwadijk et al. 2010). In sea level rise studies, this implies quantifying the magnitude or rate of sea level rise at which relevant impacts may occur for decision making. This allows for an analysis that can easily be adapted to scenario updates, as only the timing of the tipping points will change. The faster the sea level rise, the sooner tipping points occur, and also the shorter the functional lifespan of measures becomes. As an example: it can be expected that the compounded effect of intensified rainfall and sea level rise will - in the near future - lead to the impossibility to drain certain parts of the city through gravity. This will happen when certain high water levels in the rivers are present over longer periods of time. Initially such events will occur only rarely and for a short period and at some spots. Then, the increasing rainfall intensification in combination with continued sea level rise will lead to more and more frequent events with longer duration in more spots. When a previous water management practice can no longer be maintained, this is when a tipping point is reached. Hydrodynamic models in combination with climate models will allow for forecasts to be made of when and where these tipping points will occur.

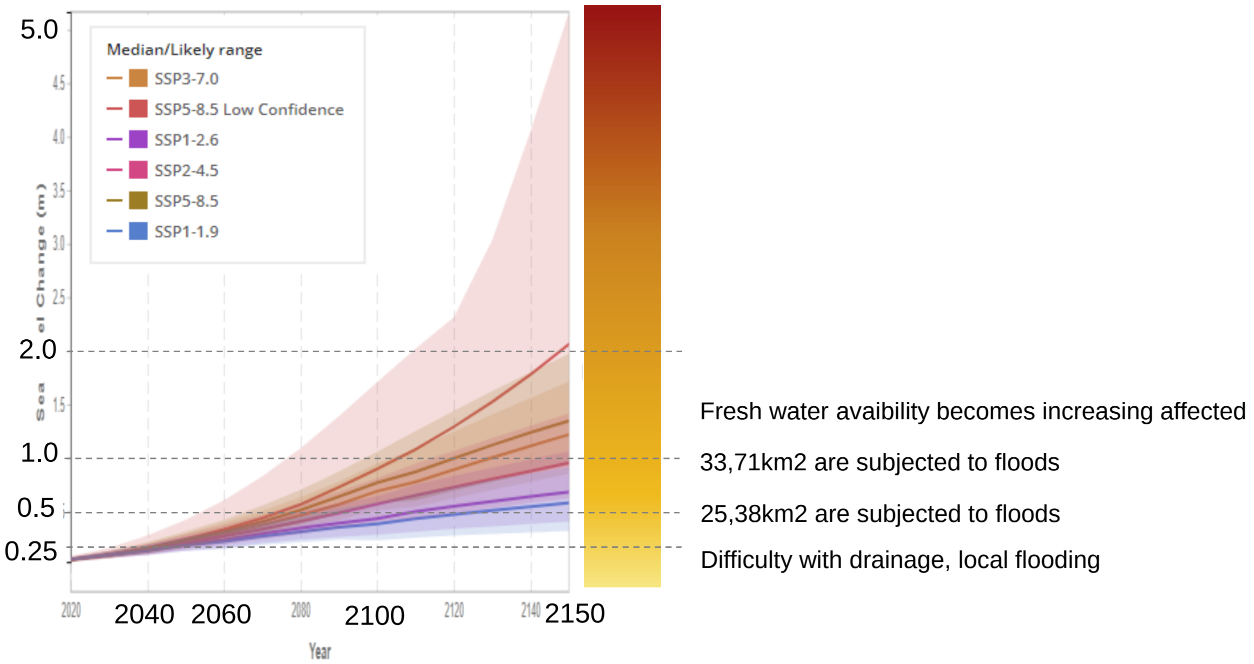


Figure 18: Burning Ember Diagram, indicating tipping points (examples for the Netherlands) and their occurrence in time under different sea level rise scenarios

A first identification of potential tipping points can be derived based on expert judgement (e.g. assess what comes first and what comes next, possible with an indication of sea level rise) and a follow-up could be based on simple models before using a complex models (e.g. the drainage models as proposed in this study). The joint knowledge of water management professionals in the city's institutions is usually a good starting point for identifying key spots and tipping points. For example, for Recife we see tipping points :

- when a drainage area (e.g. Boa Vista) can no longer be drained dry within 24 hour by gravity, pumps have to be installed to enhance drainage of these areas.
- when the contribution of gravity drainage drops below 30%, the tidal drainage sluices will have to be decommissioned and drainage will have to be secured 100% by pumps.
- When a large area becomes subjected to flooding

Once adaptation tipping points has been inventoried, hydrodynamic models can further quantify when the corresponding water levels will start to occur and with what frequency. Thus the burning ember diagram for Recife can be constructed. Based on that diagram, measures can be spaced in time, including the lead time needed to study and design them in detail, as well as the acquisition of the required financial means.

The process of strategy development for climate change adaptation can benefit greatly from the use of a 'hackathon'. A hackathon is an event where people engage in rapid and collaborative analysis, design and/or engineering over a relatively short period of time such as a few days. They are often run using specialized software that helps to develop the required insights.

In the case of Recife, a hackathon could be beneficial to gather a group of professionals to go through the steps of the above described strategy development process:

- Identification of key problem areas and discussion whether or not they constitute tipping points
- Use of a rapid assessment tool or demonstration model to analyze the occurrence of high water levels in the river systems in Recife
- Arrive at a burning ember diagram including a time table of the expected impacts
- Devise a time line with potential measures to be taken and studied further

Annex 3 presents a concept note for a potential hackathon in Recife on climate change adaptation strategy development using a hydrodynamic demonstration model.

4.3. Limits to Adaptation and Maladaptation

Adaptation has already reduced risk and can further reduce risk in the future. There are however limits to adaptation. For a particular measure, there can be soft limits, which can be overcome (e.g. finance, knowledge/institutional capacities), but can also be hard limits which require a shift to different strategies or planned relocation to avoid risk.

In the absence of a good understanding of the system and climate impacts, there is the risk of maladaptation with actions resulting in unintended consequences such as increased risk, emissions and lock-in. Maladaptation can be avoided by observing a high quality process of multi-sectoral and inclusive planning, with flexible pathways that account for long-term adaptation commitment.

Examples of maladaptation (in particular when there are reinforcing mechanisms): protection of areas which attract developments as people feel safe (Levee-effect), but when it fails the consequences are larger. Drainage which can result in compaction and oxidation depending on the soil type, which results in subsidence, requiring more drainage and increasing the difference between the sea and land. NB this does not mean that protection or drainage is always maladaptation, but it needs to be part of an integrated long-term adaptive plan that foresees such potential negative consequences.

5. Potential measures to deal with impact of climate change on the drainage system

The previous chapter shows that there are different pathways towards the future. In the short term the 'Protect – Pump' pathway is the most likely adaptation strategy. This chapter details potential measures for the short, medium and longer term for this 'Protect – Pump' strategy.

For the short-term, it is needed to assess the long-term effectiveness and feasibility of a protect-pump strategy and explore the full solution space (thus also alternative strategies), while fixing current and near-term problems with drainage and pumps.

Recommended Interventions

The mitigation of the current vulnerability of the drainage systems of Recife, expected to deteriorate further by the expected negative impacts of climate change, as diagnosed by the various agencies and consultants involved in the management of municipal water resources and confirmed by the mission team, requires a series of structural and non-structural measures for which a route has been presented below. The horizon for these measures is subdivided as follows:

Short Term: 2023 - 2030. This period refers to interventions that can be installed up to 2030, defined as no-regret measures and for which financing is most likely already available, e.g. through the already approved IBRD loan. These are also interventions that solve some of the most urgent existing flooding problems in Recife, and improve the understanding of the system to develop an adaptation plan for the next period that can be dovetailed with urban plans.

Medium Term: 2031 – 2050. This period refers to interventions that are of larger scale, complex to study and which may require financing from new sources. To a certain extent the timing of these investments also depends on the speed with which the impacts of climate change manifest themselves to the city. Current problems of street flooding will become significantly more frequent by the end of this period. For example, flooding problems of a magnitude that currently occur once a year may now occur at a frequency of at least 5 times a year.

Longer Term: 2051 – 2080. Currently there is not much doubt that, in the context of the 'Protect – Pump' strategy, the impact of climate change will require further investments in flood protection and the drainage system of Recife. In particular, SLR will have strong impacts on street flooding during this period. Pumps will have to take over the role of tidal sluices in many parts of Recife. Some form of sea walls will become a necessary solution to provide flood protection from the ocean in the low lying areas of Recife. Nevertheless, it is expected that for this time horizon Recife is still able to defend itself against the negative impacts of climate change.

It should be noted that some of the interventions proposed for each of these terms may have to be shifted along the timeline, both ways, depending on public needs, budgets available, completion of studies.

Beyond 2080. The current insight, based upon results of climate models, indicate that before the end of the current century the solution space may have to be broadened from the Protect – Pump pathway described below. Due to uncertainties related to the physical processes underlying the current climate change models, this moment can be earlier or later than 2080, depending also on the impacts of soil subsidence in the low-lying areas of Recife. At some stage, a different pathway towards the future will have to be followed by switching to the Advance or Retreat Strategies, discussed in Chapter 4, while fixing current and near-term problems with drainage structures, levees and pumps. Discussions on these strategies should not be delayed, as these solutions have an impact on decision making in the current urban planning of Recife.

