Coastal Flooding General Problem

Coastal flooding occurs when seawater inundates low-lying coastal areas. This can be caused by several factors, including:

- Storm Surges[1]: High water levels generated by strong winds and low atmospheric pressure (such as cyclones) during storms. In simple terms, storm surge is sea water being pushed on shore from the sea (Fig.1).

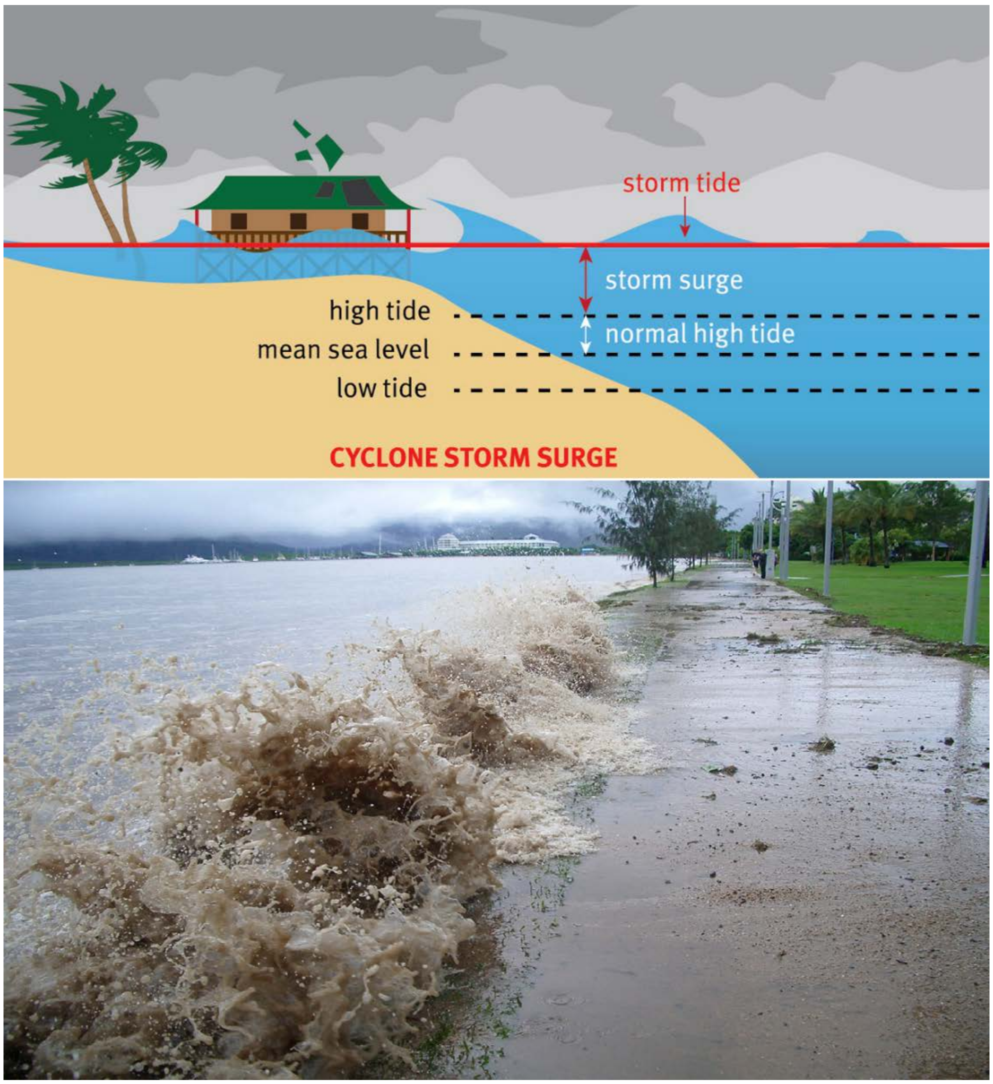

Fig.1: Storm surge flooding example in Australia[2].

[1] https://www.nature.com/articles/ncomms11969

[2] https://www.ses.qld.gov.au/storm-surge & https://www.cairns.qld.gov.au/council/news-notices/media-releases/media-releases/storm-surge

- High Tides[3]: Naturally occurring high tides that, when combined with storm surges, lead to extreme water levels (Fig.2).

Fig.2: High tide flooding example in Guernsey island (between France and UK)[4].

[3] https://repository.library.noaa.gov/view/noaa/17403
[4] https://www.islandfm.com/news/guernsey/high-tide-closes-st-peter-port-seafront/

- Sea Level Rise[5]: Long-term increases in sea level driven by climate change and melting icebergs, which is a slow-pace phenomenon, although accelerated by the quickly changing climate (Fig.3).

Fig.3: Sea Level Rise risk zones in Port Adelaide (upper), and New South Wales, Australia [6].

[5] https://link.springer.com/article/10.1057/s41278-018-0114-z
[6] https://www.unisa.edu.au/unisanews/2019/october/story10/

- Wave Overtopping[7]: When breaking waves carry water over coastal defenses.

