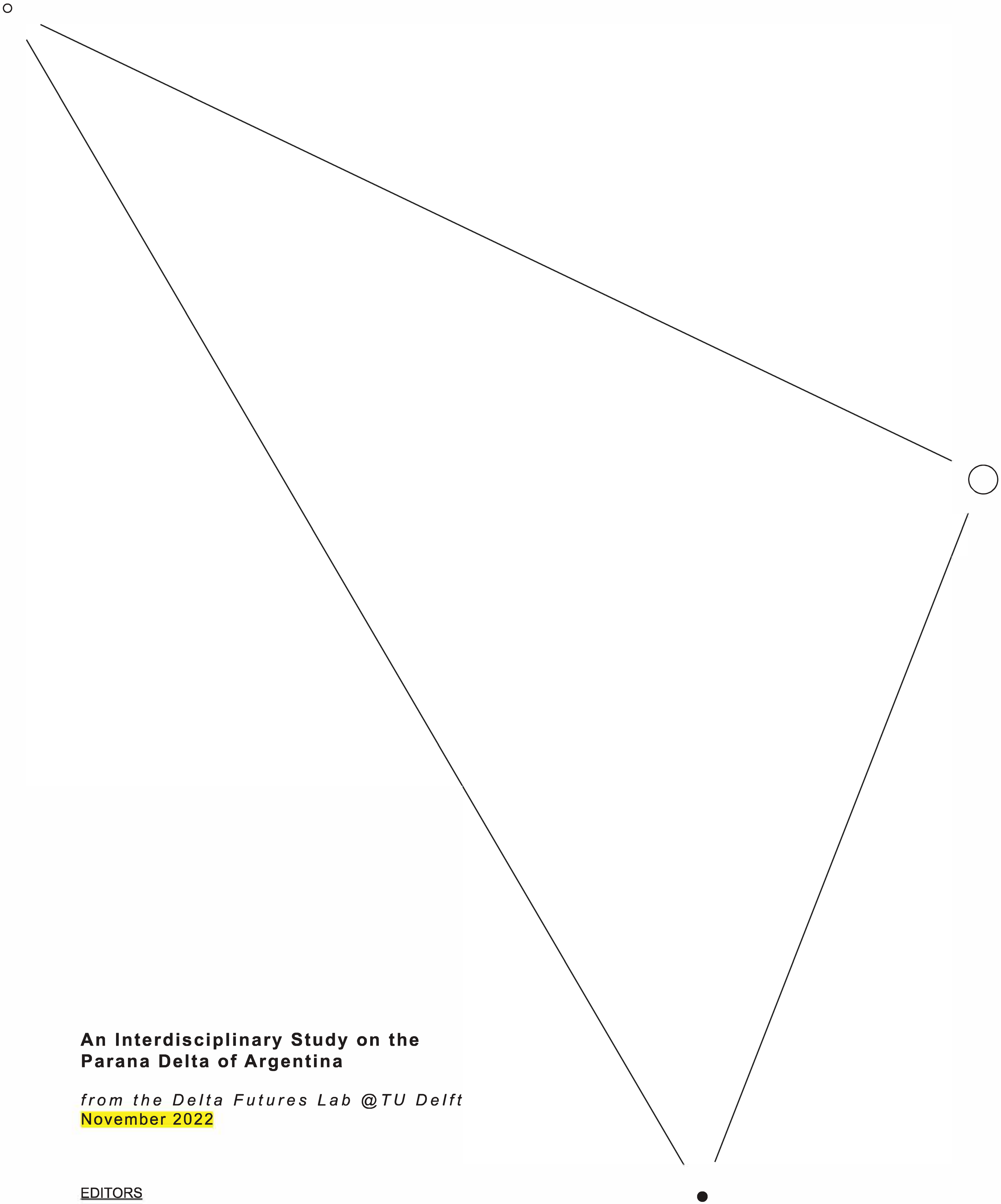


# An Interdisciplinary Study on the Parana Delta of Argentina

*from the Delta Futures Lab @TU Delft*
November 2022

EDITORS

| | |
|---|---|
| Fransje Hooimeijer | Delta Urbanism |
| Luca Iuorio | Delta Urbanism |
| Davide Wuthrich | Hydraulic Engineering |
| Olivier Hoes | Water Management |

AUTHORS

| | |
|---|---|
| 5372941 | **Patrycja Raszka** |
| 5273102 | **Ningyi Chen** |
| 5634849 | **Fynn Nikolas Mengel** |
| 5293197 | **Josh Snow** |
| 5491142 | **Kevin S.F. Lai** |
| 4353544 | **Felix Quinten Armstrong Hall** |
| 5276233 | **Victoria Imasaki Affonso** |
| 4652355 | **Siirilotta Moonen** |
| 4586174 | **Pepijn van Sabben** |

## CONTENTS

## GLOSSARY

*Resilience* the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedback (Walker et al., 2004).

*Hybridization* A "hybrid solution" would be the result of associating green (nature-based) and gray (engineering-based) solutions when dealing with a certain urban challenge

*Landscape-based urbanism* Approach that takes the physical landscape structure and associated natural processes as a foundation to generate favorable conditions for future development and to guide and shape spatial transformations. Therefore, it offers a model for urban development and transformation, the preservation of biodiversity, water resource management, improved leisure facilities, community building, stronger cultural identity, and economic development (cf. Neuman 2000) while taking the landscape as the basis.

*Casco concept* "Framework design models focus on the development of long-term and coherent landscape networks of landscape structures to support spatial development, safeguard resources and spatial coherence and create conditions for local developments.

Usually, this approach focuses on open-space planning (the inverse of the existing urban tissue). Examples include the Boston Metropolitan Park System (US), the Emscher Park (Ruhr area, Germany)."

*Interstice* The space(s) inbetween; fragments; leftovers

*Urbanization* the increase in the proportion of people living in towns and cities. Urbanization occurs because people move from rural areas (countryside) to urban areas (towns and cities). This usually occurs when a country is still developing.

*Sprawl* Also called sprawl or suburban sprawl; the rapid expansion of the geographic extent of cities and towns, often characterized by low-density residential housing, single-use zoning, and increased reliance on the private automobile for transportation.

## 01 // INTRODUCTION

*The premise of the report is an expected deliverable for the Parana Delta field-trip in Aug, 2022 funded by the DIMI and Climate Institute , and a summary of the interdisciplinary research-by-design workshops Jul-Nov, 2022. This report also constitutes part of the ongoing Honors Programme 22-23 @TUDelft followed by BK students, which will culminate into a final report with individual essays to be submitted in April, 2023.*

### .1 Context

At the confluence of the Paraná and Uruguay rivers, the Paraná delta (hereby referred to as, the delta) spans over approximately 15,000 km$^2$ (Rinaldi, Abril, and Clariá, 2006), covering the provinces of Entre Ríos (80%) Buenos Aires (18%), and Santa Fé (2%), Argentina (Deltares, 2018). At a varying width of 20-100km, and a total length of about 350 kilometers, the delta begins from the town of Diamante and results downstream into an outlet that forms the Rio de la Plata estuary, which drains approximately a quarter of the territory of South America (2,966,000 km$^2$), scaling over territories of Uruguay, Paraguay, northeast Argentina, southeast Brazil and southeast Bolivia [**FIGURE 1.1.1**].

As a transnational "geologic-hydrologic sedimentary dynamic entity" (Rinaldi, Abril & Clariá, 2006), the delta is shaped by various forms of ecological processes (e.g. hydraulic action from precipitation, tidal and fluvial actions) and anthropogenic processes (e.g. agricultural production, human settlement), resulting in a shifting morphology that is most significantly characterized by heavy sedimentation. At a rate of 70-100 meters per year, sediments are transported in suspension in the draining rivers, ultimately deposited at the estuary mouth, where complex conditions such as loss of river velocity and salinity differences occur. Approximately 160 million tonnes of sediment per year is transported (Boschi, 1987), composed of clay (28%), silt (56%), and sand (16%). Such an advancement of the delta results in the emergence of new islands in the Rio de la Plata; the delta is expected to reach the Palermo section of Buenos Aires by 2130 (Pittau, Sarubbi & Menéndez, 2004), posing new urban challenges negotiating between city and water (Zagare & van Dijk, 2014).

Widely regarded as a valuable landscape with rich biodiversity and ecological resources, the Paraná delta however cannot be regarded as a pristine territory [**FIGURE 1.1.2**]. With increasing pressure from urbanization, anthropogenic processes on the delta have resulted in a complex scenario that is not without problem. Following the industrial growth in the Argentinian agriculture sector, with an increase in export of 20 million tons to more than 100 million tons of agro-industrial products, and the heavy reliance on soy-complex (in 2020, accounting to 27% of the country's total exports, i.e. USD 54.8 billion), the rivers in the delta have become major navigation channels for the country's precarious economy, and the greater territory of the delta witnessed a spur in agricultural land-use (MLNV, 2021)[**SEE APPENDIX G**].

Parallel to agriculture, urban sprawl from the existing cities along the delta, most noticeably in the densely populated Buenos Aires Metropolitan Area, also creates a new typology that is the "gated community," spreading across the non-urbanized delta which exacerbates flood risk in adjacent neighborhoods, most often households of lower-income families. Other than the flooding risks, human settlements in the delta, estimated at 20,000 in 2018 (Deltares, 2018), also faced living challenges from the lack of potable water and reliable infrastructural support. Concentrations of several pollutants in the river were above the recommended levels for aquatic animals to thrive. For example Zn, Cu, and Cr were 1.6 to 4.9 times higher than allowed and benzo(a)pyrene even 2.8 to 5.6 times higher.

As private pleasure palaces proliferate, polders often appear in their proximity. These are effective for the immediate surrounds of the development, but are ultimately crude water management devices as they displace waters elsewhere. In the case of Buenos Aires, everyone, rich and poor alike must learn to contend with the water, however poor communities that are forced into low-lying slums and informal settlements are frequently the most impacted. As the effects of sea level rise become more pronounced in the area, this will only exacerbate an already difficult scenario.

Buenos Aires itself is a vast city, its sprawl seemingly impossible to curtail, its complexity difficult to comprehend. It also appears to be growing in every direction where land is available: to the southeast, toward La Plata; to the northwest, twenty kilometers beyond Tigre, where new private gated communities like Nordelta convert marsh into polders; and to the west and southwest, along highway corridors connecting smaller towns like Canuelas and Lujan. It is not growing to the east, simply because for the moment, only the waters of the Rio de la Plata are available [**SEE APPENDIX G**].

Since 2020, the Parana has been experiencing severe drought. This has disrupted the natural and human flows along and within the river, negatively impacting major shipping networks through which agricultural products move out to markets abroad and local fisher communities who no longer have access to essential food supplies (Bazzoni & Lovera, 2022). Further investigation of upriver conditions reveals that throughout Brazil and Argentina intense deforestation, spurred mostly by agricultural expansion, is exacerbating drought conditions (Getirana et al., 2021).

Many dams proliferate along the Parana, most of which are in Brazil, along smaller tributaries. At present, there are six hydroelectric dams on the Parana proper. Dams, which break the flow of sediment within riverine environments, can have devastating effects on downstream ecosystems and communities (Dunne & Leopold, 1978). However it is often change in land use patterns that is the primary cause for altered flow regimes (Poff et al., 1997). At its mouth, the Parana River coincides with the Uruguay River where it discharges, on average, more than 17,000m$^3$ of water every second into the Rio de la Plata estuary. The Parana and Uruguay, along with small urban streams from Buenos Aires, contribute upwards of four million kilograms of plastic debris into the Atlantic Ocean each year (Eriksen, 2014).

Given its marshlike, spongy condition, the delta acts as a collector and filter of the urban, industrial and agricultural processes that occur further upriver. As toxins from petro-fertilizers, sewage and other noxious runoff accrue, the delta and its vast regenerative biosystems are still able to maintain a sufficient standard of water quality (Primost et al., 2022). More development in the region will inevitably hamper the bioflows and systems that have remained resilient despite the intensification of anthropogenic and -centric practices that envelope it.

It is likely impossible to prevent future human interventions within the delta region. It is therefore critical to develop new types of land use patterns that can accommodate both human and nonhuman systems which enhance the functioning of each ecosystem, enabling resilient, symbiotic relationships to prevail over the current model of extraction and exploitation.

Regenerative forms of aquaculture, which optimize the existing landscape, along with its sediments, flows and fluctuations would operate in contrast to the current trajectory in the lower delta where wetlands, which are net carbon sinks, are being rapidly converted to traditional tillage farming and pasture for cattle grazing, both net carbon sources. While these precedents are useful, current trends in urbanization, population rise and climate change present a wider range of challenges, and so the return to a pre-industrial or pre-urban landscape is unlikely and possibly undesirable. Rather, an intentionally-designed series of systems that incorporate the full spectrum of complex, overlapping and interwoven processes, anthropocentric and other, could yield a more nuanced, contextually-relevant and resilient mode of habitation for human and nonhuman species alike within the Parana's diverse deltaic system.

As the Anthropocene progresses we will experience greater ecological and climatic extremes. Within the Lower Parana Delta, at the interface between urbanization and sedimentation, there are currently no proactive mitigation measures or planning policies in place. Acknowledging this urgency, we aim to develop resilient territories through the implementation of “strategic infrastructures”, based on a “hybrid approach” and “design with process.”

This research is intended as an addition to the already vast knowledge bases working within Argentina and the delta specifically. INTA, Deltares, Delta Alliance, Tigre Municipality and the Faculty of Urbanism and Architecture at University of Buenos Aires, among others, are all actively engaged in developing resilient models for the delta. Our research contributes to this critical discussion.

## .2 Problem Statement

The Paraná Delta is a complex system that, together with the Rio de la Plata estuary, holds the significance as a “geologic-hydrologic sedimentary dynamic entity” (Rinaldi, Abril & Clariá, 2006) within which a dense urban population of 22 million human inhabitants resides. The hydrological and urban systems reach beyond current administrative borders and should be considered as interrelated. Acknowledging the complexity of the deltaic system in question, this research intends to focus on the scenario(s) of current and projected extreme precipitation patterns [draught + flood] in the delta, so as to question the notion of “resilience” as the “capacity of a system to absorb disturbance and reorganize while undergoing change” (Walker et al., 2004) in the planetary trajectory along the Anthropocene towards a New Climatic Regime (Latour, 2017). Locating the study in the Lower Parana Delta at the interface between urbanization and sedimentation, this research attempts to develop a vision with principles from “landscape-based urbanism.” Utilizing the multi-disciplinary composition of the research group, this research questions the possibility of a multi-faceted, interdisciplinary design approach for the Paraná Delta.

This has resulted in the following research questions: How do we design resilience for the Paraná Delta in an interdisciplinary approach? What disturbance and changes is the Paraná Delta experiencing? How does interdisciplinary research define and react to the field of problems in the deltaic system, specifically the Paraná Delta? Why does designing for resilience matter?

## .3 Methodology

Interdisciplinary Approach

The research group utilizes an interdisciplinary approach to the complex problems embedded in a deltaic system [**FIGURE 1.3.1**]. At the onset of the project, students from different disciplines were recruited as part of the research group, including Water Management (2), Hydraulic Engineering (2), Landscape Architecture (1), and four students from Architecture later specialized as Urbanism (2), and Architecture (2). The research group organized workshops and meetings at TU Delft and field explorations around the Parana delta in Argentina. This multidisciplinary composition intends to bring together different (contrasting or complementary) perspectives of the individual disciplines to create a synergy of “necessary friction.” In a “double-diamond” process, over the course of five months (June - October, 2022), the research group coordinated themselves towards this final comprehensive synthesis report.

The notion of interdisciplinary is not limited to the working research group of students. Prior to, during and after the field trip to Buenos Aires, the group has established and maintained contacts with local knowledge experts from Argentina, including but not limited to: INTA, Delta Alliance, FADU, plantation industry in Zarate, local tour guide in Tigre, Centro Argentino de Ingenieros, Tigre Municipio, etc. These experts have become essential supports to this research, creating important anchors around the five working disciplines on the periphery, without whom the research could not have been established. On that note, we are grateful to their generous and continuous support of our research.

Process

Acknowledging the complexity of the Parana Delta, our approach integrates a “Research-by-Design” method, meaning that a design problem will foreground the project and hence become a guiding thread for further research investigations.

The interdisciplinary nature of the research required the adoption of appropriate methods and tools that allowed for the exchange of knowledge and communication of ideas between the representatives of different disciplines. The methodology of the project revolved around short, intensive workshops during which the ideas were generated and translated into spatial conditions through the creation of abstract, physical, explorative models and drawings. Acknowledging the diverse backgrounds of the group members, this tool coupled with group discussions proved to be the most productive method of working.

The process of the project consisted of several stages: kick-off meeting at the TU Delft BK faculty, exploratory workshops in Buenos Aires, synthesizing workshop at TU Delft BK faculty and finalizing the results. Working in a relatively big and interdisciplinary group posed different challenges to collaboration at each stage of the process.

In the first phase of the project the team familiarized each other with the scope of knowledge and specialization of the team members. The kick-off meeting aimed at setting and communicating the objectives of each discipline and presentation of the preliminary findings, potentials, and problems related to the topic of the research. This step allowed the group to begin the research with sufficient knowledge of the other disciplines which helped in identifying overlaps, potentials, and synergies between the different domains. **FIGURE 1.3.2** illustrates that while the goals and subgoals of the project for each discipline might differ, the tools and interfaces used to achieve this goal are often shared by more than one discipline. This underlines the need for an interdisciplinary approach and the use of the proper framework to facilitate the process.

The next step of the project was an on-site explorative workshop. which focused on intensive, interdisciplinary brainstorming sessions, largely influenced by the specific site visits and observation [**FIGURE 1.3.3**]. This stage aimed for generating and exchanging ideas. For that reason, the methods involved brainstorming sessions that used very abstract model-making as a tool [**FIGURE 1.3.4 + 1.3.5**]. The models were generated in a non-directed way out of available materials to allow for maximum creative freedom for all of the group members. Additionally, it provided tools to translate the thoughts into a spatial condition in a straightforward way which proved to be very productive in such an interdisciplinary setting. Such a mode of working proved to be very effective, especially in the communication between the designers and the engineers. The interdisciplinary group was divided into two subgroups, focusing on the specific locations of Zarate and Tigre. Both teams developed a preliminary vision for the two locations which formed a basis for generating an overarching design in the later stages. At the end of the one-week intensive workshop, a proposal was presented to an audience [**FIGURE 1.3.6**].

After returning to Delft, a second design workshop was held in late October, 2022 [**FIGURE 1.3.7**]. Its goal was to synthesize the already generated ideas and confront them with more specific technical conditions. This is why the workshop was organized in a much more rigid and organized way. Prior to the workshop, supporting material was prepared in order to streamline the discussion. It consisted of a glossary, a short presentation, 2d maps of the research areas, and a clear time schedule for the workshop which allowed the group to stay focused on specific aspects of the design. This proved to be a method that allowed for a good balance between the freedom to explore possible interdisciplinary solutions through the use of abstract model-making while keeping a focus on specific sites and conditions. The workshop resulted in a synthesized design which was finalized in the following weeks in subgroups.

The achievement of the project was the coherence and the integration of the contributions from different disciplines which proved to be a challenge in the earlier phases of the projects. Having acknowledged this difficulty, the group reorganized itself, assigning different roles (such as preparing a pitch or editing the report) to particular group members. This allowed for an overall coherence of the products.

Reflecting on the process and the interdisciplinary collaboration between the group members, each discipline brought a different quality to the project. The input from the water managers provided valuable qualitative insight, especially useful at the stage of the formulation of the problem statement. The group members from the department of hydraulic engineering contributed with very specific technical knowledge and were able to test specific variants of the design across different types of performance. Lastly, the group of architects acted as a mediator between all of the disciplines, providing their own social and cultural knowledge, but also spatial tools which were needed to translate the technical knowledge into a spatial vision.

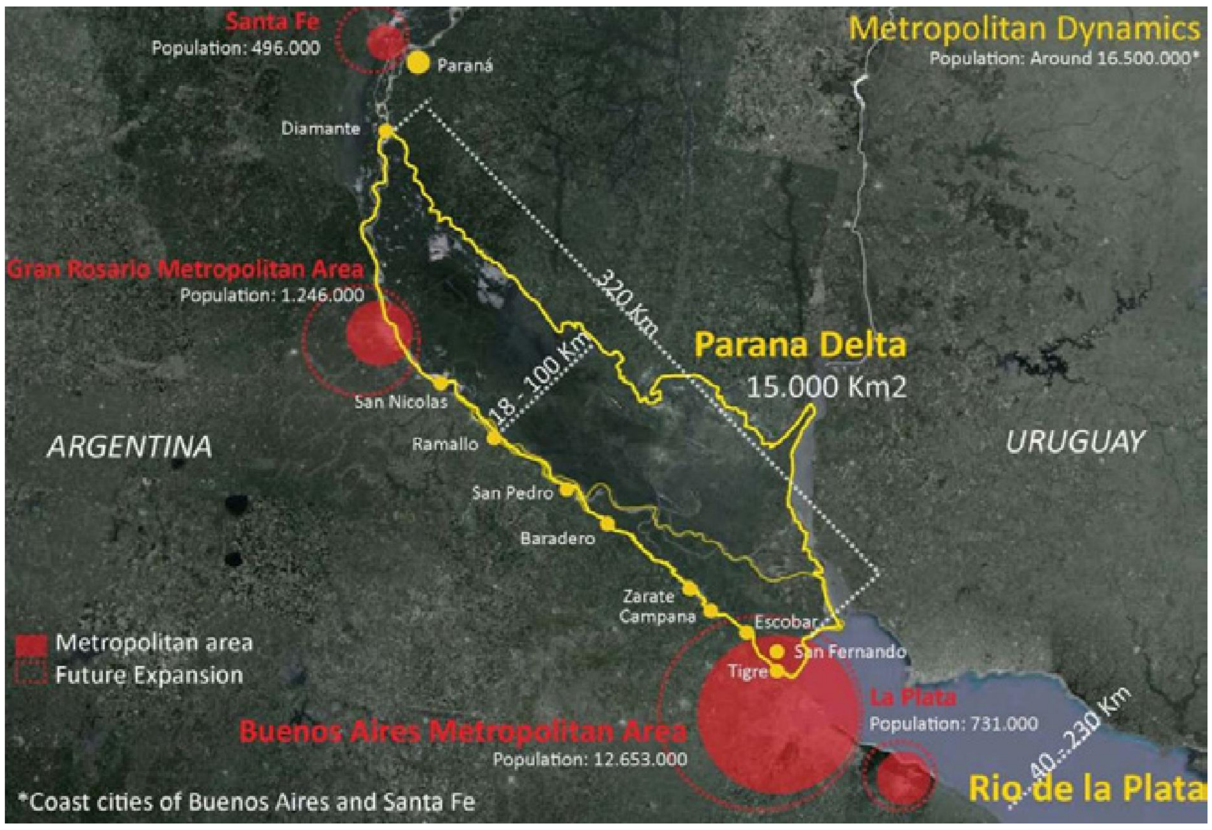
### Embed into Context

It is the position of the research group that the complexity in a deltaic system must involve an embedded way of research, that is, to be present and observe the Parana delta at eye level. With the generous support from the DIMI Fund, Climate Institute and FAST grant from Delft University Fund available at TU Delft, the research group, together with teaching members from the respective departments, were able to arrange travel to Buenos Aires for field study.

The complexities and idiosyncrasies presented in the delta require a level of criticality and keen observations from us as researchers. With the extended period of stay made viable by the funding opportunities, we were able to establish a better understanding of not only the delta, but also the city from a holistic urban point of view. To embed into the context is to establish a lens within the research that goes beyond second-hand sources, e.g. literatures, maps, etc, to a lived, qualitative experience. Part of the research group was able to travel to the Tigre delta and stay at one of the delta houses, during which a Sudestada event was observed, and a way of habitation in the delta was experienced. Embedded experiences as such allow the research group to recall an eye-level scale during design discussions, bringing in another layer of context otherwise unavailable to remote research.

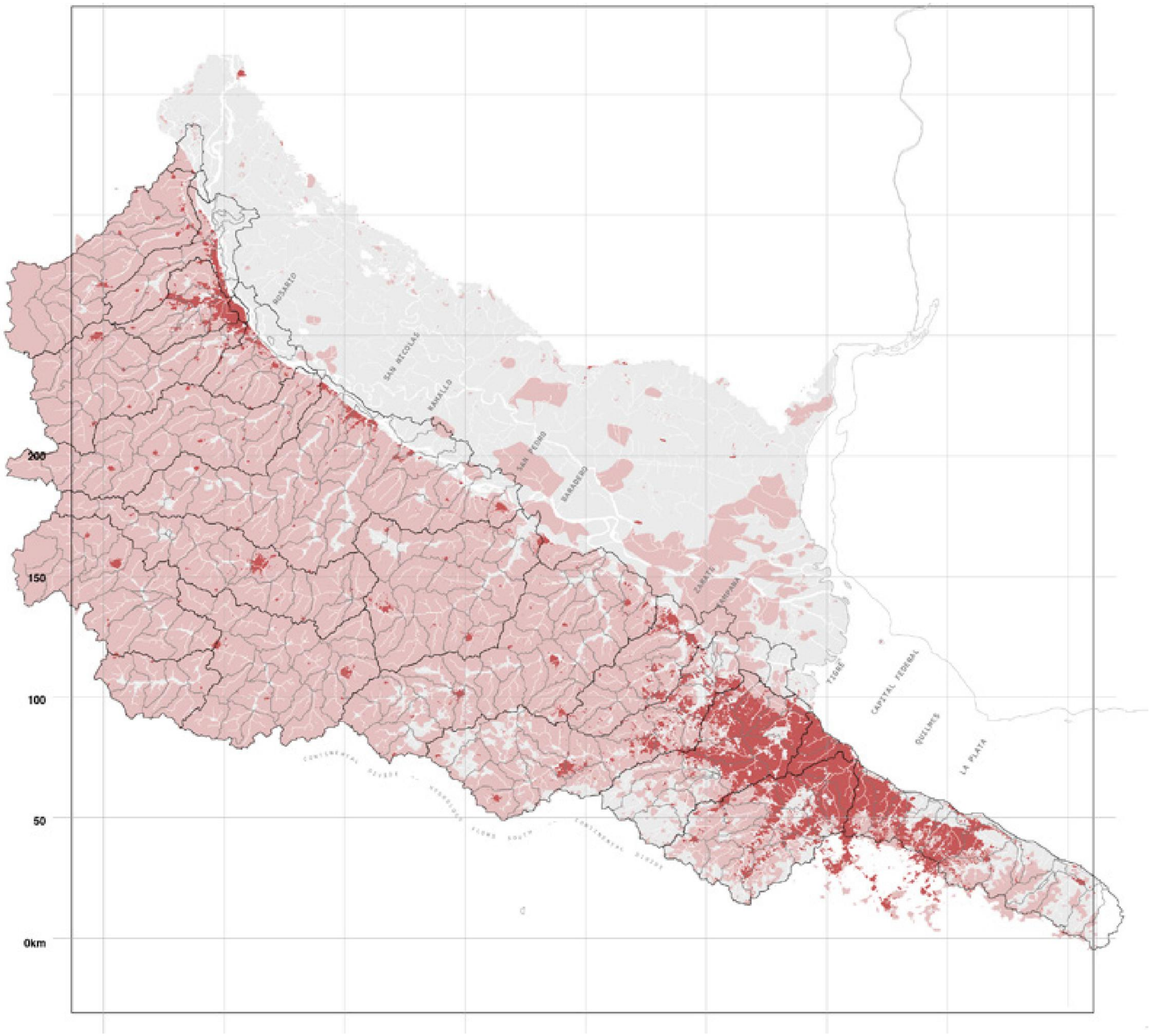
**1.1.1**

The Parana delta along with relevant metropolitan regions (Zagare, 2012).

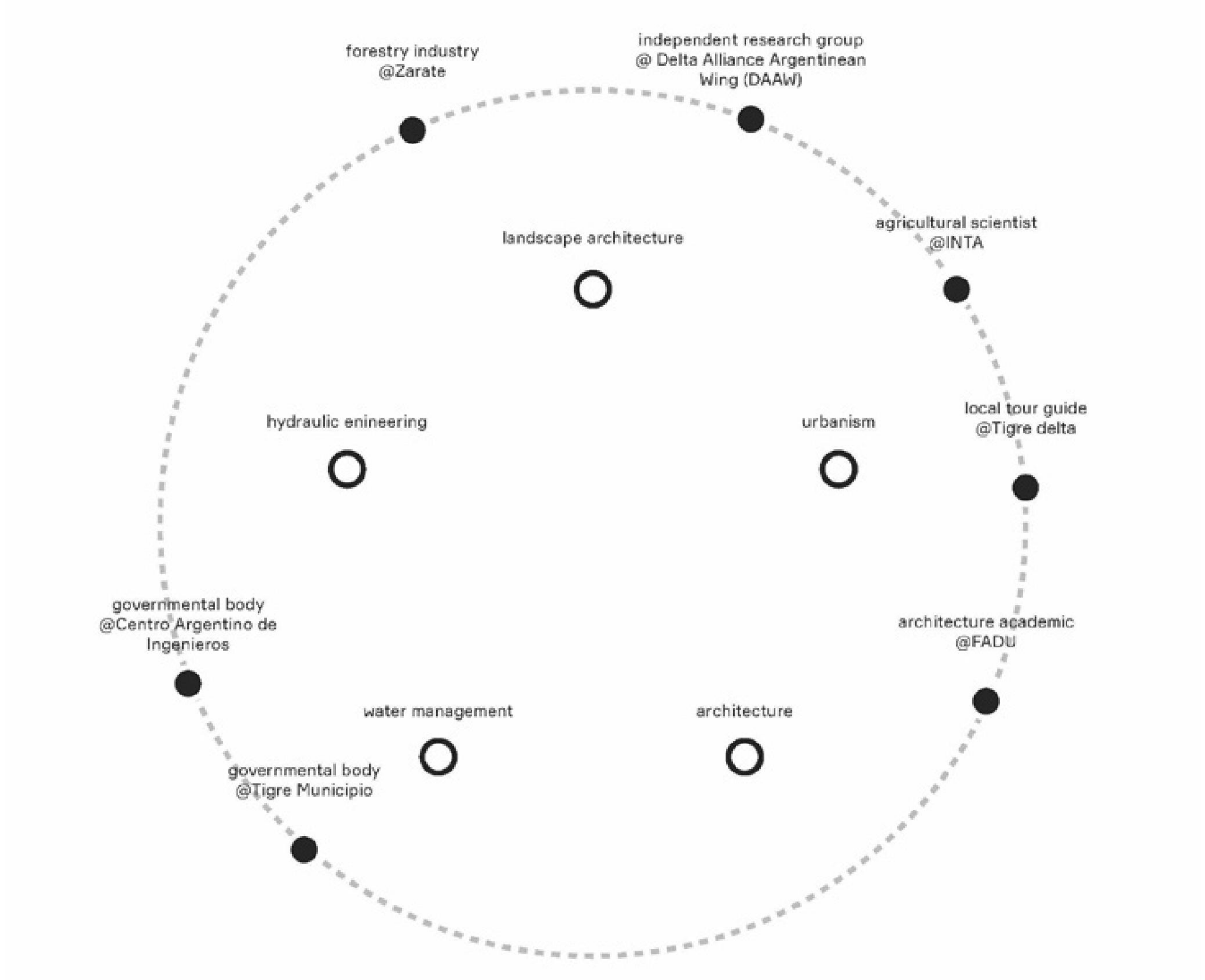


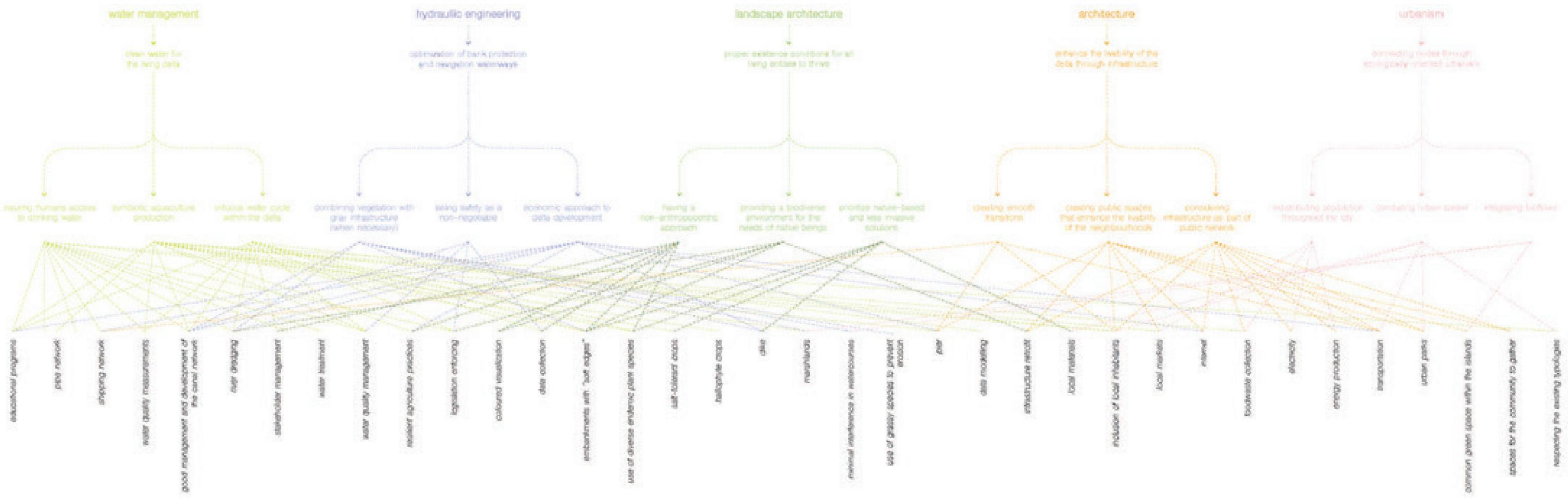
**1.1.2**

Map of land-use patterns in the delta. Red depicts urbanized areas, pink depicts agricultural areas. Adapted by authors from data retrieved from ESRI 2021.



**1.3.1**
A diagram of the disciplines and experts involved. Developed by authors.

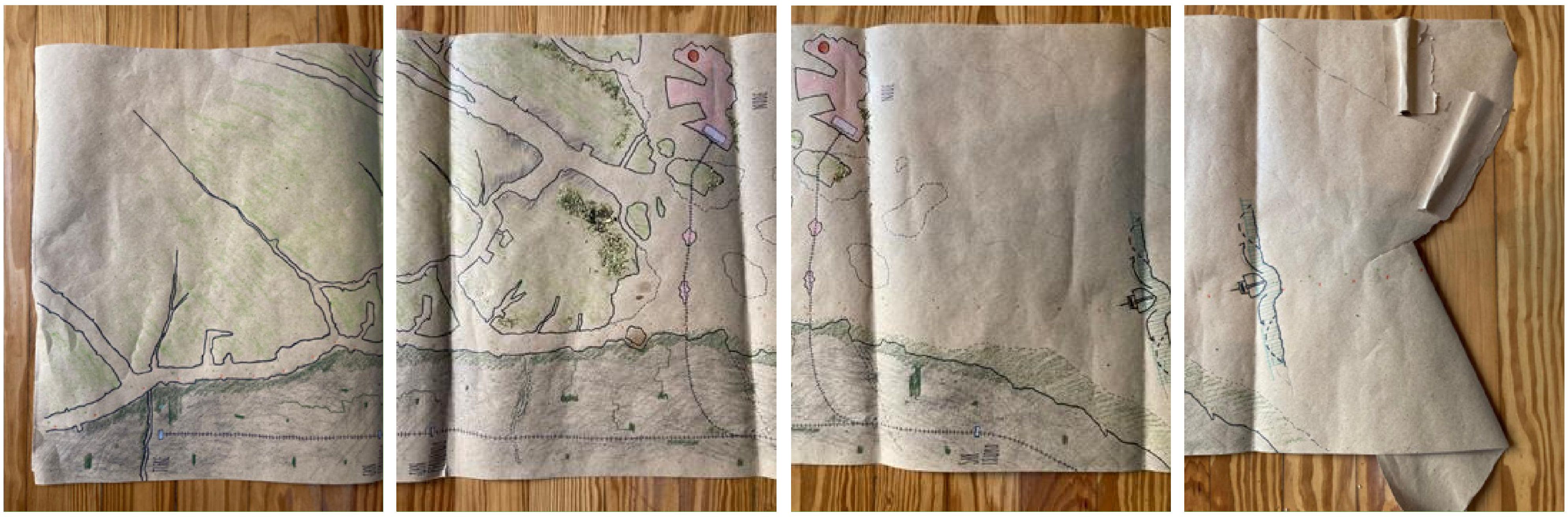




**1.3.2**
The goals, subgoals and tools of each discipline defined at the beginning of the workshop in Buenos Aires, developed by authors.

**1.3.3**
Field Trip to Buenos Aires in summer 2022, with support local tour guides and INTA. Images by authors.

**1.3.4**
Explorative models and drawings created during the workshop in Buenos Aires by the sub-group focusing on Tigre.



**1.3.5**

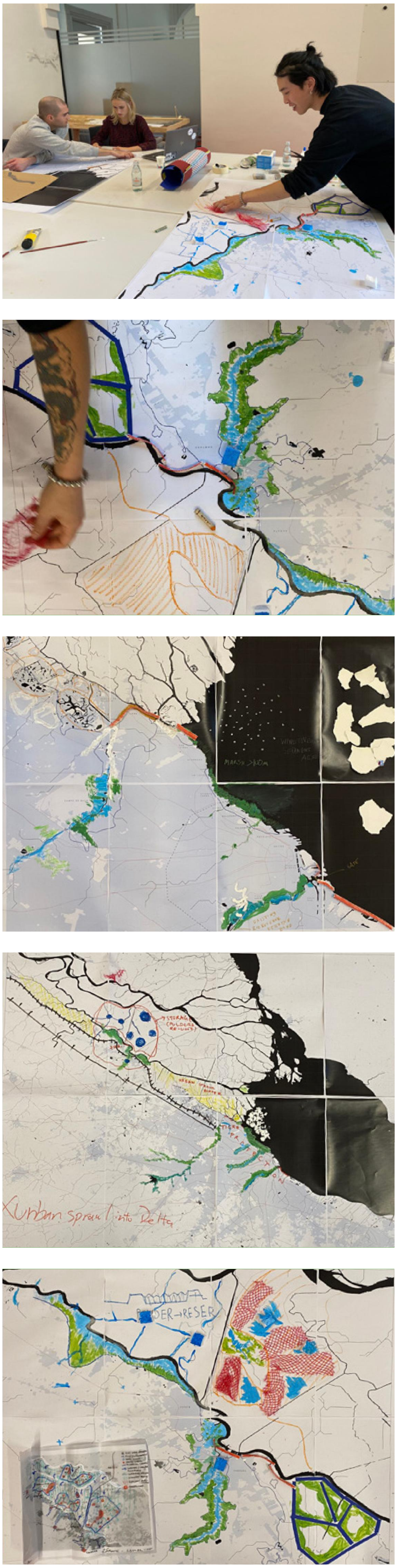
Explorative models and drawings created during the workshop in Buenos Aires by the sub-group focusing on Zarate.

**1.3.6**

Group presentation of the outcomes of the workshop in Buenos Aires

**1.3.7**

Photos from the workshop at the BK faculty.



## 02 // ANALYSIS

*This section details the broader phenomena of the delta as they happen to occur at the local scale in the towns of Tigre and Zarate, both located in the lower Parana delta. It focuses on technical and spatial processes occuring in the region. Learning from these two specific locations, a design vision is proposed.*

### .1 Overview

Hydrological Profile

Precipitation

Because precipitation within the basin at large influences the discharge rate at the Parana river's mouth, it also impacts the Rio de la Plata estuary, into which the Parana river flows. Significant precipitation upstream can lead to increased discharge downstream (López Weibel et al., 2022). As for previously observed precipitation patterns in the Parana Delta, a recent study found that precipitation patterns in the Pampas sub region have been steadily increasing in previous years. Note both Zarate and Tigre form part of the Rolling Pampa's sub region (Pérez, 2015) [**FIGURE 2.1.1**].

When considering the precipitation patterns there are two main theories regarding the state of the water cycle in the Pampas region. The first theory is that global warming is contributing to an increased thermal regime which in turn has led to increased rainfall. If this hypothesis is true then it would be extremely difficult to reverse these increased precipitation effects. The second theory is that the Pampas region is in a long term water cycle. This cycle consists of consecutive dry and wet phases with intermittent transition periods. This potentially could be observed in **FIGURE 2.1.2 + 2.1.3** whereby the mean precipitation is divided into "sub-period". With the current sub-period being a particularly wet period. Regardless of whether the increase in precipitation is caused by global warming, a unique water cycle or a combination of the two. It is clear that the Pampas region, and thus both Zarate and Tigre, will have to deal with ever increasing irregular extreme precipitation patterns. Thus both administrative areas will have to become more adept at handling large amounts of precipitation in smaller periods of time (Pérez, 2015).