Recommended interventions in Boa Vista

Short Term

- **Start urgently with the development of a functional hydrological-hydrodynamic model** as discussed in Annex 2, jointly with the **urgent installation of a water level and discharge monitoring system.** For most of the interventions recommended below, these instruments are essential for their cost-effective design.
- **Produce reference flood hazard maps** for a range of design storms combined with tides and storm surges, e.g. 1 in 1, 2, 5, 10, 20 and 50 year return periods for: (a) the current situation; and (b) the expected conditions in 2050.
- **Installation of flap gates at all micro-drainage outfalls from Boa Vista** to Rio Capibaribe along the south-eastern stretch between both connections with Canal Derby – Tacaruna and all along Canal Derby – Tacaruna, at both sides. These flap gates shall be of lighter weight than the ones currently installed at the outfall of the pump at Rua da Aurora - Rua Cap. Lima. It is recommended to standardize these flap gates for Recife and design these on the basis of current best international practices.
- **Installation of a similar flap gate** at the outlet of the currently installed pump at Rua da Aurora - Rua Cap. Lima to replace the existing heavy one. This will increase the capacity of the pump.
- **Elevate some of the flood prone stretches of Av. Gov. Agamenon Magalhães**. Efforts to do so have been made in the past, leading to a destabilization of the canal bed. However, a good soil investigation and design should lead to sustainable solutions for these stretches.
- **Investigate the functioning of Canal Derby - Tacaruna** with a 1D hydrological-hydrodynamic model to be developed as described in Annex 2 and define improvements of the functioning of this primary drainage channel through the following adaptations/other interventions:
    - Investigate the reason of **quick pump turn-off** at the northern end of this canal. Limiting factors may be: (a) small surface area of the pump sump; (b) narrow connection between pump sump and canal; (c) insufficient discharge capacity of Canal Derby - Tacaruna upstream of the pump; (d) lack of retention capacity near the pump; and (e) sensor installed too close to the pump.
    - Investigate the **overall discharge capacity** of Canal Derby - Tacaruna and investigate the impacts of deepening and widening of the canal. Space for widening seems to be available; conveyance capacity may be improved by designing vertical banks, either as Short Term or Medium Term intervention; etc.
    - **Relocate the outlet structure and pumps** to a location where Canal Derby - Tacaruna and Rio Capibaribe meet. This will allow the use of the retention area south of the Scientific Park (lake) to be used for pumping, which will improve much of their functioning (Fig. ..). It was mentioned that the area of this lake was claimed for the construction of a data centre. However, it is very possible to place this building on stilts, a practice commonly applied in the Netherlands in case land is needed for a double function (Fig, ..). Alternatively, part of Rio Capibaribe east of Av. Olinda may be used as retention space upstream of the pumps.
    - **Install pumps** also at the southern end of Canal Derby - Tacaruna and optimize their functioning. Again, find ways to create retention capacity near the pumps.
    - As water levels around the middle of Canal Derby - Tacaruna will drop slower than at the ends, investigate the possibility of **diverting flood water in these areas to Rio Capibaribe** through new diversion culverts and pumps.
    - Investigate the installation of **booster pumps** along Canal Derby - Tacaruna to speed up bringing runoff to the canal outlets.
    - **Optimize the operation** of existing and newly installed equipment.

- Besides specifying the need for investments during the Short Term, also define most of the **works needed in the Medium Term**.

- **Draft the ToR of a study** to investigate all options mentioned above and more, based upon the development and application of a well constructed hydrological-hydrodynamic model (see Annex 2) and make sure that the contract is awarded to a reliable and creative engineering firm. It is recommended to encourage bringing in international experience in this study. This study will also have to come up with a long-term vision, covering expected investment needs for the Medium and Longer Terms.

Figure 19: Derby – Tacaruna Canal north with tidal outlet (left) and the possibility to relocate this outlet to the east, allowing to mobilize the capacity of the retention basin shown north or of part of Rio Capibaribe

Medium Term

It is possible that part of the Short Term investments have to be moved to the Medium Term for their financing. For the Medium Term the following interventions are foreseen:

- **Heightening of sections of the banks** along Canal Derby - Tacaruna and Rio Capibaribe to avoid overtopping of these banks, which would lead to flooding into Boa Vista. The study defined for the Short Term investments should provide insights into this problem.
- **Increasing pump capacities** from low lying areas in Boa Vista and polders that have been or have to be constructed. Installation of pumps also require pump sumps or even somewhat larger retention basins, wherever possible. An example for creating such basin is its construction underneath the playground at the current pump location at Rua da Aurora - Rua Cap. Lima. Another example of the double use of space for retention in Recife. These needs will have to be specified already in the study defined for Short Term measures.

- Various measures to **delay runoff** towards the pumps and reduce their volumes by making use of Nature Based Solutions (NBS). Part of these may already be implemented as part of the Short Term packages of work.

Longer Term

It is expected that the impacts of climate change will require the need for raising walls around Boa Vista. This would most likely also imply that tidal flap gates will no longer function satisfactorily and most or all drainage runoff will have to be removed by pumps. The whole of Boa Vista will turn into a polder system. Most likely this will lead to a system where Boa Vista is subdivided in separate polder areas, which will pump their runoff directly to Rio Capibaribe or to Canal Derby - Tacaruna. For pumping stations to function satisfactorily it is important that near the pump sufficient retention capacity is available. Moreover, the control of the pumps, based upon water levels, should (also) be connected to locations outside the pump sump.

Recommended Interventions along Tejipió River

Short Term

- For this part of Recife it is even more important to start urgently with the **development of a functional and well calibrated hydrological-hydrodynamic model** as discussed in Annex 2, jointly with the urgent installation of a water level and discharge monitoring system. For most of the interventions recommended below, these models and data are essential for their cost-effective design.
- **Urgently start with a campaign to survey cross-sections** along Rio Tejipió and Rio Capibaribe as this information, basic for the construction of hydrodynamic models, is mostly missing. Also survey and map all micro-drains entering Rio Tejipió in the flood prone areas.
- **Produce flood hazard maps** for a range of design storms combined with tides and storm surges, e.g. 1 in 1, 2, 5, 10, 20 and 50 year return periods for: (a) the current situation; and (b) the expected conditions in 2050.
- **For flood prone areas along Rio Tejipió**, now and in the future, define the most desirable solutions to prevent flood risks, either by relocating people and properties or by embanking areas and turn these into polders drained by tidal gates and pumps. An important area to address is the **Ipsep neighbourhood**, where flood depths of up to 1 meter have been reported as combined impacts of upstream runoff and tides. Urgent study and action is needed for this area.
- **The Recife Park City initiative** has been noted and studies to support the design of linear parks along Rio Tejipió have been initiated. In principle, the linear parks will occupy the existing flood plains of Rio Tejipió. Turning these into parks will not automatically reduce flood peaks further downstream. However, the parks will offer possibilities to delay runoff and reduce peak flows by using retention volumes in these flood plains through the construction of low dikes between the parks and the river. Further studies will have to investigate how the functions of park and flood management are best combined.

Medium Term

It is possible that part of the Short Term investments have to be moved to the Medium Term for their financing. For the Medium Term the following interventions are foreseen:

- **Construction of upstream reservoirs** to reduce flood peaks along Rio Tejipió. As upstream peak floods appear to have a significant impact on flooding of areas adjacent to Rio Tejipió in the city, the study of this measure is of great importance and shall be initiated already in the Short Term. However, it is expected that readiness, dealing with quite a number of inter-municipal and ownership issues, will delay their implementation with quite some years.

- **Next steps in protecting areas along Rio Tejipió**, most likely require an extension of the polder areas and an increase in pump capacity for the polders.

- **Adaptations in agricultural practices in the upstream Rio Tejipió basin**, aiming at reducing the peaks and volumes of runoff generated by storm events. Agricultural areas would offer significant potential. However, effective measures require quite some institutional arrangements between various state agencies and between municipalities.

- **Tidal barrier in Rio Tejipió.** This option was much discussed during the mission, including possible locations. Such possible intervention will have to be studied thoroughly, supported by the use of reliable hydrological-hydrodynamic models and extensive data collection. Issues to be investigated are (though not limited to these) for current and future conditions: (a) does a tidal barrier still provide benefits in the case of coinciding flood waves from upstream river basins and high tides from the ocean? At first sight the retention capacity to absorb flood volumes from upstream seems to be rather small; (b) is such solution cost-effective? The structure has to be built on soft soils, which requires expensive foundations; and (c) what are the environmental impacts of such barrier, in particular if the selected location would also lead to severe impacts on the Parque de Manguezais?

Longer Term

It is expected that the impacts of climate change will require the need for further raising of dike levels along Rio Tejipió. This would most likely also imply that tidal flap gates will no longer function satisfactorily and most or all micro-drainage runoff around Rio Tejipió will have to be removed by pumps. A tidal barrier may get into the picture now, if placed at a location to absorb sufficiently the runoff volumes coming from upstream.