This increased irregularity of rainfall can be observed by the increased variation coefficient for the sub-period 2003-2010 which was 19.0, compared to that of 14.7 in the sub-period of 1941-1999. Note pre 1941 data was not used since the Argentine National Weather Service changed the types of rain gauges used between 1932-1940, thus the reliability of the data could not be verified. With an overall increase in mean precipitation of 33.3 mm between these two periods, which can be observed in **FIGURE 2.1.2**. It should be noted that this increase in mean precipitation is relatively insignificant (Pérez, 2015).

However, there was an increase in annual precipitation of 16% when comparing the precipitation volume from 1951 to 1970 versus the precipitation volume of 1980 to 1999. Research from Serio and Martin (2007) states that the winter months are more precipitation heavy than summer months and extremes stayed relatively the same around Buenos Aires..

Furthermore, potential increased precipitation in the Mesopotamian sub-region of the Pampas should also be taken into account as the Parana river flows between both the Rolling Pampa and Mesopotamian Pampa sub-regions (Pérez, 2015).

Another aspect related to increased precipitation is rising temperatures due to global warming, which in turn will further increase precipitation and evaporation rates throughout the region (IPCC, 2022).

Evaporation

Actual evaporation data is significantly lower on average than precipitation. In the lower regions of the delta, where Argentina is located, the measuring station of Timbues is used [**FIGURE 2.1.4**]. For this data, which is taken from the year 2003 to 2014, different models are used which represent the different coloured lines. Even though not all models give exactly the same answer it is clear that the average actual evaporation in the lower basin is in (Argentinian) summer months around a maximum of 125 mm/month and at a minimum 75 mm/month. In the upper basin which mostly lies in Brazil [**FIGURE 2.1.5**] the results are very similar with the biggest difference being the larger uncertainty boundary (Ruhoff et al., 2022). Keep in mind that this data is only until the year 2014. Recent developments of the last two years have shown more and more droughts in the region. This will be detailed in subsequent sections of this report.

River Basin

The river delta north of Buenos Aires consists of many rivers, where this report will mainly be focused on the Parana river. The Parana river is transporting the biggest discharges, where the average discharge of the Upper Parana is around 16000 m$^3$/s. Once entering Argentina, this increases to a total of around 17000 m$^3$/s. Floods are at their strongest monthly discharges at Corrientes, where the Parana and Paraguay rivers intersect, and can double or triple the mean amount. In that case the contribution to the water in the river is relatively small in Argentina itself (Camilloni & Barros, 2003).

The Lujan river flows parallel to the Parana, contributing a small discharge. The total catchment area of the Lujan river is 3300 km$^2$ where the length of the river is 130 km and the final average discharge after all smaller rivers connect to the river is 204 m$^3$/s (Pizarro et al., 2007). Relative to the Parana river this is not much but it is still important to briefly focus on this river because in the Lujan river research has been done about the water quality and salination of the water. This also gives an indication about the salinization of the water in the Parana river due to the parallel occurring *sudestadas* which will be elaborated later in the report.

### Elevation

The lower part of the Parana river delta is a low lying piece of land as can be seen in [**FIGURE 2.1.6**]. The elevations vary between one meter and eight meters. Tigre is at a lower elevation than that of Zarate. The water level in the river on average fluctuates around 2.5 meters across seasons. Maximum water depths from high discharges are difficult to determine from available data due to the differing heights of the river's banks. In the Luján river flowing past Zárate, the water height fluctuations can range between 1 and 2 meters, which can lead to minor flooding of the area (Pizarro et al., 2007). Future sea level rise combined with a *sudestada* event forecasts that substantial flooding across the study area will occur.

### Sedimentation

The Paraná river is extraordinarily rich in sediment. Between 2010 and 2018, approximately $1.7\times10^7$ tons per year of coarse, solid sediment was transported throughout the delta [**FIGURE 2.1.7**]. The amount of fine solids was even more, at $4.6\times10^7$ tons per year for the same period (López Weibel et al., 2022).

Accumulated, the river carries 160 million tons of silt a year, which is constituted of mud, clay and sand (Boschi, 1987). The average composition contains 56% mud, 28% clay and 16% sand, deriving from erosion along the river's course. Anthropogenic and ecological processes simultaneously contribute to siltation. Agricultural topsoil run-off all is observed across the basin, while natural erosion predominantly stems from the Upper Parana (Brazil), the Andean Cordillera/Chaco Plains (Bolivia) and the Pampean Plains (Argentina) (Manassero et al., 2008). Due to the comparably high siltation degree and the specific mélange of the discharging material, the deltaic landscape is actively changing and evolving (Pittau, Sarubbi & Menéndez, 2004). Sedimentation processes are shaping the bathymetry of the river along the basin, within the deltaic zone and in the Rio de la Plata estuary. This leads to an ever-shifting deltaic front (Pittau, Sarubbi & Menéndez, 2004) [**FIGURE 2.1.8**]. The specific bathymetry of the Rio de la Plata with its subaqueous platform stretching over 200 km from the deltaic front at a maximum depth of 10.0m enables these processes and represents simultaneously another result of mineral accretion of finer grain and sand (Parker, 1992; Moreita et al., 2013).

Observations and projections showcase an annual growth of up to 50 meters for distinct zones of the lower delta, in particular the islands south of the Paraná de las Palmas (Sub-frente S RPLP; Pittau, Sarubbi & Menéndez, 2004). Several factors can be made responsible for this irregular growth pattern. For instance, the Uruguay river's less silted water is converging the Paraná river from the North, diluting the northern runoff of the Paraná while there is no such effect towards the southern continental side (Menéndez et al., 2009). This area coincides to be closest to the greater Buenos Aires metropolitan region. By 2118, the delta frontier is projected to reach the provincial border of the Buenos Aires Region with the Capital Federal as the city proper (Pittau, Sarubbi & Menéndez, 2004).

### Water Quality

Research from Peluso et al. (2022) studied the quality of the Parana river in the lower delta around Zarate. The water in the river actually showed excellent quality according to a 'water quality index' (WQI), which was calculated in relation to environmental objectives and developed by the Canadian Council of the Ministers of the Environment (CCME). Though the dissolved oxygen performed low which can be harmful for aquatic life and the phosphate values exceeded the environmental objective which can be related to the high agricultural activities around the delta.

It is also interesting to look at the Lujan river, the waters of which arrive directly from Buenos Aires. Stream Claro [**FIGURE 2.1.9**] flows from the city of Buenos Aires and discharges higher concentrations of pollutants from urban and industrial origin which affects the overall water quality of the downstream river section. The Reconquista relief channel flowing from the main channel of the Reconquista River to the Lujan River contains very polluted water coming from the city and is considered one of the most polluted urban rivers of the Buenos Aires Province (Pizarro et al., 2007).

"The Lujan River receives agrochemicals as well as domestic and industrial (mostly untreated) effluents, mostly entering from the Reconquista River, one of the most polluted South American rivers [...where] detected organochlorine pesticide concentrations were 40 to 400 times the national legal level for water life protection" (Rovedatti et al., 2001, as cited in Baigun et al., 2008).

The Reconquista, along with the Riachuelo to the southeast, could serve as a concentrated microcosm of the numerous negative processes occurring throughout the region. The anthropocentric land use regimes, namely urbanization and agriculture, across the Pampas hinder the ability of nonhuman species to maintain their habitat, ultimately threatening the health and resilience of the overall ecosystem.

Covered urban streams in Buenos Aires, like the Maldonado, Viga and Ugarteche currently operate mostly as stormwater drainage channels and, along with the Reconqusita-Lujan and Riachuelo-Matanza rivers, emit more than 2.5 million kilograms of plastic waste into the delta and Rio de la Plata annually (Meijer et al., 2021).

### Extreme Climatic Events

Over the last decades, the delta has experienced more frequent climatic extremes. Due to climate change, the regions close to Buenos Aires will suffer from higher temperatures and increasing intensity in rainfall in the future. This also includes extreme events, heat waves which occur more frequently and a sea level rise (Buenos Aires Environmental Protection Agency, n.d.) and (Government of the City of Buenos, n.d.).

Evidently, droughts [**FIGURE 2.1.10**] and floods [**FIGURE 2.1.11**], of varying severity over time, have caused a great amount of damage. **FIGURE 2.1.12** shows the 1450 fire hotspots in the Parana river delta on the 22th of July in the year 2020 which is the most on one day since the year 2008 (Scarpati & Capriolo, 2013; NASA). This indicates that the droughts are getting more severe.

In 2016 the World Bank stated the following: "Extreme weather events are a threat to Argentina's economy. Floods cause 95% of the economic damages due to disaster events (World Bank, 2016a). As a result of trends of population growth and urbanization, more cities are nowadays located in low-lying and flood-prone areas. Therefore, an increasing number of people are exposed to flood risk, with large economic losses and tragic consequences."

The Buenos Aires Environmental Protection Agency has predicted that annual rainfall is expected to change in percentage as shown in **FIGURE 2.1.13**. Depending on the representative concentration pathway (RCP). It should be noted that this study used data available till the year 2005. Regardless of the RCP used, namely RCP2.6 or RCP8.5, precipitation is set to increase. However, the scale in which it does is dependent on the amount of carbon dioxide released into the environment.

Not only are floods threatening to the inhabitants of the Parana delta, droughts also have a significant impact on Argentina's economy, particularly for the agricultural sector. Droughts have affected the delta region since early 2020. The low water levels of the last two years have grounded numerous ships navigating the river. Some ships even had to lessen their cargo to make sure of passage which resulted in hundreds of millions of dollars in losses. Low water levels are not just worrying for transport across the river. Also fire activity is increased by dryer conditions. According to the Universidad Nacional de San Martin, 2020 saw a peak in fires, the biggest since 2008 (Salvia et al., 2012).

Low water levels due to low discharges uncovers more land and thus increases the chance for land to burn. Especially because, according to the Universidad Nacional de San Martin, a lot of fires are likely lit on purpose. Unfortunately, because of the increased droughts, and consequently the increase in dry biomass, these fires enjoy easier conditions to escape and burn uncontrollably (NASA, n.d.). Historically these fires have been used to provide pasture, hunt wild animals and clear vegetation cover.

### Sudestada

*Sudestada* is the brief hydrometeorological phenomena which has a significant impact on the Rio de la Plata and thus on the Uruguay and Parana rivers. Strong winds from the south-east propel the water in the Rio de la Plata towards the coastline, thus creating a hydraulic plug. This plug is responsible for blocking the outlet of the Parana river thereby stopping normal drainage. This in turn leads to significant increases in the delta's water depths as water entering the delta from upstream can't be discharged into the Rio de la Plata (Lombardo et al., 2009).

An example of the sudestadas was in the early days of April 2012, when Buenos Aires was hit by a large storm. In **FIGURE 2.1.14**, one sees the total precipitation accumulated throughout these days, based on satellite data from NASA. When one looks at the total precipitation per day on the 3rd, 4th and 5th of April the general direction of the winds, and thus precipitation, can easily be followed from the south east direction.

### Salinization due to Sudestadas

Salt intrusion into the Tigre delta is important, as when the saline water flows upstream in the rivers it could potentially salinize the surrounding ecosystem. This could have major ecological and economical impacts on potential agriculture in the region. Regarding the Sudestadas specifically, a study in 2007 into water quality was conducted on the Lujan river. The Lujan river travels through the Tigre municipality and to the south of it is Buenos Aires and to the north the Tigre Delta. It eventually flows from its source over 100 kilometers to the mouth of the Tigre Delta into the Río de la Plata. During this study multiple conductivity measurements at various parts of the river both downstream (numbered A) and upstream (numbered to F) were conducted (Pizarro et al., 2007).

No clear relation could be found between electrical conductivity and position on the river [**FIGURE 2.1.15**]. It was hypothesized that salination intrusion would lead to a decreasing amount of conductivity further upstream, however this was not the case. Furthermore, all measured ranges of values of electrical conductivity were below 1100 [μS/cm] which is, according to the United States Environmental Protection Agency USEPA, in the range of normal river water which is 50 to 1500 [μS/cm]. When one compares this to seawater which is approximately 50,000 [μS/cm] it is clear that the measured values are far beyond that saline level (Taylor, 2021).

Whilst further conductivity measurements are required in other rivers an educated guess could be made that overall salination does not yet seem to be an active threat to the Tigre delta, so long as measurements stay within the levels regulated by the USEPA (Pizarro et al., 2007).

### Rising Sea Level

To monitor how the sea level changes due to the changing environment, NASA developed a tool using the SSP scenarios. There are five SSP scenarios, in this report we will consider three of them. All the scenario's are the sealevel's compared to the end of 2020.

First, the SSP1 sees a world which will rapidly aim for more sustainable development, investing heavily in renewable energies and high energy efficiency. Furthermore this scenario entails a stagnation in population growth. Scenario SSP2 depicts the development of the world as is most likely. Lastly, scenario SSP5 is the worst of all in terms of global warming where the scenario describes a fossil fuel rich world. In the coming years the world's population would grow rapidly based on continued use of fossil fuels (Stehfest et al., 2021).

Scenario SSP1: The sustainable scenario would lead to the following predictions in sea level change according to NASA. In **FIGURE 2.1.16**, it becomes clear that the sea level will remain below one meter in the coming 100 years.

Scenario SSP2: The most likely scenario, SSP2, will lead to the following rise in sea level. Only by the year 2040 the median of the range will be almost one meter. These results are depicted in **FIGURE 2.1.17**.

Scenario SSP5: When looking at the worst case scenario and the likely range the scenario would bring it seems the sea level will only change a maximum of two meters at Buenos Aires.This is again shown in **FIGURE 2.1.18**. This is considerably more than the previous scenarios. Though, again this is considering nothing will be done in terms of flood protection.

## Urbanization

### A Transnational Urban Problem

The Parana River Basin is vast. The river flows into the sea in Argentina but there is more to the river where the Upper Parana River Basin lies mostly in Brazil. This basin has more than 65 million inhabitants and is of importance for the economic activity of Brazil. This area requires the most water resources in all of Brazil which is mostly used for energy, agriculture and industrial activities. Approximately 25% of all electricity in Brazil is generated from this basin using hydroelectric dams (Abou Rafee et al., 2022). The Itaipu dam is a shared mega project between Brazil and Paraguay with a nominal installed capacity of 14 GW, which makes Itaipu the largest electric energy generation plant in the world. Furthermore, next to generating approximately 17.4% of the total energy demand of Brazil it also covers 74.1% of the total energy demand of Paraguay (Gonzalez-Fernandez et al., 2014). Hydroelectric dams appear a green electricity alternative but it actually hurts the biodiversity of the river delta.

Building dams in the Parana river decreased the fluvial habitat of the river and this has been reflected on the health of fish populations. Besides immensely reducing the yield of fisheries it also damages other ecological processes in the delta. Even more important is the previously mentioned decline in land diversity and fish productivity due to deforestation of the floodplain and the reservoir shoreline. This reduced the food supply for the fishes and echoes in the further ecological system (Agostinho & Zalewski, 1995).

The dissolved oxygen in the river is also already too low. When even more lands will be designated to agricultural-like purposes, the concentration will only decrease further (Peluso et al., 2022).

Deforestation is also a problem in the upper basin. The original land coverage of forest and savanna biomes is removed to less than 10% of its original extent. This is all due to increased production of agriculture and livestock activities. This change in land use and cover is the main driver for increasing discharge in the Parana river after the 1970s (Abou Rafee et al., 2022).

The unpredictability also increases due to climate change where for the past two years, the Parana river was at its lowest water levels in 77 years. This problem does also have to do with the intense droughts the south of Brazil is enduring. Since October 2019 below-average rainfall has been measured across Brazil. This water would have normally flow to the delta, however the drought and increased use for agricultural purposes like livestock and crops, much less water reaches the delta. This is because when lower discharge rates flow down the river, the water for agriculture becomes a higher share of the total because minimally the same is still needed. The discharge rate decreased from a yearly average of 17,000 $m^3$/second to 6,200 $m^3$/second.

### Population Growth

As depicted in **FIGURE 2.1.19**, a twenty-five percent increase in population throughout Argentina is projected by 2070 (World Bank, 2021a). Much of the country's population already lives along the continental edge of the delta spanning from La Plata to Rosario.

The population of Brazil is likewise predicted to increase in the coming 25 years by approximately 20 million people. This will only make the demand for water resources and farmable lands higher and increase the phosphate concentrations. It will also increase the pressure on the discharge and natural biomes in the river delta, making increased population less than beneficial to the health of the river (World Bank, 2021a).

### Water Security

The United Nations named the Sustainable Development Goal (SDG) number 6 as ensuring access to water and sanitation for all, is very applicable in Argentina. In Buenos Aires, which has a population of over 15 million, many residents have issues relating to water. With roughly 3.7 million citizens lacking proper access to safe drinking water. Furthermore, 6.8 million residents lack access to proper sanitation, such as proper sewage facilities, which adds to the risk of disease and pollution in both Buenos Aires and the surrounding areas. (World Bank Group, 2021b) As for the two regions discussed here namely Tigre administrative region and the Zarate administrative region both the limitations and benefits are discussed regarding access to clean drinking water and sanitation.

In the Tigre administrative region we noticed when conducting fieldwork that there is a large discrepancy between water supply on the "mainland" and within the delta. It seemed as if the majority of those on the "mainland" had access to drinking water via traditional methods such as taps in houses etc. However, it must be noted that this is usually only in formal settlements and many informal settlements will lack access to both drinking water and sanitation. As for those living in the delta often they don't have direct access to drinking water and this could be seen in **FIGURE 2.1.20**. In this figure we can see empty drums and jugs of water that are locked to a storage rack on mainland Tigre, although limited data could be found for the precise number of residents with or without access to safe drinking water. However data from 2005 indicated that 57.7% of Tigre's population had access to "clean drinking water" whilst only 9.5% of Tigre's population had access to sanitation.

As for the Zarate region the situation is similar to that of the Tigre administrative region. Namely, that there is a large difference between the formal and informal settlements regarding their access to water supply. Many of those living in the wetlands will lack direct, pipeline, access to both drinking water and sanitation. However, similar to the Tigre region people can use the waterways or boreholes to access water, whilst those in the city of Zarate itself have access via the water pipe network. Sadly, no data could be found for the Zararte region.

Regarding water treatment, Greater Buenos Aires, which includes Tigre has two wastewater treatment plants namely, Planta Depuradora Sudoest which is the southern facility and the Planta Depuradora Norte which is the northern facility. The northern facility, Plata Depuradora Norte, supplies the Tigre administrative region. As for those living in the Tigre delta they either make use of septic tanks or have no access to sanitary facilities and discharge their waste directly into the river. Therefore, when considering the future of Tigre it is important that some form of waste disposal is introduced (Cirelli & Ojeda, 2008).

### Agriculture

Argentina is heavily reliant on soybean and cattle production within the agricultural sector. These very select species sanctioned by market logic are often grouped in monocultures reliant on the use of petrochemicals, which supplants native flora, alters soil conditions and essentially functions as a desert to pollinators and other native fauna. Livestock is a huge consumer of water, where one kilo of beef uses around 50 times more water than growing a kilo of vegetables. This mode of agriculture produces immense yields that have historically benefited humans at the expense of everything else. Declining biodiversity, runaway carbon emissions and the total collapse of the climate suggests a rapid paradigm shift is necessary and urgent. In order to prevent drought and desertification in Argentina and Brazil, the countries have to immediately transition from meat production and monoculture crops (Mekonnen & Hoekstra, 2010).

## .2 Learning from Two Locations

*This section summarizes the challenges & opportunities in Tigre and Zarate respectively, based on field observations, literature reviews, and map analysis.*

Tigre

The city of Tigre [FIGURE 2.2.1 + 2.2.2] is characterized by a unique relationship between the continent and the highly recreational area of the delta. It is known for its unique, off-the grid character.

Tigre is located 28 km north of the city of Buenos Aires (connected by train Mitre in 1 hour), covering 1,520 km$^2$, with a total population of 376,381 according to the 2010 census (INDEC, 2017). The city includes both continental and deltaic land, with subdivision into Benavidez (54,797), Dique Luján (5650), Don Torcuato Este (39,886), Don Torcuato Oeste (31,470), El Talar (50, 426), General Pacheco (55, 197), Los Troncos del Talar (42, 018), Ricardo Rojas (20,474), Rincón de Milberg (45, 013), Tigre (25, 982), and Islas (5, 468). The overall density of Municipio Tigre is 247.6 habitant /km2, compared to that of Palermo at 14, 485 habitant /km2. Despite the low density, Tigre is constituted by a diversity of land-use, with urban density concentrating around the Estación Tigre, and industrial warehouses along the Luján river and further inland. In terms of residential land, gated communities with American suburb types spread over the region, sitting in stark contrast to the informal settlements on both the continental and delta side. Vacation houses on stilts are popular along river channels in the delta, connected by ferry piers, juxtaposed with households of lower income and security.

Given the not insignificant human settlement in Tigre, living with the water means more than an idealized lifestyle, but an everyday survival tactic. Indeed, suburban floods are commonly observed in Tigre, with insufficient flood protection measures to protect the community. The researchers observed a *sudestada* event during their field research, where water levels rose from 0.7m to 2.5m overnight, submerging households along the river banks, whose raised foundations help alleviate flood damage. Understanding the hydrology of the region, as well as the anthropogenic processes in tandem with the ecological actors, is instrumental to display the complexity and precarious settlement in the Tigre.

Suburban floods

Suburban floods are a common phenomenon to be observed in Tigre, since flood protection measures are not as present as they should be to protect the community. Tigre is located downstream of the Paraná river. The city center is located next to the Luján river, whereas on the other side of the city banks the delta environment changes drastically. Houses are scattered among this high flood-risk area in the 'wilder' delta. The villages don't consist of cemented roads and shops in buildings, but piers and vessels bring around errands and most importantly, fresh water in large jugs, since a piping network is completely missing. Most houses have front yards with a single pier. The banks are not protected against the wave generation of passing vessels, so overtopping, which weakens the soil drastically, is clearly visible. Additionally, in the deeper soil, the water is very saline.

Infrastructure

Ad-hoc water supply: Given the lack of regional infrastructure of the water supply system, the residents in the delta area rely on potable water supply from the continental side, with lines queuing up at the public pier to fill up their polystyrene bottles which are transported by hand back home. For water usable for non-drinking purposes, a filtration system is set up at each household, providing a minimum of essential water supply to the delta stilt houses.

Pier-ferry transport: The primary mode of transport in the delta is by ferry [FIGURE 2.2.3], which connects individual units by their private piers. Public piers are evident, but only in limited locations and lack adjacent amenities as a viable social hub. The pier-ferry transport has a regular schedule of 3-4 times a day, connecting residents between delta and city. It is therefore also popular for individual units to own their speedboats, which allows more flexibility and convenience in terms of transport. The frequent river traffic for commuting poses disturbance to the fluvial ecology, but also challenges to existing riverbank design. In sections with hard edges, waves are trapped in the channel without necessary dissipation, creating volumes of channel water displacement. Soft edges such as marsh, on the other hand, become a useful strategy to maintain a viable channel traffic.

Zarate

The city of Zarate paints a very different picture of the delta [FIGURE 2.2.4 + 2.2.5]. Characterized by intensive agriculture it is an example of a very extractive human interaction with the region.

Zárate is located in the province of Buenos Aires, with an territorial extent of 1,202 km$^2$ (to the northeast with the Paraná Guazú River, to the SE with the Partido de Campana, to the S with the Exaltación de la Cruz and San Antonio de Areco and, to the northwest with Baradero.) In terms of population, based on the 2011 census, Zárate has 98,522 inhabitants (Indec, 2010), and now approximately 130,000 inhabitants according to the official website of the Municipality of Zárate. Together with Campana, it forms an urban agglomeration of 185,382 inhabitants (Indec, 2010).

Zárate has a population density of 108 habitant/km$^2$, with a majority of rural land between the Paraná de las Palmas and the Paraná Guazú, where an intensity of tree-farming and agricultural practices are observed, and the urban density is concentrated on the south bank of the Paraná de las Palmas, with a mix of residential and industrial land-use, with international businesses such as Toyota, Quilmes, Isenbeck, Papelera del Plata, Monsanto, Merisant, Petrobras, TFL Argentina, Bayer and Lanxess etc. Given its strategic geography along the Paraná River, a major navigation route for Argentina, Zárate is characterized as a port-industrial city, and perhaps most noticeably is the Terminal Zarate [**FIGURE 2.2.6**].

The terminal offers services including “vehicle storage” (with a 1,530,000 m$^2$ of “paved, fences and illuminated yards"), “container port” (with a container capacity of 270.000 TEUs /year), and “Project Cargo" (with 480m long pier) (terminalzarate.com.ar). Adjacent to the port industry, the agricultural industry also has a great presence in Zárate, with tree-plantation farms spreading over the delta landscape between the two Paraná rivers. Polders are created around the tree farm for plantation, disrupting the fluvial processes in the region. With more frequent extreme precipitation events observed, most noticeably the severe droughts beginning in 2019, there calls for a rethink on the existing industrial practices in the region in the light of building resilience for the city and the delta.

### Hydrology

The two main rivers flowing through the delta are the Parana de las Palmas and the Parana Guazu [**FIGURE 2.2.7**]. The bifurcation in the river Rio Parana formed the Parana de las Palmas which retains 23% of the flow from Rio Parana while the other 77% runs through the Parana Guazu. The Parana de las Palmas has a large contribution of sediments of 160 million tons per year, of which 100 million come from the Bermejo River. This has consequences because the front delta is growing about 100 meters per year on the side of the Buenos Aires coast and 25 meters on the Uruguayan side.

The increased sedimentation rate of the Parana de las Palmas has partly been caused by the construction of a canal called Emilio Miter decades ago because it caused heavy dredge tasks. On the contrary, it does not affect the Parana Guazu to the same extent since it is mainly fed by the Rio de la Plata.

The Parana Guazu River is the largest branch of the Parana. It has a great depth of 12-30 meters, a width that varies between 370 and 1800 meters, and a length of about 107 kilometers until it flows into the Rio de la Plata. The average flow discharge is approximately 14000 m$^3$/s. This river was historically used for navigation because it is the main river artery.

Canal Irigoyen is an artificial navigation route, 15.92 km long and 60 meters wide that joins the Parana de las Palmas with the Pasje Talavera, making it possible for ship navigation to the Parana Guazu. According to the literature, this canal will be dredged deeper for future navigation with the increase of the ship size (Barletti, 2021).

These rivers and waterways are also projected in **FIGURE 2.2.8**, which aims to identify the various zones within the delta area. **FIGURE 2.2.9** shows the zoning of the Parana River delta in Zarate and Campana area where the blue shaded areas represent the areas that are likely and allowed to be flooded during high water levels. The green shaded areas mean that there are some agricultural activities such as farming and forestry, meaning these areas are protected by some type of flood defense. The black arrows show the direction of the flow in the river or to the floodplain. The blue lines are the small rivers in the delta and some canals for ships. The orange line is the highway connecting the Zarate city to the other side where some industry areas and the lagoons are found.

Since the flow data of the Parana River close to Zarate is difficult to find, here we use the flow data at the location of Santa Fe which is approximately 900 km upstream. Since no major bifurcation is present, it is assumed this data is applicable to Zarate.

From **FIGURE 2.2.10**, we can conclude that the average flow discharge is 14,000m$^3$/s and the design discharge for a flood event is 39,000m$^3$/s with a return period of 10 years. Applying the discharge ratio of the bifurcation from Rio Parana: For average flow, Qavg,LP=3220 m$^3$/s (23%) goes into Parana de Las Palmas and Qavg,G 10780 m$^3$/s (77%) goes into Parana Guazu. For design discharge, Qd,LP=8970 m$^3$/s and Qd,G=30030 m$^3$/s.

The relevant water levels have been found by finding the suggested evacuation water level from a local measuring station which is found to be at +2.25 m IGN [**FIGURE 2.2.11 + 2.2.12**]. This will be used as our design water level that represents the flood event. The value for low water, which is assumed to correspond with a period of drought, is found to be at +0.3 m IGN. This will be used as the reference level for the operation of the retention reservoir.

Agriculture

Agriculture is a byproduct of urbanization; the two function in tandem. The success of the earliest cities depended on the success of the annual harvest. In the twenty-first century, globalization has skewed the once circular model of local food production. Today, soybeans grown in Argentina are shipped to China to be processed into feed for livestock and other soy products like milk and tofu which are then sold across Asian markets. Further demonstrating the illogic of the system, in order to secure its own agricultural production machinery, Argentina then imported more soybeans from the United States, becoming the number one importer in 2018 (Larmer, 2019).

The transition from food as a nutrient to a commodity has in turn altered the way humans engage with native ecologies, a relationship that was once fundamental to farming communities. Frequently, the land and soil is exploited for short term profit over long term sustainability, with little consideration given to local soil and hydrological conditions. Land that was once an interwoven mosaic of biological flows is now a disconnected patchwork of fragmented forests and dried up marshlands [**FIGURE 2.2.13 + 2.2.14**].

Looking at satellite imagery of the delta on Google Earth can be misleading. At first glance, there are seemingly healthy forested areas. Upon further analysis, it is understood many of these 'forest' patches are in fact tree plantations within polders [**FIGURE 2.2.15**]. This approach to water level management is mostly practiced by large companies, "where the plantation is totally surrounded by levees to protect trees from floodwaters" (Quintana, Kalesnik in press, as cited in Baigun et al., 2008).

At the same time, smaller producers tend to use an "open-ditch" method which "involves the construction of a network of ditches and channels in order to increase the water run-off [... and] has introduced what could be regarded as positive alterations to the islands' original landscape. Now, this forestry landscape has a high level of connectivity for these species and the aquatic network which facilitates their access to the foraging, resting and shelter areas" (Baigun et al., 2008).

Conversely, polders have an overall negative impact on the hydrological system as they separate river channels and cut off flows of sediment and the habitability of wetland species. "Flood pulses are critical components of floodplain river integrity" (Poff et al., 1997, as cited in Baigun et al, 2008) and "influence biodiversity by producing seasonal disturbances (Ward et al.,1999, as cited in Baigun et al., 2008), thus marshland must be restored where possible.

On the continental side of Zarate, in the Pampas, what isn't built is agricultural, extending across the entire sub basins, many of which flow into the delta Beginning in the 1990s, spurred by the rapid decline in soil health, a no-till method was implemented throughout much of the agricultural sector. This coincided with the widespread adoption of genetically modified soybean as the overwhelmingly favored cash crop in the country (OECD, 2019). While no-till agriculture can promote healthier soils, reliance on monoculture crops reduces overall soil biodiversity (Altieri, 2009). In 2021, products derived from fossil-intensive and pollutive cattle feedlots and soybean monocultures were some of the county's top agricultural exports (MEA, 2022). Agriculture is the primary source of carbon emissions in the country, accounting for more than 32% of the country's total emissions in 2019, by far the largest emitter by sector (CAIT, 2020).

## .3 Worst Case Scenarios

Although, compared to the continent, some parts of the delta have until now remained relatively unimpacted by human incursion, that is beginning to change. The ongoing drought from 2019 has created new incentives for commercial interests in the delta that threaten to transform more marshland into poldered, dry turf. [**FIGURE 2.3.1 + 2.3.2**] .Anthropocentric land use in the delta proliferates as a mere copy-paste of the same land regimes that are practiced on the continent. Fires, accidental or not, disturb soils and vegetation, exacerbated by the ongoing drought (Schmitz, 2022)

Wetlands and marshland are essential ecosystems with many benefits. "Among the important hydrological functions provided by the system are the reduction in water flow rate and turbulence, the increased short- and long-term water retention and the storage and regulation of evapotranspiration. Different biochemical processes enhance water quality including storage, transformation, and degradation of nutrients and pollutants and salt regulation" (Kandus & Quintana, 2018).

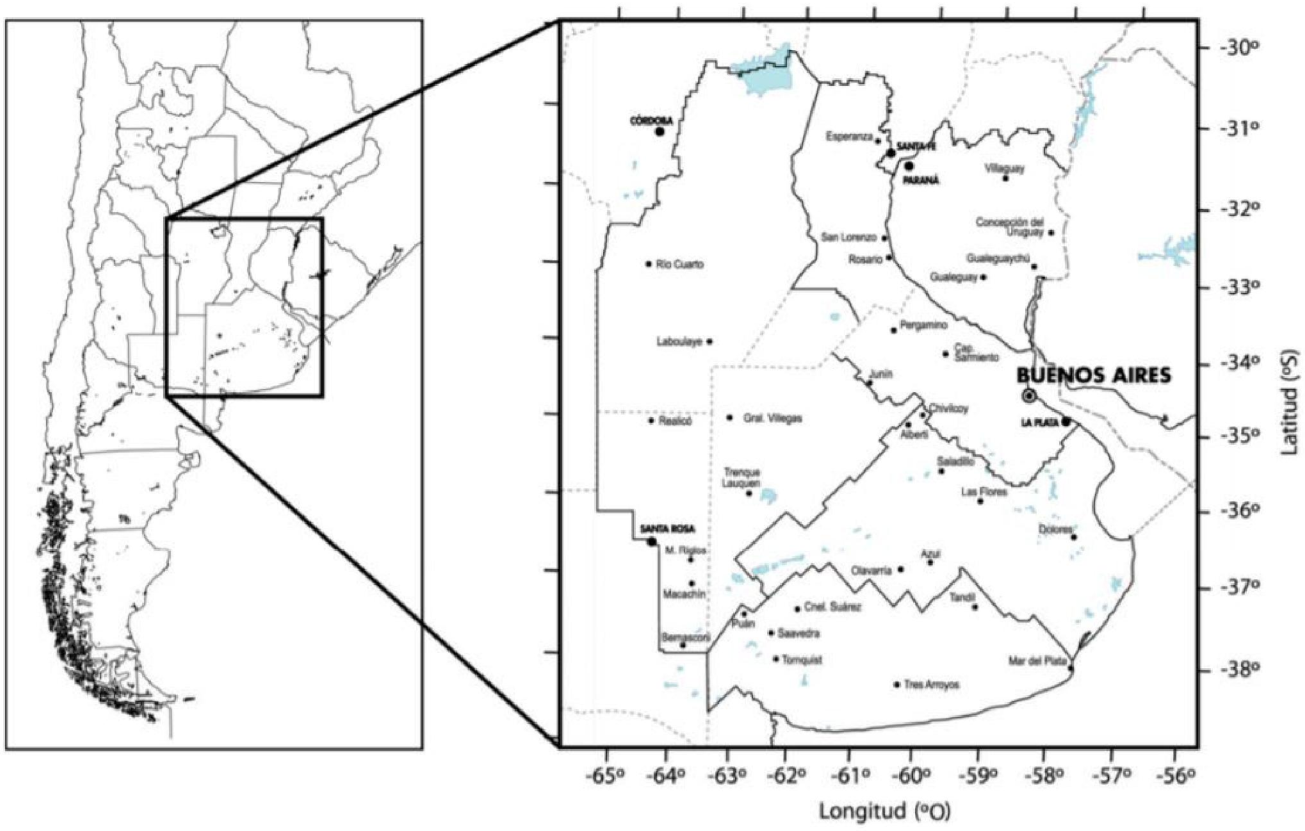
The ecosystem services provided by these ecologies must not be underestimated. At the same time, the New Climatic Regime (Latour, 2017) requires that humans accept that the entirety of the Earth is not for their unrelenting consumption. The delta, with all of its entangled, messy, fluctuating, interwoven processes and relations, must be preserved.

## .4 Conclusions

The analysis leads to the conclusion that the delta in its current state is not pristine. It has already undergone the process of urbanization and the impacts of these human actions are observed both in Tigre and Zarate. Comparing the two, Zarate presents a case of a much more extractive approach, which causes greater interference in the natural processes of the delta. The creation of the polders and intensive agriculture negatively impacted the region and led to issues such as prolonged periods of drought and fires which were observed during the site visit. On the other hand, the anthropic activity in Tigre seems to be more in tune with native ecological systems, focusing mostly on recreational use. Although the visitors of the region are faced with a number of nuisances caused by the lack of infrastructure, such as infrequent public transport and the lack of drinking water, the area offers unique positive qualities.

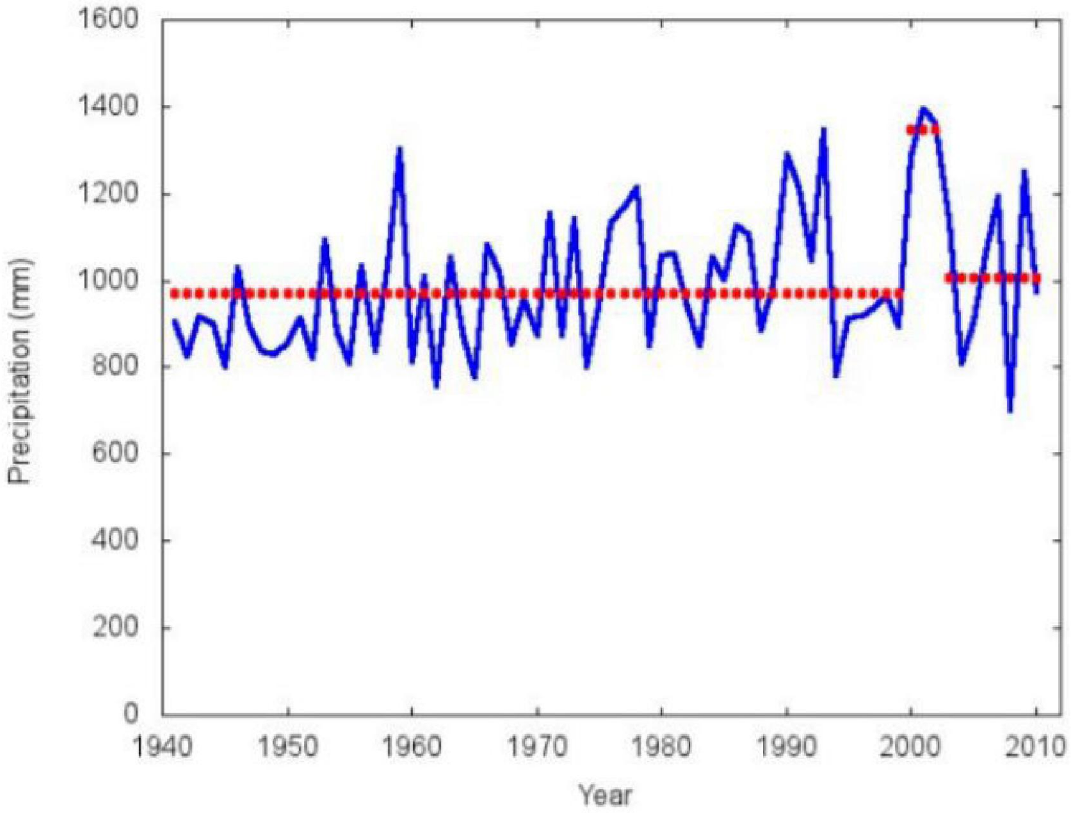
**2.1.1**

The various Pampas sub-regions along with the cities which inhabit them (Pérez, 2015).



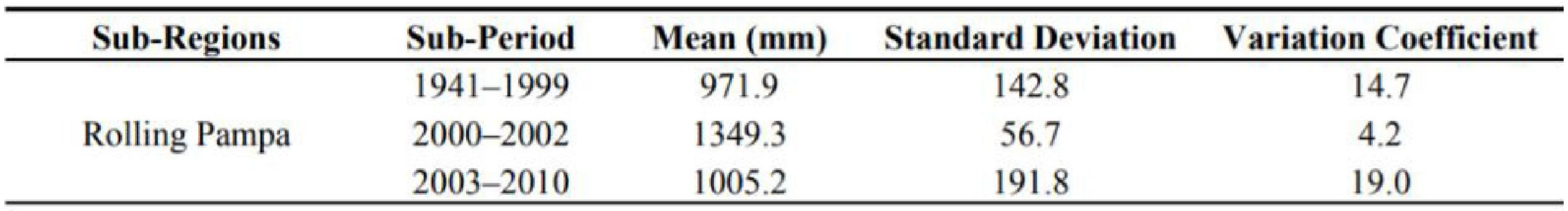
**2.1.2**

Mean and annual precipitation in the Rolling Pampa sub-region using Hubert's segmentation method (Pérez, 2015).