Recommended interventions in Boa Viagem

Short Term

- **Start urgently with the development of a functional hydrological-hydrodynamic model** as discussed in Annex 2, jointly with the urgent installation of a water level and discharge monitoring system. In addition, define a survey to measure cross-section profiles for Rio Jordão and Canal de Setubal as, so far, these are based upon the Recife LiDAR survey results. For most of the interventions recommended below, these instruments are essential for their cost-effective design.
- **Produce reference flood hazard maps** for a range of design storms combined with tides and storm surges, e.g. 1 in 1, 2, 5, 10, 20 and 50 year return periods for: (a) the current situation; and (b) the expected conditions in 2050.
- **Installation of flap gates at all outfalls along Rio Jordão and Canal de Setubal**. See recommendations on flap gates in the Section on Boa Vista.
- **Investigate the functioning of Rio Jordão and Canal de Setubal** with a 1D hydrological-hydrodynamic model to be developed as described in Annex 2 and define improvements of the functioning of these primary drainage channels through adaptations/other interventions:
    - Investigate the overall **discharge capacity of Rio Jordão and Canal de Setubal** and investigate the impacts of deepening and widening of the canal. Space for widening seems to be available; conveyance capacity may be improved by designing vertical banks, either as Short Term or Medium Term intervention; etc.
    - **Install pumps** at the northern outlets of Rio Jordão and Canal de Setubal and optimize their functioning. Provide sufficient retention basin capacity at these pumps. This may go at the cost of some of the area of the Parque de Manguezais.

    - As water levels around the middle of Canal de Setubal will drop slower than at the ends, investigate the possibility of **diverting flood water** in these areas to the ocean through new diversion culverts and pumps.
    - Investigate the installation of **booster pumps** along Canal de Setubal and Rio Jordão to speed up bringing runoff to the canal outlets.
    - **Optimize** the operation of existing and newly installed equipment.
    - Besides specifying the need for investments during the Short Term, also **define most of the works** needed in the Medium Term.
- **Draft the ToR of a study** to investigate all options mentioned above and more, based upon the development and application of a well constructed hydrological-hydrodynamic model (see Annex 2) and make sure that the contract is awarded to a reliable and creative engineering firm. It is recommended to encourage bringing in international experience in this study. This study will also have to come up with a long-term vision, covering expected investment needs for the Medium and Longer Terms.

Longer Term

It is expected that the impacts of climate change will lead to the need for further **raising walls around Boa Viagem** and its primary drainage canals. This would most likely also imply that tidal flap gates will no longer function satisfactorily and most of all drainage runoff will have to be removed by pumps. The whole of Boa Viagem will turn into a polder system. Most likely this will lead to a system where Boa Viagem is subdivided in separate polder areas, which will pump their runoff directly to Rio Jordão and Canal de Setubal and subsequently the Parque de Manguezais and (for Canal de Setubal) to the ocean and Lagoa de Olho d'Agua. Other recommendations are similar to those given for the Boa Vista area.

6. Recommended studies and data collection

This Chapter describes the strategy to arrive at a good understanding of the functioning of Recife's drainage system, both in the qualitative and quantitative sense. During the mission it was noted that, although there was a good understanding of the importance of various processes, such as tides, river basin runoff, storm surges, soil subsidence, local rainfall, etc., their interrelationships were less clear. Knowledge on how the system functions is an important requirement to define cost-effective interventions for flood risk reduction.

State of the art these days is the **development of hydrological-hydrodynamic models** to simulate water levels and flows in the system and the impact of interventions. Various models were shown at various stages of development. However, it was noted that quite some work was still needed to make these various components to work in a consistent environment, showing also the influence one model domain would have on other model domains. For example, the model developed for Rio Tejipió did not include the influence that Rio Capibaribe has on its downstream boundary. For this reason, it has been recommended to develop one Drainage Master Model for Recife, which can than be used for detailing studies for certain target areas (see also Annex 2).

It is recommended to develop such Drainage Master Model in a 2-step approach:

1. **Develop a Recife Pilot Model** covering the basins of Rio Tejipió and Rio Capibaribe, as well as the primary drains of Boa Vista and Boa Viagem, including their sub-catchments providing runoff to these main waterways (see Annex 2). The model can be set up in a 1D hydrodynamic schematization and have between 100 and 200 sub-catchments describing the rainfall-runoff process, with a size depending on their urban or rural character. In this pilot version information on channel bathymetry is largely lacking and quite some inputs have to be assumed based upon Google Earth images and best assumptions of channel depths. Calibration will be limited to adjusting to hear-say flood levels in areas adjacent to the channels. This model will be very useful to gain insight into the overall functioning of the system under various conditions. It will also be a useful instrument to support the Hackathon proposed (see next section on follow up and Annex 3). Construction of this pilot model could be completed within a period of 6 months on the basis of inputs provided by the participants of the Master Class with some guidance provided by the DRR Team. Annex 2 provides guidelines on the construction of this model, including the way macro- and micro-drains interact in the schematization to provide a realistic representation of the urban runoff processes. The advantage of this 1D pilot model is the speed of execution of simulations as it will provide results within 5 to 10 minutes for each scenario defined. It shall have an interface which presents flood hazard maps as output.
2. **Develop the Recife Drainage Master Model** (RDMM) covering the same area, now calibrated on the basis of monitored and surveyed data as discussed below. This Master Model will basically still be based upon a 1D schematization, though with detailing in 2D for focal areas. This detailing can either be permanent of allocated for each individual application of the model. This model can only be finalized after a water level and discharge monitoring system has been installed and data are available for at least 6 months to serve model calibration. Realistically, this model can only be completed by the end of 2024. This work may be best delivered as part of an update of the Recife Master Drainage Plan, as discussed below.

A choice will have to be made for the modelling system to be used. Most models already available for the study of Recife's flooding and drainage problems have been developed on the basis of HEC-RAS and a 2D (two-dimensional) schematization of the hydrodynamic processes. Annex 2 discusses the importance of developing these models also with a partly 1D schematization, in particular to connect the modelled domain of interest with the overall network of rivers and canals. Various modelling systems are available on the market providing low-cost options for using this software.

Besides HEC-RAS, which is free, though does not have a support desk, options may be PCSWMM, distributed by CHI in Canada or SOBEK, developed and distributed by Deltares in the Netherlands. PCSWMM has already been applied by one of the participants of the Master Class, while SOBEK was used in the Master Class in February 2023 to demonstrate tidal propagation in Jordão River.

It is recommended that the team that participated in the **Master Class continues to meet** to exchange experience with the development and application of their models. Monthly meetings may be organized to cooperate on the joint development of experience. Joint testing of modelling systems may be taken up to lead to the best choice of the modelling system to be selected for Recife from the perspective of functionality of the description of tidal gates, pumps and their operation options, both in 1D and 2D, functionality of the user interface and robustness and speed of simulations. For the coming months the DRR Team Senior Drainage Expert can connect to part of these meetings online and provide further guidance.

During the mission it became clear that studies on Recife's drainage system still lack many data that are of utmost importance. Hardly any water level measurements are available. Recife does not have a permanent tidal gauge at its port. Coastal water levels have been monitored in the past with various interruptions. It is recommended to install a permanent and well-maintained tidal gauge at the entrance to the port. Some water level records have been made for the past months at the tidal gates at the northern end of the Canal Derby - Tacaruna. Also, gate operations have been recorded. Along Rio Tejipió one station has records of water levels at the crossing with Av. Recife. However, currently this station is out of order. No discharge measurements along the rivers are available. There is also a great lack of information on river and canal cross-sections.

Recife has an extensive network of 25 rainfall stations that were installed by the Federal Agency Cemaden. This system appears to be working well and provides online rainfall data at these stations, as demonstrated during a visit to APAC, the Agency that runs the monitoring rainfall and climate system. The coverage is sufficient to provide information on the distribution of rainfall across the city, both for model calibration as for the definition of design events.

As information on water levels is largely missing, it is recommended to start urgently with the installation of a monitoring system. No information is currently available on river discharges. Both sets of data are crucial for the analysis of peak discharges in the city, which are the main cause of flooding problems along the rivers and canals. Figure 20 provides a map with 15 proposed locations for water level monitoring with 3 locations where also discharges have to be measured to generate rating curves. For water level monitoring there will be a choice between radar sensors, looking vertically down from structures such as bridges or pressure sensors, which are positioned on the channel bed and connected to a point where data can be transmitted. State of the art is direct transmission of data via a GSM network with local backing up.

Discharges are usually derived from rating curves, which define discharges from a relation between water level and discharge. Such relationships can only be established at locations outside the influence of tides and backwaters. The map provides locations where such rating curve can be established. To define this relationship, at least 5 times a discharge has to be measured covering a range from normal to extreme events. The national water agency ANA contracts consulting firms to set up a scheme of discharge measurements, usually using ADCP equipment. Such companies are also active in Pernambuco. Usually, this work is quite costly. New technologies have recently been developed in the Netherlands on the basis of camera recordings of the flow pattern at the river surface to generate such rating curves at much lower cost. It is recommended to take this up for Rio Tejipió at the crossing with Av. Recife. This location would provide an ideal opportunity to serve as a pilot option. It is recommended to involve universities in such project.

There will also be a need for establishing a reliable data base, based on data quality checks, easy data retrieval options, backing up guarantee, etc. The Delft-FEWS system, developed by Deltares in the Netherlands, may serve such purpose as it also would provide the option to develop into flood and inundation forecasting support services. Also, APAC may provide support to such a need.

Currently, no information is available on the **potential occurrence of storm surges**. During the visit to the Universidade Federal de Pernambuco it was stated that storm surges could add as much as 50 cm to peak tide levels. This is backed up by the understanding that the difference between normal and extreme spring tides is of the order of 60 cm. Existing records of sea levels will have to be used to analyze the correct value and its statistical properties. This uncertainty demonstrates the need to install a permanent and robust tidal gauge at the port of Recife.