**2.1.3**

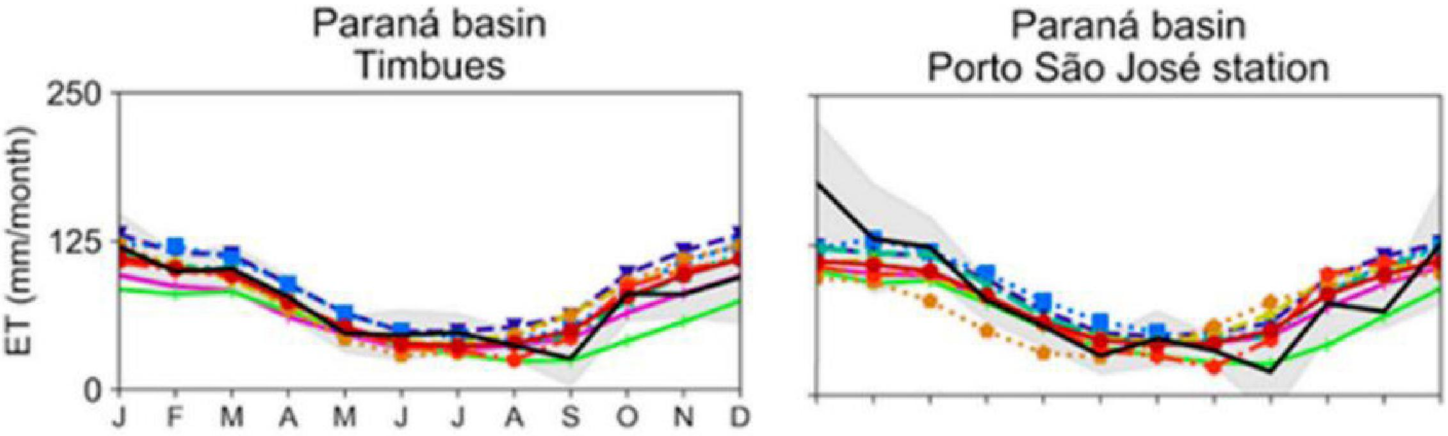
Mean precipitation in the Rolling Pampa region, along with its standard deviation and variation coefficient, in various sub-periods (Pérez, 2015)



| Sub-Regions | Sub-Period | Mean (mm) | Standard Deviation | Variation Coefficient |
|---|---|---|---|---|
| Rolling Pampa | 1941–1999 | 971.9 | 142.8 | 14.7 |
| | 2000–2002 | 1349.3 | 56.7 | 4.2 |
| | 2003–2010 | 1005.2 | 191.8 | 19.0 |

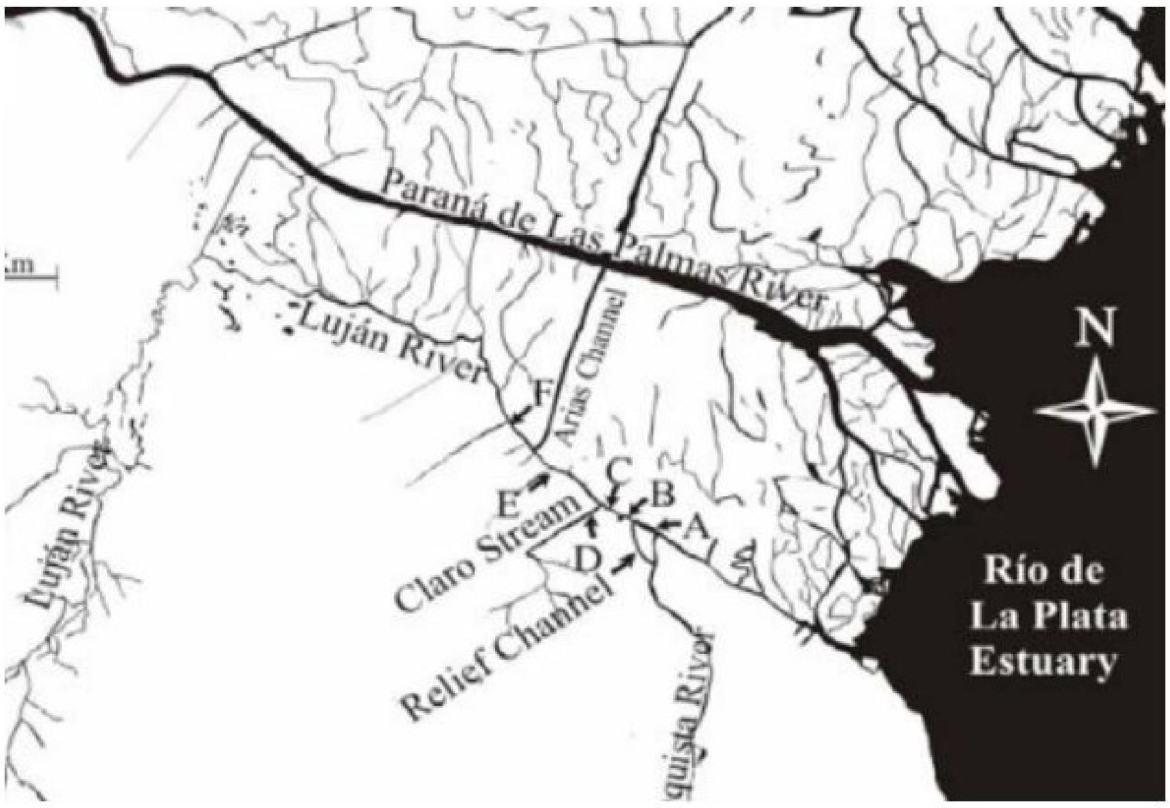
### 2.1.4

Mean and annual evaporation in the Rolling Pampa sub-region using Hubert's segmentation method. Note the sub-periods in the figure above are the same as those in Figure 2.1.3, namely; 1941-1999, 2000-2002 and 2003-2010 (Pérez, 2015)



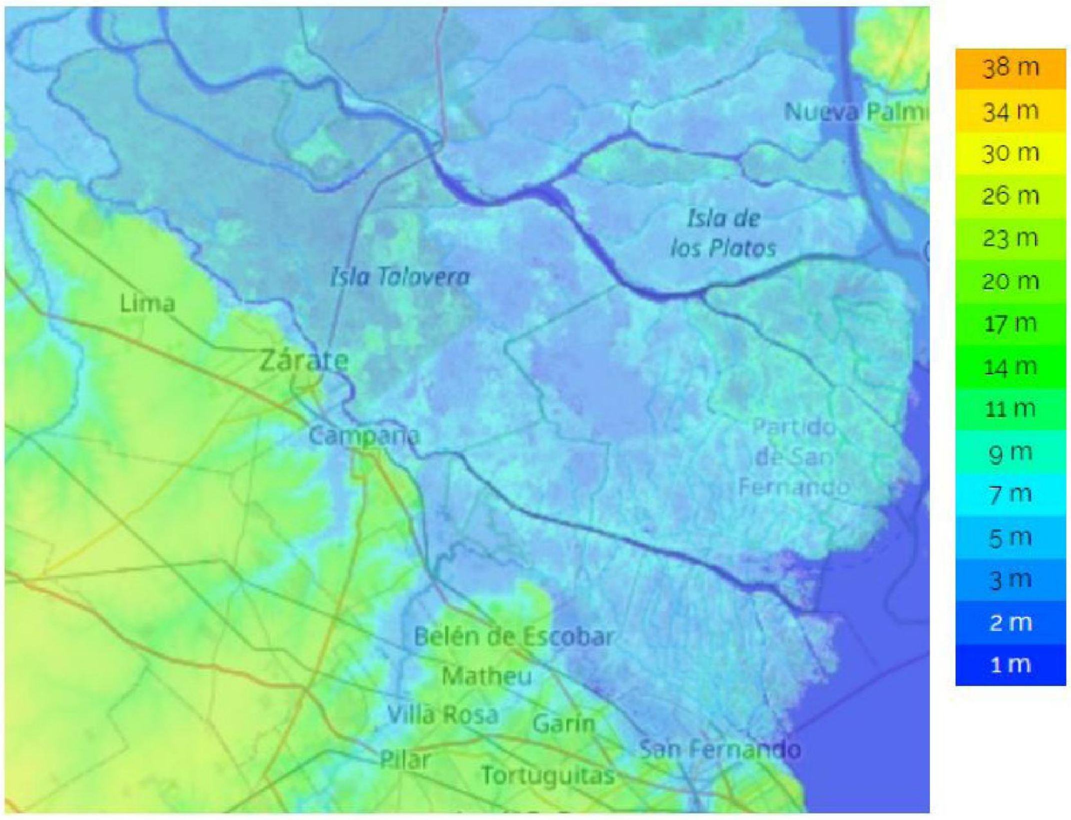
### 2.1.5

Río de La Plata Estuary (Pizarro et al., 2007)

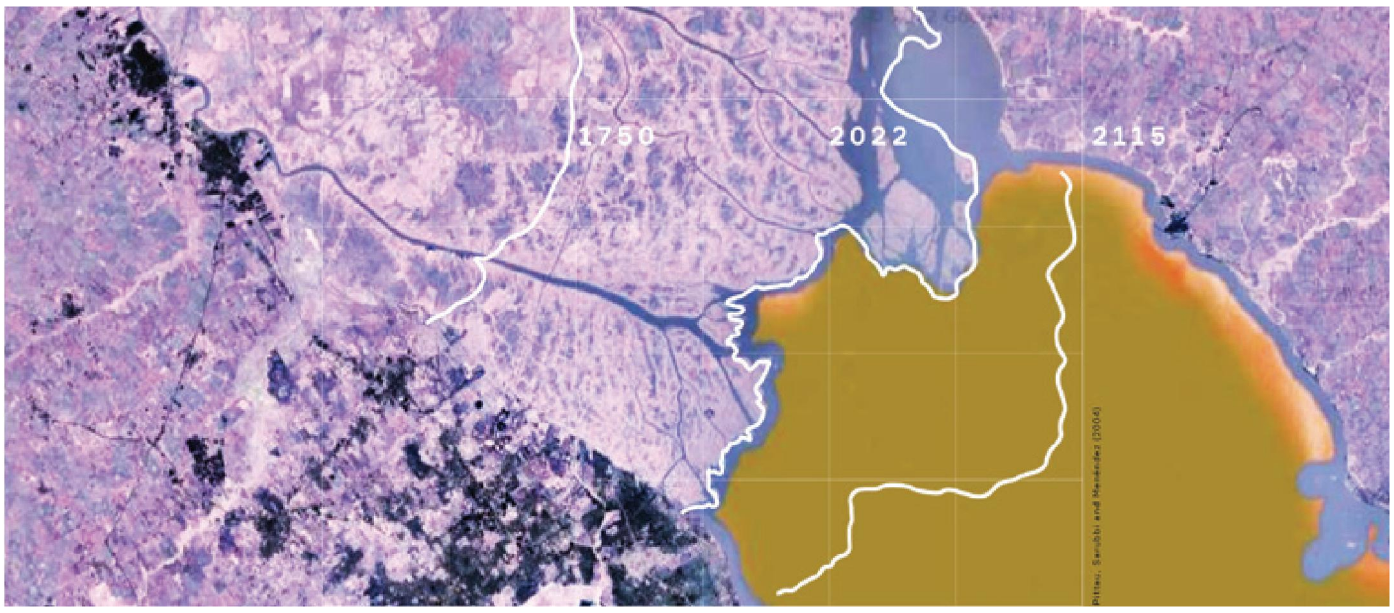


### 2.1.6

Topographic map of the lower delta



**2.1.7**
Map showing sedimentation at the Parana Delta, which grows by approximately 100 meters annually. Created by authors, developed from Google Earth, 2022.



**2.1.8**
First sediment at the delta front, photographed by authors during field trip, summer 2022

**2.1.9**
Water pollution in the mouth of the Rio Matanza-Riachuelo at La Boca in Buenos Aires, photographed by authors during field trip, summer 2022.

**2.1.10**

Warning of the fire on the delta from the Tigre Municipality's Instagram account @alerttigre and a photo of a fire event near Zarate, photographed by authors during field trip, summer 2022

alertatigre ···

CÓMO ACTUAR EN CASO DE

INCENDIO EN CASA

- Intente apagarlo con el uso de matafuegos, sólo si está capacitado.
- No sea imprudente. No arriesgue inútilmente.
- Si no es posible controlar el fuego, desaloje la zona. Cierre puertas y ventanas.
- Mantenga la calma.
- En caso de evacuación, no corra y retírese del lugar caminando.
- No use ascensores, utilice la escalera.
- Llame al 100 (Bomberos).

TIGRE MUNICIPIO

INTENDENTE JULIO ZAMORA

「いいね！」8件

alertatigre 👷 #DCTigre nos comparte éstas importantes recomendaciones sobre como actuar en caso de incendio en casa🏠.
Mirá 👆

1日前・翻訳を見る

alertatigre ···

**2.1.11**

Warning of flooding from Sudestada in the delta from the Tigre Municipality's instagram account @alerttigre and a photo of the event of floodings of delta settlement, photographed by authors during field trip, summer 2022

alertatigre ···

AVISO POR CRECIDA

Domingo 28 de Agosto de 2022 - 02:30hs

ALTURA ACTUAL: 1.85mts ⬆⬆⬆

Pleamar: 2.50mts > 10:00hs

Bajamar: 1.75mts > 17:00hs

Viento: Sudeste a 13 km/h

SERVICIO DE HIDROGRAFÍA NAVAL

TIGRE MUNICIPIO

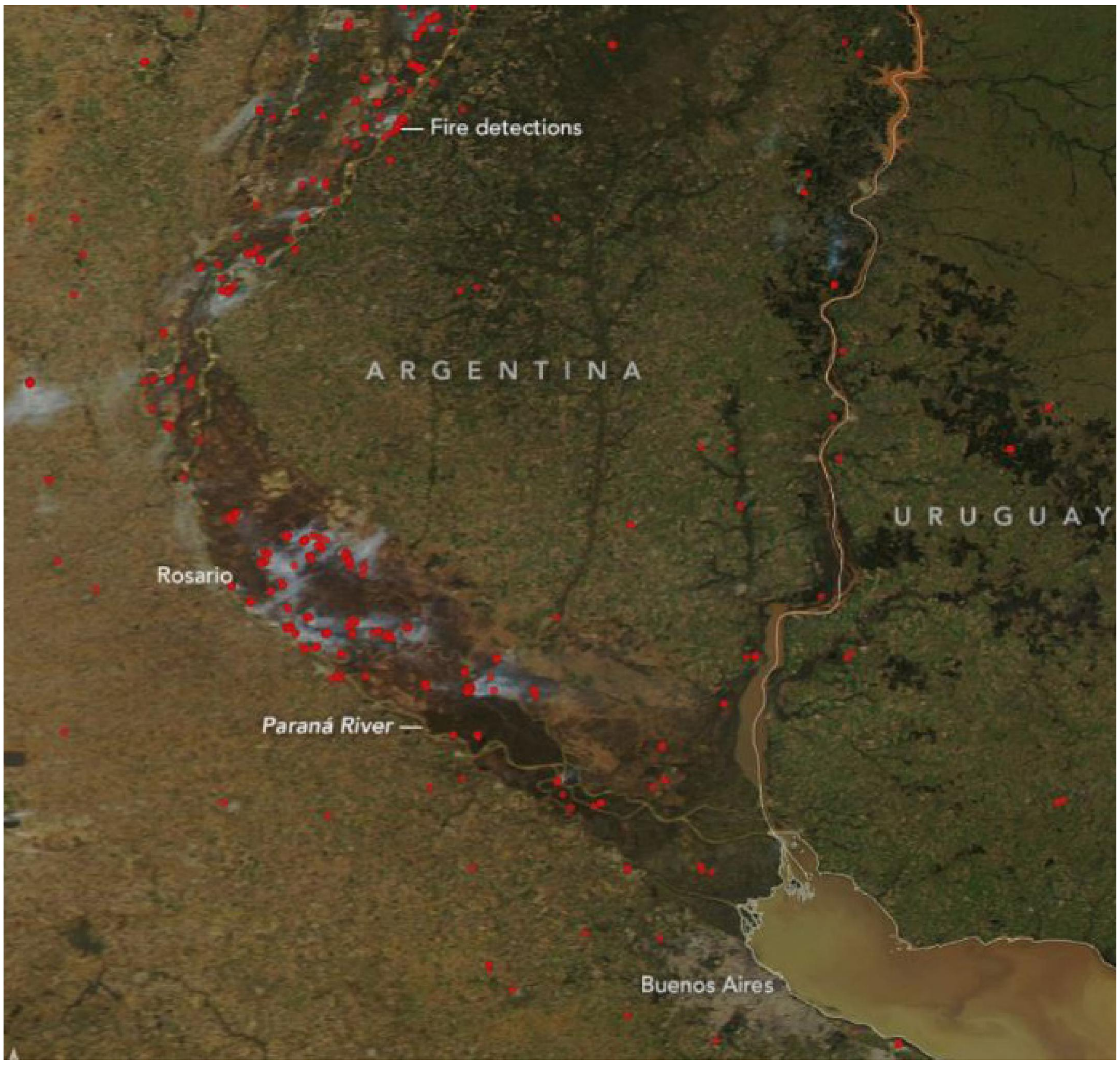
INTENDENTE JULIO ZAMORA

「いいね！」12件

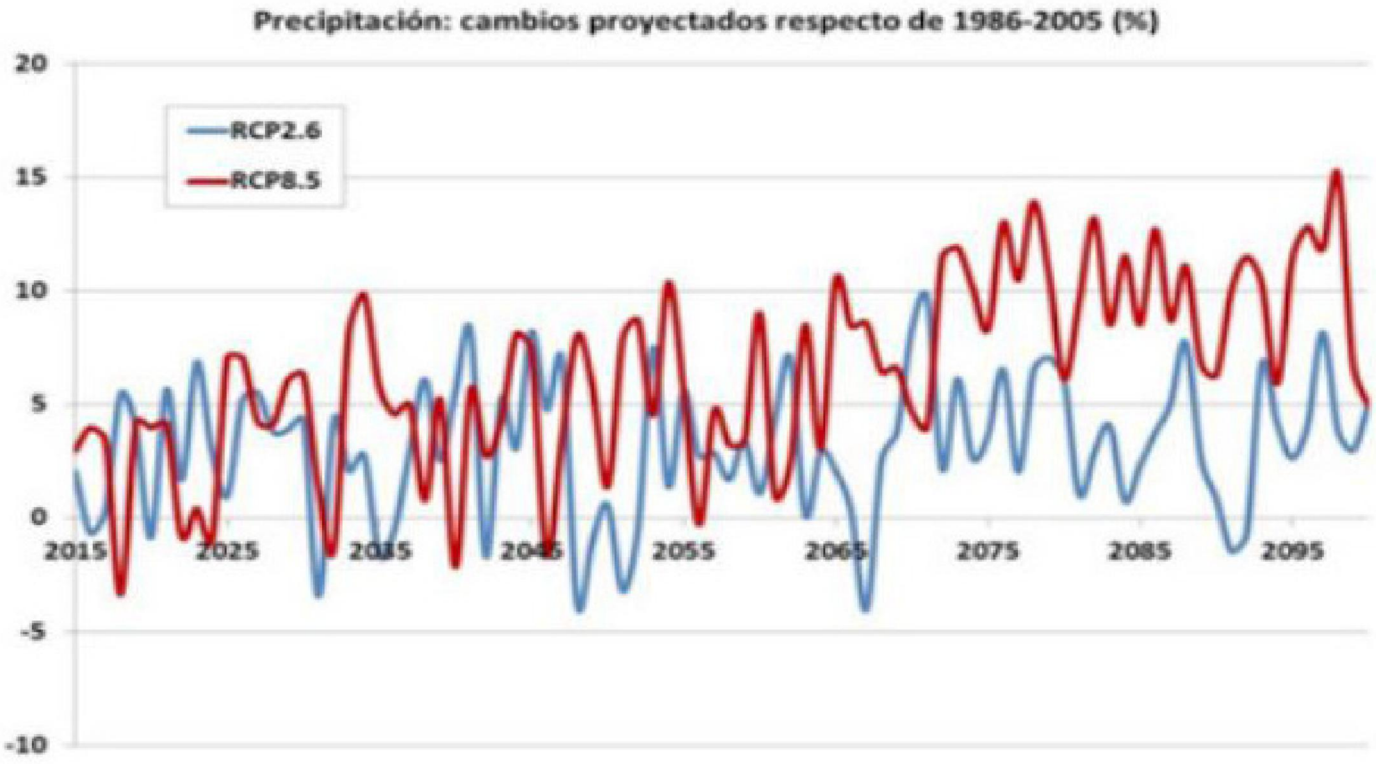
alertatigre #DCTigre informa: AVISO POR CRECIDA DEL RÍO en @tigremunicipio
Dudas, consulta, emergencias?
☎ 103
☎ 5288-3411
#COT

8時間前・翻訳を見る

**2.1.12**
Map of fire events in the Parana delta and the greater basin (Scarpati & Capriolo, 2013; NASA).

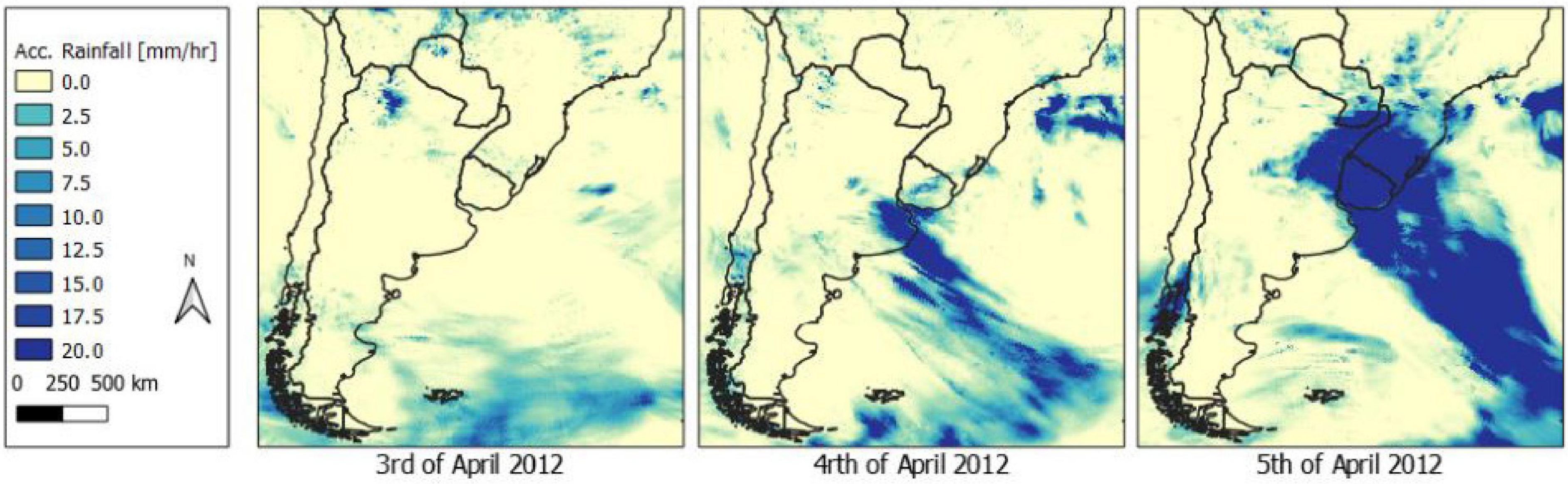


**2.1.13**
Precipitation predictions (Buenos Aires Environmental Protection Agency, n.d.)



**2.1.14**

Accumulated rainfall intensity during a sudestadas hydrometeorological phenomena during the 3rd, 4th and 5th of April 2012 in [mm/hr]. Note the general southern-eastern winds. (NASA, n.d.)



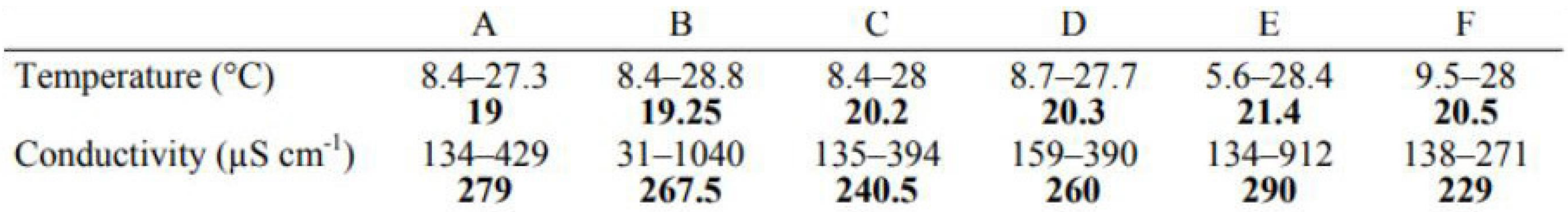
3rd of April 2012

4rth of April 2012

5th of April 2012

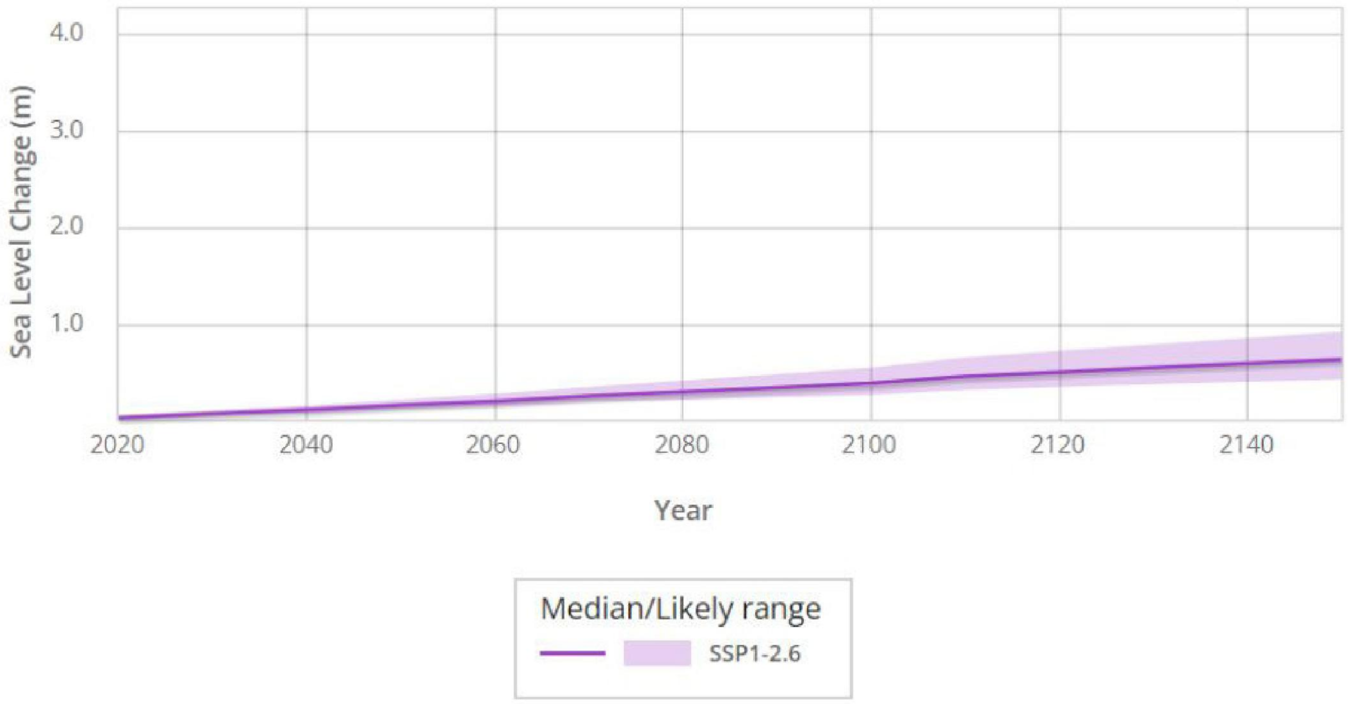
**2.1.15**

Various conductivity [µS/cm] measurements from various locations, A through F (Pizarro et al., 2007)

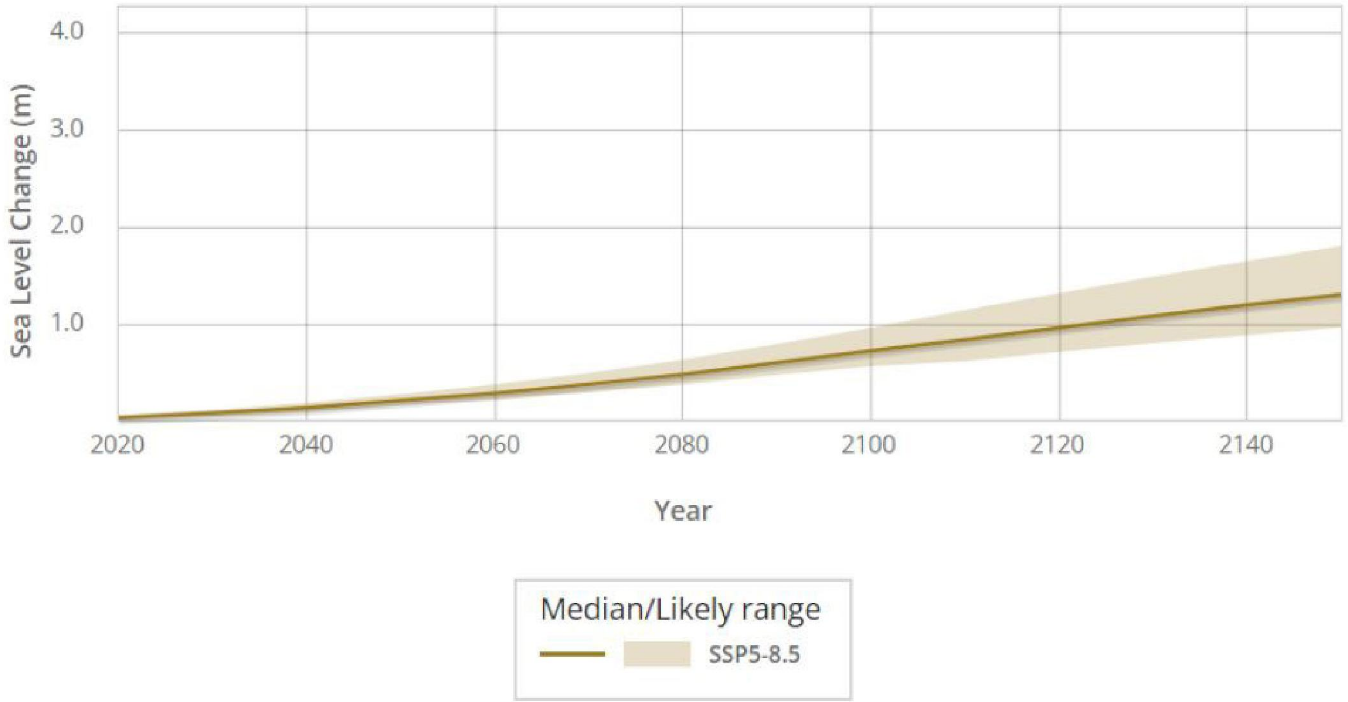


| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Temperature (°C) | 8.4–27.3<br>**19** | 8.4–28.8<br>**19.25** | 8.4–28<br>**20.2** | 8.7–27.7<br>**20.3** | 5.6–28.4<br>**21.4** | 9.5–28<br>**20.5** |
| Conductivity (µS $cm^{-1}$) | 134–429<br>**279** | 31–1040<br>**267.5** | 135–394<br>**240.5** | 159–390<br>**260** | 134–912<br>**290** | 138–271<br>**229** |

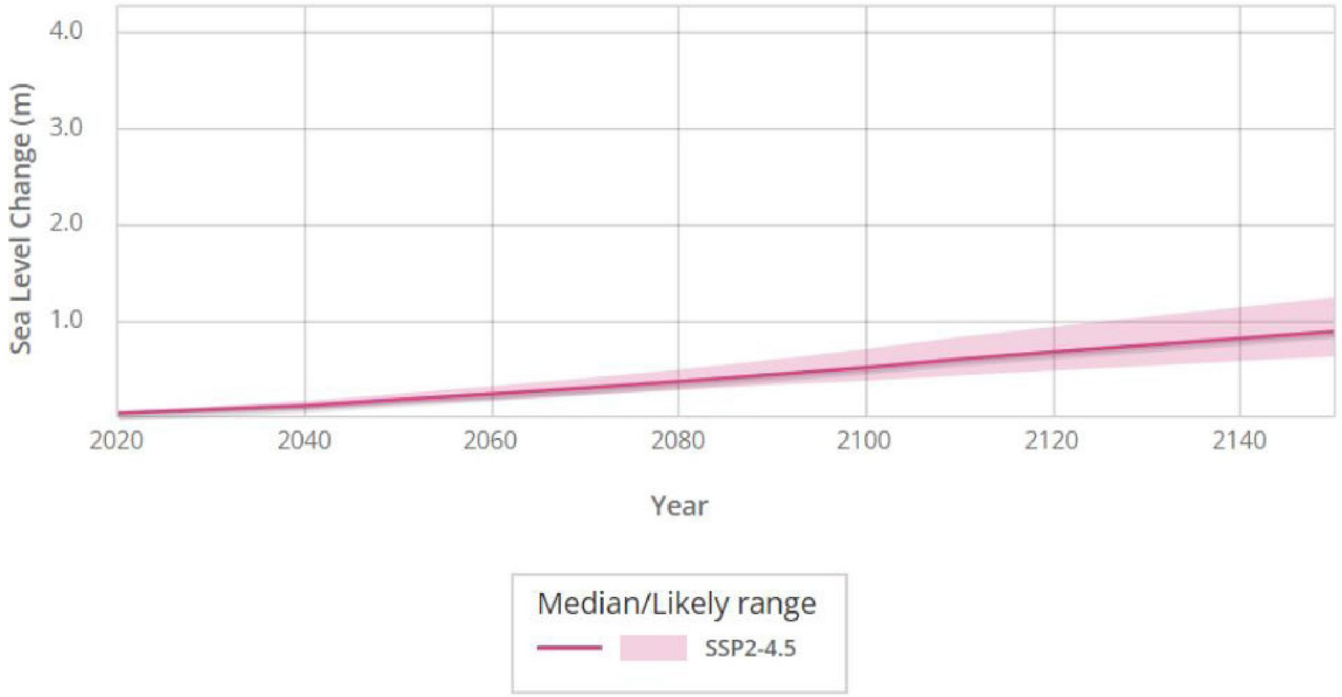
**2.1.16**
SSP1



**2.1.17**
SSP2

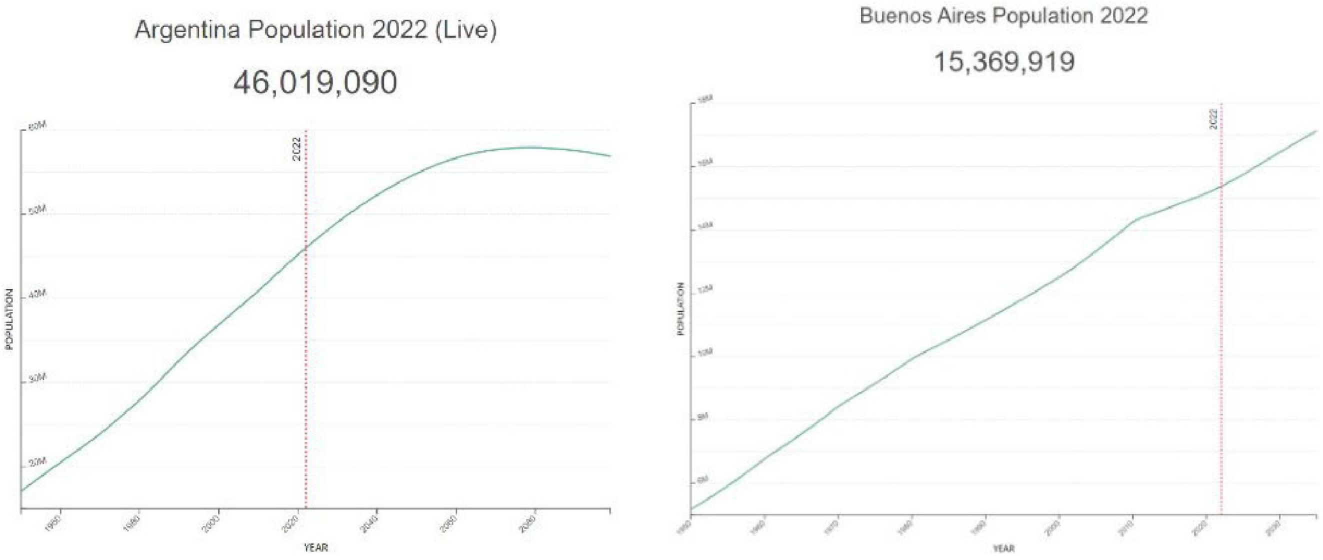


**2.1.18**
SSP5



**2.1.19**

Projection of population for Buenos Aires and Argentina (World Bank, 2021a)

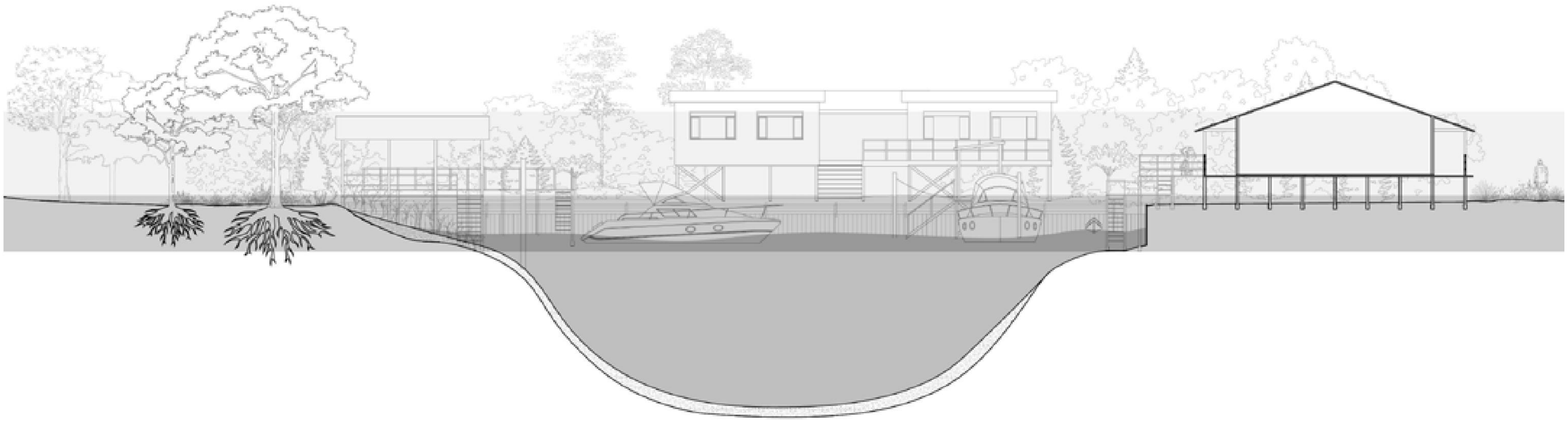


**2.1.20**

Informal water facilities available at the main port in continental Tigre, which is the most immediate source of potable water for residents living in the delta, photographed by authors during field trip, summer 2022

**2.2.1**
Photo of the occupation of the delta in Tigre, photographed by authors during field trip, summer 2022

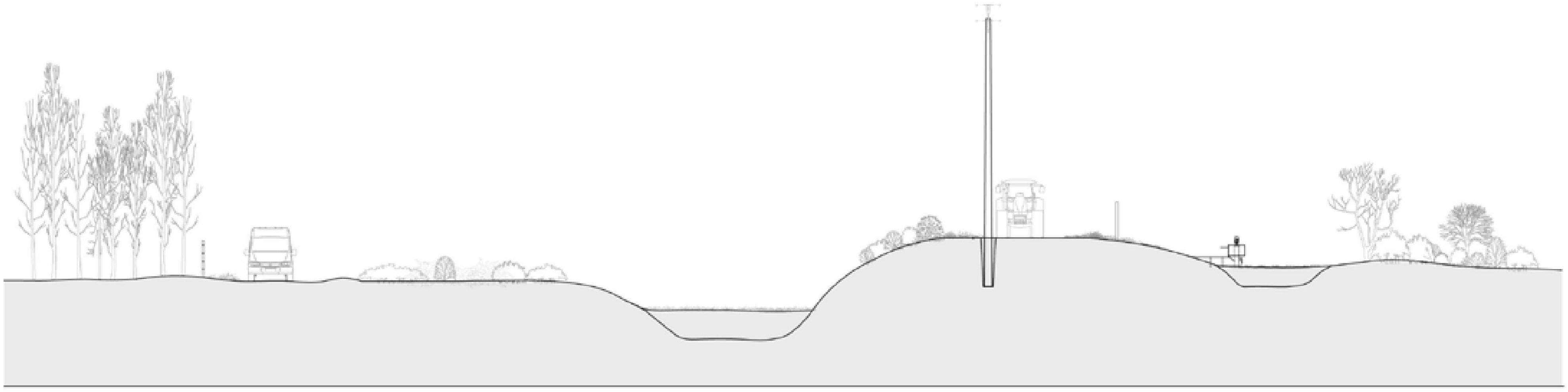
**2.2.2**
Section of the delta in Tigre, created by authors



**2.2.3**
Pier-ferry facility offered to local residents, which is the main mode of transport in and out of the delta, photographed by authors during field trip, summer 2022

**2.2.4**
Photo of the agricultural activity in of the delta in Zárate, photographed by authors during field trip, summer 2022

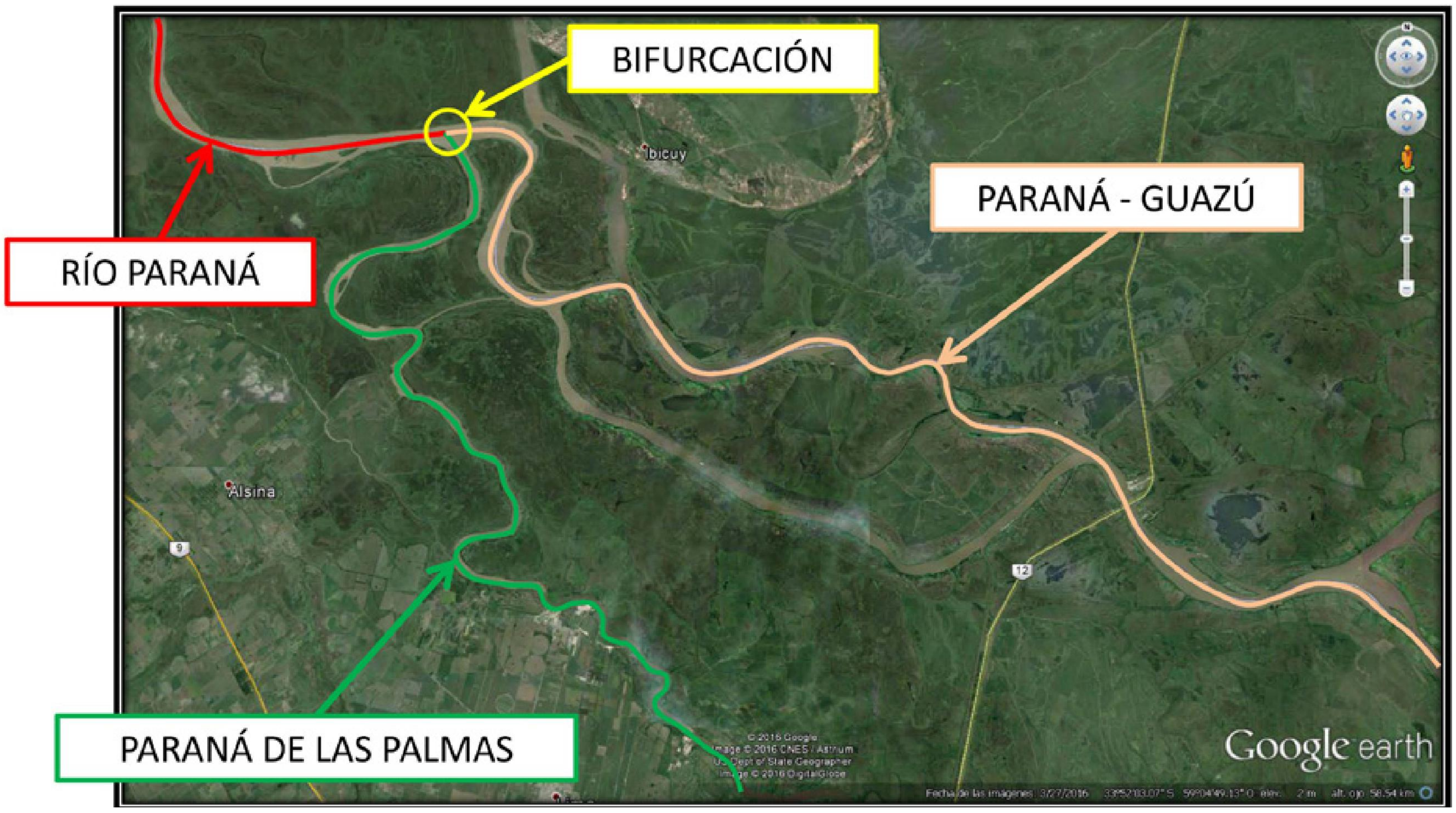
**2.2.5**
Section of polder situation from exiting forestry visited in Zarate, created by authors

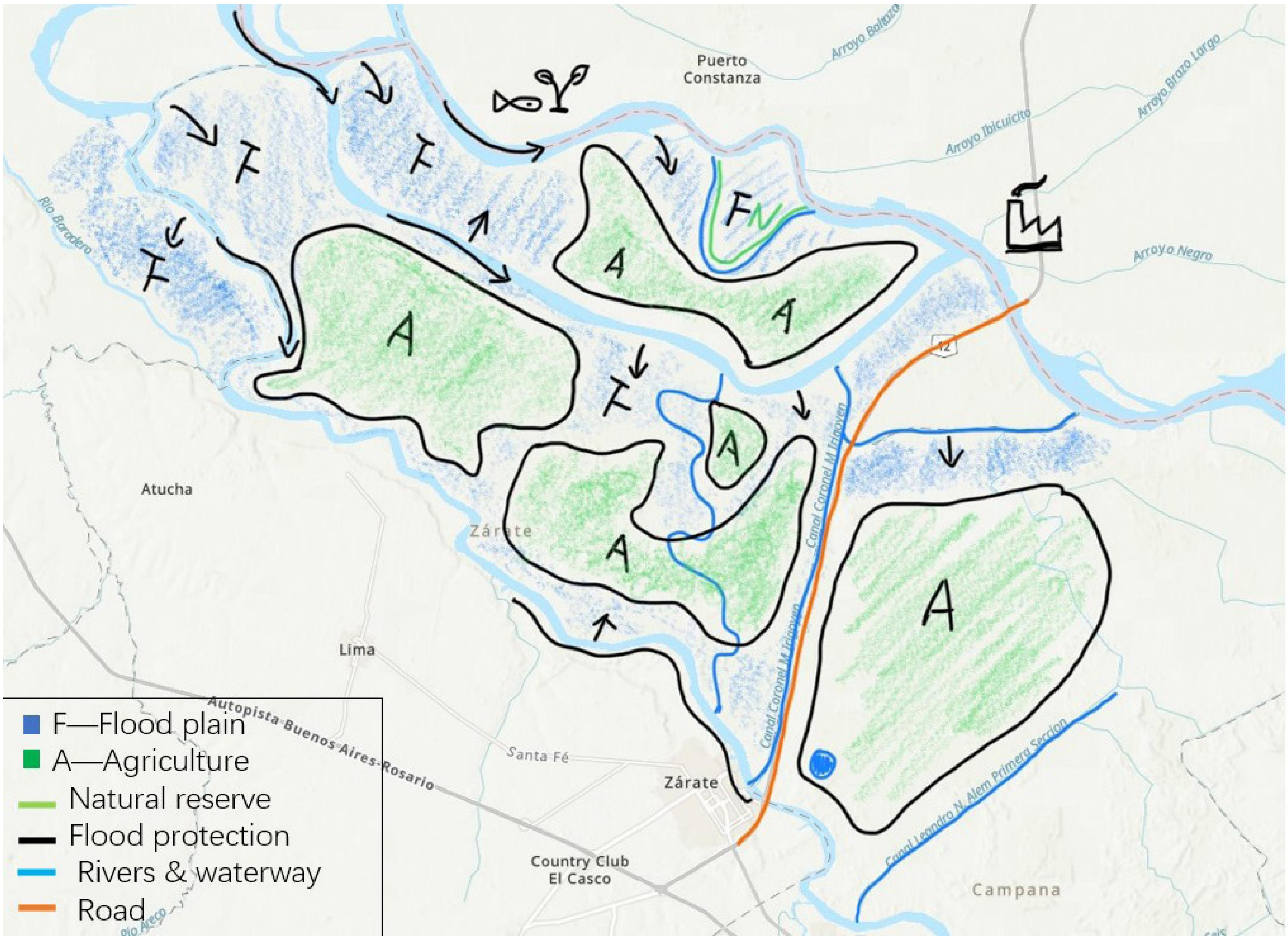


**2.2.6**
Terminal Zárate
(from terminalzarate.com.ar)

**2.2.7**
Bifurcation of the main channel of the Parana River in the lower delta. Developed from Google Earth, 2022

**2.2.8**
Canal Irigoyen (in red) near Zarate. Developed from Google Earth, 2022



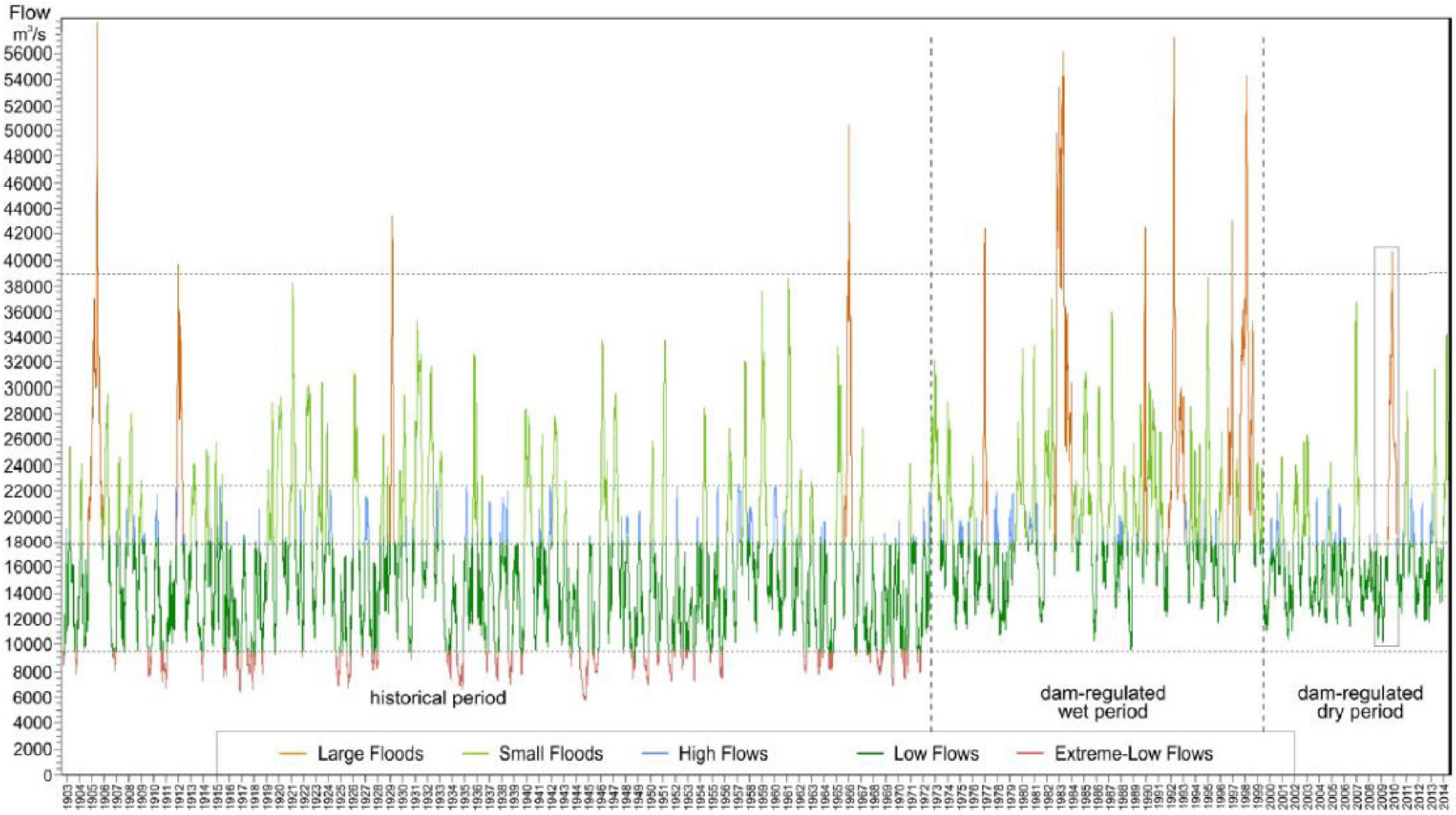


**2.2.9**

Zoning of the delta near Zarate. Image by authors

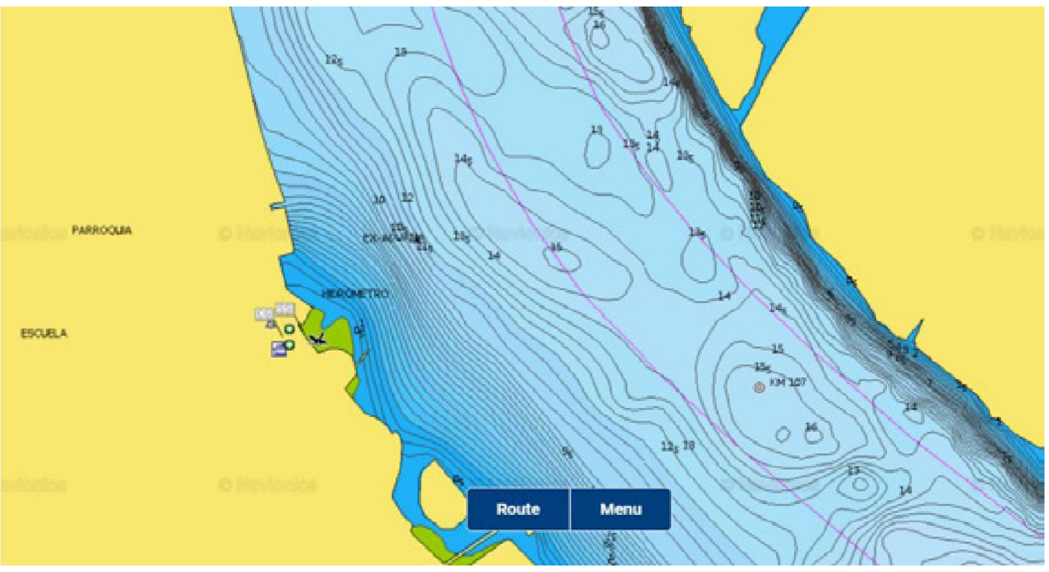
**2.2.10**

Flow discharge data at Zarate (Puig, Salinas & Borus, 2016). This graph is used to make an estimation of average flow discharge, design discharge and return period.



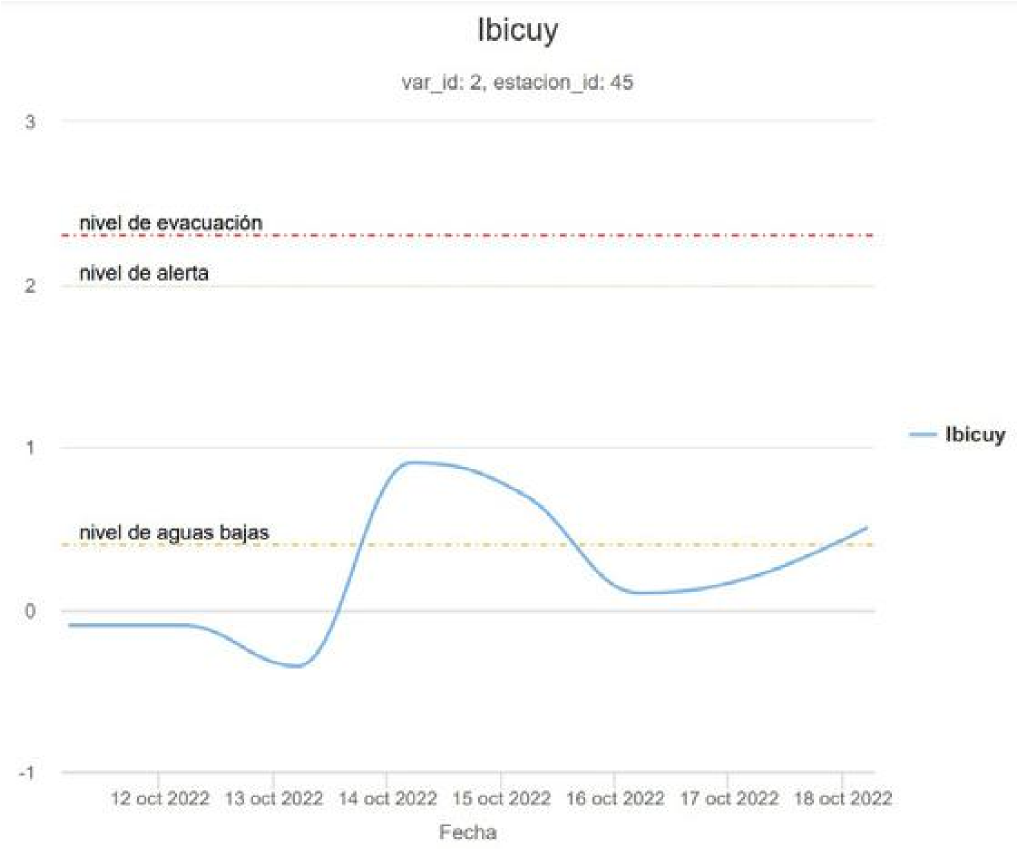
### 2.2.11

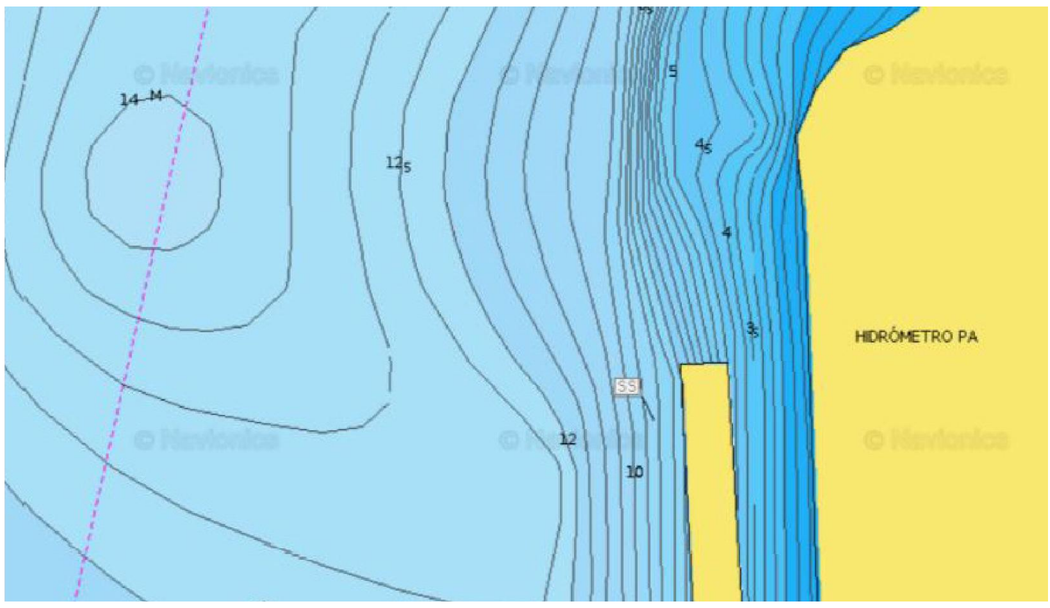
Water depth distribution in the Parana de las Palmas near the city of Zarate (retrieved from ina.gob.ar).



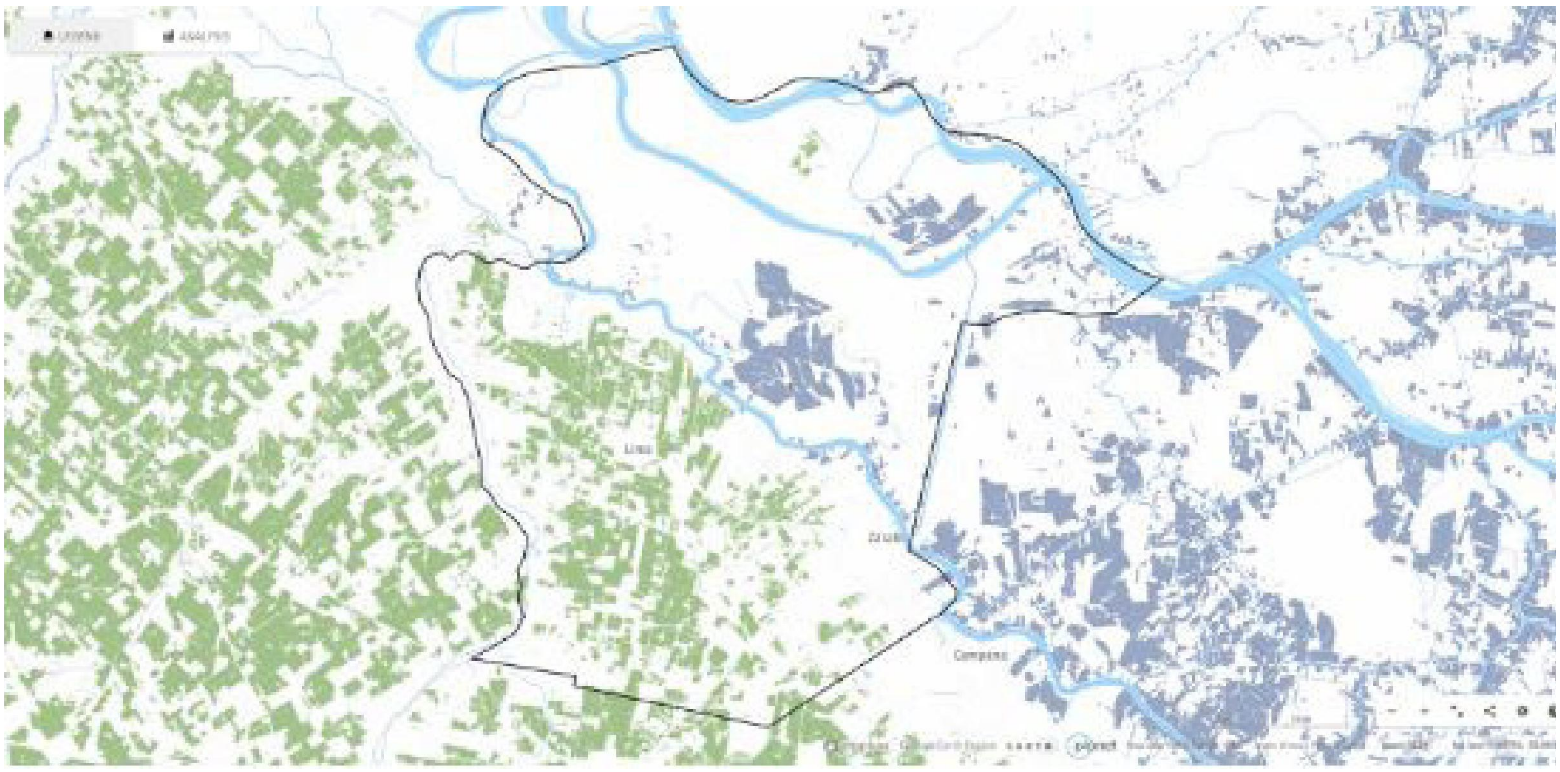
### 2.2.12

The figures show water level and water depth in a part of the river Parana Guazu and it will be a condition for further design calculations for the gates that lead towards the reservoir. The design level for extreme weather conditions is found to be the same as for the Parana de las Palmas, we can assume these levels are constant throughout the delta (retrieved from ina.gob.ar).



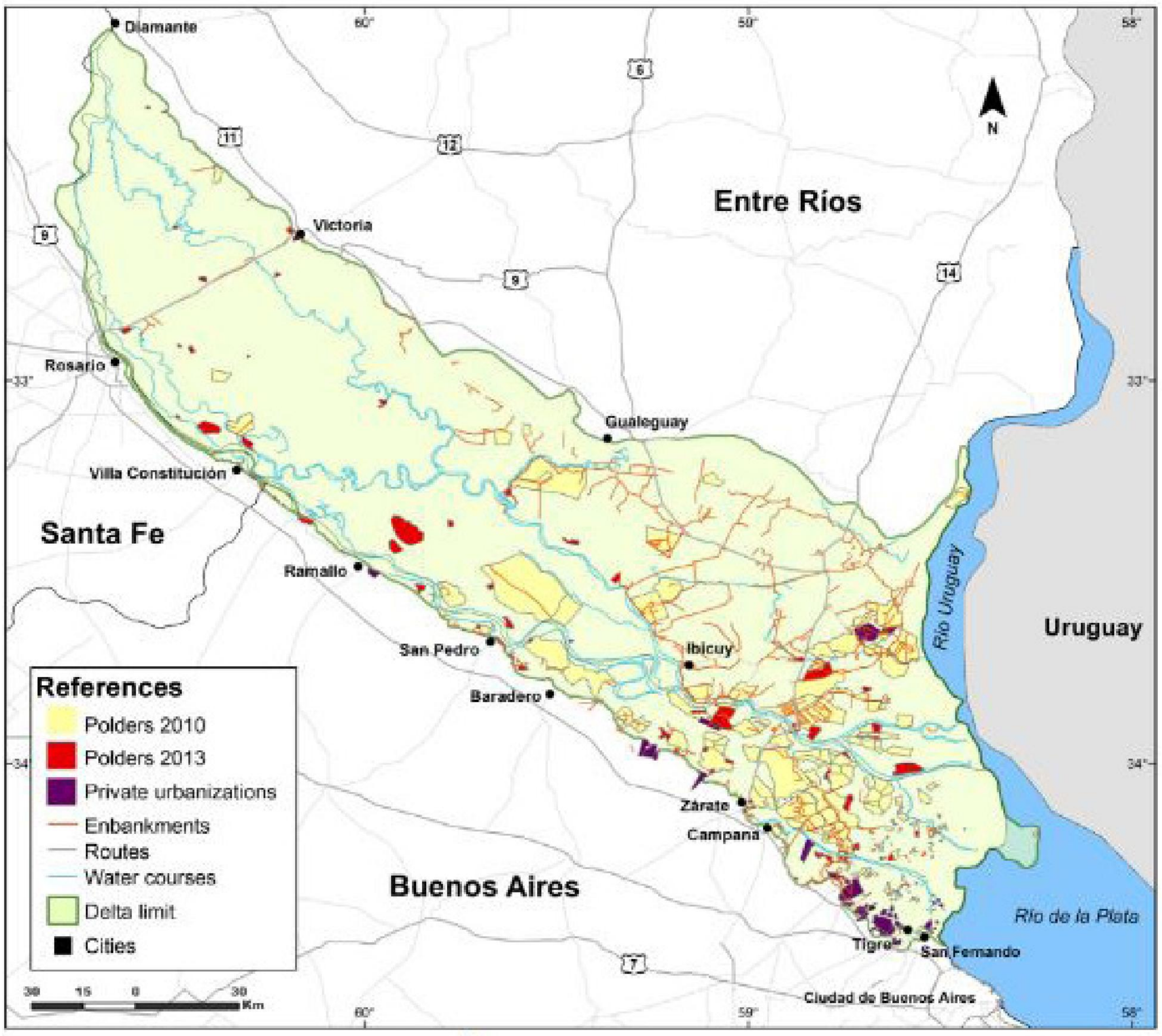


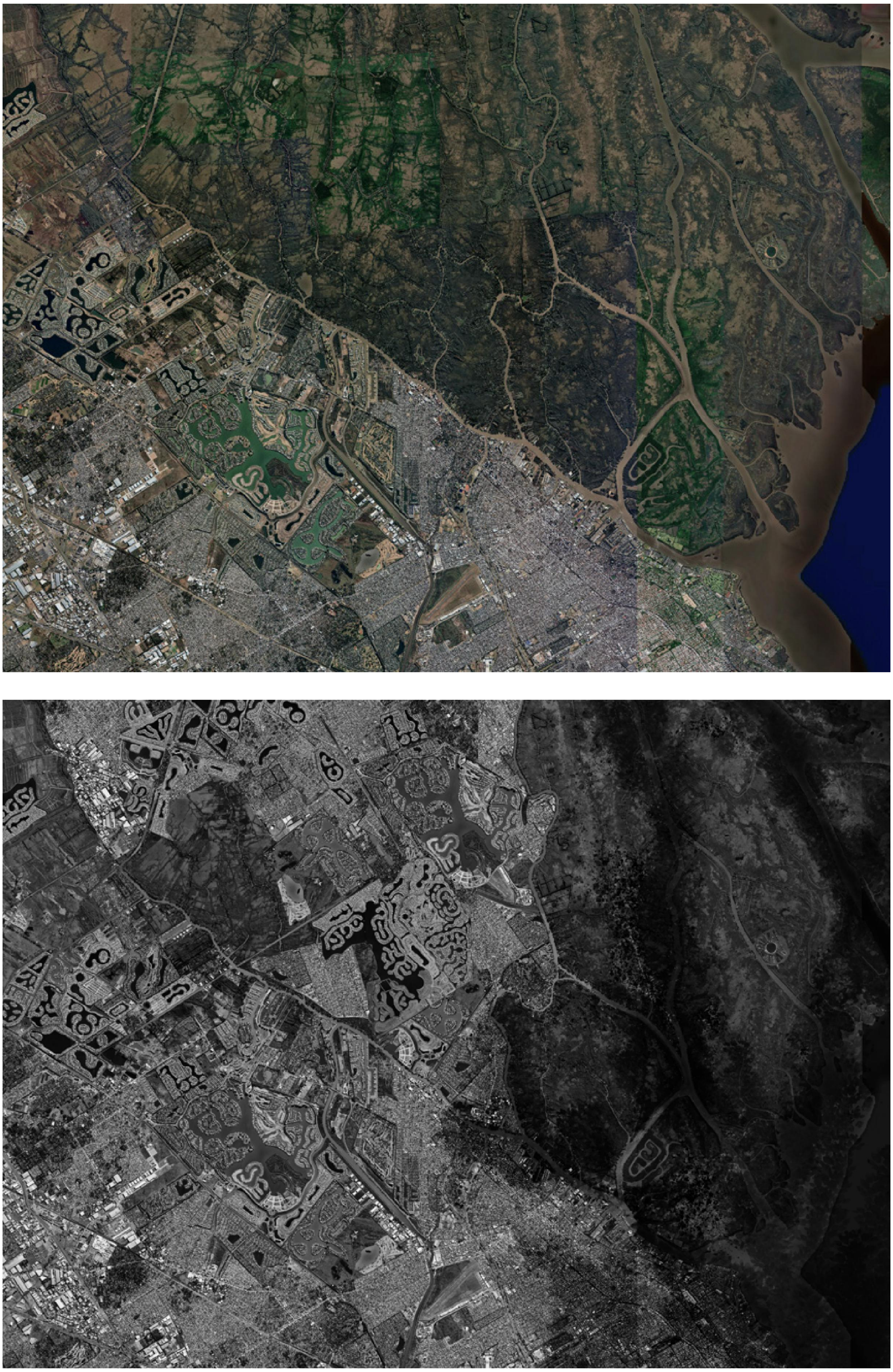
**2.2.13**
Pumps at the poldered forestry area of Zarate, photographed by authors during field trip, summer 2022



**2.2.14**
Global Forest Watch. “Plantations in Zárate, Buenos Aires, Argentina”. Accessed on 26/10/2022 from www.globalforestwatch.org; Song et. al. 2021. “Soy Planted Area”. Accessed through Global Forest Watch on 26/10/2022; “In Zárate, wood fiber / timber represent the largest plantation area by type, spanning 6.59kha and 5.4% of land area.”

**2.2.15**
Map of polders





**2.3.1**
Current state of the delta in 2022 and a "worst-case scenario" of Tigre, if poldered development that is currently overtaking many marshlands continues unbated. Developed by authors from Google Earth

**2.3.2**

Current state of the delta in 2022 and a "worst-case scenario" of Zarate, if agriculture continues to expand into the delta. Developed by authors from Google Earth

## 03 // PROPOSITION

### .1 Vision

The challenges to climate adaptation facing the delta are overwhelming. As soon as one issue begins to be addressed, many more unforeseen challenges pop up. It is clear the region must make big decisions in a relatively short time in order to prevent the worst effects of a warming climate and an urbanizing territory. Not everything can be saved, in fact, in a kind of triage, direct and strategic action must be implemented. The most easy course of action might be the ability for local and national governments to set aside currently less than used (anthropocentrically-oriented) land to provide space for ecological systems that are otherwise confined by human activity, in turn enhancing resilience and promoting biodiversity (Ahern, 2011). Governments and policies must prioritize long term solutions over quick ones. In the end, everything is connected and a systems analysis approach is essential for future development.

Land use patterns in the delta and on the continent often ignore the local hydrological conditions. In order to successfully (re)integrate ecological flows into the city and delta, hydrological considerations must form the basis of any intervention (McHarg, 1969; Nijhuis, 2022). In order to critically identify spaces where the most can be achieved with the least, the conceptual and design lens of ‘interstitial space’ is applied to strategically locate proposed interventions. In lesser populated places, wetlands, forest, grassland and cropland are used; in urban settings parking lots, housing complexes, underpasses and abandoned lots. Essentially any land use pattern can host more ecological and hydrological processes.

Because the conditions of the delta are unpredictable and prone to extreme hydrological events, further changes in the climate will exacerbate already difficult scenarios (IPCC, 2022). In essence, the region must be prepared to accommodate periods of flood and drought, simultaneously. By 2150, the mean sea level in the Rio de la Plata will have increased by between two and three meters. Combined with a drastic *sudestada* event that level rises to over five meters, placing many parts of the city underwater. At the same time southern Brazil and northern Argentina continue to experience record drought. To cope with such varied extremes, a series of strategies that implement resilience measures within a hybrid approach are proposed that can increase the overall ‘sponge capacity’ of the territory, consequently improving the ability to withstand episodes of flood and drought.

Hybrid engineering systems can provide redundancy and enhance overall resilience across the region. Rather than rely solely on traditional (gray) infrastructure, the strategy aims to implement nature-based solutions that work in tandem with existing and planned gray systems, to achieve optimal results through the incorporation of ecosystem services and design with nature principles (McHarg, 1969). Through a series of context specific interventions that address the hydrological issues within the delta, ecologies (and hydrologies), that are currently under threat from the dominance of anthropocentric models currently in place, can be positively reinforced with hybrid infrastructures.

Future urbanization is subject to policies and market realities that we can not predict. For this reason, we do not plan the future of the city, rather we plan where the city is not. Integrating hybrid infrastructures into ugly, unwanted spots can transform them into vibrant, flourishing ecosystems. The perceived patchiness at the beginning will eventually yield to a robust mosaic (Forman, 1995) of interwoven, eco- and hydrologically designed network of systems. This is a territorial approach that encourages redundancies, as opposed to traditional linear systems. It takes clues from its context; it displaces no one.

### .2 Theoretical Framework

Land burdened by decades of adherence to a market logic based on exponential growth on a finite planet has resulted in fragmentation, isolation, incongruity and mass extinction (Monbiot, 2021). Throughout the delta region empty lots, abandoned rails, car parks, awkward strips between box stores along highways, neglected streams, polluted rivers and the streets themselves present ample opportunity to foster the complexity of life within (un)built form. These are the interstices, the spaces between one destination and another, overlooked, undervalued, ripe for transformation.

The interstice is where life happens. It’s where the sediment accrues in the corners; it’s the goop, the smelly processes that permit the evolution of life forms in all their messy entangled, interwoven ways. As a space of *involution* it “offers a way to story the ongoing, improvised, experimental encounters that take shape when beings as different as plants and people involve themselves in one another’s lives” (Hustak & Myers, 2012 as cited in Myers, 2017). If modernity was the attempt to control the various ecological processes, design in the 'New Climatic Regime' (Latour, 2017) is about surrendering to them, observing, and harnessing the nonlinearity of their various covert and not-immediately-comprehensible processes. It's about embracing the process rather than the end result. There is no end, only continuation, change, in-/evolution. An ecosystem is never finished, our built environment should take such clues.

While Koolhaas derides these spaces as the undesirable junk of modernity (2002), Berger gets it right: "In the urbanized world, the In-between landscape should be valued because it provides a threshold, or platform, for liminal cultural phenomena to play out" (Berger, 2006).

Utilizing interstitial space is a critical lens by which we must design future urbanism. Its objective: densify and diversify; its antithesis: destruction and displacement. Interstitial space integrates objects and processes into the existing context, making use of what is already there, locating potential connections and prioritizing symbiotic relationships over exploitative ones. This is the post-car city, the post-cow agriculture.

Perpendicular to the main axis of the Parana River, urban streams serve as intervals of urbanization. As urban agglomerations grow into one continuous megaregion, hydrology sets the pace and defines the positive. If buildings are the black of a figure ground, hydrology is the white of everything in between. Like a Casco concept (Sijmons, 1991), we design the Not City, the buffer zones where life happens, unobstructed by human processes. Like urban acupuncture, the interstitial corridors transfer nutrients and sediment, penetrating the city, creating porosity in plan and infiltration in section. Inhabiting a terraqueous world, acupuncture becomes *aquapuncture*: Aquapuncture in the interstices.

## .3 Strategy

In order to preserve the delta, interventions must first occur on the continent, where much of the varied negative anthropic land use patterns that are now beginning to proliferate within the delta originate. As the Anthropocene progresses and the climate destabilizes, it is clear that infrastructure developed in the nineteenth and twentieth centuries will not suffice in the twenty-first.

Interstitial Aquaculture works with the myriad flows of the territory — nutrients, sediment, wind, rain, nonhuman organisms and all their affiliated functions — that impact and contribute to a healthy ecosystem. It then attempts to reconcile the anthropogenic processes unfurled by humans onto landscapes that all too often dominate and overwhelm natural ecologies. 'Nature' is not being restored, rather ecologies are being adapted from those that have operated under extractive modalities, or agrilogistics, as preferred by Morton (2016), to modes that support symbiosis and regeneration.

Interventions can be deployed across scale to form a resilient megaregion, adequately prepared to adapt to climate change over the coming decades. However, it can also function at a micro scale, along one river or even a section of that river. As the connected patches proliferate, enhanced resilience follows.

The strategy unfolds through three principle designs:

1. **Riparian edge**s are planted in underutilized spaces along waterways like the Reconquista-Lujan and Riachuelo-Matanza. Streams like the Maldonado, Viga, and Ugarteche all run under existing streets, and must be uncovered in critical locations. This will in turn catalyze a larger transformation of street use within the city, transitioning Buenos Aires from a car-centric, congested metropolis to one that favors the pedestrian. Streets become the green corridors, streams, the blue, each functioning as crosstown conduits for species migration on wheels, feet, wings or fins.

2. At the mouth of each stream and river, depending on the topography of the location, the waters will flow into a **marsh-dike** where sediment from the Parana and its tributaries build out resilient ecosystems for birds, amphibians and fish, overtime creating effective flood defense for the future rising seas. Not all areas will be immune to flooding: we strategically designate protected areas behind a dike from those that will be given over to marshland. Dredged materials from the main shipping channel in the Parana can be applied to the marsh-dike to accelerate sedimentation along the coast.

3. Existing polders within the delta are to be transformed into water **reservoir**s which become a strategic mitigation method against drought around Zarate and other poldered areas. As much as possible, the delta's ecosystem integrity is to be preserved; human interventions with negative effects are to be undone. In the lower patches of the continent, reservoirs serve as both detention and retention basins, depending on a flood or drought event.

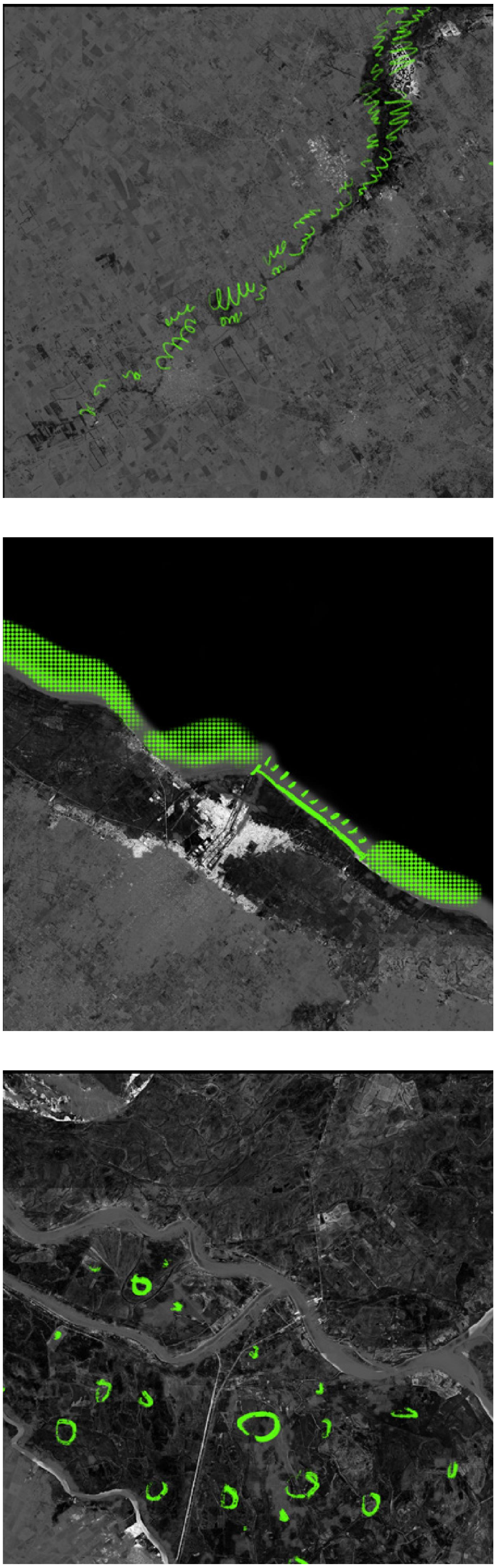
These designs are detailed in the following section.