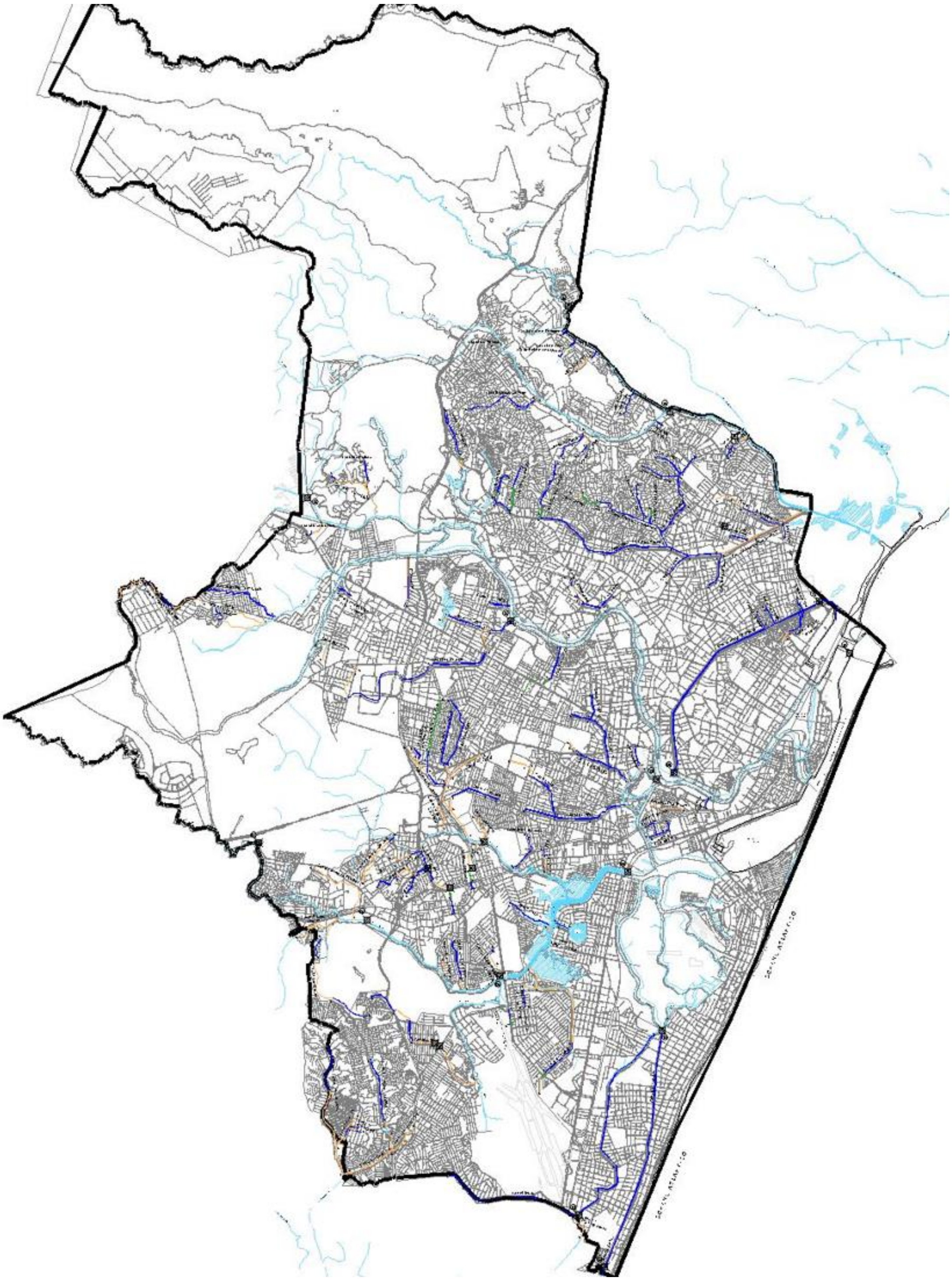


Figure 20: Map showing the locations of the proposed water level and discharge monitoring stations

Data is also large lacking on soils subsidence. Soil subsidence is primarily a problem in soft soils and their impact is similar (though in opposite direction) to that of SLR: decreasing terrain levels reduce the possibility to drain rain water by gravity. It was stated that in Boa Vista soil subsidence of 1 meter in 40 years had been observed. This is substantially more than the sea level rise that occurred over this period. It is worth investigating if satellite based information is available on soil subsidence in Recife, such as for cities like Paramaribo and Georgetown based upon the InSAR processing of the Copernicus Sentinel data.

Models developed so far define **channel cross-sections derived from the digital terrain model (DTM)** of Recife. A DTM for Recife has been constructed on the basis of a LiDAR survey. However, such survey sees channel bed level as water surface level, which will require correction. Moreover, the DTM derived from the LiDAR survey has not filtered out most of the buildings, the tops of which still appear as terrain levels. As a result, there is an urgent need to survey river and canal cross-sections as essential input into the hydrodynamic models. It is recommended to contract a survey company to measure cross-sections for the development of the RDMM. The ToR for such survey has to be developed. Distance between surveyed cross-sections will have to be of the order of 200 metres. This work could also be commissioned as part of the updating of the Drainage Master Plan.

During the mission it has not become clear which point density forms the basis of the available **LiDAR survey**. For urban applications such survey should produce at least 16 effective points per m^2 (blocks of 25 * 25 cm per point), or at least the double of this in the survey, as at many places points get lost due to vegetation and various other reasons. It may be considered to take up a new LiDAR survey with focus on Recife alone.

There is an urgent need for an **update of the actual Drainage Master Plan (DMP) for Recife**. The ToR of this current plan was defined in 2011 and the work was completed in 2016, showing the long time needed for preparation and contracting of such study. The current plan has a focus primarily on needs identified 10 years ago. No hydrological-hydrodynamic model was developed and applied to support the design of works. The plan did not yet take into account adaptations needed to handle the impacts of climate change.

The updated plan will have to take a **wider time horizon, suggested to be set at 2050** and be based upon defining a more pro-active set of measures. Data monitoring, surveying, modelling and climate change projections will be integral parts of this study. The updated Drainage Master Plan shall come up with proposed investments for the period until 2050 to deal with climate change impacts on flooding and drainage problems of the city. The DRR-Team suggests to prepare a core set of tasks for the consultant developing this Master Plan as a follow-up activity of the current mission. It is recommended to solicit the participation of an international consulting firm as part of a consortium to be contracted for this DMP study.

7. Proposed Follow Up

Key messages:

I. Urgent Actions to the Drainage System

Chapter 5 of this report presents a list of proposed follow up actions in relation to the drainage system of Recife. The proposed measures to the system for the period until 2030, presented in the chapter, are urgent and would best be undertaken immediately. The measures for later periods, until 2050 and until 2080, will need to be studied further, also in the light of potential alternative adaptation pathways.

→ A key benefit of this action will be an immediate improvement of the drainage situation in some areas.

II. Urgent attention to data collection and the development of analytical tools

Chapter 6 of this report presents key issues related to data collection of water levels and river runoff. Such data are a prerequisite for the development of analytical tools such as hydrological-hydrodynamic models. Without the use of such simulation models it will not be possible to quantitatively evaluate the impact of climate change, and of potential measures.

→ A key benefit of this action will be an immediate and quantified insight into climate change impacts on the river system of the city to provide a quantitative approach to cost-effective flood risk reduction investments in Recife.

III. Urgent attention to strategy development

For the short-term, it is urgently needed to assess the long-term effectiveness and feasibility of a protect-pump strategy and explore the full solution space (thus also alternative strategies), while fixing current and near-term problems with drainage and pumps.

The use of hydrological-hydrodynamic models, including well schematized simple 1D demonstration models, will allow for the qualitative and quantitative assessment of the occurrence of climate change impacts, and of the needs and cost-effectiveness of potential measures, e.g. tidal gates and/or pumps at drainage area outlets, linear parks along the rivers, dikes or small or large scale tidal barriers, as well as exploring limitations to the protect-pump adaptation pathway.

A key follow up action would be to hold a **Hackathon** on strategy development, making use of a 1D demonstration model. Annex 3 presents a concept note for such a Hackathon.

→ A key benefit of this action will be to allow rational decision making in the short term on investment decisions such as tidal gates and linear parks, and a time line of required actions and investments for the longer term exploring, alternative adaptation pathways.

Summary of Recommended Actions

- **There is an urgent need to develop an integrated hydrological-hydrodynamic Recife Drainage Master Model (RDMM)** as specified in this report, covering the whole area of Recife and its upstream river basins. This model will provide much improved understanding of Recife's drainage and flooding problems and provide quantitative support to the cost-effective design of flood risk reduction measures.
- The development of this tool will have to be followed by **studies on specific flood prone areas based on local refinements of this model**, sensitivity analyses of the impacts of possible

interventions and the impacts of climate change, in order to avoid maladaptation and destruction of invested capital.