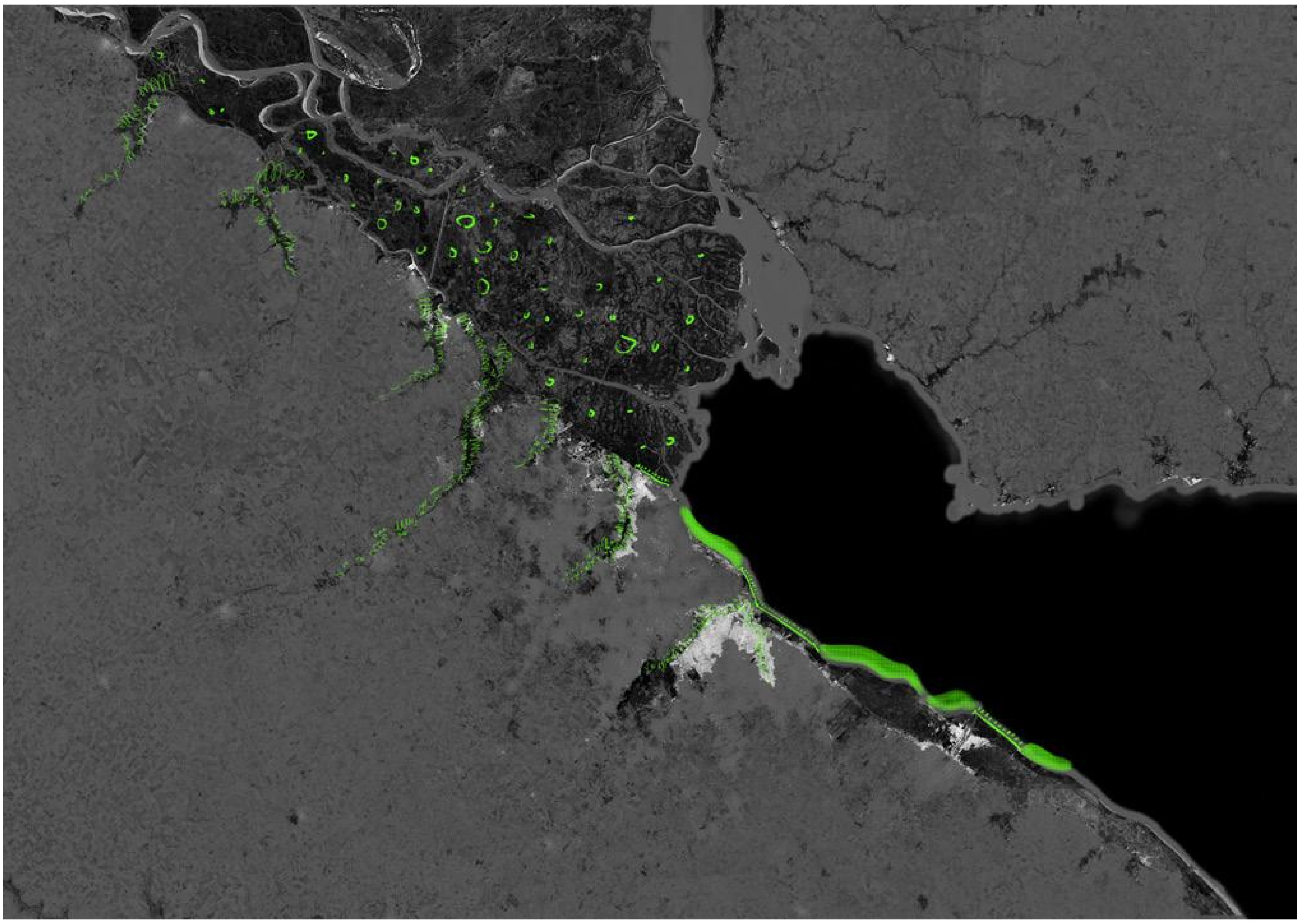
**3.1.1**

Interstitial Space! Image by authors.

**3.3.1**

Proposed strategies: the riparian edge, the marsh-dike and the reservoir. Image by authors





**3.3.2**

Interstitial Aquapuncture. The delta penetrates the continent, filling it up with viscous, sinewy substances. A thousand appendages meander the contours. Like tentacles wiggling, thick excretions flow in and out their infundibula. Sediment and seed, cycles of giving and receiving, yield fertile grounds. The proliferation of multispecies diversity, fecund, pungent, entangled. Image by author

## .1 Riparian Edge

A riparian zone or edge is a space located along the margins of rivers and streams [**FIGURE 4.1.1**]. It hosts unique species along its corridor and functions as a buffer zone between water bodies and the surrounding land typologies, reintroducing gradient transitions. In the Pampas, in both agricultural and urban patches, existing riparian edges can be strengthened and new ones can be integrated into interstitial spaces along healthy and polluted waterways. Within patches where soil pollution from agriculture or industry is of concern, the riparian edge can be planted with specific plant species that will remediate the soil and filter out toxins from runoff before entering waterways, preventing eutrophication. The riparian edges will then have a cleansing effect for chloride and nitric acid ions, which is relevant to counter the water pollution in the rivers and streams (Anbumozhi et al., 2005). The necessary buffer width to protect different species varies, but a width of 330 feet could benefit small mammals and 150 feet already benefits certain fish species (Hawes & Smith, 2005). In urban and rural settings, given the proper conditions, the riparian edge can be a strategic site of harvest of edible and workable plant species.

Sub zones within the riparian edge can be further delineated. Closest to the water's edge, clusters of amphibious vegetation are the interface between land and water, where shallow waters serve as respite for migrating birds. Moving inland, small shrubs appear, followed by the riparian forest. Because the Pampas is native grassland, afforestation would not be suitable across the region, however within the riparian edge, tree growth occurs naturally. Within this strip, agroforestry methods can be planted in the form of food forests, reintegrating native species, making use of the natural biome, and increasing overall soil integrity (Barrios et al., 2012).

Moving beyond the trees, shrubs and grasses appear upland before merging into cropland. At the moment the fossil-intensive monocultures present in the Pampas are detrimental to the overall health of the ecosystem. Farmers and researchers in Iowa have begun to experiment with 'strip prairies' [**FIGURE 4.1.2**] that reintroduce native grassland typologies along the edge of monocultures like maize and soybean. Results have demonstrated that these strips can "reduce erosion and nutrient loss from soil and support birds and insects" as well as absorb nitrogen runoff from fertilizer and store carbon (Moore, 2021).

In cities and urban developments on the continent, the riparian edge offers other solutions. The Riachuelo-Matanza and Reconquista-Lujan, heavily polluted, would benefit most from the phytoremediation capabilities of the vegetation within strategically located river sections. The Maldonado Stream in Buenos Aires city center is not currently, in fact, a stream. The city covered and canalized it in the 1930s [**FIGURE 4.1.3**]. Since then, it has operated mainly as a stormwater drainage canal. Other streams like the Viga and Ugarteche share the same history. In our overall approach to work with and value the hydrological regimes of the delta and the city, the opportunity to uncover these formerly free-flowing streams reintroduces ecological flows into dense urban areas. The riparian edge filters chemical pollutants in water through phytoremediation and can "provide many ecological functions and services as biological corridors and buffer zones to retain pollutants that may enter from urban runoff while mitigating flooding" (Gomez et al., 2020).

Plastic pollution is a serious concern along these urban streams and rivers, thus part of the remedial technique will implement filters that collect this debris before it enters into the marshland downstream. Gates that have been put in place as flood defense during *sudestada* events will double as filtration devices. Ideally, waste management within urban centers will improve over time so pollution will not enter the rivers and streams at all, however as the region continues to confront such challenges, this remains a necessary strategy.

Uncovered streams will not be entirely reconverted to a 'pristine' or 'natural' state; the density of the city surrounding them prevents this. Rather, there will be pointed locations in which restoration occurs, softening edges and reintroducing native vegetation, which in turn will serve as habitat for native fauna. For human residents of the city, these spaces will increase much needed access to green space, improving overall living conditions. Finally, these streams will eventually flow into and connect with the marsh-dike, detailed in the next section.

## .2 Marsh-Dike

### A highly dynamic environment: Nature, navigation and dredging

Sea level rise, as projected for 2150, combined with a substantial Sudestada event could result in waters as high as 5.4 meters above 2022 levels. More effective flood defense solutions are clearly necessary in the metropolitan area. According to the simulation presented in **FIGURE 4.2.1**, the most dramatically impacted areas are in the municipality of Tigre, along the Reconquista River, and in the municipality of Buenos Aires, along the Riachuelo-Matanza River. The high demographic density of these areas aggravates the flood scenarios. Apart from these two very threatened areas, the simulation also shows a continuous "strip" of flooding along the city center's riverfront. Currently much of this area consists of open space and parkland, the domestic airport terminal and some light industry. Due to the lower human density of the area this strip is regarded as less severely impacted.

Since each stretch of coastline has specific characteristics, different solutions are advised by the group. Building upon the design workshops that happened in Buenos Aires and at the Faculty of Architecture of the TU Delft, a hybrid solution between green and gray infrastructure is proposed [**SEE SECTION 1.3 METHODOLOGY**]. That would consist of a coastal flood defense that is closer to a standard engineering solution, as a dike, in the most threatened areas (Reconquista and Riachuelo-Matanza Rivers), and an ecology-based solution, a constructed marshland, along the less threatened riverfront areas.

There is a very significant characteristic of this area that facilitates these design proposals. The Parana River is not only a body of water, it is also the most significant navigation route in the continent: it is referred to as "South America's Super Grain Hydroway." However, its turbid waters make dredging a constant maintenance need to keep the channel navigable; Last year alone more than 2,692,600m$^3$ of soil was removed in just the Parana de las Palmas, the lowermost, final stretch of the hydroway. A dredging scheme could be put in practice, where strategic soil disposal sites are thought to be in accordance with the proposed flood defense infrastructures [**FIGURE 4.2.2**].

The most downstream part of the Paraná river (de Las Palmas) has a positive bottom slope. This is due to high sedimentation rates and means that the average bed level rises as the flow approaches the estuary. The bed level further from the estuary (~40 km) is rather uniform, whereas after 50 km it starts sloping upward with a slope in the order of 10-4. Currently, dredging activities are counteracting the effects of sedimentation, but only in the 150 m main navigation channel approaching Isla Lucha (Leon, 2022). The small Luján river which flows through Tigres forms the natural border between the delta and the urbanized area. Within the boundaries of the interest area around Tigres, i.e. downstream of the junction between man made canal Gobernador Arias and the Luján river, the average bed levels are around -3m to -5m + IGN, with a thalweg slope of approximately 10-4. According to numerical simulations by Leon (2022), if no dredging is performed or no new canals are excavated, the Paraná de las Palmas bed increases and the artificial channel bed levels become 2 m + IGN (Leon, 2022).

Keeping the Paraná de las Palmas at the required depth to permit navigation is crucial. Comparing two simulations by Leon (2022) [**FIGURE 4.2.3 + 4.2.4**] a sedimentation pattern is observed on the south side of the Paraná de las Palmas and on the north side a more erosive pattern. However, with newly excavation channels like the Canal Gobernador Arias and La Serna [**FIGURE 4.2.5**] this sedimentation pattern on the southern side is decreased.

In **FIGURE 4.2.2**, gray lines indicate current navigation routes, and the red ones indicate navigation routes that should be improved or reinforced. The gray crosses indicate current disposal sites, and the red ones indicate proposed locations in order to use the material in construction of flood defense infrastructure. The volume that can be applied for construction is estimated by first determining the new navigation depth (see Formula 1), to then make an estimate with a project calculator [**SEE APPENDIX B**] which will be mentioned later in this section. The dredged material generally corresponds to the soil composition of these channels, which stand for approximately 50% of silt, 30% of clay and 20% of sand. A challenge the dredging scheme might face is the fact that this soil might be contaminated. According to Ronco et al. (2016), a study in the chemical composition of several rivers in the region shows above-average levels of pollution (the Luján river has a concentration of over 3000 µg/kg of glyphosate and 5000 µg/kg of AMPA), which can be explained by the fact that these rivers cross many populous urban areas before reaching the delta. Nevertheless, the dredged material could still be used for building the dike or the marshlands, if it could be filtered.

The design dredging depth based on future simulations is estimated according to the biggest vessel that has to pass Paraná de las Palmas. The New design with Kvaerner-Moss has a capacity of 125'000m$^3$, a LOA of 270 m, B of 43 m and D of 11.7m. With this information a first estimate can be made (van Koningsveld et al., 2021).

[**FORMULA 1**]

$$d = D_s - T^2 + s_{max} + r + m + projection$$

$$d = 11.7 - 0.5^2 + 0.5 + \frac{1.14}{2} + 0.3 + 1$$

$$d \approx 13.82\, m$$

With $D_s$ the draught of the design vessel at rest, T the tidal restriction, $s_{max}$ the squat, r the response to waves, m the safety margin i.e. the minimum under keel clearance and finally the $projection$ based on futuristic scenarios. The corresponding unit of every parameter is meter. As a rule of thumb, the squat is 0.5 m and the response to waves is half of the significant wave height. For a soft silty bottom the minimum under keel clearance is 0.3 m. T is dependent on the tides and the differences between low water and high water, according to water level measurements of Leon (2022), this value is estimated to be 0.5. The tides change relatively fast in the Delta.

Concluding, the navigation depth estimate is 13.82 m. Assuming the projections in previous sections, the new dredging volume of the Luiján River and Paraná de las Palmas is 4,500,000 m$^3$ [**SEE APPENDIX B**]. As a reference, the total dredged volume of 2,692,600m$^3$ ensured navigation waterways in the Rio Paraná de las Palmas in 2019. The significantly larger new volume indicates that dredging efforts will be very costly and the estimate can also be applied to determine the economic feasibility of the dredging efforts. Note that dredging, more specifically deepening, has an influence on various aspects like sediment transport capacity and flow partitioning, which are not considered in this report but are relevant.

Ideally, the flood defense infrastructure should be enriched with other values. It could be able not only to protect inhabitants against sporadic flood events, but to offer opportunities for different species, especially because of its large dimensions and its impact on the landscape. Therefore, we aim at multi-purpose infrastructures that can act as the backbone for new practices and values in the territory.

The 5-meter high dike could be a landscape of cultural relevance, of metropolitan significance. As a public promenade, it can offer opportunities for leisure, recreation, sports and the improvement of public health. It can be seen as an axis along which spaces for different activities are distributed, such as sports courts that can act as detention reservoirs (multi-functional spaces). Retention spaces behind the dike are advised because there is always the risk of overtopping and because there are urban streams flowing towards it, which can be managed with gates that can be opened and closed but could still use a buffer space in case of mismanagement. A possible location for the marsh-dike is suggested in **FIGURE 4.2.6.**

A dike design is discussed according to Dutch standards for classic 'gray' infrastructures, but also nature-based solutions are proposed as an alternative. Boundary conditions for the hydraulic system can be found in **APPENDIX A.**

Design Method 1

Firstly, the principal equation to determine a maximum value of the overtopping discharge in the European Overtopping Manual 2018 is implemented. Overtopping is a common and often prominent failure mechanism in dike constructions.

[**FORMULA 2**]

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = a \cdot e^{-\left(\frac{b\, R_c}{H_{m0}}\right)^{1.3}}$$

With:

$$a = \frac{0.026}{\sqrt{tan\alpha}} \gamma_b \cdot \varepsilon_{m-1,0}$$

$$b = \frac{2.5}{\varepsilon_{m-1,0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta}$$

With:

| | |
|---|---|
| $q$ | overtopping discharge $[m^3/s/m]$ |
| g | gravitational constant $[Nm^2/kg^2]$ |
| $H_{m0}$ | estimate of significant wave height from spectral analysis [m] |
| $R_c$ | overtopping height [m] |
| $\varepsilon_{m-1,0}$ | breaker parameter [-] |
| tan α | berm slope[-] |
| $\gamma_b$ | influence factor for a berm [-] |
| $\gamma_f$ | influence factor for the permeability and roughness of the slope [-] |
| $\gamma_\beta$ | factor for oblique wave attack [-] |

The parameters are mostly chosen according to statistical data of the Río de la Plata, ignoring the standard deviations as a first semi-probabilistic estimation for the design. The breaker parameter (see Formula below) is greatly dependent on the slope of the outer berm. The mean and maximum significant wave height are 1.14 m and 4.89 m respectively. Analogically with a period of 5.4 s and 10.4 s (Martin et al., 2012).

**[FORMULA 3]**

$$\varepsilon_{m-1,0} = \frac{tan\alpha}{\sqrt{H_{m0}/L_{m-1,0}}}$$

$$\varepsilon_{m-1,0} = \frac{1/3}{\sqrt{1.14/45.52}} = 2.11$$

With the deep water wavelength being $L_{m-1,0}$:

$$L_{m-1,0} = \frac{g \cdot T_{m-1,0}^2}{2\pi} = \frac{9.81 \cdot 5.4^2}{2\pi} = 45.52\,m$$

With:

$T_{m-1,0}$ wave period calculated with $m - 1/m_0$, in which m is the moment of the energy density spectrum
[s]

The factor taking the influence of the berm into account is determined based on the formula below.

**[FORMULA 4]**

$$\gamma_b = 1 - \frac{B_B}{L_B}[0.5 + 0.5\cos\left(\frac{\pi h_B}{x}\right)]$$

$$\gamma_b = 1 - \frac{5}{11.84}\left[0.5 + 0.5\cos\left(\frac{\pi \cdot 0}{x}\right)\right] = 0.57$$

With $B_B$ as the berm width, $L_B$ as the influence length of the berm, $h_B$ the water depth above the berm being and $x$ being the influence height of the berm. $X$ is $R_{2\%}$ if the berm is above SWL and $x$ is 2 $2H_B$ if the berm is at or below SWL. The berm at storm surge level is most efficient, the optimal width of the berm in this case would be $B_B \approx 0.4L_B$ and also $B_B < 0.25L_{wave}$. From previously stated bottom levels, average water level heights and storm surges the design storm surge level and berm is located at +3.93 m + IGN (d'Onofrio et al., 2008).

**[FORMULA 5]**

$$\gamma_\beta = 1 - 0.0033\,|\beta|\ for\ 0° \le \beta \le 80°$$

$$\gamma_\beta = 0.736\ for\ \beta > 80°$$

The factor taking the permeability and roughness of the outer slope into account concrete blocks or block mats is $\gamma_f = 0.95$. For a different surface of the outer slope, like cubes in random order, the factor could reduce drastically to 0.5 or even smaller. The factor for oblique wave attack is determined by Formula above. β is the angle between the direction of propagation of waves and the axis perpendicular to the structure. The mean observed wave direction is $153^{\circ}$, which relates to the south-easterly direction as the most frequent direction of wave propagation. This means that $\gamma_\beta = 0.736$, according to the formula above. Substituting the values in previously stated Formulas gives:

**[FORMULA 6]**

$$a = \frac{0.026}{\sqrt{tan1/3}} \cdot 0.57 \cdot 2.11 = 0.054$$

$$b = \frac{2.5}{2.11 \cdot 0.57 \cdot 0.95 \cdot 0.736} = 2.938$$

$$\frac{q}{\sqrt{9.81 \cdot 1.14^3}} = 0.054 \cdot e^{-\left(\frac{2.973 \cdot 1.72}{1.14}\right)^{1.3}} \overset{\square}{\Leftrightarrow} q = 2.01 \times 10^{-4}\ \mathrm{l/s/m}$$

In conclusion, after iteration with smaller freeboards, the freeboard of 1.72 m (dike height minus design water level, including sea level rise) proves to be a safe value. The overtopping discharge is close to zero and suffices for a safe dike design.

Design Method 2

Note that if the area behind the dike is adaptable to certain overtopping discharges, the freeboard could be lowered. A maximum allowable overtopping discharge between 1-10 l/s/m results in no damage to the crest and rear face if the embankment is composed of clay and grass covered. Typically, a storm passes in less than an hour. If the overtopping discharge reaches 10 l/s/m, the total volume in the retention area behind the dike is 720,000m$^3$. This means that the total area behind the dike, assuming a dike of 20 km covering vulnerable parts of Buenos Aires, should be at least 103,000m$^2$ (~15 football fields) to withstand a storm with overtopping discharge 10 l/s/m before the area behind the dike is completely filled up and fails. Additional to the ultimate limit state, the serviceability limit state within these limits is agreeable if the area behind the dike is adapted to the expectancy of getting wet. Building structure elements can withstand the overtopping consequences around a discharge of 1 l/s/m (European Overtopping Manual, 2007). In this context in the next sub-section, a minimal freeboard is calculated when the maximum allowable discharge is assumed to be 1 l/s/m.

Freeboard

The design equation for overtopping height according to the European Overtopping Manual 2018 is displayed in formula 7:

[**FORMULA 7**]

$$R_c = \frac{\varepsilon_{m-1,0} \cdot H_{m0} \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_b}{2.5} \cdot \{-\ln(\frac{q\sqrt{tan\alpha}}{\sqrt{g \cdot H_{m0}^3 \cdot 0.026 \cdot \gamma_b \cdot \varepsilon_{m-1,0}}}))\}^{1/1.3}$$

$$R_c = \frac{2.11 \cdot 1.14 \cdot 0.95 \cdot 0.736 \cdot 0.57}{2.5} \cdot \{-\ln(\frac{1 \cdot \sqrt{tan1/3}}{\sqrt{9.81 \cdot 1.14^3} \cdot 0.026 \cdot 0.57 \cdot 2.11}))\}^{1/1.3}$$

$$R_c = 0.55 \text{ m}$$

With a minimum of:

$$R_c > \frac{H_{m0} \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma^*}{1.35} \cdot \{-\ln(\frac{q}{\sqrt{g \cdot H_{m0}^3} \cdot 0.1035}))\}^{1/1.3}$$

$$R_c > \frac{1.14 \cdot 0.95 \cdot 0.736 \cdot 0.57}{1.35} \cdot \{-\ln(\frac{1}{\sqrt{9.81 \cdot 1.14^3} \cdot 0.1035}))\}^{1/1.3}$$

$$R_c > 0.318 \text{ m}$$

In conclusion, the freeboard has to be minimal 1.55 m (including sea level rise) if the design is based on the maximum allowable q. Since the result only differentiates 20 cm from the result in design method 1, a freeboard of 1.72 is chosen. The choice of q is dependent on the hazard type of the area. The dike is assumed to be protected by a rear face of grass covered embankment of clay, so no damage will come to the crest and rear when the maximum overtopping discharge according to the ULS is assumed to be 1 l/s/m. Pedestrians can still use the recreational area behind the structure within reasonable limits, but there is a probability to get wet. For Tigres the presence of port facilities, small to moderate vessels and the safety of residents and pedestrians are the dominant factors to limit the maximal overtopping discharge.

### Hydrological Properties, Microstability and Macrostability

*Hydrological Properties*

Before the preliminary dike design can be subjected to safety checks regarding the ultimate limit state, some properties are determined, like the piezometric height and the exit gradient.

[**FORMULA 8**]

$$\varphi_{exit} = h_p + \beta(h - h_p) \approx 1.1 + 0.4(3.93 - 1.1) \approx 2.232$$

With:

| | |
|---|---|
| $\varphi_{exit}$ | potential at exit point [m] |
| $h_p$ | piezometric height inland [m] |
| β | damping factor [-] |
| h | river water depth [m] |

The piezometric height in the hinterland is equal to the HWL (1.1 m + IGN), the design water level (3.93 m +IGN). The damping factor is dependent on extent and permeability of the levee, foreshore and the blankets. Since the foreshore is long, the damping factor will be relatively low i.e. $\beta = 0.4$. Thus, the potential at the exit point is approximately equal to 2.

[**FORMULA 9**]

$$i = \frac{(\varphi_{exit} - h_p)}{d} \approx \frac{2.232 - 1.1}{2} \approx 0.57$$

With:

| | |
|---|---|
| $i$ | exit gradient [-] |
| d | depth aquitard [m] |

Below ground level, larger than a depth of 2, salinized sandy soils are present (Milione et al., 2020). The exit gradient is defined as the gradient in the blanket at the exit point. This parameter is heavily dependent on the thickness of the aquitard, which is assumed to be at least 2 m but has to be artificially supported if the natural soil doesn't provide a homogeneous, naturally occurring aquitard, which is likely in the case of the land-river interface at Tigres.

*Microstability*

In order for the dike design to be resistant to microstability, three sub-mechanisms are relevant: Heave, uplift and piping. In theory, since microstability is a parallel failure mechanism, consequently only one needs to suffice the ULS unity check.

Heave: The limit state for heave is determined by the ratio of the critical gradient and the exit gradient.

[**FORMULA 10**]

$$FoS = \frac{i_{c,h}}{i} \approx \frac{0.99}{0.57} \approx 1.73 \geq 1$$

With:

| | |
|---|---|
| $i_{c,h}$ | critical gradient [-] |

With the critical gradient being:

[**FORMULA 11**]

$$i_{c,h} \approx 1.65(1 - 0.4) \approx 0.99$$

The porosity ( is based on natural soil data between grain sizes of 0 and 10 cm in Argiudolls (large grouping of Mollisols, soils of grassland ecosystems). Note that in heavily cultivated areas, the porosity drops significantly, which would be beneficial in preventing heave (Alvarez et al., 2018). The soil is mainly based on silt and sand, so a volumetric weight of 26 $kN/m^3$ is safe to assume. According to the assumptions made, heave suffices the design criterium (see Formula above).

Uplift: The uplift is mostly common in situations where there is a very high pressure along a rather thin aquitard. For this reason, the aquitard layer has to be thick enough to not allow uplift. If this holds and the unity check is indeed larger than one, uplift will not occur.

**[FORMULA 12]**

$$FoS = \frac{\Delta\varphi_{c,u}}{\Delta\varphi} \approx \frac{2}{1.132} \approx 1.77 \geq 1$$

With:

$$\Delta\varphi_{c,u} = \frac{d\ (\gamma_{sat} - \gamma_w)}{\gamma_w} \approx \frac{2\ (20 - 10)}{10} \approx 2$$

$$\Delta\varphi_{\square} = \varphi_{exit} - h_p \approx 2.232 - 1.1 \approx 1.132$$

With:

| | |
|---|---|
| $\Delta\varphi_{c,u}$ | critical potential uplift [m] |
| $\Delta\varphi$ | potential difference [m] |
| $\gamma_{sat}$ | saturated volumetric weight $[kN/m^3]$ |
| $\gamma_w$ | volumetric weight of water $[kN/m^3]$ |

Uplift will not be an issue if the blanket height is respected.

Piping: Piping is a common failure mechanism if the subsoil is highly permeable and erodible, although it is also dependent on other parameters. The method of Lane gives a fair estimation of the length of the impermeable layer that is needed to withstand piping. The piping equation by Lane:

**[FORMULA 13]**

$$L \geq \gamma C_L \Delta H$$

$$L \geq 1.5 \cdot 8.5 \cdot 2.83 = 36.41\ m$$

With:

$$L = \frac{1}{3} \cdot\ L_{hor} = \frac{1}{3} \cdot\ 50 = 16.67\ m$$

With

| | |
|---|---|
| L | total seepage [m] |
| $\gamma$ | safety factor [-] |
| $C_L$ | Lane's constant [-] |
| $\Delta H$ | differential head across structure [m] |

The length of the dike without piping screens doesn't suffice. Implementing two piping screens of 5 meters will result in a larger seepage length.

**[FORMULA 14]**

$$L = \frac{1}{3} \cdot\ L_{hor} + 4 \cdot 5 = 36.67\ m$$

The safety factor is set to 1.5 to ensure the design is not underestimated. The constant $C_L$ for a silty/sandy soil profile is 8.5. The head difference of the foreshore and hinterland is 2.83 m. The water levels are based on the tidal levels and ground water levels. Note that the ULS for the piping mechanism is tested on the theory of Bligh and Lane, since Sellmeijer requires more parameters to rely on. The most influential factors of the factor of safety are the design water levels at the foreside and the hinterland. Additionally the thickness of the aquitard is of importance once more and causes the largest uncertainty in the design formula.

Conclusion: All sub mechanisms mentioned in previous sections don't have to satisfy the ultimate limit state. If only one mechanism, i.e. piping is prevented, the overall microstability of the dike satisfies the design requirements (Delft University of Technology, 2022). This means that the design is safe in terms of microstability.

*Macrostability*

Macrostability is a failure mechanism usually caused by sliding and shearing of the soil in a circular slip plane. To test the dike design against this failure mechanism, a model is created with the D-stability software from Deltares and various objects like trees (point loads) and people (distributed loads) are implemented in the model to show it is adaptable to architectural wishes in terms of the use of space.

The inner slope is most vulnerable to macrostability failure when there is high water. At low water however, also the outer slope may be subjected to critical sliding. Both governing design models are given in **APPENDIX C.**

According to the model in D-Stability, the factor of safeties regarding macrostability for the preliminary dike design suffices for different set-ups, i.e. in combination with trees on the inner slope, or large groups of people (10 people per square-meter) on top of the crest.

Conclusion: Dike Cross Section Lay-out and Corresponding Water Levels Differentiating the calculation methods leads to the following: The freeboard based on q being close to zero is chosen to be the design freeboard out of safety considerations and because the difference between design methods was relatively small.

Thus, the final design levels of the dike are schematised in **FIGURE 4.2.7**. The crest level takes the surges, minimal freeboard and sea level rise into account.

Note that the core of the dike is preferably made of sand, while the interfaces between soil, water and air are made of clay. The construction is designed for a service time of one hundred years. From the dike cross section and the estimated length of the dike (approximated by 20 km), and taking into account not all dredged material can be used as building material (so an estimate of only 20% pure sand of the total volume 4'500'000m$^3$), the construction time could take approximately 5 years. From practical examples, a construction time of 10 years is possible if resources are limited, but it should preferably not be exceeded. Preventive maintenance should be done in time spans of a few years. Floating cranes can be used to install the dike, f.e. a crane put on top of a barge.

Simulations show that if the area immediately behind the dike is prepared to receive water, the crest height can be shorter, which creates a more interesting and closer experience between visitors and water. Simulations also show that the safety factor regarding macro stability for the preliminary dike design is good enough to imagine different set-ups, such as adding trees on the inner slope or receiving large groups of people (around 10 people per square meter) on top of the crest.

The rear slope of the dike should be "softened" to facilitate the access from the public promenade to the rear leisure facilities, as seen in **FIGURE 4.2.8 + 4.2.9**. As the promenade along the dike continues, it slowly drifts inland and creates room for a salty marshland, as seen in **FIGURE 4.2.10**.

The main idea of the marshland is to offer an ecology-oriented solution for flood defense in the less sea-level rise threatened area. Diversity in solutions is a key factor for increasing resilience in the area. The marshland is protected from the action of wind and waves by a row of sandy dunes, which can be initially formed by accumulating dredged material and stabilizing it with rocks (at the bottom, where waves collide), and pioneering species, which will lead to natural succession. Over time, the rocks and the vegetation start contributing to dune formation, because they also trap sediments from the water and from the wind. Other mechanisms can be put in place for building and stabilizing the system, such as a Mud Motor or Reef Balls. The basic concept of a mud motor is a machinery system that serves as a semi-continuous source of sediment. It maintains the balance of desired gradients in the development of salt marshes. A mud motor in normal operation conditions generates less recirculation towards the port basins – and consequently less maintenance of dredging, promotes salt marsh growth – creating new ecosystems and protection towards sea level rise, and stabilizes dike foreshores – requiring less maintenance works on the dike rings (U.S. Army Engineer Research and Development Center, 2022).

At the points where the canalized streams reach the marshland system, the water becomes more brackish, being sometimes tide-dominated and sometimes stream-dominated (fresher). Such fluctuations bring new nutrients and sediments into the system. There is a severe issue with pollution at these tributaries coming from the Metropolitan Area of Buenos Aires. Even though there are engineering solutions to filter such polluted water before it reaches the marshland, this issue should preferably be solved along their paths, in a scattered way (solving the source of the problem instead of remediating it afterwards).

### .3 Reservoir

The increased frequency and intensity of extreme weather events such as floods and droughts due to human-made climate change has led to manyfold negative implications to ecology, but also the agriculture in the Paraná Delta. Drought periods with negligent and intentional forest fires call for a resilient and effective solution for a delta in climatic and human-incinerated extremes.

During the delta visit near Zárate, numerous agricultural polders within the delta were observed against the group's original expectations [**FIGURE 4.3.1**]. They tell an ongoing story of terraforming, of agriculture and forestry appropriating the deltaic landscape. The objective is intentional water regulation and irrigation of mostly foreign tree species by embankments and pumps. While this makes water inflow and outflow controllable, it bears questions about landscape fragmentation, ground subsiding and increased flood risks for other areas, including the continent.

The proposal is to adaptively reuse the existing infrastructures to create a semi-engineered network of buffers all over the delta. The water retaining capacity of the delta is prolonged, with the proposed retention reservoirs serving irrigation of agro-ecological and ecological areas in the delta during periods of drought and fire.

The intervention simultaneously is a proposal to rethink agriculture and ecology of the delta as a dichotomy. In fact, both are relying on the same resources and can form synergies within polycultures, silvopastoral systems and food forests. We want to abandon the notion of creating the perfect habitat for endless rows of monocultural foreign tree species in a delta which consists of an astonishing biodiversity to work, experiment and live with itself.

While the delta has a number of low-lying, unprotected floodplains increasing the basin’s storage capacity during periods of high water levels, the water promptly leaves the system after the flood period by surface runoff. The opportunities of the variation in water levels are not utilized. In the proposed scheme, river, flood and rain water are temporarily stored in a basin. This concept can be schematised as a “bucket” by looking at the water input and output flows [**FIGURE 2.2.13**].

The groundwater table is locally elevated due to the soil infiltration of the water, satisfying ecosystem needs, replenishing the delta and increasing territorial biodiversity. The reservoir does not only supply a drought bypass, but the retained water re-humidifies the land, diminishing fire likelihood and supplying the means to extinguish eventual fires. The retention strategy improves the agility of the delta in extreme climatic events, making it more resilient in the ongoing effects of climate change.

To plan necessary adaptations to the current polder infrastructure, it is vital to grasp the existing situation and determine the adaptation potential. The elements of the reservoir, namely the systems around inlet, storage and outlet are designed accordingly.

### Reservoir Basin

The total capacity of the reservoir is determined by the surface area of the polder and the weir height in the case of an ungated inlet. However, if the inlet system is the only adaptation to the existing system, resilience is not yet established. Allowing flood flows in the polders does not result in an extended storage period, as soil with low porosity can not keep the water from leaving the reservoir through groundwater flow during extended water potential difference on both sides of the dike. In order to ensure water to stay within the reservoir system, diverse strategies for the reservoir are proposed. There are three different alternatives that are considered in detail:

A) Sheet pile wall: The soil morphology shows a number of clay layers in the Post Pampeano formation [**FIGURE 4.3.4**]. Without an additional CPT test, the exact depth determination of the water-retaining layer is lacking, however it will be the stiff clay layer. By installing a sheet pile wall reaching this stiff clay layer, we can form a physical barrier to prevent the water from leaving the reservoir horizontally, in short: creating a ‘bucket‘ [**FIGURE 4.3.5**].

B) Artificial swale: So-called swales represent another feasible option. Depending on the water storage demand, ditches are excavated in the polder with a depth of a few meters [**FIGURE 4.3.6**]. The surface of the ditch is made impermeable by means as a clay layer or a plastic LDPE foil to prevent water fluctuation. However, water can only leave through evaporation, direct use or a pumping system. Swales are therefore recommended to be built close to vegetation such that pumping activity can be minimized to cut costs.

C) Deep rooted plants to store water: Some plants have the capacity to take up considerable amounts of water in their deep root system and even provide it to neighboring species in case of a drought [**FIGURE 4.3.7**]. An example of this is the *Ethiopian Enset*, but other species are feasible, too.

| Options | Constructability | Effectiveness | Sustainability | Maintenance | Total |
|---|---|---|---|---|---|
| 01 Bucket | 8 | 10 | 6 | 8 | 8.2 |
| 02 Swale | 6 | 8 | 7 | 7 | 7.3 |
| 03 Roots | 6 | 6 | 8 | 6 | 6.6 |
| Weights | 10 | 40 | 30 | 20 | |

According to a weighted multi criteria analysis with four factors, we conclude that A) is the preferred choice among the three. The constructability of installing the sheet piles is the most developed technique among the three but it gives a bad score for sustainability due to the emission of CO2 during the construction process. The efficiency for A) is highest since it makes the optimal use of the polder area. Concludingly, the sheet piles can be in position for more than 50 years if well installed and conserved. Compared to the other two options, which might require continuous maintenance, A) is therefore superior.

### Inlet System

The forestry polders are currently flood-protected by dike rings. In order to ensure an inflow of water from the river, lowering parts of the dike ring is necessary. Other options such as the installation of a pumping system exist but are less sustainable, less efficient and shall therefore be avoided. The lowered dike section can be seen as a weir and the flow rate over a weir is given by the equation in **APPENDIX D**, where free flow over the weir is assumed since this would lead to the highest design values for the discharge and flow velocity over the weir compared to the submerged flow.

Broad-crested weir behaves differently than sharp crested weir. For sharp crested weirs, the discharge is larger than for broad crested weirs due to the curved streamlines above the weir, **FIGURE 4.3.8** also illustrates these two cases.

Since the concept is to try to keep the current situation, the rectangular broad crested weir is preferred. From the discharge equation, which will be shown later, for the broad crested weir with a certain friction loss on the crest we can understand that the height and width of the weir as well as the discharge coefficient determine its efficiency.

The reservoir can be constructed by simply lowering the embankment or by constructing and placing a separate weir structure. For the latter option, the design can achieve optimized over-weir discharge. However, in order to keep the current infrastructure as unchanged as possible while minimizing 'gray infrastructure', a natural soil-made weir made of soil with grass and rocks as bed protections on it is preferred. The inlet structure's technical design is the embankment slope at the inner side to ensure embankment stability and to avoid inflowing stream flow separation with regards to the slope, causing a plunge down on the reservoir bottom. This slope angle therefore depends on the soil material's internal friction angle and the flow separation angle down a slope. In case of high river water levels, the flow velocity over the weir might cause scour of the embankment. Bed protection placement on top of the weir can mitigate the scouring effect. The location is relevant because inlet system efficiency correlates with proximity to the river direction. For choosing the weir height, the two extreme scenarios are 1) The weir is high enough that only the extreme flood can flow inside (rare). 2) The weir height is equal to the floodplain [**FIGURE 4.3.9**]. The reservoir can capture a high amount of water but the capacity of the reservoir is limited due lower weir height - flowbacks to the floodplain with full reservoir.

In summary, the necessary design components are listed below:

1) location
2) width of the crest
3) height of the crest compared to the floodplain level
4) bed protection at the crest and on the spillway.

Weir Design

The maximum water level on top of the floodplain is at 2 meters, since the level at which evacuation of the surrounding area is at a value of 0.25 meters above the floodplain. In the extreme situation, the water level will continue to rise during extreme floods but it will not reach the top of the polder dike, which is at +2.5 meters with regards to the floodplain level. For the design of the weir, several choices must be made.

First, the height of the weir is chosen to be 1 meter above the level of the floodplain since this is a reasonable value between the two extreme cases that have been discussed earlier. The total width of the inlet can be varied based on the need of the reservoir which is not specified in our case, a width of 50 meters section is chosen for an example to ensure a sufficient amount of inflow and the weir is expected to behave as a broad-crested spillway which is reasonable since the cross sectional width of the spillway is larger than 2 times the maximum water level above the spillway.

According to the calculation from **APPENDIX D** the critical velocity over the spillway for the design water level is equal to 2.5 m/s, this value should also be used for the design of the bed protection. It must be noted that the efficiency of the weir can be changed by increasing its width or lowering the height.

Bed Protection

To protect the surface of the crest, rocks should be placed on the top to prevent erosion. See **APPENDIX E** for the calculations. According to literature, the grading is CP90/250. The layer thickness will be  for placement purposes. This completes the design of the bed protection on top of the weir, the result is shown in [**FIGURE 4.3.10**].

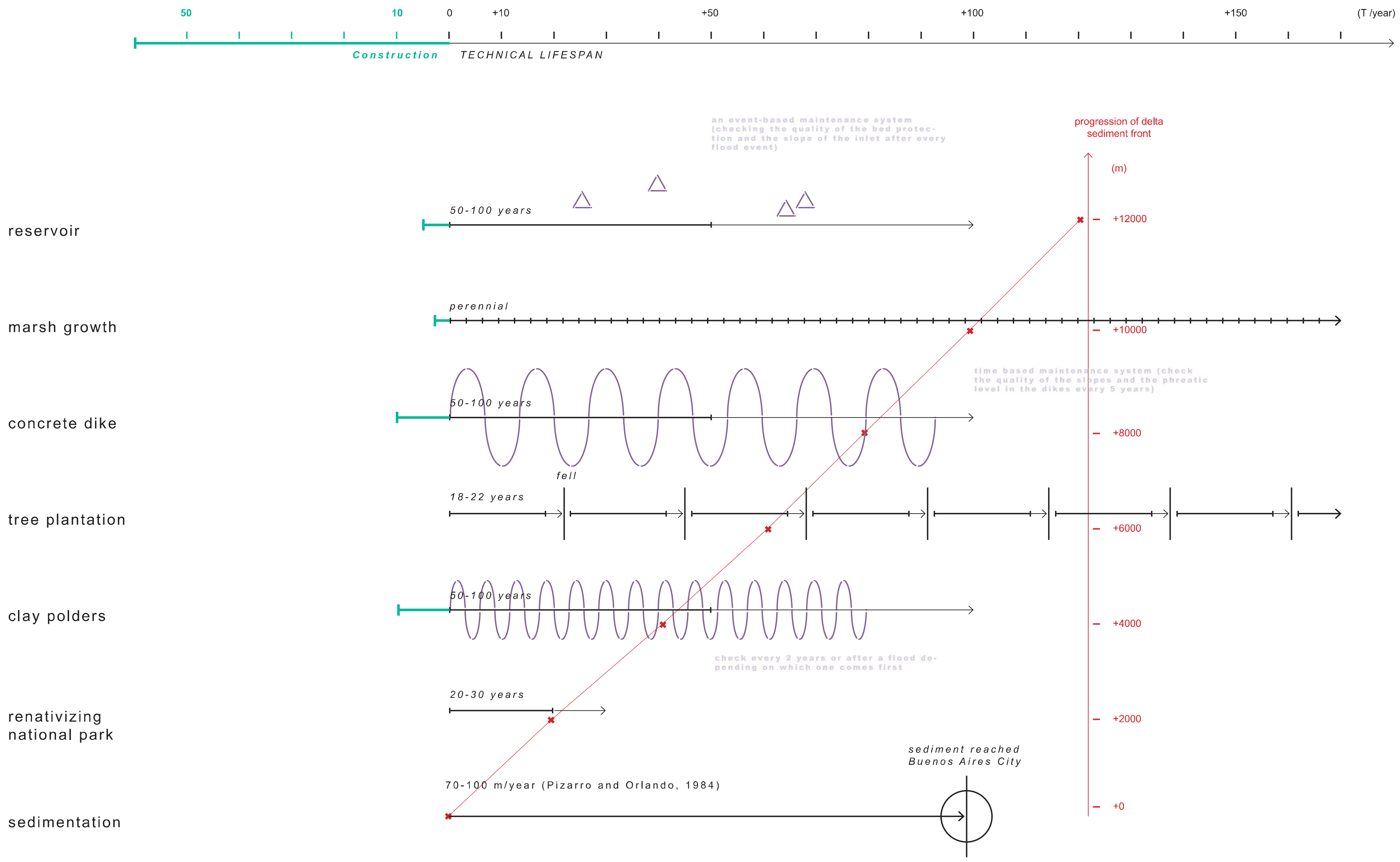
Outlet System

Since the reservoir has the function to retain water, an outlet system that brings the water back to the floodplains is not necessary. Instead, the aim of the outlet system should be to service the available storage water in periods of drought. To transport water from underneath the soil to the surface, it is possible to 1) install a well reaching into the aquifer, filling itself up with water which can be brought to the surface by a pumping system; 2) digging additional channels for irrigation, which is a more natural way to irrigate the delta.

A combination of these two options is also possible, installing a pumping system that extracts from the aquifer and brings it to a system of irrigation channels.

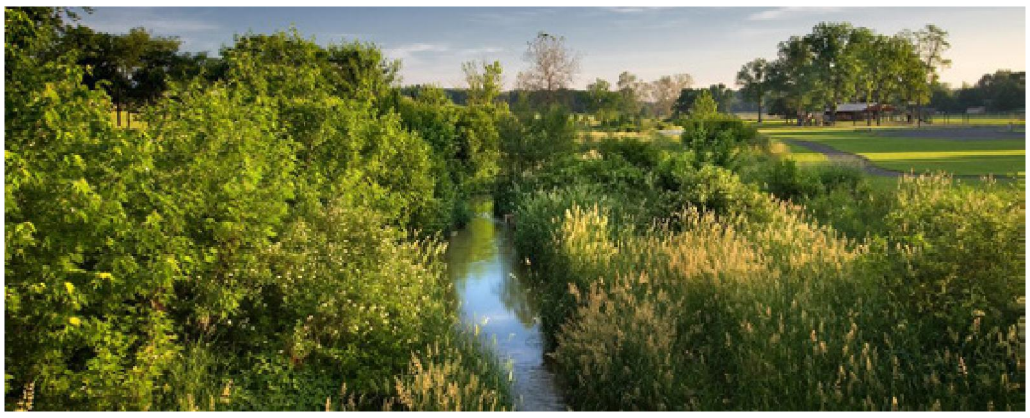
All in all, these adaptations increase the water retaining ability of the polder infrastructure. During this process, the focus has been on keeping the current polder infrastructure unchanged as much as possible, while drastically changing its use and purpose. The formerly monocultural inside of the polder can become a mixed-use wetland, a recreational pond for humans and non-humans, a fertile ground for multi-species resilience. Not only are processes affected within the polder, also outside the adaptation has implications. Allowing water to enter the former polders breaks the vicious circle of ongoing poldering of the delta. So far, each new polder creates incentives for even higher flood protection of other areas, including the heavily urbanized and populated continent. Allowing and using extreme events for natural growth circles of crops and synergetic biodiverse species while creating holistic drought resilience marks a paradigm shift in dealing with hazards of the climate emergency.

There is a certain irony in these fenced-off anthropic landscape ventures becoming the hubs for life in a drying-up delta, that we deliberately want to bring forward with our design.



**4.0.1**

Time horizons of the proposed interventions. Image by authors

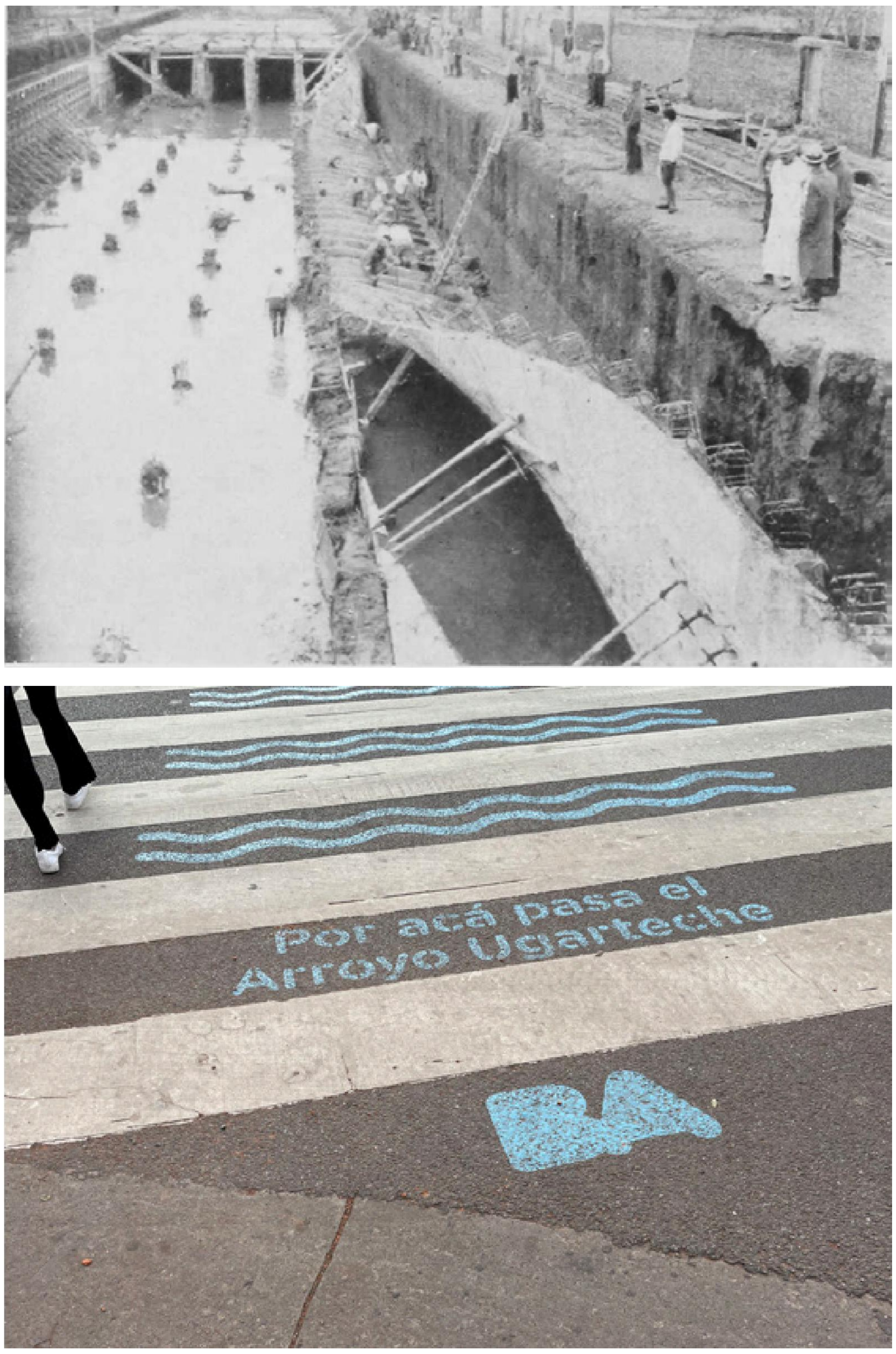


**4.1.1**

A riparian edge. Image from LandStudies.

**4.1.2**

A prairie strip. Image from Iowa State University STRIPS

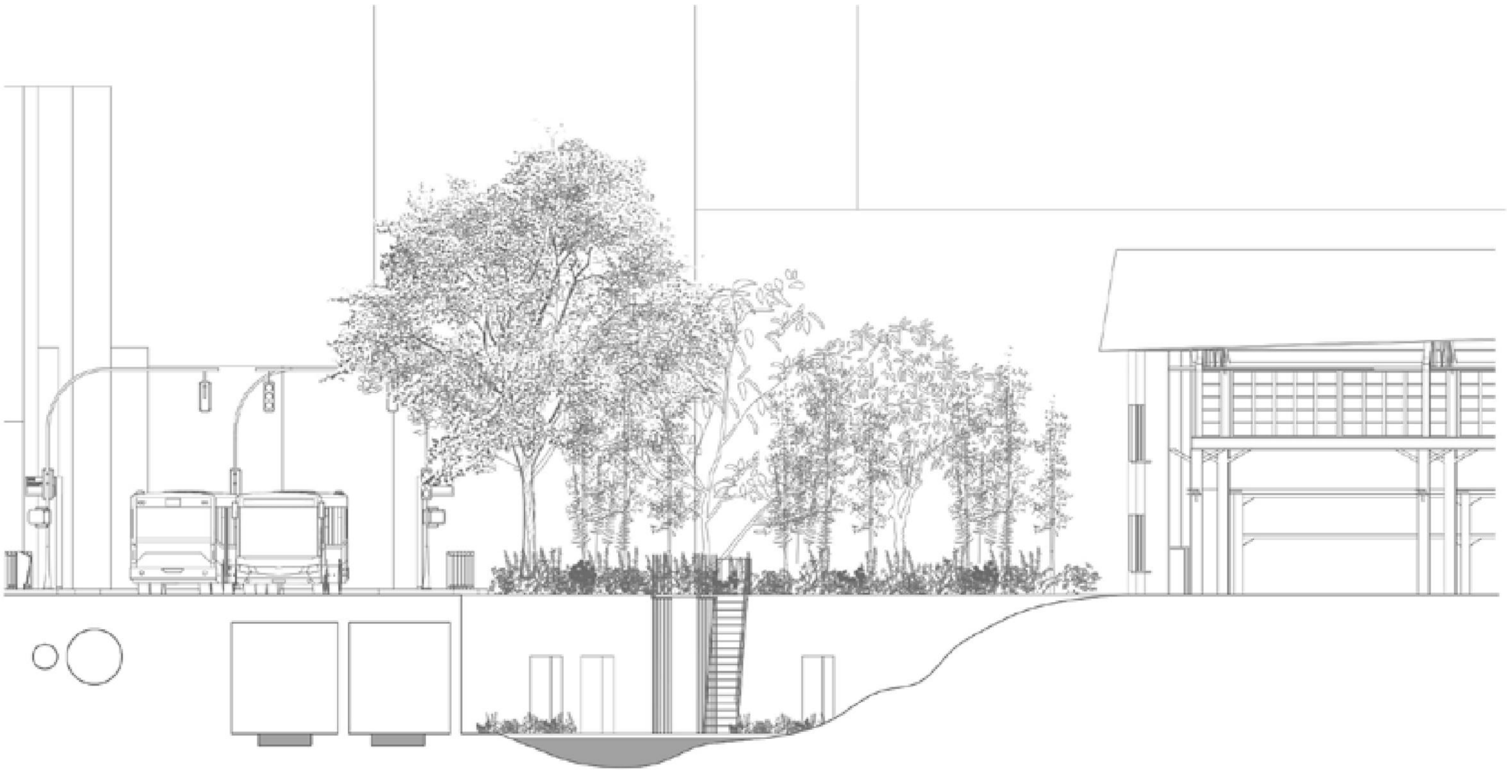


**4.1.3**

Canalization of Arroyo Maldonaldo in 1933. Image by Julio Vela Huergo. After canalization, many of the streams in Buenos Aires were paved over, becoming streets. This is still visible today. The image at right was taken by authors in sumer 2022. The city has acknowledged the existence of these streams by painting notifications of their subterranean presence, but for now, they remain as entombed drainage canals.

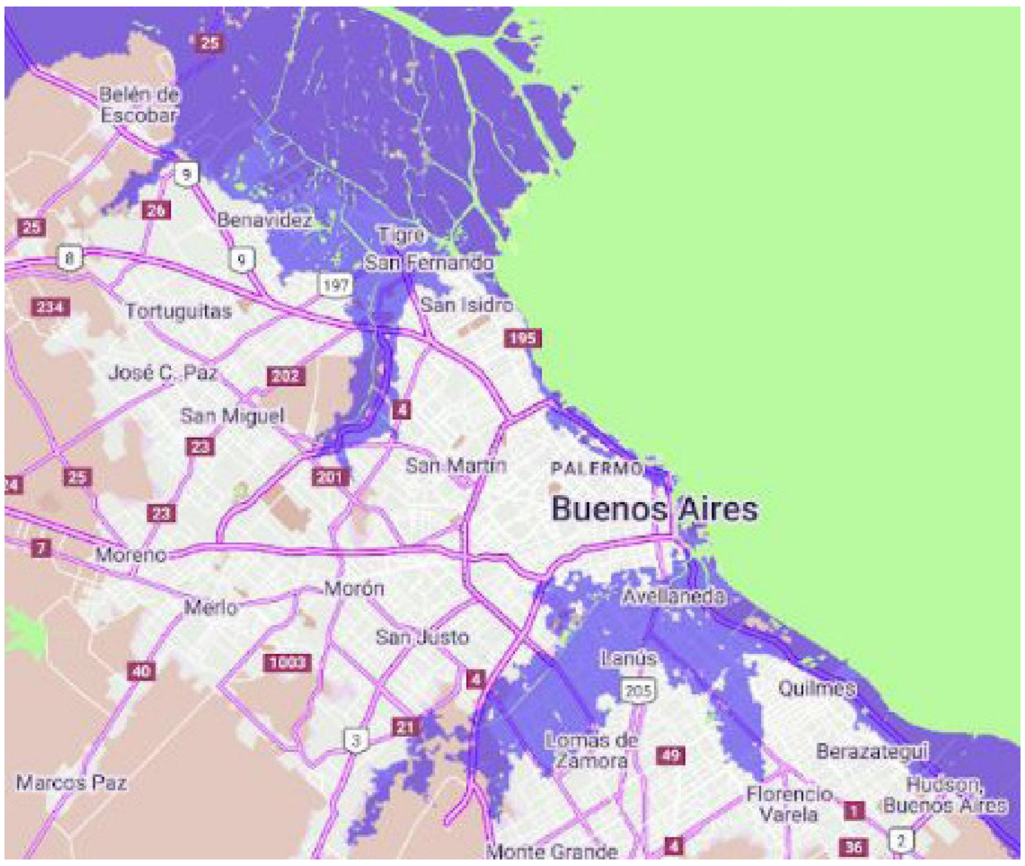
**4.1.4**

Illustrations of possible riparian edges along the Matanza-Riachuelo and Maldonado Stream in Buenos Aires. Image by authors.



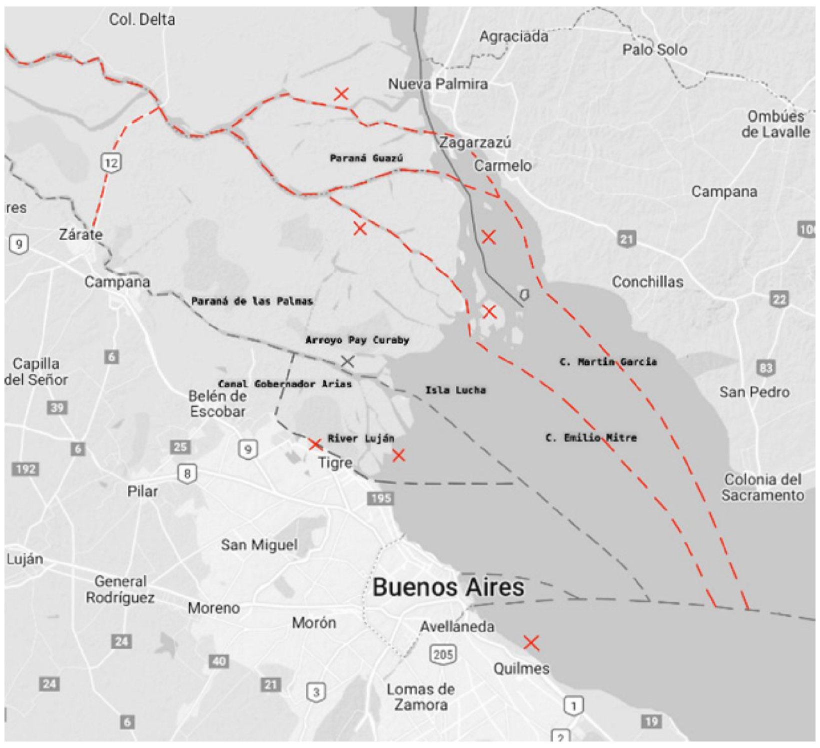
**4.2.1**

Flooding simulation based on sea-level rise projections by NASA, generated by climatechangecentral.org



**4.2.2**

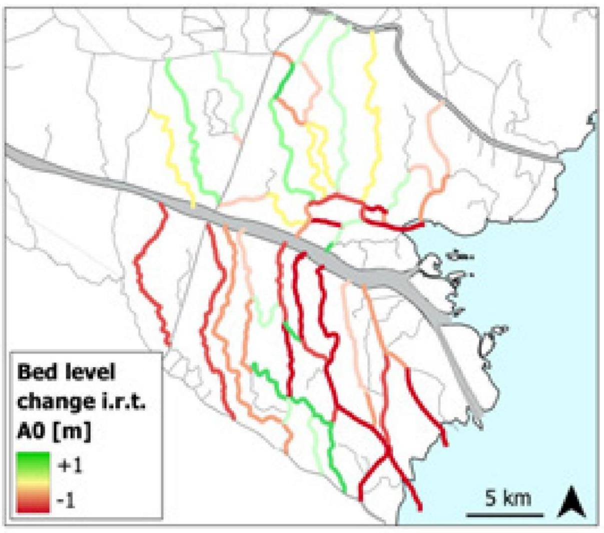
Proposed dredging scheme for the region, where gray represents current navigation routes, red represents new routes to be reinforced, and the crosses represent strategic disposal sites.

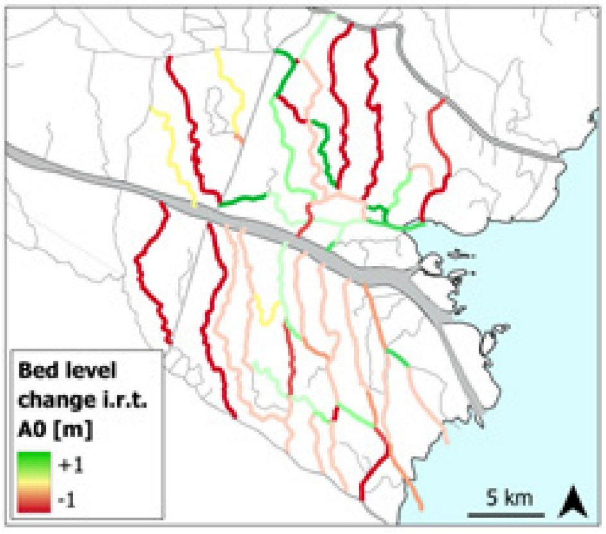


**4.2.3**

**4.2.4**

Simulation of sedimentation pattern in the Paraná River delta. Source: Leon, B. (2022). Channel Network Morphodynamics in the Lower Paraná Delta: Modeling the Influence of Natural Processes and Anthropogenic Activities on Morphological Changes in the Lower Paraná Delta Channel Network. Delft: Repository TU Delft.



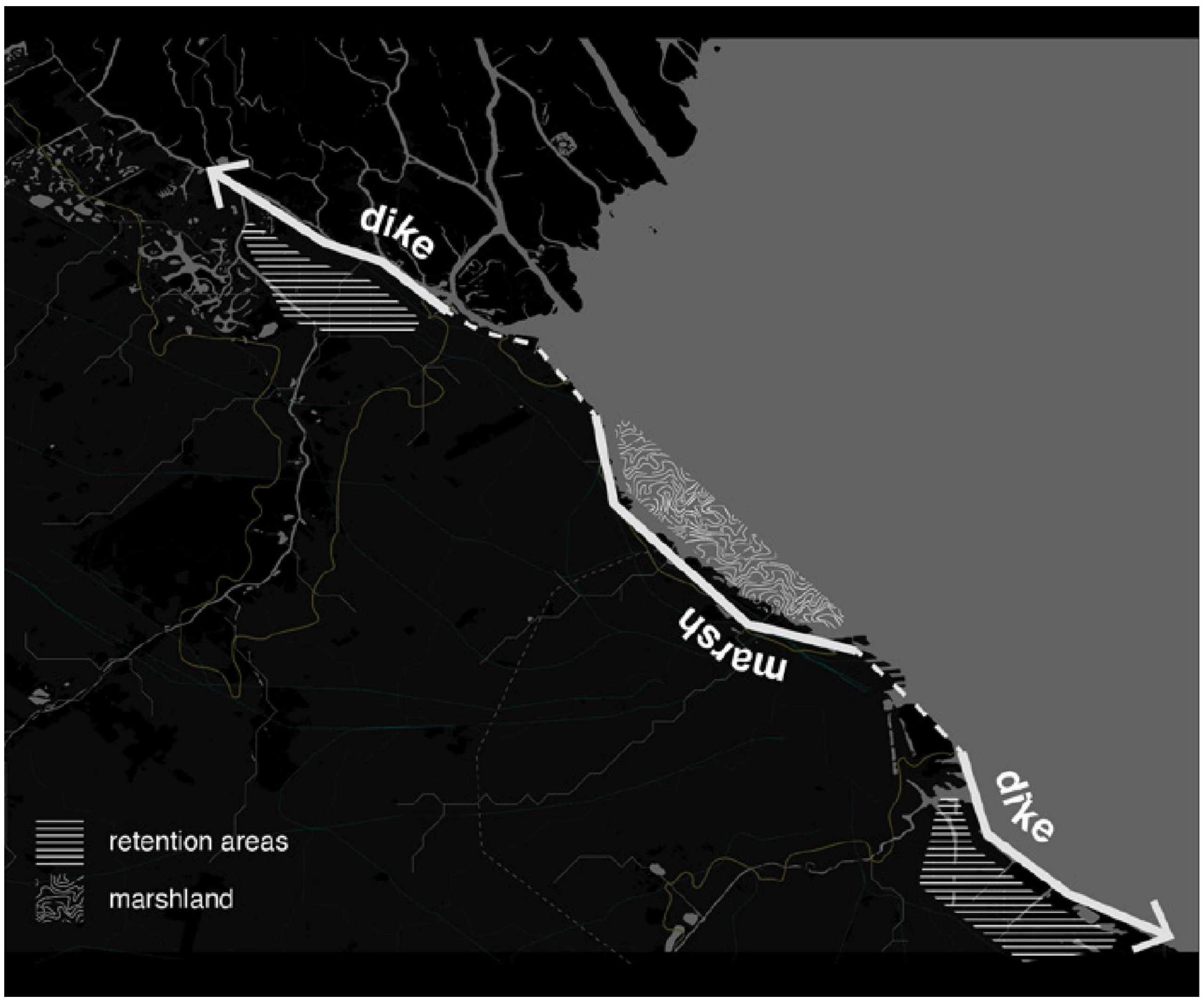


**4.2.5**

Dredging in the Canal Gobernador Arias. Image by authors.

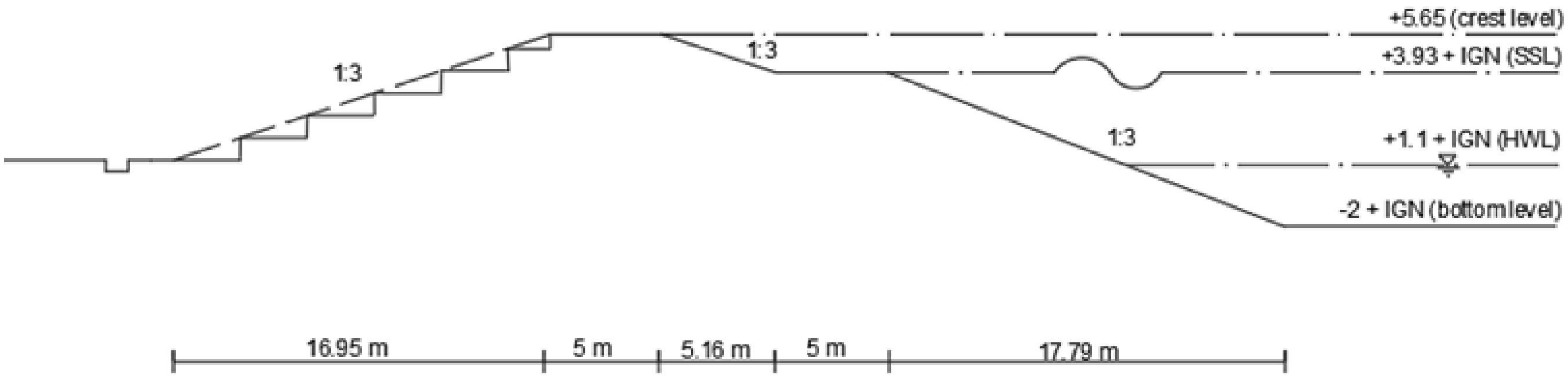
**4.2.6**

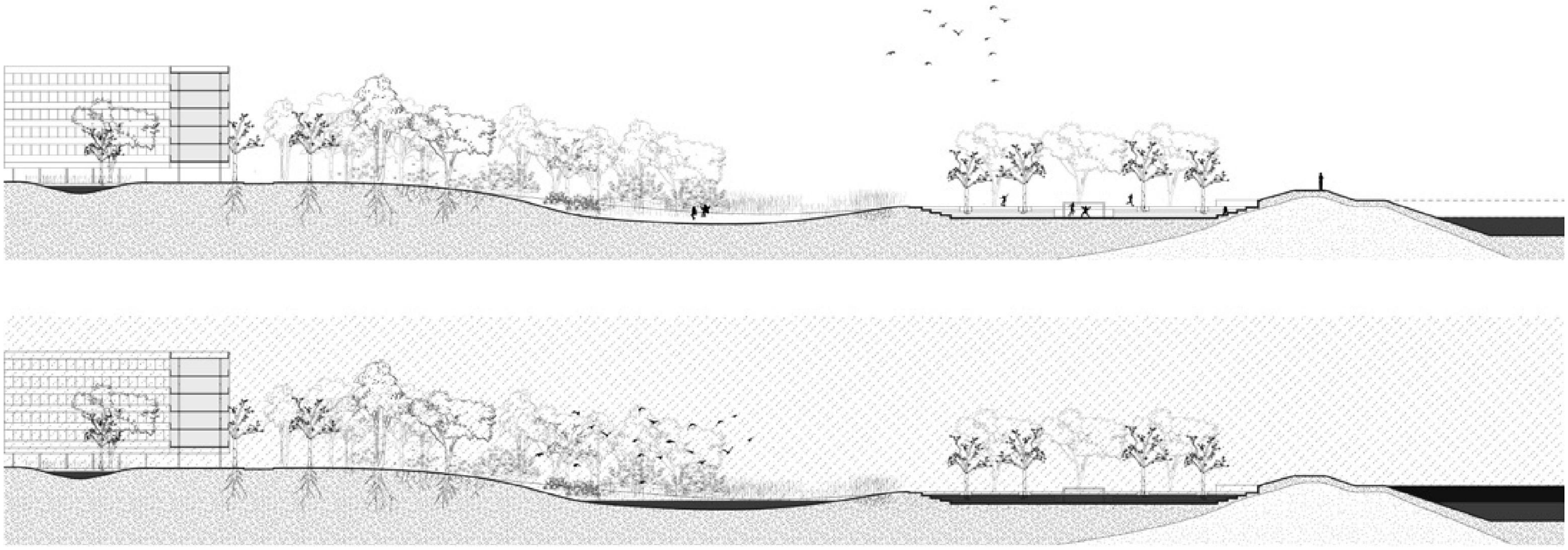
Proposed location for the marsh-dike system. Image by authors.

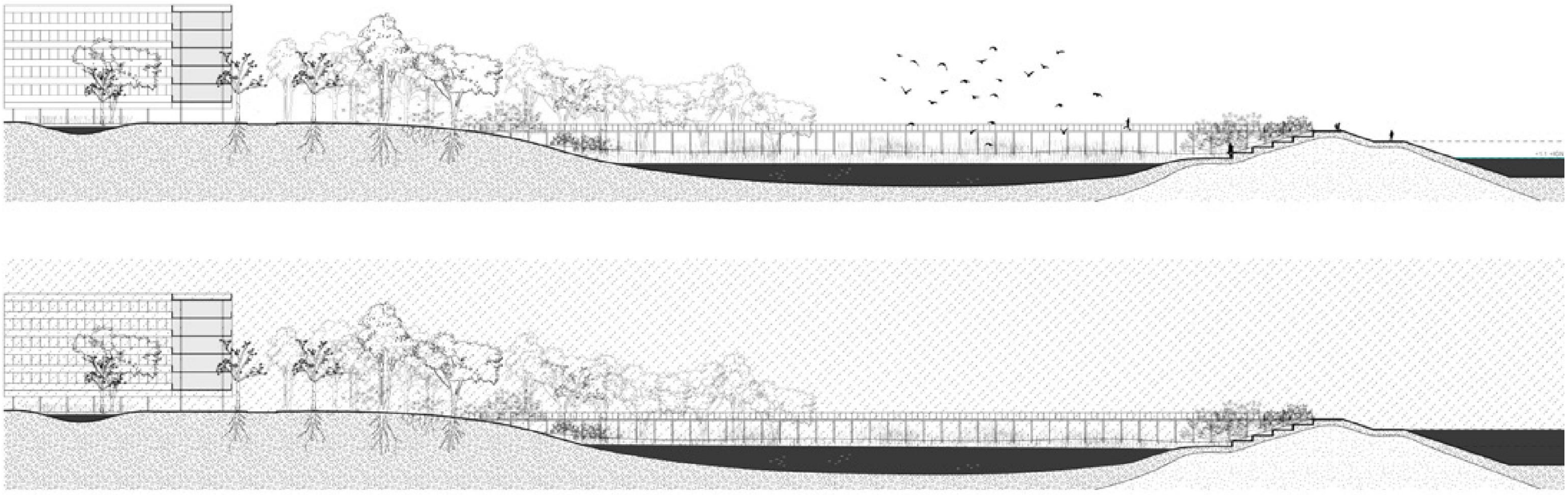


**4.2.7**

Section cut of the proposed dike design. Image by authors



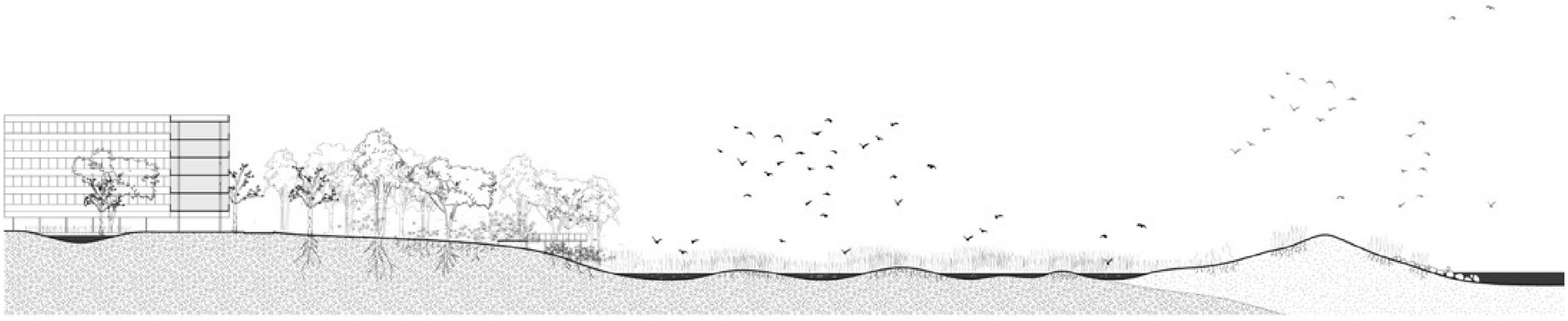




**4.2.8**
Section cut through the dike enriched with cultural values: sports and leisure fields that can function as water detention reservoirs. Image by authors.

**4.2.9**
Section cut through the dike enriched with cultural values: green open space with a water retention pond. Image by authors.

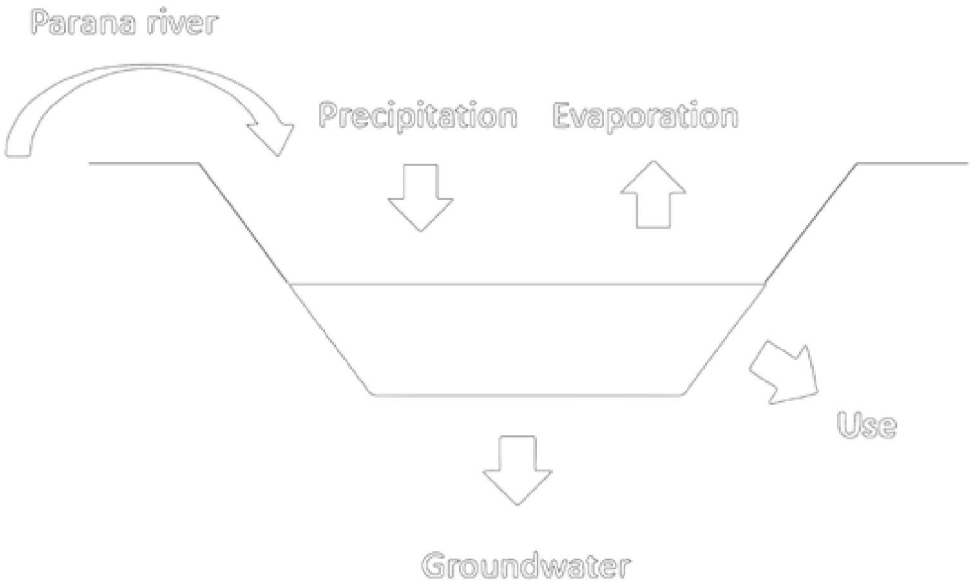
**4.2.10**
Section through marshland stretch with shallow waters and grassy vegetation, where bird populations can nest. Image by authors.



**4.2.11**
Depictions of the marsh-dike at La Boca and Tigre. Image by authors.

**4.3.1**

Impressions of the existing polder inlets and pumps, floodplain in the background. Image by authors.

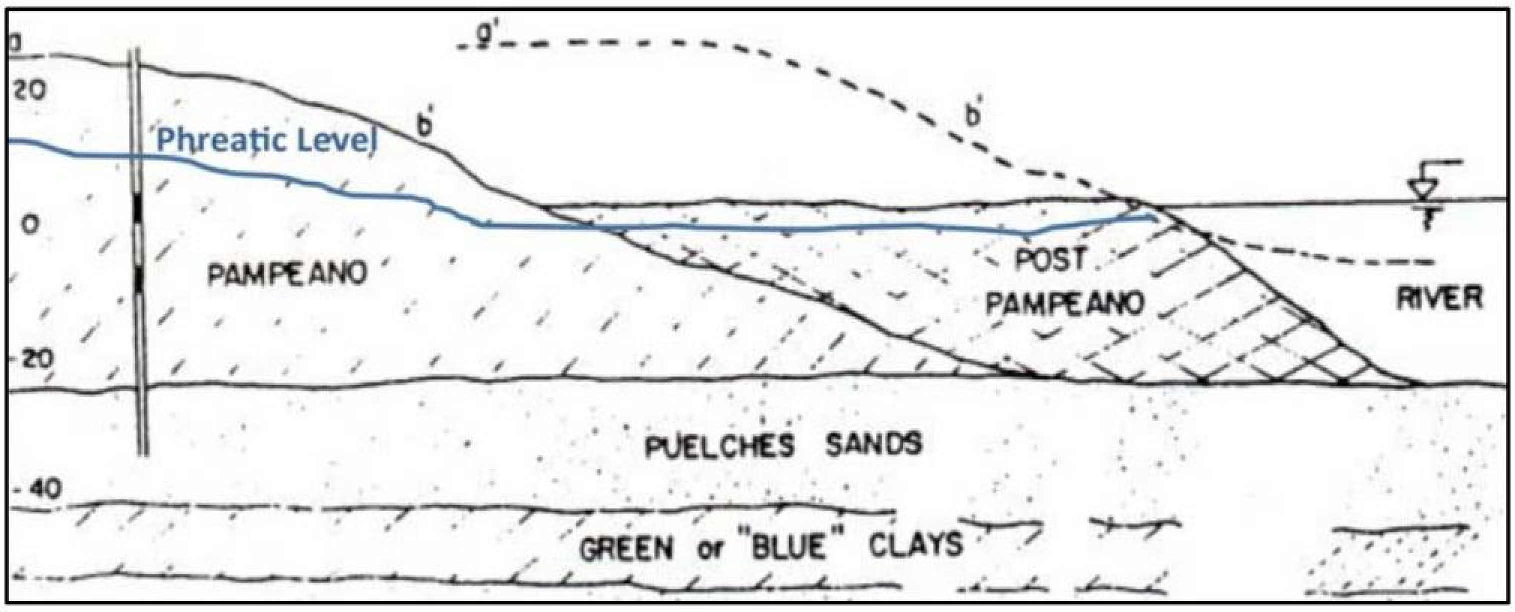


**4.3.3**

The primary water source, river water, is entering in a desirable amount according to the inlet system design. Precipitation as a secondary water source is directly influenced by the surface area of the reservoir. Water can leave the system through natural processes such as evaporation or soil fluctuation (replenishing aquifers and groundwater instead of running off) or through the outlet irrigation system in the case of droughts. The current floodplain polder system overlaid with the schematization of the situation with some dimensions. It consists of the floodplain, usually close to the river; the dike, which prevents the floods into the polder, and the polder that holds all the agricultural activities. Drawing and photo by authors, 2022

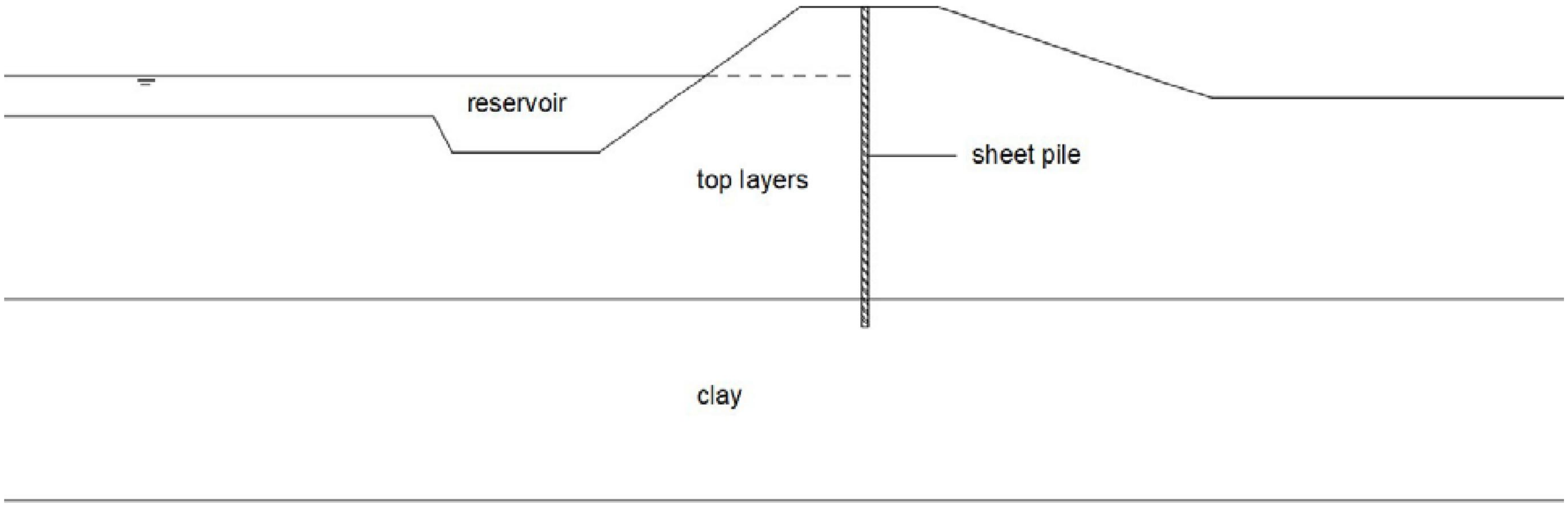
**4.3.4**

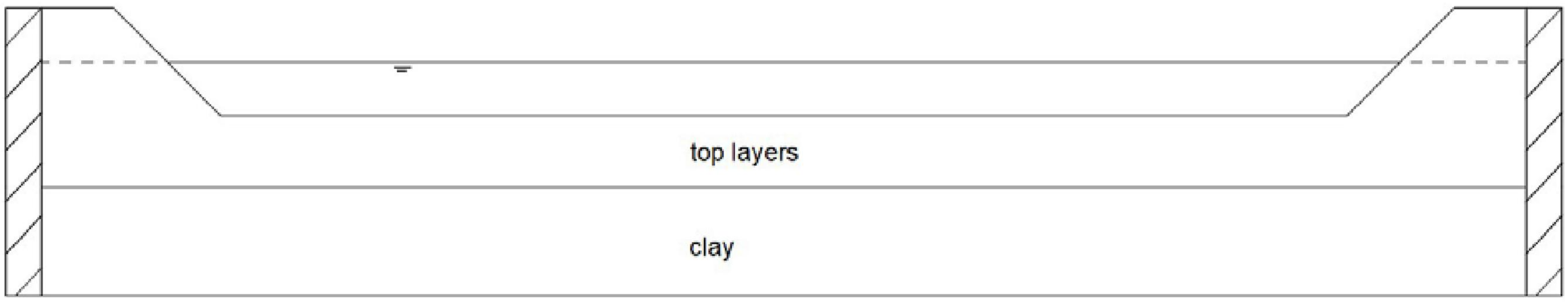
Schematic section of the Postpampeona formation (Codevilla, 2019).