- **There is an urgent need to start with the collection of data** supporting Recife's flooding and drainage studies. Most urgent is the installation of a hydrological monitoring network across Recife, including a robust tidal station, as specified in this report. In addition, bathymetric surveys of rivers and drainage canals will have to be taken up.
- **There is an urgent need to develop a better insight into the impacts of storm surges from the ocean and perceived soil subsidence processes** in the coastal zone of Recife, to support the decision making in the design and implementation of flood reduction measures in Recife. Given these uncertainties it is strongly recommended to install a robust tidal gauge at the Port of Rectify, for the analysis of SLR and its guidance on flood risk protection needs in Recife the coming decades.
- **The updating of the Recife Drainage Master Plan**, which is due the coming years and shall be supported by the RDMM, shall focus more on pro-active measures to be taken as a result of city densification and the impact of climate changes, in particular sea level rise. Within the coming two decades, significant investments will be required, starting with the implementation of no-regret measures the coming years to more complex and costly interventions, subsequently.
- The built-up area of **Recife has a severe lack of retention space for water**. Such retention is badly needed for slowing down the runoff of storm water into the primary drains and, even more so, to secure the robust functioning of tidal sluices and pumps. Such retention space is difficult to find and it has to be considered to maximize usable space in the city by giving terrains a double function, e.g. the construction of buildings on foundation piles above retention basins.

Follow-up on Master Class

It is recommended that the team, composed of staff of the Municipality of Recife, State of Pernambuco, consulting firms and academics, that participated in the **Master Class, continues to meet** on a monthly basis to exchange experience with the development and application of their models. Focus initially should be on the development of the hydrological-hydrodynamic Pilot Model for Recife and the selection of the most appropriate modelling system. For the coming months the DRR Team Senior Drainage Expert can connect to part of these meetings online and provide further guidance.

Hackathon

It is recommended that a hackathon can be held to explore the **impact of rainfall intensification and sea level rise** on the performance of the current drainage system of Recife, as well as evaluate the potential **impact of measures** such as linear parks and other green areas, small dikes and levees, or tidal gates. This way, qualitative insight into the impacts of short term decisions can be achieve, while the more detailed full Drainage Master Model is being developed in the coming years.

The Hackathon should also evaluate potential **alternative adaptation pathways**.

Annex 1 – mission program

Mission dates: 6 – 10 February 2023

Data e hora	Local e propósito	Participantes
SEGUNDA 6-fev		
9:00 (Prefeitura)	Reunião no Gabinete do Prefeito 9.10 Introdução Prefeito 9.15 Palavras Embaixador Holanda 9.20 Apresentação Time Recife 9.30 Apresentação Time DRR	Prefeito João Campos, Embaixador e Adido Económico, Consul Honorário Holanda em Recife, DRR Team, Secretários de Infraestruturas, Ambiente, Planejamento Urbano, Diretora EMLURB
10:30	Revisão da programação da semana	Equipe Recife / DRR team
14:00 – 17.00	Visita de campo para ver o potencial impacto do aumento do nível do mar. Locais: 1. Obra da Concórdia (Pico De Maré) 2. Largo da Paz – Final Da Imperial (Visualizar o braço morto do rio Capibaribe) 3. Ponte Motocolombó (Visualizar A Foz Do Rio Tejipió) 4. Estações de bombeamento: Rua Da Aurora e Agamenon 5. Ponte Governador Paulo Guerra (Encontro do Capibaribe/ Bacia do Tejipió)	Equipe EMLURB; DRR team; equipe Embaixada
TERÇA FEIRA 7-fev		
8:00 – 10:00 (Sede EMLURB)	Plano Diretor de Drenagem: apresentação detalhada e discussão de infraestrutura, modelos, conjuntos de dados, DTM e precipitação. Alargamento, implantação de parques lineares/alagável, novas comportas, micro reservatórios (pretensão), lei do teto verde.	Equipe EMLURB/DRR team especialistas em drenagem
10:30 (Sede SMAS)	Reunião com o Secretário Carlos Ribeiro, discussão do projeto ICLEI sobre instrumentos de adaptação às mudanças climáticas	Secretário Carlos Ribeiro/ Líder da Equipe DRR
10:30 – 12:00 (Sede EMLURB)	Apresentar a proposta de "soluções para cidade do recife" do desafio UNIT x PCR. Áreas de influência de mare (costeiras, não costeiras) e soluções para cada região do Recife.	Equipe EMLURB/DRR team especialistas em drenagem

14:00 – 17:00 (UFPE) Auditório do CEERMA	Visita à Universidade Federal de Pernambuco, discussão com professores da área de oceanografia e drenagem sobre aumento do nível do mar, mudanças na precipitação, proteção costeira e medidas de adaptação às mudanças climáticas	Equipe EMLURB/DRR team; Prof. Marcus Silva, Prof. Jaime Cabral, e outros
QUARTA FEIRA 8-fev		
9:00 – 11:00 (PCR - INSTITUTO PELÓPIDAS)	Discussão do planejamento urbano em relação às mudanças climáticas e especialmente ao aumento do nível do mar, com apresentação do ICPS e da ARIES.	ICPS, ARIES e DRR team
11:00 – 11:30	Continuação das discussões sobre a temática e definição das atividades	Equipe EMLURB/DRR team
14:00 – 16:00 (Visita de Campo)	Visita de campo a locais que se tornarão problemáticos com o aumento do nível do mar: estações de bombeamento, saídas de drenagem. Locais a serem visitados: 1. Ipsep /Av. Recife (Posto), Av. Dois Rios 2. Alargamento do Rio Tejipió	Equipe EMLURB/DRR team
QUINTA FEIRA 9-fev		
08:00 -–– 12:00	Continuação da discussão sobre o impacto do sistema de drenagem, modelagem e conjuntos de dados.	Equipe EMLURB/DRR team – Adri e Frederico
10:30 -–– 11:30	Reunião sobre o projeto de orla marítima da RMR e discussão aprofundada sobre o Plano de Adaptação Setorial	Sec. Carlos Ribeiro e equipe, Cinthia Mello
12:00 -–– 12:30	Reunião com o Silvio Meira (online)	Equipe DRR
14:30 – 15:30 (Sede APAC)	Reunião com a Agência Pernambucana de Águas e Clima sobre o sistema de monitoramento de águas da cidade.	Recife/DRR e especialistas em drenagem, APAC
SEXTA FEIRA 10-fev		
Manhã	Preparação da apresentação	DRR team
10:00 – 12:30	Encontro de alinhamento final	Equipe EMLURB/DRR team
13:00 (PCR)	Debriefing: Apresentação de resultados preliminares	Recife/DRR teams, Sec. Felipe Matos, Sec. Marília Dantas, Sec. Exec. Beatriz Menezes, Cinthia Mello

Annex 2 – Short report of Master Class on Model Development and Application

Dates: February 13 – 15, 2023 at the Recife Town Hall

1. Introduction

Subsequent to the formal mission, a **Master Class on Model Development and Application** was held at EMLURB to provide support to their role of improving the Recife drainage system and reduce the occurrence of urban inundations through studies and investments. In this Master Class the focus was primarily on mitigating impacts of climate change. The Master Class was guided by the DRR mission team member Adri Verwey and attended by staff of EMLURB, the Estado de Pernambuco and consulting firm TPF. The group was composed of the following persons:

- Alisson Caetano da Silva - Prefeitura da Cidade do Recife
- Gastão Cerquinha - Secretaria de Recursos Hídricos do Estado de Pernambucu
- Yuri Tomaz - TPF Engenharia
- Alexson Caetano - TPF Engenharia
- Edinilson de Castro - TPF Engenharia

All these persons are also connected to the Universidade Federal de Pernambuco, either as lecturer or as PhD student.

The objective of this Master Class was the improvement of capacity of the Recife Municipality and their academic and consultancy knowledge providers to support the evaluation of cost-effective interventions in the drainage system with a view on longer term developments in the city, including result of impacts of climate change on sea water levels and precipitation.

The Master Class was organized in a rather informal setting, where participant presented the hydrological and hydrodynamic models they were working on in their role as Municipality staff, academic research and consultancy. Models presented by the participants were discussed in the light of:

- Objective of developing the model.
- The focus area of application.
- The level of detailing needed at various parts of the model domain.
- Areas of the model domain where a hydrological model (rainfall-runoff) model would be most appropriate.
- The issue of choice between 1D(imensional) and 2D hydrodynamic modelling.
- The importance of speed of turn around of model results.
- The resulting choice of model schematization.

2. The Jordão River model development and application

Model Development

The model, as presented by Yuri Tomaz under development by the consulting firm TPF, focussed on the schematization of the canalized Jordão River, with its source in Boa Viagem and discharging into the Parque de Manguezais, an approximately 300 ha wetland under the influence of tides from the River Tejipió. The Jordão River was schematized in 1D with rainfall-runoff models set up for 5 sub-basins. The most western part of the receiving wetland area with channels and mangroves was represented by a 2D hydrodynamic model. This model domain will have to be extended to include the full wetland.

It appeared that the objective of developing this model was the study of inundation problems along the south-western border of Parque de Manguezais, under the influence of tides and possibly storm surges entering from the ocean and drainage runoff from Boa Viagem. With the group of professionals, the best way of schematizing the model domain was discussed in the light of the objective of the model and the relative importance of the various physical processes that had to be represented. As a result, it was recommended to modify significantly the schematization of this model.

In the model, developed so far, the total Jordão basin was schematized with 5 sub-basins. Runoff from storm events was discharged directly into Jordão River at 5 different locations. It was recommended to refine the schematization of the hydrological model by defining 20 to 30 sub-basins. In addition, the runoff from these sub-basins should not be discharged directly to the river. This would lead to unrealistically high water levels, in particular at moments where storm events would coincide with high tides.