**4.3.5**

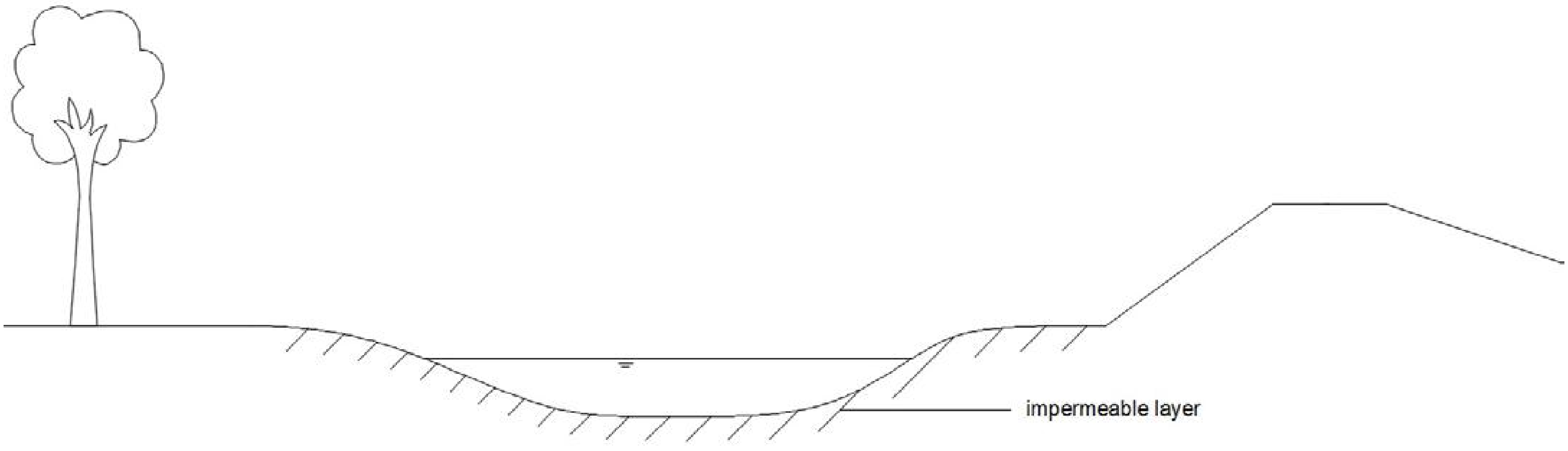
Schematic sections of Scheme A - Sheet pile wall. The sheet pile is increasing the stability of the dike. Common failure mechanisms of a dike include micro-instability resulting in piping and macro-instability (sliding) of the inner slope. The sheet pile increases the seepage length of the groundwater for piping. For the macro-instability, the sheet pile disrupts the phreatic line going through the dike that would decrease the effective strength of the soil which could eventually lead to failure. Sheet piles can be installed underground, leaving no visual obstruction by keeping the strategy minimal-invasive. Corrosion is an issue steel-made sheet piles can face in the soil for hundreds of years, especially with a varying groundwater level. This can be prevented in several ways, for example by thickening the sheet pile with a few millimeters.





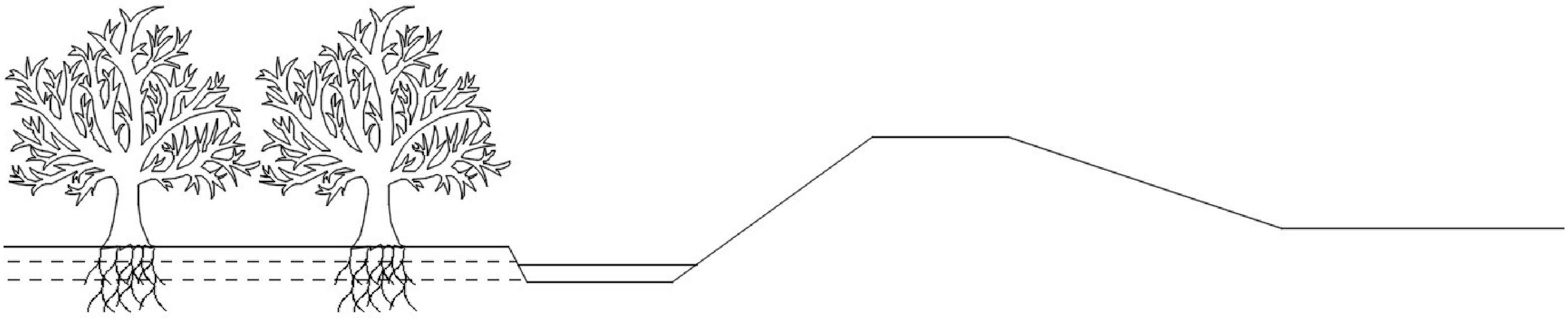
**4.3.6**

Schematic section of Scheme B - Artificial Swale. Drawing by authors, 2022



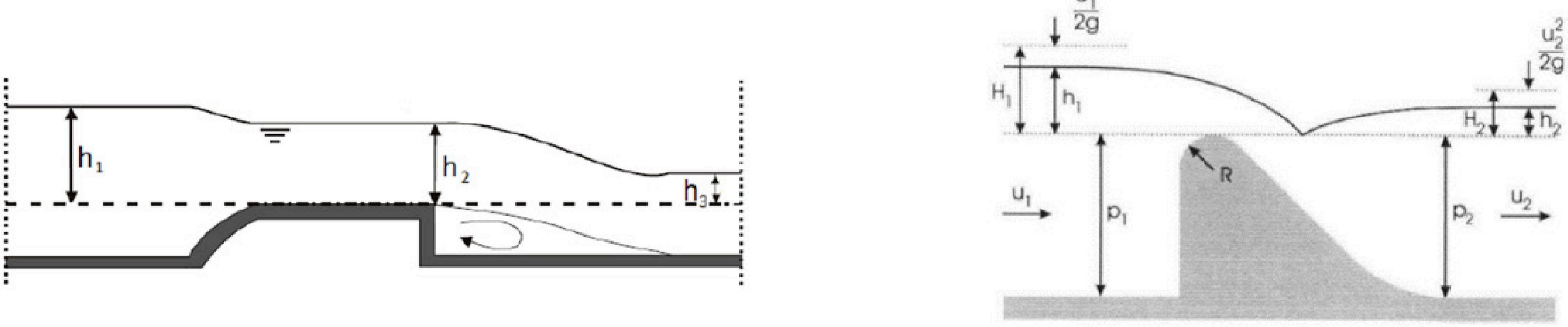
**4.3.7**

Schematic section of Scheme C - Deep root storage. The main question here is if these species can store the water long enough to survive a prolonged period of drought. The main benefit of this alternative strategy is the increase of the biodiversity in the polder, making use of ecological synergies for proposed food forests etc. Drawing by authors, 2022.

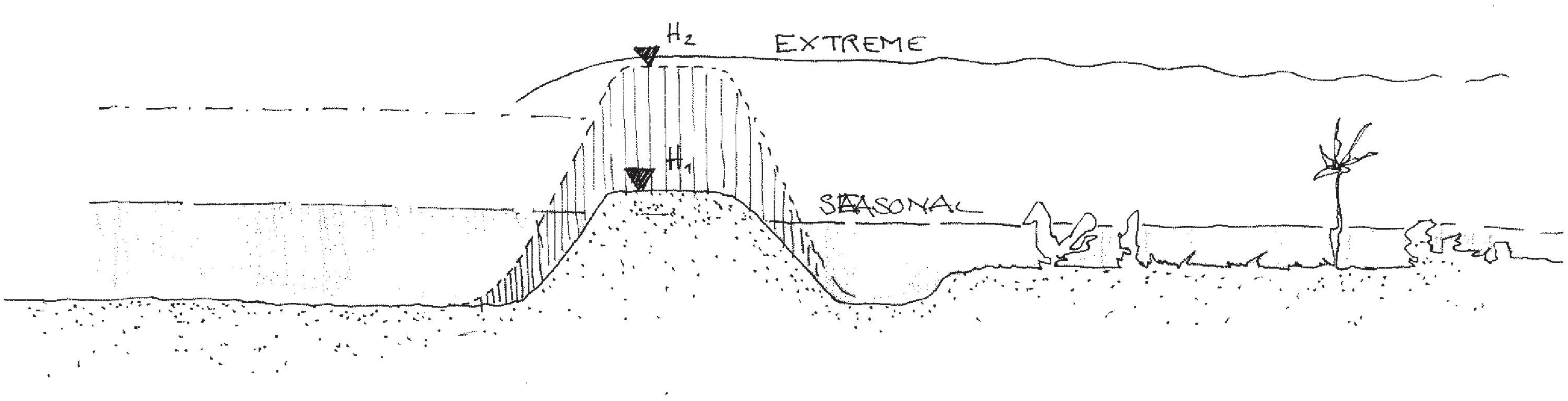


**4.3.8**

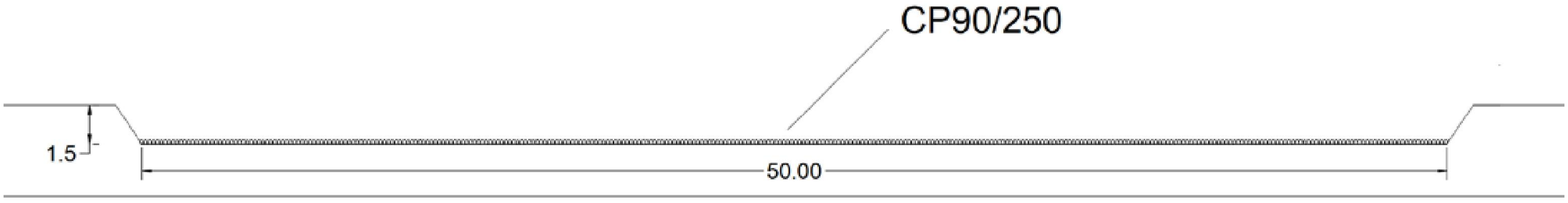
Broad-crested weir and sharp crested weir (Molenaar, 2016)

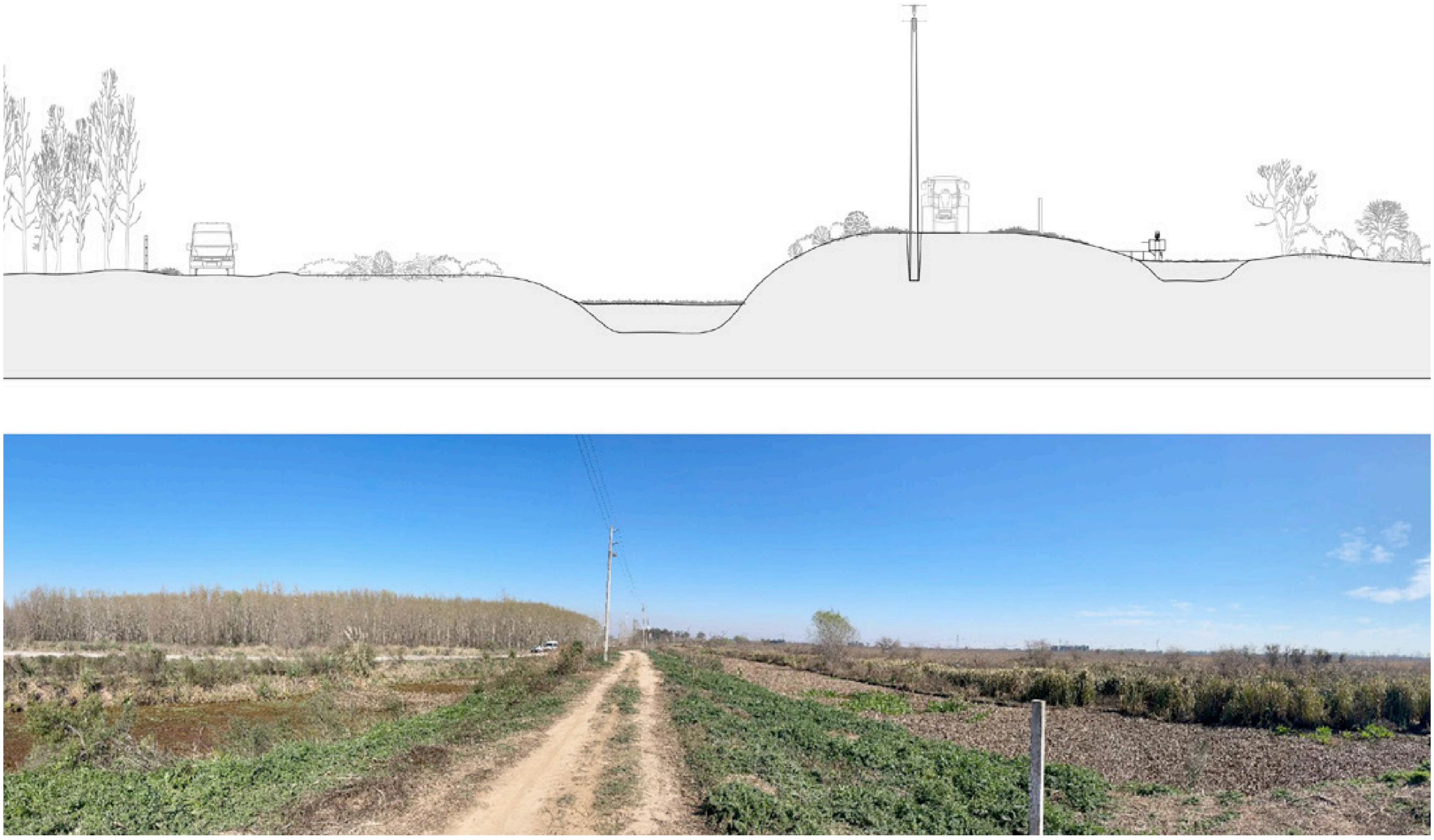


**4.3.9**
Schematic section of the different weir solutions. Sketch by authors, 2022



**4.3.10**
Drawing of rock protection on the weir. Image by authors.

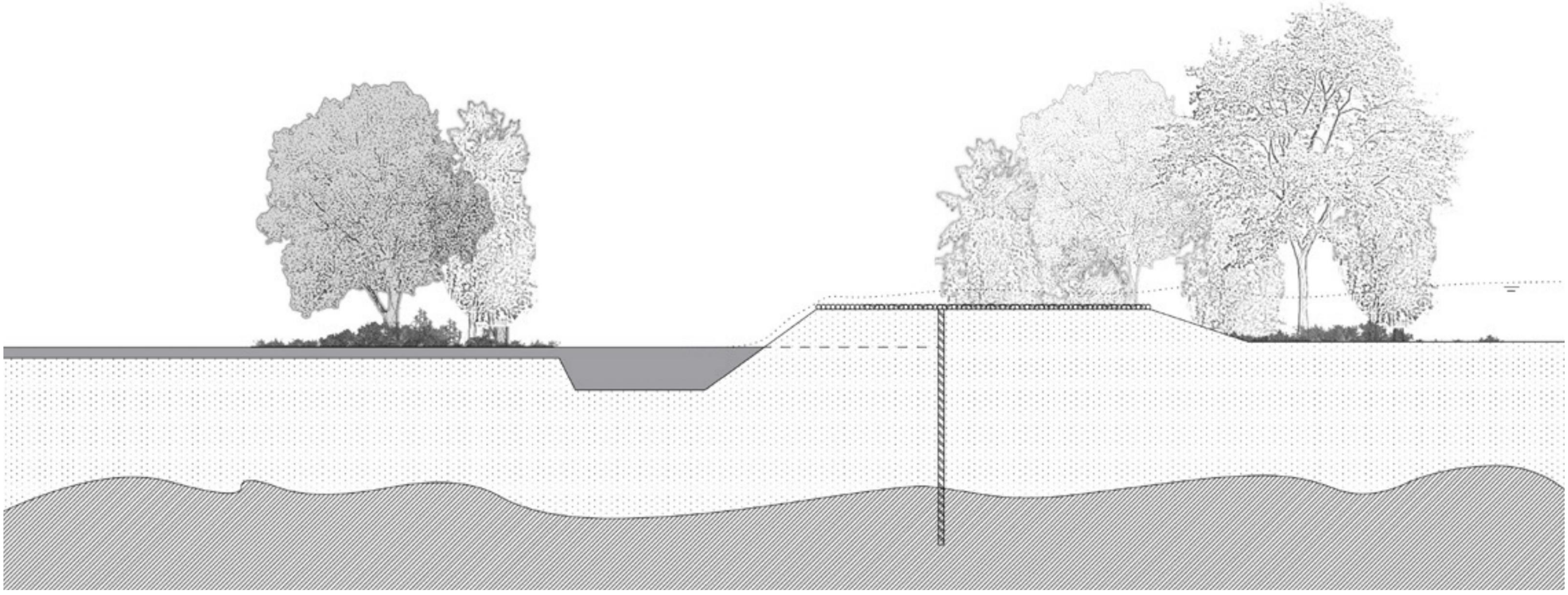




**4.3.10**
Status quo section of the poldered landscape. Images by authors, 2022

**4.3.11**
Final collated reservoir section following the sheet pile wall approach. Image by authors, 2022

**4.3.12**
Final collage of the intervention. Work by authors, 2022



## 05 // DISCUSSION

This research set out to investigate the methods of designing resilience for the Paraná delta through an interdisciplinary approach. Over the course of five months (June - October, 2022), the working group operated within the interdisciplinary framework in defining and tackling the field of problems in the deltaic system that is the delta. Comprised of five distinct disciplines, namely, Hydraulic Engineering, Architecture, Landscape Architecture, Water Management, and Urbanism, the working group has utilized the multi-disciplinary resources in multiple occasions in Buenos Aires and Delft, such as the ***charette method***, where disciplinary opinions were distributed from experts to non-experts, and the ***design workshops*** (as designed by our working group, with details to be found in **SECTION 1.3 METHODOLOGY**), where different disciplinary opinions can be discussed based on a common vision that is a working physical scaled model of the delta.

Beyond the working group, the research also acknowledges the available knowledge-experts on the delta in the field, from hydraulic engineering consultancy, agricultural scientists, to local tour guides from Tigre and the many others encountered during field research. Through proactively connecting with such knowledge-experts, in-person and virtually, this research wishes to have expanded the notion of "interdisciplinary" in designing resilience by including voices outside of the five disciplines within the working group. It is then laying all the opinions on the table, discussed through active model-making and co-creation process, that the working group came to value and learn from other perspectives on understanding the delta.

The interdisciplinary research method created a helpful synergy in informing the resilience design for the delta. However distinct the disciplinary perspectives could be, there emerged a common vision in the group of designing resilience in a landscape-based approach, with an emphasis on hybrid solutions integrating gray and green engineering. This research posits that an *Interstitial Aquaculture* can be a guiding strategy for designing resilience in the future of this deltaic system. As elaborated in the preceding sections, this research believes that designing a strategy, rather than location-specific interventions, would yield more productive speculations over the Paraná delta. Indeed, it is also to acknowledge the limitations of the research within a five-month multidisciplinary framework that the eventual deliverable of this research paper manifests in a design strategy. It is the intention of this research paper to remain at a strategic level, with elaborations of some three possible design interventions, namely, *Riparian Edge, Marsh-Dike, Reservoir*, so that future scholarship can explore the possibilities of implementation in specific locations with much more careful deliberations.

Designing resilience for the delta matters in the backdrop of the ongoing climate crisis. Extreme precipitation patterns, along with socio-economic challenges observed but yet to be elaborated in the construct of this paper, figure in the discussion of the delta's future(s). This paper does not intend to provide answers to all challenges in this deltaic system, but nonetheless wishes to offer some insights over the methodology of designing with resilience in such a system. It is acknowledged that the paper could offer only so much a perspective from a European institute over a limited research period. Despite such limitations, it is hoped that this paper can contribute to the ongoing discussions over the deltaic futures, with particular emphasis on regarding the deltaic system in multiple scales. Resilience matters as much as the scale in question. Future scholarships could inquire into this problem of *scale* in addition to the interdisciplinary method explored in this research.

## 06 // CONCLUSION

While the scope of this paper only addresses land use in the Lower Parana delta, between Zarate and La Boca, it is intended as a methodology that can be extrapolated across the entire delta region up to Rosario and Santa Fe, with accommodations for local conditions in mind. For now this is a working model, a point of departure, rather than a final realizable plan that we hope is able to add to the discourse regarding the future of urbanism in the Parana delta. As an answer to previously stated research questions: designing resilience for the Paraná Delta in an interdisciplinary approach is multi-dimensional. However, these dimensions overlap. For example, resilience against forces of nature and resilience against the consequences of urbanization patterns are interwoven by the discussed design solutions. A truly resilient design matters because it provides opportunities for now and the future and can only be achieved with input from architectural, hydraulic and water management disciplines.

## BIBLIOGRAPHY

Abou Rafee, S. A., Uvo, C. B., Martins, J. A., Machado, C. B., & Freitas, E. D. (2022). Land Use and Cover Changes versus climate shift: Who is the main player in river discharge? A case study in the Upper Paraná River Basin. *Journal of Environmental Management*, *309*, 114651. https://doi.org/10.1016/j.jenvman.2022.114651

Agostinho, A. A., & Zalewski, M. (1995). The dependence of fish community structure and dynamics on floodplain and riparian ecotone zone in Parana River, Brazil. *The Importance of Aquatic-Terrestrial Ecotones for Freshwater Fish*, 141–148. https://doi.org/10.1007/978-94-017-3360-1_13

Altieri, M. (2009). *Green desserts: Monocultures and their impacts on biodiversity*. FIAN International.

Alvarez, M.F., Osterrieth, M. & Cooper, M. Changes in the porosity induced by tillage in typical Argiudolls of southeastern Buenos Aires Province, Argentina, and its relationship with the living space of the mesofauna: a preliminary study. *Environ Earth Sci* **77**, 134 (2018). https://doi.org/10.1007/s12665-018-7313-x

Anbumozhi, V., Radhakrishnan, J., & Yamaji, E. (2005). Impact of riparian buffer zones on water quality and associated management considerations. Ecological Engineering, 24(5), 517–523. https://doi.org/10.1016/j.ecoleng.2004.01.007

Argentina Population 2022 (Demographics, Maps, Graphs). (2022). World Population Review. https://worldpopulationreview.com/countries/argentina-population

Baigún, C. R., Puig, A., Minotti, P. G., Kandus, P., Quintana, R., Vicari, R., Bo, R., Oldani, N. O., & Nestler, J. A. (2008b, January). Resource use in the Parana River Delta (Argentina): moving away from an ecohydrological approach? Ecohydrology &Amp; Hydrobiology, 8(2–4), 245–262. https://doi.org/10.2478/v10104-009-0019-7

Barletti, A. (2021). *Canal Martin Irigoyen: Hacia una nueva vía navegable*. Look Impresores. https://en.calameo.com/read/006200032d58f8de1a30f

Barrios, E., Sileshi, G. W., Shepherd, K., & Sinclair, F. (2012). Agroforestry and Soil Health: Linking Trees, Soil Biota, and Ecosystem Services. *Soil Ecology and Ecosystem Services*, 315–330. https://doi.org/10.1093/acprof:oso/9780199575923.003.0028

Barros, V. (2005). *Global Climate Change and the Coastal Areas of the Río de la Plata.* Buenos Aires: University of Buenos Aires.

Bazzoni, C., & Lovera, C. (2022, February 11). “In Argentina, Female Fishers Persevere as the Paraná’s Water Level Drops.” Dialogo Chino. https://dialogochino.net/en/climate-energy/51063-parana-river-argentina-women-fishers/

Berger, A. (2006, June 1). *Drosscape: Wasting Land in Urban America* (1st ed.). Princeton Architectural Press.

Boschi. (1987). A arte da associação: política de base e democracia no Brasil.

Buenos Aires Environmental Protection Agency. (n.d.). Buenos Aires Climate Change Action Plan English Summary. Buenos Aires Ciudad.

Buenos Aires Population 2022 (Demographics, Maps, Graphs). (2022). World Population Review. https://worldpopulationreview.com/world-cities/buenos-aires-population

Camilloni, I. A., & Barros, V. R. (2003). Extreme discharge events in the Paraná River and their climate forcing. *Journal of Hydrology*, *278*(1–4), 94–106. https://doi.org/10.1016/s0022-1694(03)00133-1

Cirelli, A. F., & Ojeda, C. (2008). Wastewater management in Greater Buenos Aires, Argentina. *Desalination*, *218*(1–3), 52–61. https://doi.org/10.1016/j.desal.2006.10.040

Delft University of Technology. (2022). *Manual Hydraulic Structures.*

Deltares. (2018). Deltares Onderzoeksplan 2018. https://deltares-deltares-p01-website.s3.eu-central-1.amazonaws.com/app/uploads/2018/02/Onderzoeksplan-2018_Deltares.pdf

Dinápoli, M. G., Simionato, C. G., & Moreira, D. (n.d.). Model sensitivity for the prediction of extreme sea level events at a wide and fast-flowing estuary: the case of the Río de la Plata Area of interest and numerical model Proyecto Freplata-FFEM. Environmental Protection of the Río de la Plata and its Maritime Front / French Fund for the Global Environment View project. https://www.researchgate.net/publication/341386498

Dunne, T., & Leopold, L. B. (1978). Water in Environmental Planning (1st ed.). W. H. Freeman.

d'Onofrio et al, E. (2008). Changes in the Regime of Storm Surges at Buenos Aires, Argentina. Researchgate. Retrieved from https://www.researchgate.net/publication/250083789_Changes_in_the_Regime_of_Storm_Surges_at_Buenos_Aires_Argentina

EDDM. (n.d.). Retrieved from https://www.eddm.nl/dredger.html

Eriksen, M., “Plastic Pollution in the World’s Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea.” PLoS ONE 9, no. 12, (2014)

Forman, R. T. T., & Wilson, E. O. (1995). *Land Mosaics: The Ecology of Landscapes and Regions* (1st ed.). Cambridge University Press.

Getirana, A., Libonati, R., & Cataldi, M. (2021). Brazil Is in a Water Crisis — It Needs a Drought Plan. Nature, 600(7888), 218–220.

https://doi.org/10.1038/d41586-021-03625-w

Gomez, B. M., Reale, M., El Kassisse, Y., Mujica, C., Gómez, C., de Cabo, L., & Rodríguez Salemi, V. (2020). Metals Uptake by Sagittaria montevidensis in Contaminated Riparian Area of Matanza-Riachuelo River (Argentina). *SN Applied Sciences*, *2*(12). https://doi.org/10.1007/s42452-020-03816-6

Gonzalez-Fernandez, R. A., Oviedo-Sanabria, R. E., & da Silva, A. M. L. (2014). Generating capacity reliability assessment of the Itaipu hydroelectric plant via sequential Monte Carlo simulation. *2014 Power Systems Computation Conference*. https://doi.org/10.1109/pscc.2014.7038436

Government of the City of Buenos. (n.d.). Climate Action Plan 2050 City of Buenos Aires.

Greenhouse gas emissions from agriculture, measured in tonnes of carbon dioxide-equivalents. (2020). [Dataset]. CAIT Climate Data Explorer via Climate Watch. https://www.climatewatchdata.org/data-explorer/historical-emissions

Hawes, E.., & Smith, M. (2005). Riparian Buffer Zones: Functions and Recommended widths

Impact Observatory for Esri. (2021). Esri Land Cover 2021 [Dataset]. https://tiledimageservices.arcgis.com/P3ePLMYs2RVChkJx/arcgis/rest/services/Esri_2020_Land_Cover_V2/ImageServer

Kandus, P., & Quintana, R. D. (2018). The Paraná River Delta. The Wetland Book, 813–821. https://doi.org/10.1007/978-94-007-4001-3_232

Koolhaas, R. (2002, April). *Junkspace*. October, 100, 175–190. https://doi.org/10.1162/016228702320218457

Larmer, B. (2019, January 30). What Soybean Politics Tell Us About Argentina and China. The New York Times. Retrieved October 20, 2022, from https://www.nytimes.com/2019/01/30/magazine/what-soybean-politics-tell-us-about-argentina-and-china.html

Latour, B., & Porter, C. (2017, August 14). Facing Gaia: Eight Lectures on the New Climatic Regime (1st ed.). Polity.

Leon, B. (2022). Channel Network Morphodynamics in the Lower Paraná Delta: Modeling the Influence of Natural Processes and Anthropogenic Activities on Morphological Changes in the Lower Paraná Delta Channel Network. Delft: Repository TU Delft.

Lombardo, R. J., O'Farrell, I., & dos Santos Afonso, M. (2009, May). Spatial and Temporal Ion Dynamics on a Complex Hydrological System: The Lower Luján River (Buenos Aires, Argentina). Springer. https://doi.org/10.1007/s10498-009-9064-5

López Weibel, C., Szupiany, R., Latosinski, F., Amsler, M., & Repasch, M. (2022). Sources and temporal dynamics of suspended sediment transport along the middle Paraná River. *Journal of South American Earth Sciences*, *119*, 103968. https://doi.org/10.1016/j.jsames.2022.103968

Martin et al., P. (2012). Numerical simulation of wind waves on the Río de la Plata: Evaluation of four global atmospheric databases. Researchgate. Retrieved from https://www.researchgate.net/publication/262661756_Numerical_simulation_of_wind_waves_on_the_Rio_de_la_Plata_Evaluation_of_four_global_atmospheric_databases#pf5

Meijer, L. J. J., van Emmerik, T., van der Ent, R., Schmidt, C., & Lebreton, L. (2021). More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Science Advances, 7(18). https://doi.org/10.1126/sciadv.aaz5803

Mekonnen, M.M. and Hoekstra, A.Y. (2010) The green, blue and grey water footprint of farm animals and animal products, Value of Water Research Report Series No. 48, UNESCO-IHE, Delft, the Netherlands.

Milione, G. M., Mujica, C. R., Daguer, D. D., Bea, S. A., Fernández, M. E., & Gyenge, J. E. (2020). Influence of Soil Texture, Climate and Vegetation Cover on Secondary Soil Salinization in Pampas Plains, South America. In CERNE (Vol. 26, Issue 2, pp. 212–221). FapUNIFESP (SciELO). https://doi.org/10.1590/01047760202026022700

Ministerie van Landbouw, Natuur en Voedselkwaliteit. (2021, July 22). Argentine State takes control of the Paraná-Paraguay Waterway. Nieuwsbericht Agroberichten Buitenland. https://www.agroberichtenbuitenland.nl/actueel/nieuws/2021/07/22/argentine-state-takes-control-of-the-parana-paraguay-waterway

Monbiot, G. (2022, January 10). *Capitalism is killing the planet – it's time to stop buying into our own destruction*. The Guardian. https://www.theguardian.com/environment/2021/oct/30/capitalism-is-killing-the-planet-its-time-to-stop-buying-into-our-own-destruction

Moore, L. S. (2021, April 28). Climate-friendly farming strategies can improve the land and generate income for farmers. The Conversation. https://theconversation.com/climate-friendly-farming-strategies-can-improve-the-land-and-generate-income-for-farmers-157220

Morton, T. (2016). Dark Ecology: For a Logic of Future Coexistence. Amsterdam University Press.

Nijhuis, S. (2022). Landscape-Based Urbanism: Cultivating Urban Landscapes Through Design. In Design for Regenerative Cities and Landscapes (pp. 249–277). Springer International Publishing. https://doi.org/10.1007/978-3-030-97023-9_11

OECD. (2019). *Agricultural Policies in Argentina*. https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=TAD/CA(2018)9/FINAL&docLanguage=En

Peluso, J., Pérez Coll, C. S., Rojas, D. E., Cristos, D., & Aronzon, C. M. (2022). Ecotoxicological assessment of complex environmental matrices from the lower Paraná River basin. *Chemosphere*, *305*, 135385. https://doi.org/10.1016/j.chemosphere.2022.135385

Pérez, J. C., Díaz, J. P., & Taima, D. (2015). High-Resolution Future Projections of Temperature and Precipitation in the Canary Islands. Journal of Climate, 28(19), 7846–7856. https://doi.org/10.1175/jcli-d-15-0030.1

Pizarro, H., Rodríguez, P., Bonaventura, S. M., O'Farrell, I., & Izaguirre, I. (2007). The sudestadas: a hydro-meteorological phenomenon that affects river pollution (River Luján, South America). Hydrological Sciences Journal, 52(4), 702–712. https://doi.org/10.1623/hysj.52.4.702

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E., & Stromberg, J. C. (1997). The Natural Flow Regime. BioScience, 47(11), 769–784. https://doi.org/10.2307/1313099

Primost, J. E., Peluso, L., Sasal, M. C., & Bonetto, C. A. (2022). Nutrient dynamics in the Paraná River Delta: Relationship to the hydrologic regime and the floodplain wetlands. Limnologica, 94, 125970. https://doi.org/10.1016/j.limno.2022.125970

Rinaldi, V. A., & Abril, E. G. (2006). Aspectos geotécnicos fundamentales de las formaciones del delta del río Paraná y del estuario del río de la Plata. Revista Internacional De Desastres Naturales, Accidentes E Infraestructura Civil, 6(2). https://www.scipedia.com/public/Rinaldi_Abril_2006a

Ronco et al., A. (2016, Juli 9). Retrieved from Springer Link: https://link.springer.com/article/10.1007/s10661-016-5467-0

Rovedatti, M., Castañé, P., Topalián, M., & Salibián, A. (2001). Monitoring of organochlorine and organophosphorus pesticides in the water of the reconquista river (buenos aires, argentina). Water Research,35(14),3457–3461.https://doi.org/10.1016/s0043-1354(01)00058-6

Ruhoff, A., de Andrade, B. C., Leipelt, L., Fleischmann, A. S., Siqueira, V. A., Moreira, A. A., Barbedo, R., Cyganski, G. L., Fernandez, G. M. R., Brêda, J. P. L. F., Paiva, R. C. D. D., Meller, A., Teixeira, A. D. A., Araújo, A. A., Fuckner, M. A., & Biggs, T. (2022). Global Evapotranspiration Datasets Assessment Using Water Balance in South America. *Remote Sensing*, *14*(11), 2526. https://doi.org/10.3390/rs14112526

Salvia, M., Ceballos, D., Grings, F., Karszenbaum, H., & Kandus, P. (2012). Post-Fire Effects in Wetland Environments: Landscape Assessment of Plant Coverage and Soil Recovery in the Paraná River Delta Marshes, Argentina. *Fire Ecology*, *8*(2), 17–37. https://doi.org/10.4996/fireecology.0802017

Scarpati, O. E., & Capriolo, A. D. (2013). Sequías e inundaciones en la provincia de Buenos Aires (Argentina) y su distribución espacio-temporal. *Investigaciones Geográficas*, *82*, 38. https://doi.org/10.14350/rig.31903

Schiereck, G. J. (2019). *Introduction to Bed, Bank and Shore protection.* Delft Academic Press / VSSD.

Schmitz, E. (2022, August 26). Both ENDS: Fires in the Paraná Delta show urgent need for a Wetlands Law. Both ENDS. https://www.bothends.org/en/Whats-new/News/Fires-in-the-Paran%C3%A1-Delta-show-urgent-need-for-a-Wetlands-Law/

Serio, L., & Martin, P. (2007). MONTHLY RAINFALL IN BUENOS AIRES CITY (1861-2000) ANALYSED USING THE GAMMA DISTRIBUTION FUNCTION. In researchgate.net. Orientación Gráfica Editora. Retrieved January 16, 2023, from https://www.researchgate.net/publication/284030356_MONTHLY_RAINFALL_IN_BUENOS_AIRES_CITY_1861-2000_ANALYSED_USING_THE_GAMMA_DISTRIBUTION_FUNCTION

Sijmons, D. F., (Utrecht). (1991). Het casco-concept: een benaderingswijze voor de landschapsplanning. Informatie- en Kenniscentrum/NBLF.

Stehfest, E., Gernaat, D., de Boer, H. S., Daioglou, V., Doelman, J., Edelenbosch, O., Harmsen, M., van Zeist, W. J., van den Berg, M., Dafnomilis, I., van Sluisveld, M., Tableau, A., De Vos, L., de Waal, L., van den Berg, N., Beusen, A., Bos, A., Biemans, H., Zapata Castillo, V. (2021). The 2021 SSP scenarios of the IMAGE 3.2 model. *PBL Netherlands Environmental Assessment Agency*. https://doi.org/10.31223/x5cg92

Taylor, N. (2021, May 6). *Electrical Conductivity – Water Quality Measurements.* Greenspan. https://www.greenspan.com.au/2021/05/06/electrical-conductivity/

*The Parched Paraná River*. (n.d.). Earth Observatory NASA.https://earthobservatory.nasa.gov/images/147031/the-parched-parana-river

Topographic-map. (n.d.). Autonomous City of Buenos Aires. Topographic-Map.Com. Retrieved July 12, 2022, from https://en-gb.topographic-map.com/maps/a3pj/Autonomous-City-of-Buenos-Aires/

Zagare, V. M. (2012). Spatial Analysis of Climate Change Effects on Urbanized Delta Territories as a Tool for Planning: The Case of the Lower Parana Delta. The International Journal of Climate Change: Impacts and Responses, 3(4), 19–34. https://doi.org/10.18848/1835-7156/cgp/v03i04/37138

VU Amsterdam. (2015, October 1). Think Hazard - Buenos Aires - Water scarcity. Think Hazard. Retrieved July 12, 2022, from https://thinkhazard.org/en/report/429-argentina-buenos-aires/DG

Think Hazard - Buenos Aires - Urban flood. (n.d.). Think Hazard. Retrieved July 12, 2022, from https://thinkhazard.org/en/report/429-argentina-buenos-aires/UF

U.S. Army Engineer Research and Development Center. (2022). *Engineering with Nature - An Atlas.*

World Bank Group. 2021. *Brazil Population Estimates and Projections*. [Dataset]. https://databank.worldbank.org/source/population-estimates-and-projections

World Bank Group. (2021, February 26). Argentina: 500,000 People Will Have Access to Better Water, Sanitation Services and Social Housing. World Bank. Retrieved July 12, 2022, from https://www.worldbank.org/en/news/press-release/2021/02/25/medio-millon-de-personas-accederan-a-mejores-servicios-de-agua-saneamiento-y-viviendas-sociales

## APPENDIX A

Boundary conditions for the hydraulic system and parameter design choices are further elaborated below.