It was shown that it would be much better to store this runoff temporarily in a storage basin, representative for the surface storage in the whole sub-basin. By providing a connection between this storage basin and the river, emulating the role of micro-drainage pipes, a quite realistic schematization of the physical system would be achieved. In case of high water levels in the Jordão River, the runoff generated by the storm would be held back temporarily, quite similar to what happens in reality. Moreover, this form of schematization would allow for the simulation of backflow from Jordão River to the neighbouring urban areas, as observed at various locations during the occurrence of high tides.

The model discussed above is only part of the overall model required for this study. Flooding of the vulnerable areas along the western borders of the Parque de Manguezais is subject to propagation of tides from River Tejipió into this complete wetland. A first extension of the Jordão River model is needed by coupling it to a 2D hydrodynamic model for the approximately 300 ha Parque de Manguezais. It is recommended to develop this part of the model based on an integrated 1D2D model schematization approach.

In a first approximation, the seaward boundary condition for this model, where the Parque de Manguezais connects to River Tejipió, can be defined by the values of the tidal levels at the Atlantic Coast. This model will be the fist step in showing the impacts on the vulnerable areas as a result of the combined effects of drainage flows generated along the Jordão River and the penetration of tides into the wetlands of Parque de Manguezais and along Jordão River. In addition, also the runoff from the Setubal Canal will have to be included in this model.

As a next step, the tidal boundary set in the model will have to be improved. As reported by the participants, the tidal boundary of the Parque de Manguezais model is impacted significantly by the Tejipió and Capibaribe rivers and the branch connecting these. This impact is even more significant during extreme flood events. For this reason it will be necessary to extend the model to include the full Tejipió and Capibaribe river basins up to the ocean. A hydrological and 1D hydrodynamic schematization of these river branches will provide sufficiently accurate results. The extended model shall have its sea boundary at the entrance to the Port of Recife and have runoff from sub-catchments or reservoirs specified as inflows from upstream.

Without such model extension it will not be possible to judge the deformation of the tide in its propagation from the Atlantic Ocean towards the entrance to the Parque de Manguezais. The deformation of the tide will have to be validated in the model with observed water levels, in particular at the entrance of the Parque de Manguezais (see Proposed Monitoring Network).

If a 2D schematization of the downstream part of the Tejipió - Capibaribe river network would be applied, simulations with a focus on local problems along the borders of the Parque de Manguezais would take much more time than for a 1D schematization. A fast (still sufficiently accurate) hydrological-hydrodynamic model will allow for the development of a good understanding of how the physical system functions. This understanding is the basis for testing and comparing a variety of possible interventions that could reduce the flooding problems.

Summarizing the model development for the investigation of flooding problems of the area along the south-western side of the Parque de Manguezais, the following steps are recommended:

1. Develop the 1D hydrological-hydrodynamic model for the Jordão River basin, including the schematized connections of the river and its drainage area via underground micro-drainage pipes.
2. Similarly, develop the Setubal Canal model (see further details below).
3. Develop the 1D2D integrated hydrodynamic model for the wetland of the Parque de Manguezais and connect this model to the 1D models for the Jordão River and Setubal Canal basins.
4. Develop the 1D hydrological-hydrodynamic model for the Tejipió and Capibaribe river network and connect this to the model developed in steps 1, 2 and 3.

Application

Use this model to study the impact of combined rainfall and high tide events on the flooding of the areas adjacent to the Parque de Manguezais, taking also into account the possible impacts of storm surges and future soil subsidence.

This model can also be used to study the impacts of tides entering Boa Viagem through Jordão River and Setubal Canal and the resulting flooding of the streets, even in the absence of rainfall. In particular, simulations of the combined effect of tides and rainfall will be of interest in designing solutions for flooding of the streets in Boa Viagem.

Scenarios to be studied for the inundation problems in Boa Viagem would focus on simulations of the following suggested conditions/interventions:

- **Study the functioning** of the drainage system through a range of simulations for a variety of combinations of rain storms, tides and storm surges.
- **Produce reference flood hazard maps** for a range of design storms combined with tides and storm surges, e.g. 1 in 1, 2, 5, 10, 20 and 50 year return periods for: (a) the current situation and (b) the expected conditions in 2050, including the impacts of sea level rise, increased rainfall and soil subsidence.
- **Create polders** (enclosed areas) for low lying parts of Boa Viagem and design flap gates to prevent backflow into the micro-drainage system.
- If flooding problems in these polders remain unacceptable, **add pumps** to find the optimum management of controlling street flooding. Test the required capacity and operation of these pumps in a sensitivity analysis.

- **Construct tidal gates** at the Parque de Manguezais end of the Jordão River and Setubal Canal and optimize the operation of these gates to provide storage in the canal section prior to intense rainfall. Best option might be to combine both sets of gates into one combined set and create some retention space at the southern end of the Parque de Manguezais.
- As a next option, **install pumps at these gates** to release runoff water from the canal to the Parque de Manguezais in cases where this would be needed as complementary measure.

3. The Boa Viagem Canal de Setubal model development and application

Model Development

This canal connects the Parque de Manguezais with the Lagoa de Olho d'Agua in the Municipality of Jaboatão dos Guararapes. Runoff caused by rainfall will be directed either way under the influence of tides. There is no upstream or downstream in this situation. During the Master Class it was discussed that the tidal fluctuations in Lagoa de Olho d'Agua would most likely be of the order of one or two decimeters at most. Insight in this would only be obtained if the model of the Canal de Setubal would be extended all the way to the ocean. Data for such model extension may have to be assumed from Google Earth images. The lack of institutional arrangements between municipalities in Pernambuco pointed at the complexity of obtaining data from Jaboatão dos Guararapes and it is recommended to arrive at agreements to cooperate on optimizing the drainage systems in both municipalities.

The objective of modelling the Boa Viagem Canal de Setubal would be the study of inundations caused in the surrounding streets under the influence of spring tides alone and even more so in combination with extreme rainfall events. The impact of climate change will certainly exacerbate these problems.

During the Master Class it was concluded that the best model schematization for this study would be a hydrological-hydrodynamic model based upon a rainfall-runoff concept for sub-basins connected to the main channel via a schematized gallery representing the discharge capacity of all pipes connecting that sub-catchment to the canal. This would be much similar to the schematization for Jordão River and its sub-catchments, as presented in Section 2.

Application

Scenarios to be studied for the inundation problems along Canal de Setubal will be much similar to those proposed for the sub-catchments of Jordão River.

4. The Tejipió River model development and application

Model Development

A 2D HEC-RAS model was developed by Alisson Caetano da Silva of the Prefeitura da Cidade do Recife with the objective of studying the Linear Parks which were projected along River Tejipió, as well as studying the inundations of urban areas along River Tejipió, in particular the Ipsep neighborhood, where flood depths of the order of 1 meter have been observed. The model consists of a domain within the Municipality of Recife, starting in the west at BR 232 and ending in the east at the Bacia do Pina, similar to the location of the Parque de Manguezais.

Rainfall has been applied directly on the 2D grid with a grid size of approximately 50 m and the process of runoff has been described on the basis of the SCS method. Typical simulations take approximately 2 hours to produce results of a modelled extreme event.

Although the model developed definitely has some strong points, also a number of weak points were discussed. These are:

- The process of modelling rainfall-runoff and subsequent routing of this runoff on the 2D grid is not the most effective way of describing the rainfall-runoff process. It leads to unnecessary long turn-around times for simulations without offering more accuracy than that obtained by using the SCS method for larger sub-catchments.
- The inflows at upstream model boundaries have to be estimated while no discharges have been measured at these locations. The model still requires the schematization of the upstream Tejipió Basin in sub-basins to provide runoff generated by rainfall-runoff models for upstream sub-basins.
- The downstream boundary requires tides, which are now copied from tides applicable at the ocean boundary. However, as discussed in Section 2, these tides will undergo a deformation on their way to the eastern boundary of the current model, which is difficult to estimate without the use of a hydrodynamic model for that domain.
- The River Tejipió has been schematized in a 2D grid with cells covering approximately half the river width. In the meetings, it has been pointed out that such schematization will not use the correct river depth, hence its conveyance capacity. In addition, such a small number of cells with highly varying flow velocities will create an artificial flow resistance in the model, most likely severely underestimating the river flow capacity, resulting in higher flood depths in the flood affected areas.

For these reasons, the following recommendations have been made to arrive at an efficient and accurate model (see also Section 2) to study inundation problems along River Tejipió in the current situation, the future situation and the flood protection works that could be implemented:

- Set up a 1D model schematization, including the following:
    - Complete River Tejipió basin from its most upstream sub-basins to the ocean (entrance to the port).
    - River Capibaribe up to the Barragem de Carpina (and other reservoirs), where measured discharges are available and in downstream direction also up to the entrance to the port.
    - Connection(s) between Tejipió and Capibaribe.
    - Parque de Manguezais, which has an impact on the deformation of tides in River Tejipió. This area shall be represented by a coarse grid integrated 1D2D hydrodynamic model of this area.

These are the areas and their physical processes which influence most of the propagation and deformation of tides along River Tejipió.

- Define the sub-basins describing rainfall – runoff in the complete Tejipió and Capibaribe river basins. It is expected that at least 50 and possibly more basins will be needed to provide this information at sufficient detail and accuracy. The SCS method already used will be a satisfactory choice.
- Define the areas of interest in model application and provide for locations being flooded (e.g. linear parks, Ipsep, etc.) a 2D hydrodynamic model schematization, define the grid and its grid size and couple the 1D and 2D model components. Make sure that double counting of storage areas in 1D and 2D is avoided. If HEC-RAS will be used, it is recommended to test such couplings on much simpler models to build up experience with this coupling, as from various sources problems with the stability of such connections have been reported.

- Collect all necessary hydraulic structure data and river cross-sections. In case of missing data, make the best assumptions, e.g. based upon Google Earth and estimated river depths. Not all data of the model require the same accuracy. The influence of the quality of assumed data can be tested in a sensitivity analysis. For example, accuracy of data on Tejipió River is significantly more important than the accuracy of data on the Capibaribe River, in case the flooding problems of Tejipió River are being studied. Investigate the uncertainty of assumptions on water levels at locations that are of real interest.
- Calibrate the model once the network of water level and discharge monitoring stations has been implemented and first results have been produced (see Proposed Monitoring Network).

Application

Use this model to study the impact of combined rainfall and high tide events on the flooding of the flood prone areas along Tejipió River, taking also into account the possible impacts of land use changes, storm surges and soil subsidence.

Scenarios to be studied for the inundation problems along River Tejipió would focus on simulations of the following suggested conditions/interventions:

- **Study the functioning** of the River Tejipió hydrodynamic system through a range of simulations for a variety of combinations of rain storms, tides and storm surges.
- **Produce reference flood hazard maps** for a range of design storms combined with tides and storm surges, e.g. 1 in 1, 2, 5, 10, 20 and 50 year return periods for: (a) the current situation and (b) the expected conditions in 2050, including the impacts of urban developments, sea level rise, increased rainfall and soil subsidence.
- **Create polders** (enclosed areas) to protect flood prone areas adjacent to River Tejipió by constructing dikes around such polders, e.g. the Ipsep neighborhood. Design flap gates to prevent backflow into the polder area through the micro-drainage system.
- If flooding problems in the polders requiring flood protection remain unacceptable, **add pumps** to find the optimum management of controlling street flooding. Test the required capacity and operation of these pumps in a sensitivity analysis.
- In the case of **linear parks**, design ways to optimize the expected use of these areas, including their flood mitigation function, by testing the possibilities of using low dikes and other structures to delay the use of available retention volume in order to maximize peak flow reduction downstream, wherever this is functional.
- Study the impact of the **construction of upstream reservoirs** to reduce flood peaks along River Tejipió downstream.
- Study the impact of other measures in the upstream basins to reduce the speed of rainfall generated runoff, including **possible adaptations in agricultural practices**.
- Study the possible impact of **a tidal barrier** in the downstream part of River Tejipió to reduce the impacts of tides and storm surges. Investigate how runoff from the upstream basins will negatively impact the functioning of such barrier.
- Repeat all simulations above also for conditions applicable to **2050 conditions.**

5. The Boa Vista Canal (Derby – Tacaruna) model development and application

This canal drains a significant part of Boa Vista and is connected in the north to the confluence of Rio Capibaribe and Rio Beberibe via tidal gates and additional pumps with a total capacity of 3 m^3/s. In the south the canal is connected to Rio Capibaribe via tidal gates only. During high tides and intense rainfall, the runoff cannot be drained through the tidal gates. It has also been reported that the pumps stop working shortly after these have been put in operation. Currently, the reasons are not clear.

Model Development

The model to be developed for this canal would have the primary objective of finding alternative ways of composing the drainage system, to avoid the inundation of streets and properties. The model needed is much similar to the models needed for Jordão River and Setubal Canal (see Section 2). This implies the development of a 1D model for the canal, based upon the following schematization:

- Define a 1D model schematization for the Derby – Tacaruna Canal, with its tidal gates and pumps.
- Define the runoff areas around this canal (at least 20 or more) and set up the rainfall-runoff models for these (SCS concept) and release the runoff in storage basins (nodes) defined as area – level functions, derived from the processing of the DTM for these sub-basins.
- Connect the sub-basin storage basins to the canal via a gallery representative for the conveyance capacity of the pipes of the micro drainage system for the sub-basin.
- Collect and enter all data of hydraulic structures, canal cross-sections and boundary tidal levels as necessary for the completion of this model.
- Validate the model based upon water level monitoring already in place and the additional water level monitoring as recommended under the Proposed Monitoring Network as part of this support programme.

Application

Focus on the use of this model would be the optimization of the combination of tidal gates, pumps, booster pumps, diversion routes, additional retention space and their joint operation. A first step in model application will be the investigation on why the pumps become de-activated shortly after these are put in operation.

Proposed investigated on the basis of this model are:

- In the first place, **study the functioning of the drainage system** through a range of simulations for a variety of combinations of rain storms, tides and storm surges.
- **Produce reference flood hazard maps** for a range of design storms combined with tides and storm surges, e.g. 1 in 1, 2, 5, 10, 20 and 50 year return periods for: (a) the current situation and (b) the expected conditions in 2050, including the impacts of sea level rise, increased rainfall and soil subsidence.
- Study the reason why pumps are not able to operate continuously. Most likely, the **pump sump has an insufficient volume and has a narrow connection to the canal**. Part of the solution may imply the widening of this connection to speed up the supply of water to the pump sump from the canal. However, it is also possible that it will be better to install the sensor controlling the pump operation further upstream.
- The **retention area of the pump sump** may be enlarged by connecting it to the park area just north of the outlet near the Espaco Sciencia Pernambuco and re-installing the pumps at a location at the Av. Olinda Dom Helder Camara (Fig. 1).

- **The canal is unable to convey 3 m^3/s to the pumps** shortly after these have been activated. The canal may be too shallow and deepening of it would be the first intervention to be investigated. Also widening can be considered. Space seems to be available. Most likely both measures would imply the use of sheet piles or concrete canal walls to allow for vertical walls over a larger depth. Soil stability has been mentioned as a problem to deepen the canal. It is expected that a thorough analysis of soil stability, based upon soil sampling and the use of anchors will enable the design of sustainable solutions.
- It is also possible that **conveyance capacity of the canal** is not the most important limiting factor in bringing the water to the pumps. When pumping starts, the water in the canal has to be accelerated through the hydraulic gradient in the canal. If this acceleration takes too much time (as will be shown by the model) the water will have difficulties in arriving at the pumps. In such case, the impact of the installation of **booster pumps** along the canal may be investigated.
- As inundation problems are most likely be most problematic **around the middle of the Derby – Tacaruna Canal,** the possibility of **diverting runoff water** around halfway the canal could be investigated. Diversions from the canal to a point further north of Capibaribe River, either to the west or the east, might provide interesting options. This would require the construction of a gallery and pumps. Also here, the availability of sufficient retention capacity at or near the pump sump will be necessary.

It is expected that a combination of above investigations and subsequently proposed interventions will alleviate the currently existing flooding problems significantly. Further analysis of the situation expected in 2050 will have to show if this also leads to sustainable solutions for the flooding problems up to the year 2050.

Figure 1: Derby – Tacaruna Canal north with tidal outlet (left) and the possibility to relocate this outlet to the east, allowing to mobilize the capacity of the retention basin shown north.

Annex 3 – Concept Note Hackathon

Recife Climate Change Adaptation Strategy Development Hackathon 2023

Concept note version 27 March 2023

This concept note explores the possibility of a policy hackathon in Recife, with participation of international experts, for rapid climate change adaptation strategy development.

1. Background

Findings of the February 2023 DRR-Team mission to Recife include:

1. Recife wants and needs to take measures to reduce flooding in the city, with measures such as the creation of storage and infiltration areas (green areas) for which people have to be relocated, or large hydraulic infrastructure such as tidal gates, levees and pumps.
2. DRR-Team Recife established that decision making on such measures in the Recife river basins is hampered by the absence of a full diagnostic analysis and of hydrological-hydrodynamic modelling to simulate and thus investigate the impact of such interventions.
3. It also established that insufficient water level and discharge monitoring is performed in the Recife river basins, leading to a near total absence of hydrological water level and runoff data.
4. The impact of sea level rise, soil subsidence and intensification of rainfall on the existing system is thus poorly understood, while a qualitative analysis of the DRR-Team shows that even limited sea level rise will aggravate existing problems well before 2050.
5. Recife has an established, locally developed vision for incorporating green areas and water areas in the urban landscape, the Park City concept. Making space for these processes of greening and water storage will be a challenge. Institutional and financial aspects of the implementation of the vision are an area of study.

Following the Recife DRR-Team mission, a 3-day hydrodynamic modelling workshop was held by the DRR-Team Senior Drainage Expert with Recife municipality staff and associated professionals and students. The modelling workshop allowed the participants to advance their efforts, a full report of which can be found in annex 2 of the DRR Recife report. The development of a full 2D hydrodynamic model for Recife, on which decision making can be based, is expected to take no less than 2 years, even with professional assistance.

<u>About hackathons:</u>

Hackathons (composed from 'hack' and 'marathon') originate from competitive coding events focused on technology development. They have grown to include new forms and topics. A 'policy hackathon' serves as a creative pressure-cooker setting to answer a policy question in limited time. It is particularly useful in situations where time or available data do not permit more in depth research and studies, and as a basis for the design of data monitoring systems and modelling efforts. The outcome of the hackathon can provide detailed guidelines for these investments in monitoring and modelling.

In the Netherlands, policy hackathons were used to make first-order quantitative estimates of the impacts and potential strategies to adapt to accelerated sea-level rise and to assess consequences of extreme rainfall ('waterbomb-experiment').