Extreme Design Scenarios

A water level of 3.93 + IGN corresponding with a return period of 100 years is applied as the extreme design level (according to Figure ?)(Barros, 2005). The data were measured in the port of Buenos Aires and due to the conservative value of the extreme for the return periods of annual maximum level, it is applied for the location of Tigres as well.

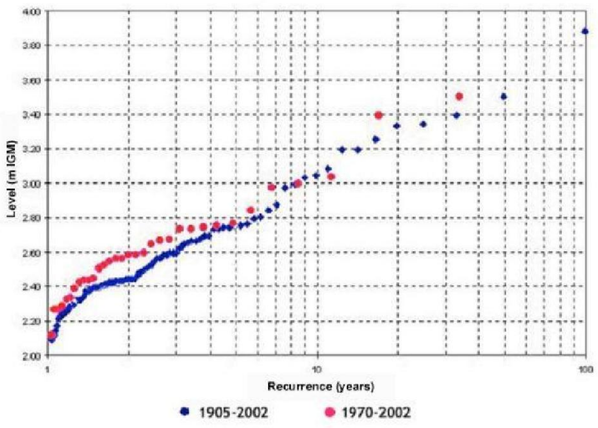


*Fig. 2.43: Return period of the annual maximum level in Buenos Aires port*

Return period of the maximum annual water level in Buenos Aires port

Sea Level Rise

According to the SSP2-scenario, the sea level rise is estimated to be almost 1 m by 2040. An interpolation to estimate the value within a service time of 100 years for climate change gives a design value of 1 m.

Waves and Set-up

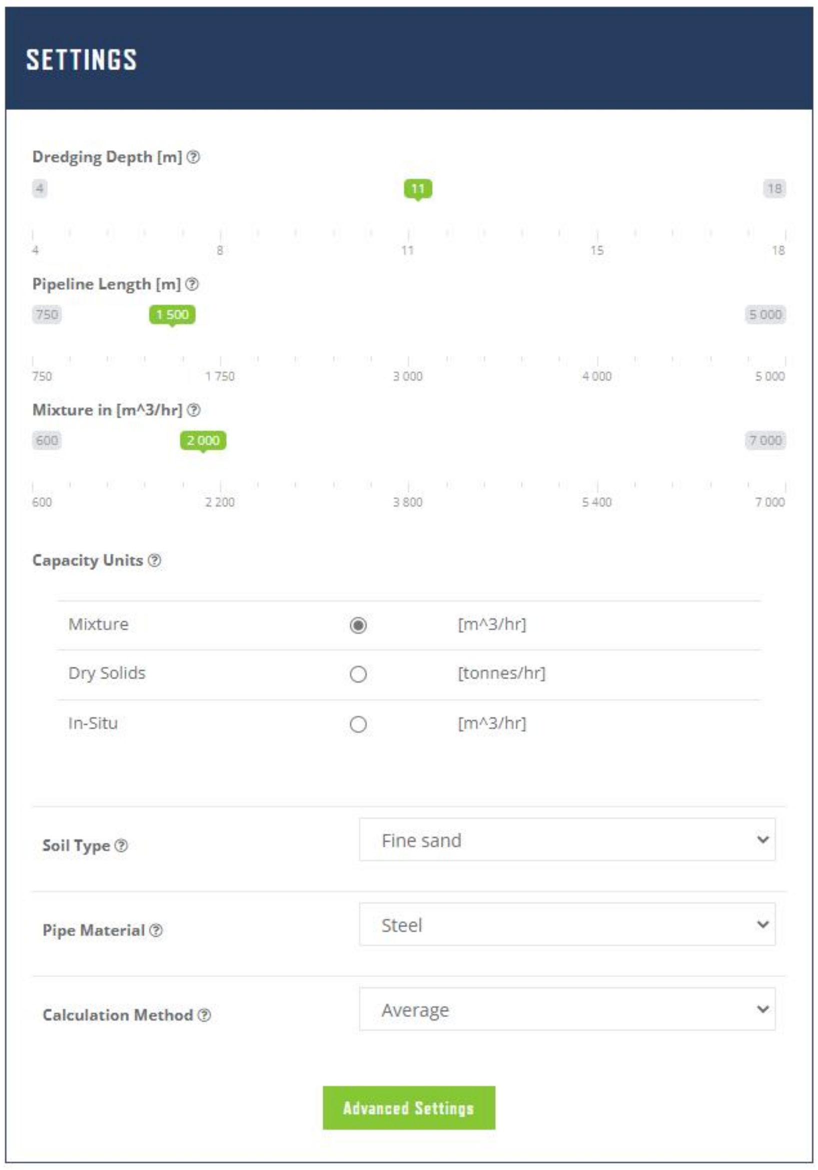
Tigres is relatively sheltered and exposure to large waves or a large set-up are not dominant when looking at a preliminary design. The southern-eastern waves however play a role in storm events.

Storm Surges (Sudestadas)

A SSH of 3.5 m was recorded in Palermo in 2000 during one of the Sudestada events. The event in 2000 was heavily influenced by southern-eastern wind speeds and the discharge being relatively high.

## APPENDIX B

To make a relatively easy estimation of the required dredging volume according to the calculated navigation depth, a project calculator is applied. The most influential parameters in this calculator are the dredging depth, the dredging path (width, length), but also the soil type, the dredging equipment and mixture characteristics. This estimation puts into perspective the efforts and the outputs and ultimately indicates how economically feasible the dredging efforts are.



SETTINGS

Dredging Depth [m]: 11

Pipeline Length [m]: 1 500

Mixture in [m^3/hr]: 2 000

Capacity Units

| | | |
|---|---|---|
| Mixture | ● | [m^3/hr] |
| Dry Solids | ○ | [tonnes/hr] |
| In-Situ | ○ | [m^3/hr] |

Soil Type: Fine sand

Pipe Material: Steel

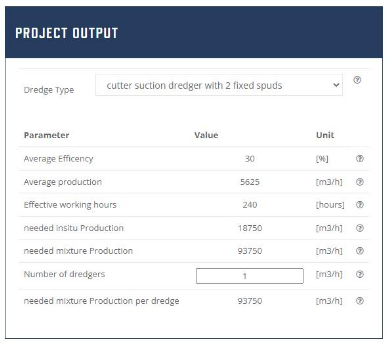
Calculation Method: Average

MIXTURE OUTPUT

| Parameter | Value | Unit |
|---|---|---|
| Density Grains | 2650 | [kg/m3] |
| In-situ Density | 1824 | [kg/m3] |
| Mixture Density | 1330 | [kg/m3] |
| Soil d50 | 0.05 | [mm] |
| Soil d85 | 0.115 | [mm] |
| SPT | 5 | [-] |
| Cvd By Volume | 20 | [%] |

DREDGER SPECIFIC OUTPUT

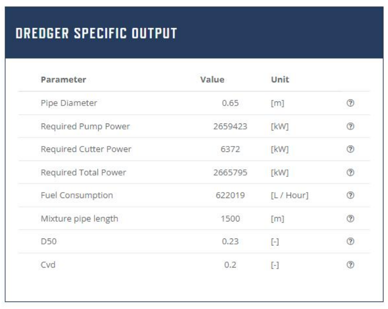
| Parameter | Value | Unit |
|---|---|---|
| Pipe Diameter | 0.45 | [m] |
| Required Pump Power | 278 | [kW] |
| Required Cutter Power | 92 | [kW] |
| Required Total Power | 369 | [kW] |
| Fuel Consumption | 86 | [L / Hour] |
| Mixture | 2000 | [m3/hour] |
| In-situ | 400 | [m3/hour] |
| Dry Solids | 1060 | [tonnes/hr] |



PROJECT OUTPUT

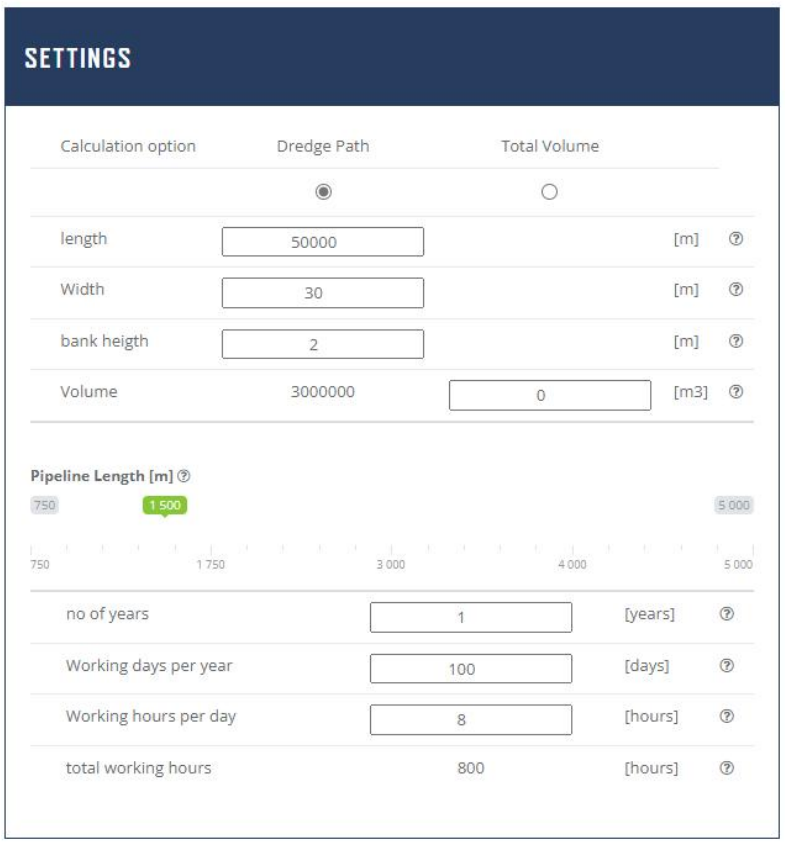
Dredge Type: cutter suction dredger with 2 fixed spuds

| Parameter | Value | Unit |
|---|---|---|
| Average Efficency | 30 | [%] |
| Average production | 5625 | [m3/h] |
| Effective working hours | 240 | [hours] |
| needed insitu Production | 18750 | [m3/h] |
| needed mixture Production | 93750 | [m3/h] |
| Number of dredgers | 1 | [m3/h] |
| needed mixture Production per dredge | 93750 | [m3/h] |



DREDGER SPECIFIC OUTPUT

| Parameter | Value | Unit |
|---|---|---|
| Pipe Diameter | 0.65 | [m] |
| Required Pump Power | 2659423 | [kW] |
| Required Cutter Power | 6372 | [kW] |
| Required Total Power | 2665795 | [kW] |
| Fuel Consumption | 622019 | [L / Hour] |
| Mixture pipe length | 1500 | [m] |
| D50 | 0.23 | [-] |
| Cvd | 0.2 | [-] |

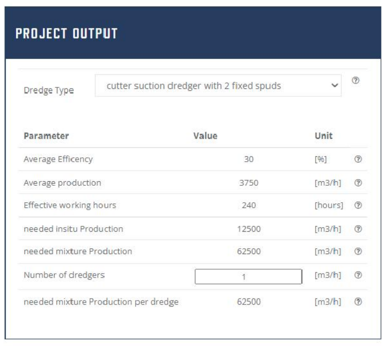


SETTINGS

| Calculation option | Dredge Path | Total Volume | |
|---|---|---|---|
| | ● | ○ | |
| length | 50000 | | [m] |
| Width | 30 | | [m] |
| bank heigth | 2 | | [m] |
| Volume | 3000000 | 0 | [m3] |

Pipeline Length [m]: 1 500

| | | |
|---|---|---|
| no of years | 1 | [years] |
| Working days per year | 100 | [days] |
| Working hours per day | 8 | [hours] |
| total working hours | 800 | [hours] |



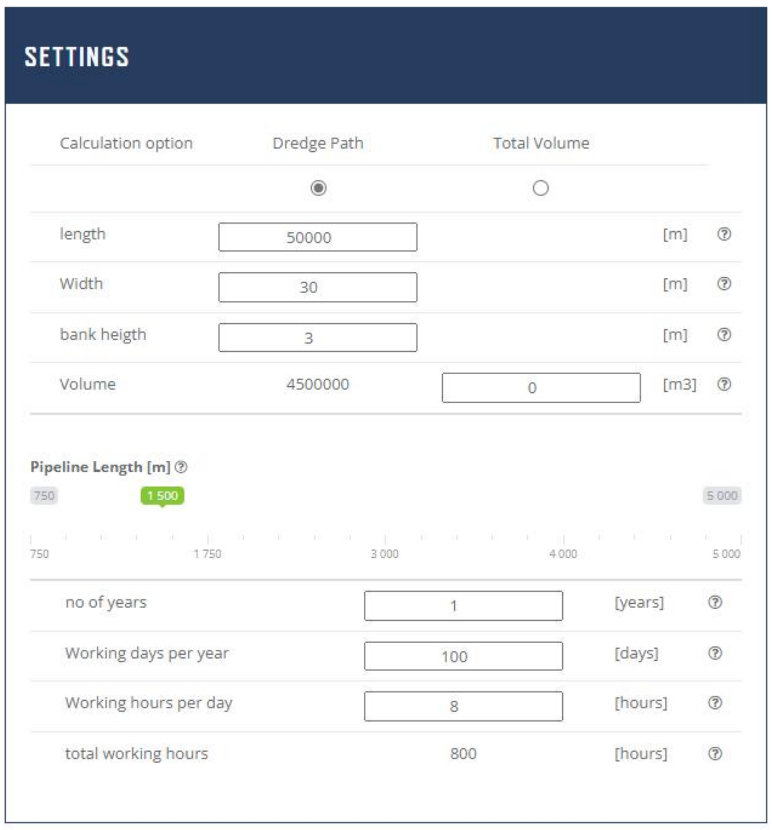
PROJECT OUTPUT

Dredge Type: cutter suction dredger with 2 fixed spuds

| Parameter | Value | Unit |
|---|---|---|
| Average Efficency | 30 | [%] |
| Average production | 3750 | [m3/h] |
| Effective working hours | 240 | [hours] |
| needed insitu Production | 12500 | [m3/h] |
| needed mixture Production | 62500 | [m3/h] |
| Number of dredgers | 1 | [m3/h] |
| needed mixture Production per dredge | 62500 | [m3/h] |

DREDGER SPECIFIC OUTPUT

| Parameter | Value | Unit |
|---|---|---|
| Pipe Diameter | 0.65 | [m] |
| Required Pump Power | 812793 | [kW] |
| Required Cutter Power | 4248 | [kW] |
| Required Total Power | 817040 | [kW] |
| Fuel Consumption | 190643 | [L / Hour] |
| Mixture pipe length | 1500 | [m] |
| D50 | 0.23 | [-] |
| Cvd | 0.2 | [-] |



SETTINGS

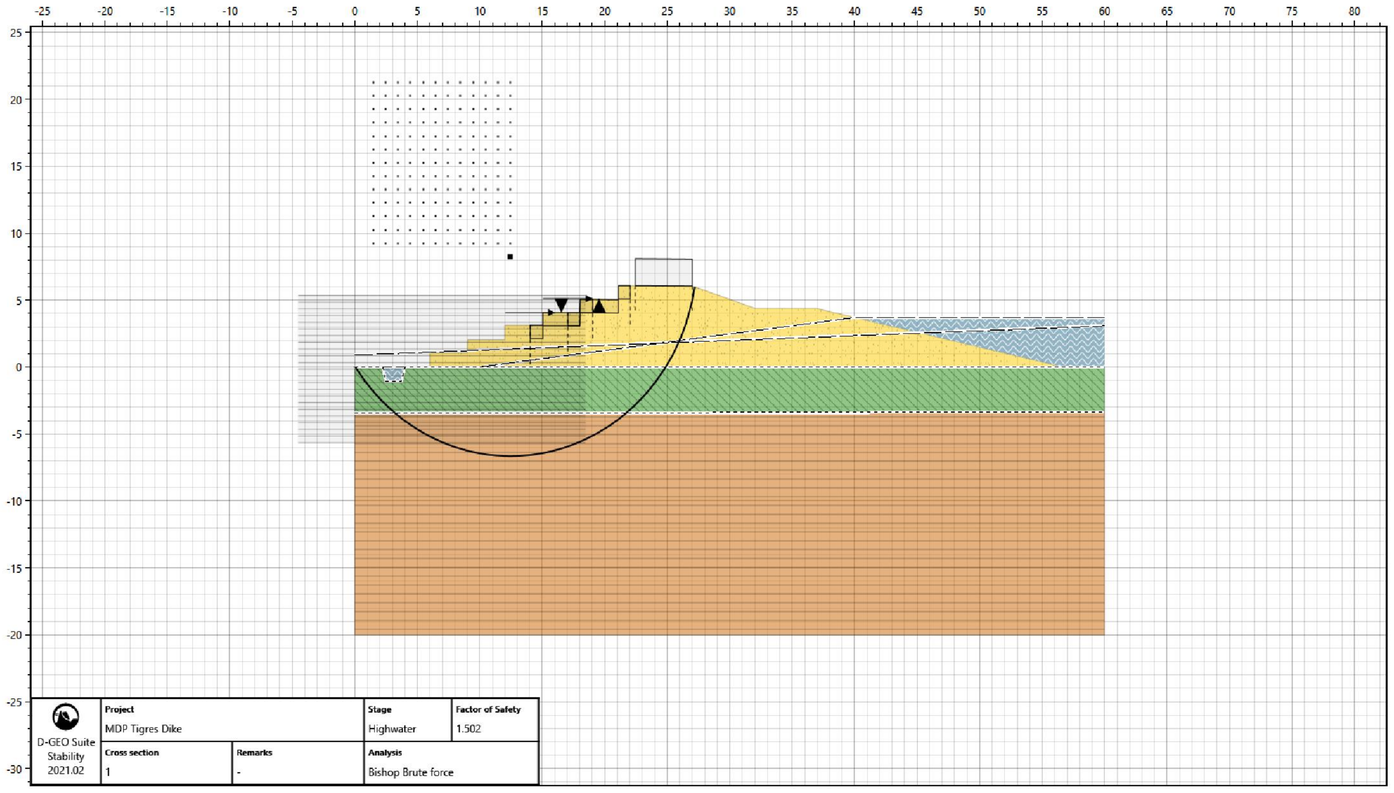
| Calculation option | Dredge Path | Total Volume | |
|---|---|---|---|
| | ● | ○ | |
| length | 50000 | | [m] |
| Width | 30 | | [m] |
| bank heigth | 3 | | [m] |
| Volume | 4500000 | 0 | [m3] |

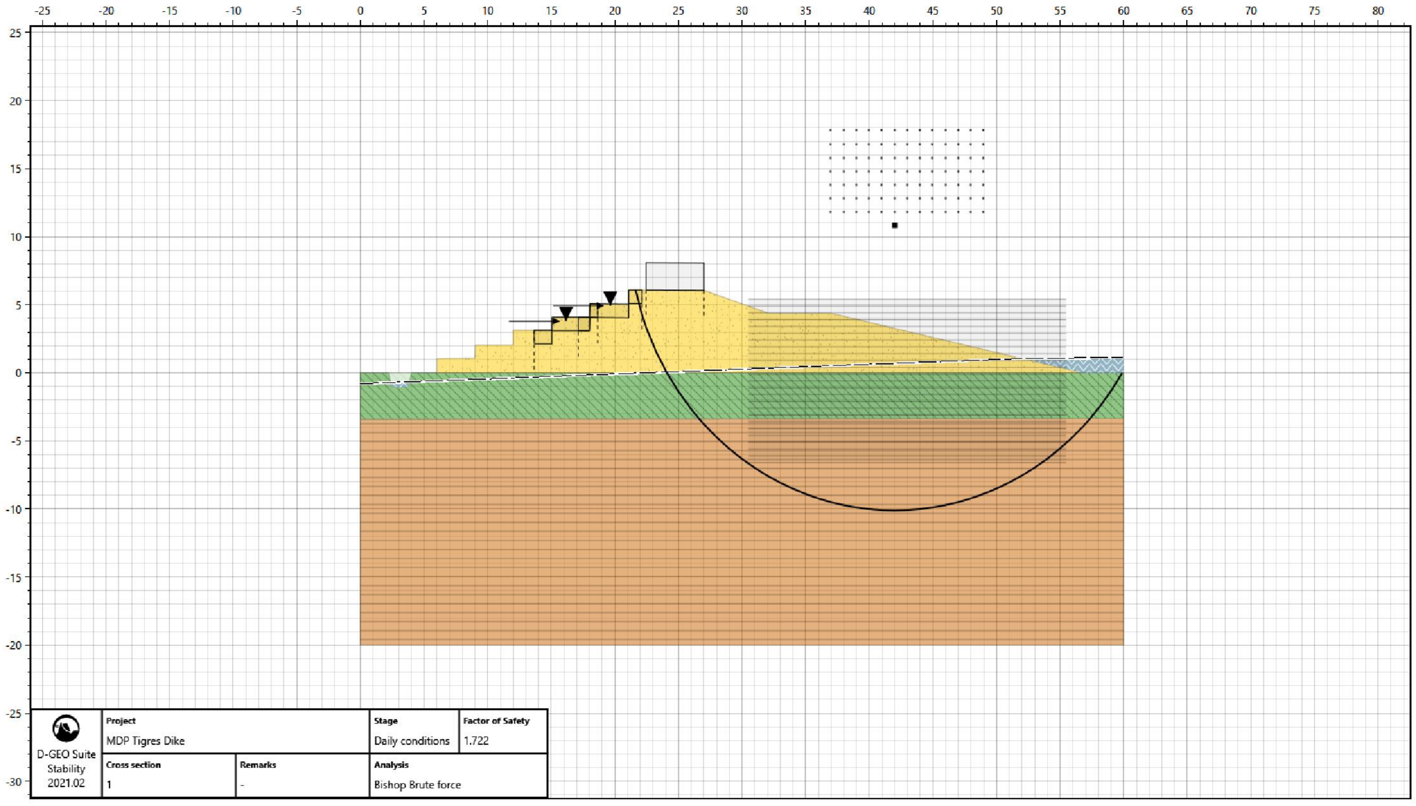
Pipeline Length [m]: 1 500

| | | |
|---|---|---|
| no of years | 1 | [years] |
| Working days per year | 100 | [days] |
| Working hours per day | 8 | [hours] |
| total working hours | 800 | [hours] |

Project calculator for an estimation of the total dredging volume. Figure: (EDDM, sd)

# APPENDIX C





Macrostability model in D-stability: High water and low water

## APPENDIX D

Design Discharge Calculation

The discharge over the rough broad crested weir, which is described by the formula below,

$$Q = C_d * (\frac{2}{3})^{3/2} * g^{1/2} * B * h_1^{3/2}$$

in which:

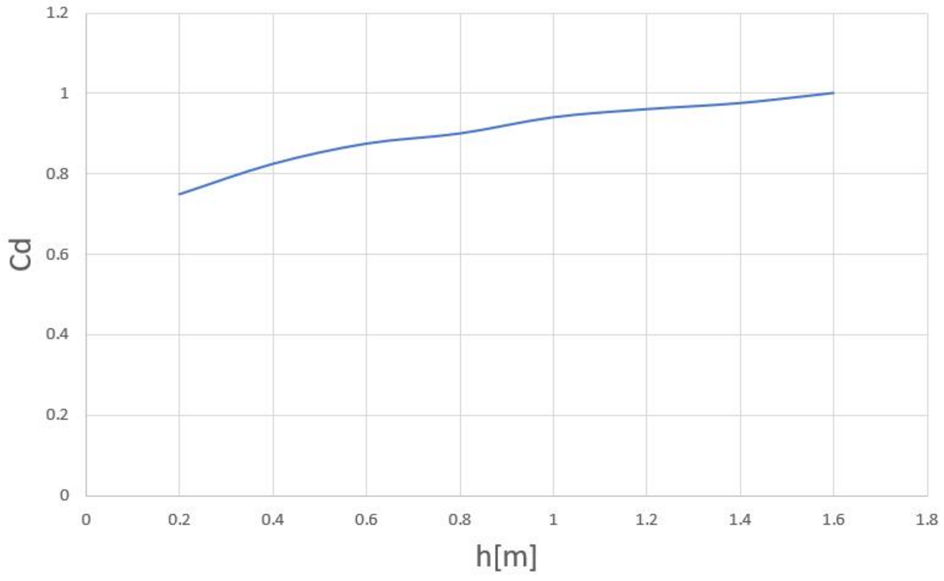
$C_d$ is the discharge coefficient

$B$ is the width of the weir

$h_1$ is the water level of the river above the height of the weir

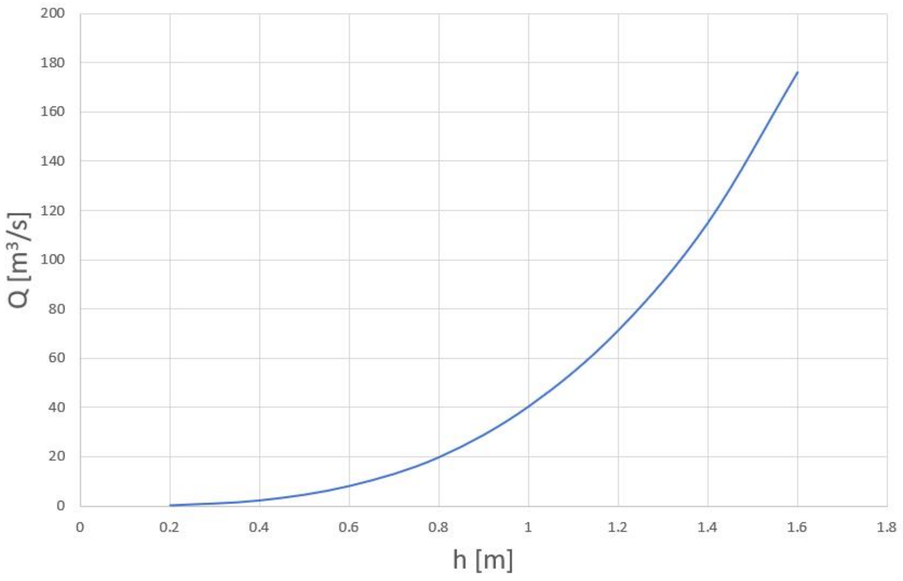
$Q$ is the overflow discharge through the weir

It is noticeable that in hydraulic calculations it is usually assumed the overflow surface is very smooth, but in our case the idea of placing rocks as bed protections on the top would influence the discharge coefficient in the formula above. According to experimental research of the selected scenarios on the effect of weir surface roughness on the discharge coefficient (Pařílková et al., 2012) that fits into our case, the following graph for $C_d$ can be applied in the formula above.



Discharge coefficient related to overflow head

Discharge can now be plotted against the water level over the spillway.



Head-discharge relations

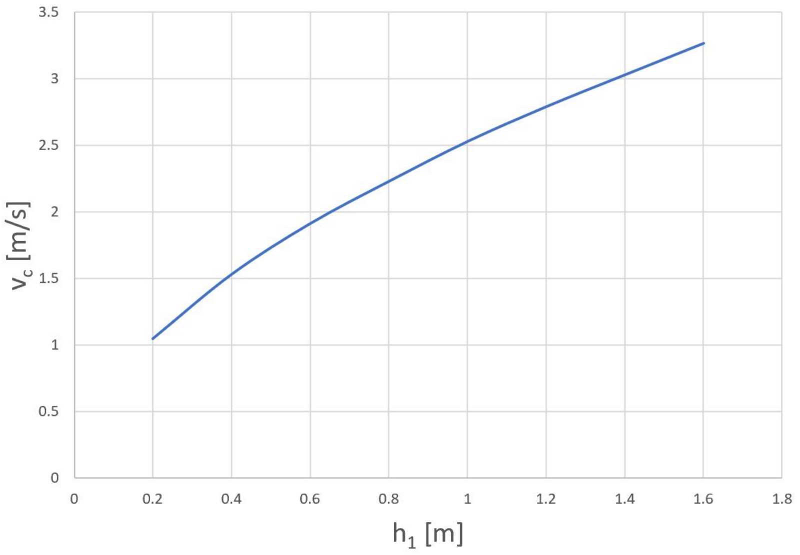
With the chosen design of the spillway, the maximum value of $h_1$ is equal to 1 meter, so the maximum discharge over the weir is equal to approximately 40 m3/s. The corresponding flow velocity has been calculated:

$$v_c = \frac{Q}{B*h_c}$$

With the critical flow depth on the top of the crest

$$h_c = (\frac{Q^2}{gB^2})^{1/3}$$

The critical velocity with regards to the overflow head can now be seen in the graph below:



Velocity-head relations

## APPENDIX E

Rock Grading Calculation

The general rock grading equation is as below, using a Shields method (Schiereck, 2012):

$$d_{n50} = \frac{K_v^{2} * \bar{u}_c^{2}}{K_s * \psi_c * \Delta * C^2}$$

Where:

- $D_{n50}$ is the nominal diameter of the rock grading [m]
- Kv is a velocity factor [-]
- $\bar{u}_c$ is the critical flow velocity over the spillway
- $K_s$ is a correction factor for the slope, in our case $K_s$=1 since we have a flat bed
- $\psi_c$ is the critical Shields parameter, in our design we maintain a safe value of $\psi_c = 0.03$
- Δ is the submerged weight of the rocks, typically $\Delta = 1.65$
- $C$ is the Chezy coefficient, describing the roughness of the bed

Since we want to design a bed protection that can resist the most unfavorable condition, the $\bar{u}_c$ can be taken as the maximum velocity we assume which is 2.5 m/s from the velocity graphs above.

The Chezy coefficient is commonly determined with the following relation:

$$C = 18 log(12R/K_r)$$

$$with\ K_r \approx 2d_{n50}$$

For the top of the spillway which is flat, $K_s = 1$. Due to the acceleration on the top, there is an increase in shear stress and a decrease of turbulence which makes $K_v = 1$. Here we can do iteration with $\psi_c$ of 0.03. Chezy value of 37 is chosen corresponding to the vegetated bank. Then $d_{n50} = 0.15\ m$ is calculated.

## APPENDIX F

*This is a direct excerpt from a separate report produced by the Water Management students.*

### Flood Risk

Another water related problem is flood risk. All area's in the scope of the project cope with a high urban flood risk. Although we are not entirely certain how the sea level rising will affect the Sudestadas, we can make an educated guess based on the model by Dinápoli and his colleagues. As previously discussed their model had a strong correlation between sea level and the effect on *sudestadas*. (Dinápoli et al., n.d.) If this is the case then when the sea level rises further the effect of Sudestadas will get worse and the areas will flood more often. Therefore adequate steps must be taken such as making room for the river and improving flood defenses at key economic areas where a natural solution is not possible. This hybrid defense should be a key component of the future landscape and architectural design of the region. (Think Hazard, n.d.; (Dinápoli, Simionato & Moreira, n.d.).

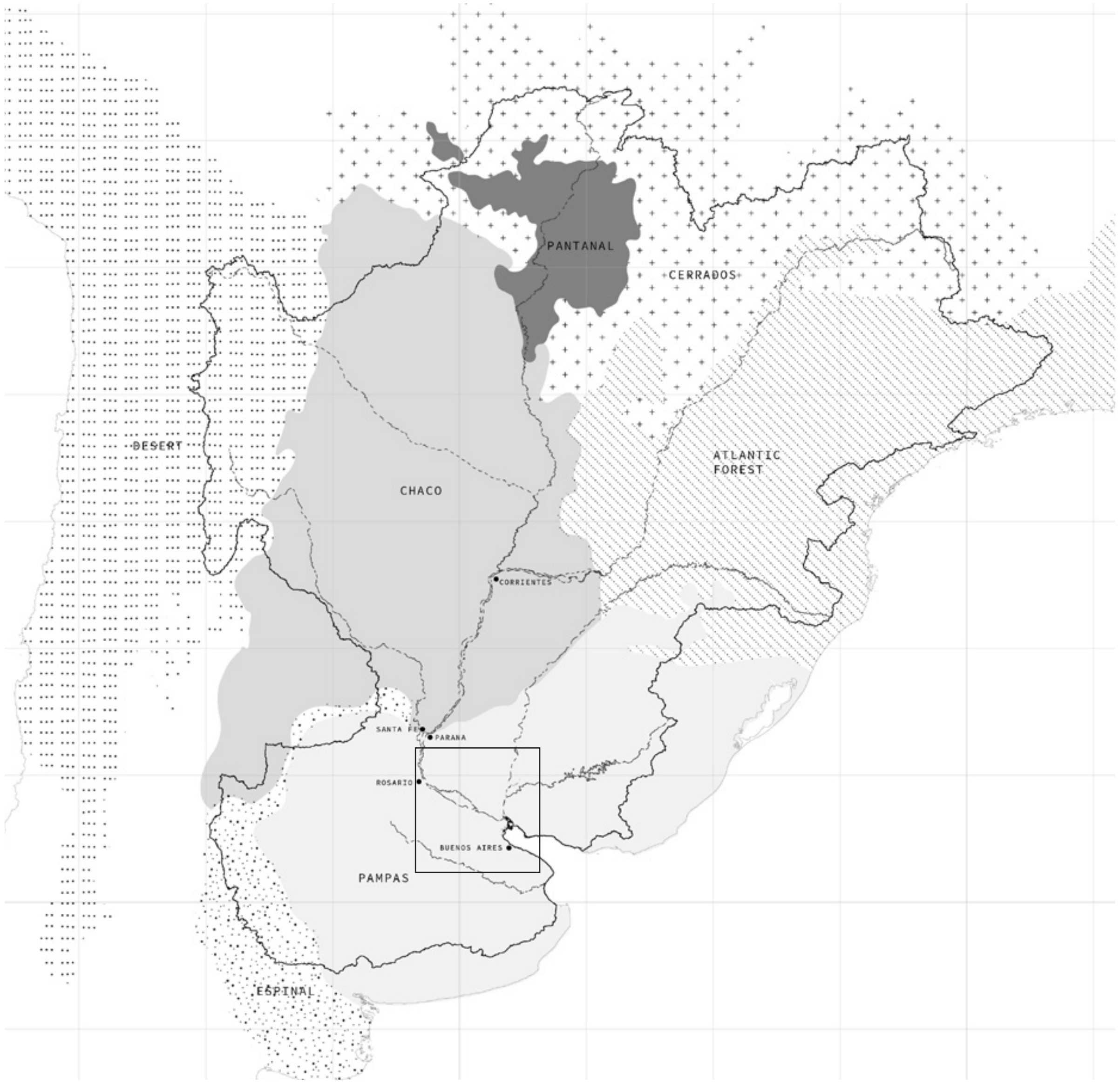
### Drought and Diplomacy

In the scope area the water scarcity was classified as medium in 2015. This meant concretely that for every project droughts must be considered regarding personnel, stakeholders, and the design of the project. In the future it was unclear what would happen to the water scarcity since the current model projections are inconsistent in their estimates of change in the drought hazard. (VU Amsterdam, 2015) Though lately we have seen an enormous drought increase. Two intensely dry years have come to pass. Although this is something that is not easily solvable, the countries of Argentina, Brazil and Paraguay could try to use diplomacy to limit the use of water in the river. All drought that occurs has an immediate effect on the river discharge because the usage of water from the river will not decrease if there is less water availability. This is why the countries should try to limit their water usage of the Parana river delta. This can be done by giving the river its own entity, thereby helping the river to defend itself from pollution, too much water extraction, land transformations and overfishing. Lands used for cattle should be transformed back to nature or farmlands for crops which use a meagrely amount of water. New lands downstream in the delta should be used for nature using little reservoir lakes to retain the water or create farmlands for crops.

# APPENDIX G

## biome

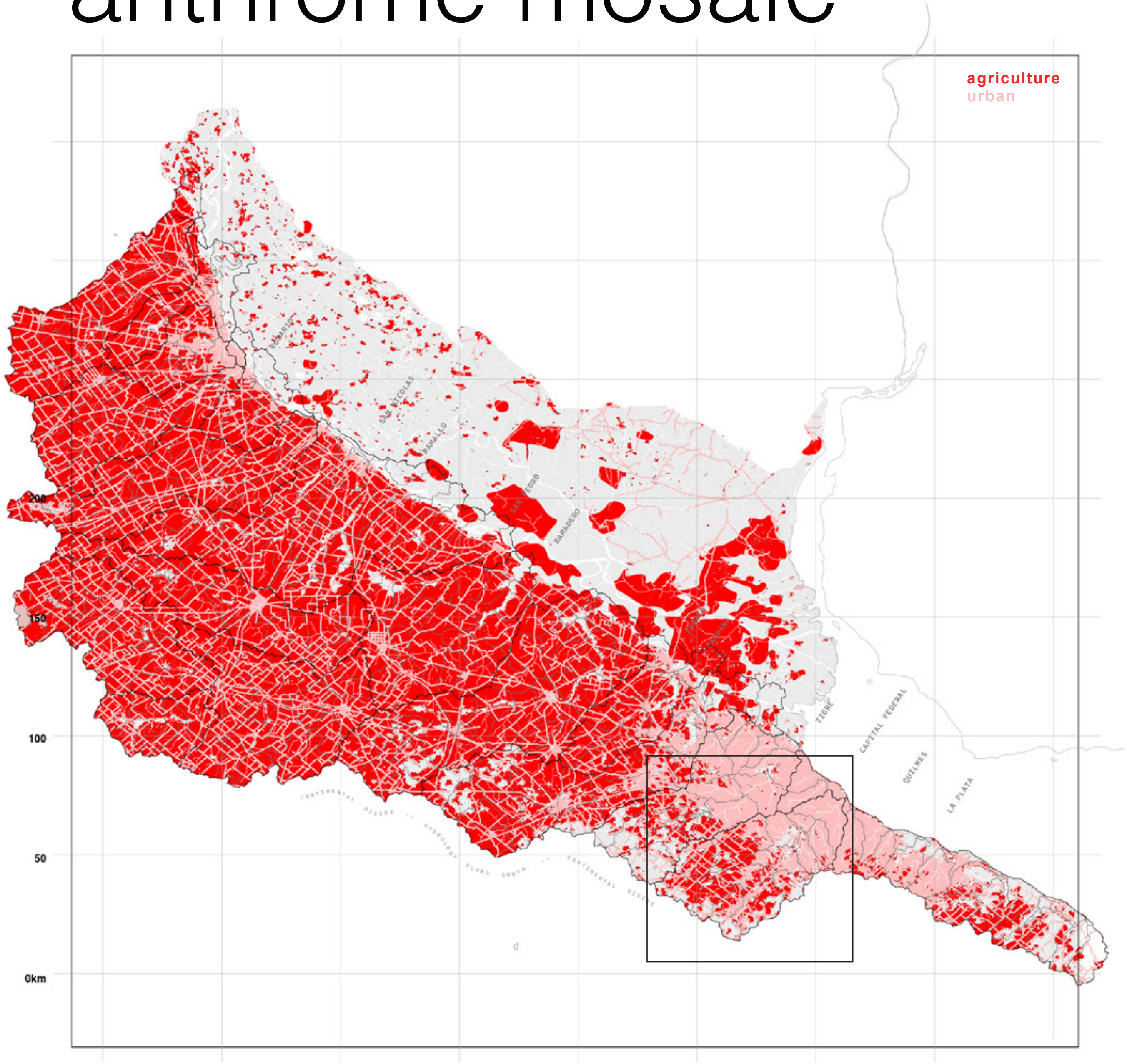
**Biomes of the Rio de la Plata Basin. Buenos Aires is located within the Pampas, a region of native grasslands and seasonal wetlands. Intensive agriculture, mostly in the form of soybean monocultures and cattle farming, has displaced much of the native biodiversity in this ecosystem.**



even the “green” (shown in grey) areas are anthromes due to their related influence from human activity. they are highly fragmented.

landscape as

# anthrome mosaic



## anthrome

Between Rosario and Buenos Aires, a 350 kilometer axis along the continental edge of the Parana Delta, approximately 40% of the Argentine population and more than 60% of economic activity is located. Historically, the delta, a 15,000km2 area of wetlands and submerged forests, has been isolated from much of the frenzied anthropic activity on the continent. In recent decades however, human presence in the form of poldered tree plantations has become increasingly prevalent. This land use form is detrimental to the complex biodiversity within the delta as it disrupts the hydrological cycle by cutting off vast stretches from the Parana River’s flow regime.

Agriculture is responsible for 30% of all greenhouse gas emissions within Argentina. Urban areas like the Buenos Aires Metro Region continues to sprawl outward, paving over land, compacting soil, homogenizing ecosystems and generating immense amounts of waste. 96% of this waste is sent to landfill, generating high amounts of methane and carbon.