The hackathons work best with good preparation to:

a. define specific questions that participants can work on and 'hack' in a limited time,

b. collect tools and available data (even when available data is scarce), and

c. identify required expertise among the participants.

In practice this means that a bigger question is split into clear sub questions. See the examples below.

Hackathons: Sea Level Rise Impact and Adaptation strategies for the Netherlands

For sea level rise 3 hackathons were held. The first hackathon focused on impacts and was held in 2017 with experts of Deltares. One of the questions in this hackathon was to quantify the amount of sand that would be needed to maintain the coast at different rates of sea level rise, as well as the pump capacity to discharge excess water to sea and the closure frequency of the storm surge barriers at different amounts of sea level rise (e.g. 0.5, 1, 1.5, 2, 2.5, 3 m).

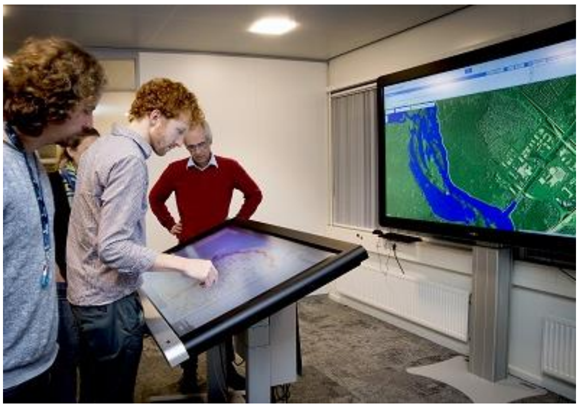
In a follow-up study a hackathon served the exploration of adaptation strategies. Five professors were asked to give their view on adaptation options. With experts from different universities and water managers, options and pathways were mapped for different regions. In addition, a hackathon was carried out by a group of students from various disciplines and universities, supervised by professors and expert practitioners. Duration was 2 days. Stakeholders were involved at the beginning, halfway and at the end when results were presented.

Hackathon 2: Extreme Rainfall in the Netherlands

This hackathon was held in 2021 after the extreme rainfall in western Europe resulted in over 200 casualties and a lot of damage. Most of the rain fell in Germany and Belgium. This raised the question what would happen if this event would have happened in the Netherlands? With the participation of Deltares Institute (main organizer), water boards and national water managers a hackathon was prepared. First, main questions were identified and discussed with experts. Next, it was decided to look at different archetypes in more detail and assess flood impacts and potential options. Various models and gis tools were used. Results were discussed with stakeholders before finalizing the report.

After each hackathon a small group of analysts integrated results, finalized the loose ends of the analysis and wrote a report on the findings.

Identifying adaptation tipping points



Mapping solutions space to adaptation over time

Hackathons have been found to strengthen networks through knowledge exchange, interdisciplinary collaboration and the sense of urgency created by working under pressure for a defined duration. This atmosphere serves as an accelerator and creative setting for innovation, idea generation, development and evaluation. Hackathons were also a low-commitment exercise that could be supported by government and domain experts, without large budgets and time-intensive studies.

Different from workshops and similar activities, hackathons are designed to produce tangible outcomes. In the Netherlands, the hackathons resulted in findings that were agenda-setting and led to a spin-off of studies by researchers, student's research and private companies.

Such a Hackathon typically is part of the phase "preparing the ground for adaptation", where you make a rapid assessment on the risks, the adaptation options and the assessment of these options.

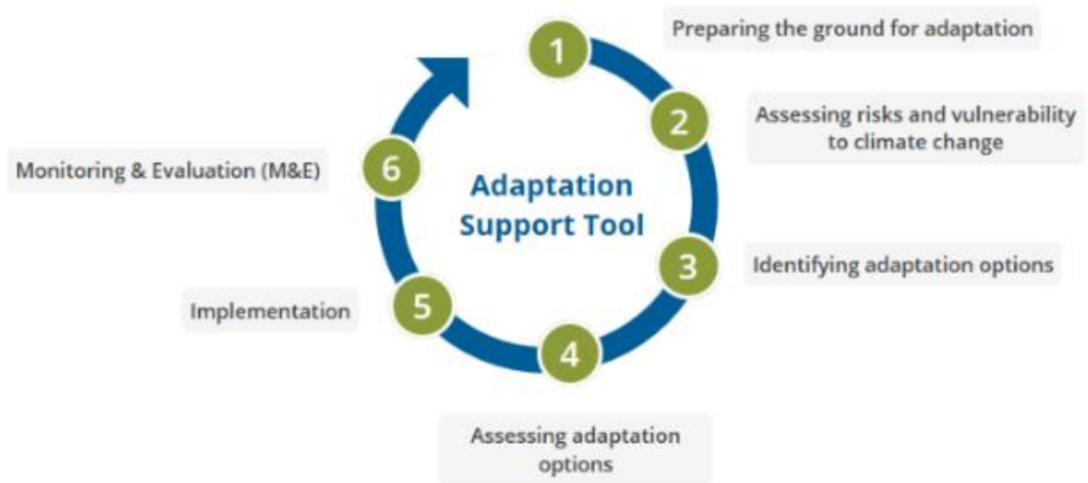


Figure 1 - The Climate-ADAPT 'Adaptation Support Tool'[2]

2. **Objectives of the Recife Hackathon**

The leading questions that the hackathon should respond to include:

1) What would be the effect of 10, 20, 50, 100 or 200 cm of sea level rise (or soil subsidence) on the river and drainage system of Recife?
2) What would be the effect of rainfall intensification of 10%, 20%, 50%, 100% and 200% on the river and drainage system?
3) What would be the compounded effect of the two?
4) Which tipping points can be distinguished and when are these expected to occur?
5) What would be the effect of measures such as tidal gates in the Teijipió river or elsewhere, of green parks along the river, of other potential measures?
6) At what point in time will measures become inevitable, and what kind of measures should these be (short term strategy)?
7) When is the Protect – Pump strategy likely to reach its limits? Which alternative strategies can be envisaged? What does that mean for decisions in the short term?
8) What are the urban planning implications of the above scenarios and strategies?
9) What data and monitoring will be required to support further research and studies into the above questions?

This list is to be revised and expanded during the preparation with input from Recife. Based on these leading questions, the program of the hackathon can be designed.

Next to these leading questions, the following issues can be part of the hackathon program:

About assessment instruments:

- Discussion of types of rapid 1D assessment tools, and the more advanced 2D hydrodynamic modelling applications and how / in which time frames these are useful for Recife
- Identification of suitable methods of hydrological monitoring and the creation of data sets for modelling and forecasting
- Discuss the potential of advanced applications such as digital twins and the smart city initiative
- Consider the aspect of institutional sustainability of the use of advanced hydrodynamic models

About urban planning implications:

- Magnitude and location of areas needed for green / blue spaces
- Establishing current occupancy of these spaces and quantifying the impact of freeing that space
- Developing scenarios for stepwise development of green / blue spaces and
- Creating a perspective for the current occupants of the space, in particular poor communities
- Investigating inclusive financial and governance mechanisms to realize the required blue/green spaces with positive outcomes for current occupants

3. Expected Outcomes and Benefits

I. Clear and quantitative insight into the effects of climate change on Recife

II. Answers to the questions of effectiveness of measures such as tidal gates, small dikes, pumps, green parks

III. A short term program of measures in the context of the Protect – Pump adaptation pathway

IV. Mapping of the longer term solutions space

V. Strengthened networks between professionals in Recife and the Netherlands

4. Participants of the Recife Hackathon

Brazilian parties	Netherlands and other international parties
1) Recife Municipality – including EMLURB, Infrastructure Department, Environment Department, Urban Planning Department as well as staff and consultants of BID ProMorar project 2) Universities – to be established exactly which, in any case including the departments of prof. Jaime	1) National Research Institute Deltares 2) Municipalities of Amsterdam and/or Rotterdam, urban planning departments including Amsterdam Land Development company 3) UNESCO IHE

Cabral (drainage) and Marcus Silva (Oceanography), prof. Montezuma (urbanism) 3) State institutions such as APAC (hydrological monitoring at state level) 4) Porto Digital expertise in other domains 5) NGO's like ARIES and others 6) Specialized consultancy companies already playing key roles 7) Artists to capture the process and outcomes in a non-technical way 8) …	4) DRR Team program 5) Netherlands' Embassy and Consulate Pernambuco 6) …

Target number of participants: 15-20, possibly in parallel programs.

5. Organization of the Recife Hackathon

Location	Recife, Brazil (suitable location to be identified)
Lead organizer Brazil	Recife Municipality
Lead organizer Netherlands	RVO with Deltares Institute
Funding (proposed, to be confirmed)	Recife Municipality RVO, others
Language	Portuguese with translation to and from English

Required data sets to prepare rapid assessment tools and other inputs for the hackathon:

i. Digital Terrain Model based on LIDAR, made available by Recife (alternatively use global free data, for info on accuracy see: https://gisgeography.com/free-global-dem-data-sources/)

ii. Meteo data from APAC (alternatively use global free data)

Implementation planning:

→ March 2023: Delivery of draft DRR-Team report and joint decision about Hackathon.

→ April/May 2023: Install Hackathon preparation team (joint Recife/NL); define dates and participants, send invites. Prepare HYDROMT/SFINC rapid assessment tool to be used in preparation of and during the hackathon. Define reporting roles.

→ June/July 2023: hold the first "Recife Climate Change Adaptation Strategy Development Hackathon 2023"