Fig.4: Wave Overtopping flooding example in the Isle of Man[8].

The impacts of coastal flooding, of all types, can be significant and include property damage, loss of life, environmental degradation, and disruption of local communities.

Below, we discuss some major common types, for the case of a port:

- **Storm surge** – driven by meteorological forces (e.g., low pressure and high winds) that push seawater onto the coast;
- **Sea-level rise**, climate change – induced, e.g. icebergs melting;
- **High tides** – naturally occurring;
- **Rainfall contribution** – a precipitation event running off into the sea, directly adding water (*during a heavy precipitation event, rainfall directly accumulates on impervious surfaces like a concrete port, where runoff cannot infiltrate. This sudden input of water adds to the local water level, effectively contributing an extra height to the flood water, similar to a small surge*).

[7] https://www.sciencedirect.com/science/article/abs/pii/S0378383914000775 & https://www.nature.com/articles/s41598-023-32175-6

[8] https://www.iomtoday.co.im/news/significant-coastal-overtopping-and-some-flooding-expected-at-high-tide-on-sunday-677761

In the general problem we present below, we model (Fig.5):

- the natural bathymetry (seafloor) with a gentle slope, reaching the port (an engineered structure representing the port)
- the engineered port, where ships dock, which is modelled like a rectangular structure,
- the sea-level surface.

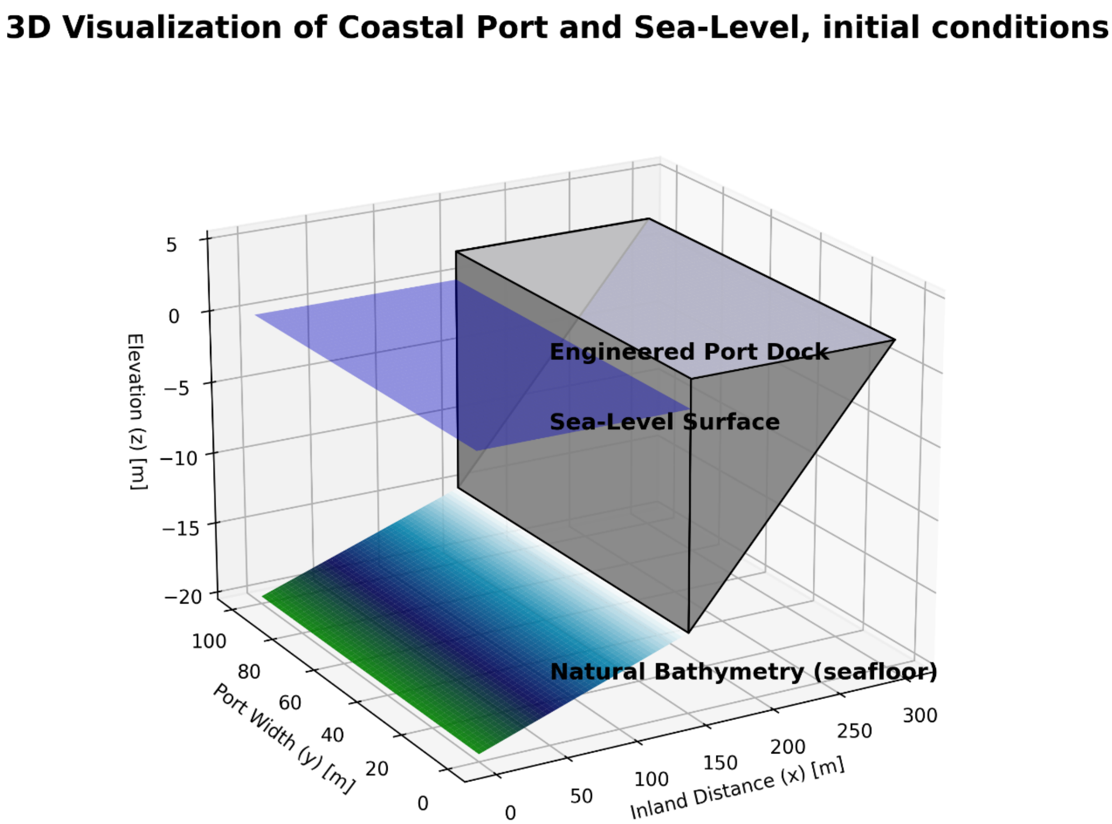

Fig.5: The 3D model's components at initial conditions, with sea-level at the elevation of z=0.

We will explore two cases: one where flooding is caused by a storm and another where flooding is due to sea-level rise.

In both cases, we also introduce a simple relation to account for rainfall changes (or, more generally, climate characteristics, e.g. climate change – induced rainfalls, that might add to the water level).

Simple Storm Surge port flooding example

In our port system, flooding is driven by a combination of:

- **Astronomical Tide n_{tide}** : The normal sea level considering the tidal levels and water movements resulting solely from the gravitational forces of the earth, sun, and moon, without any atmospheric influences.
- **Storm Surge n_{surge}** : The additional water elevation due to a storm.
- **Rainfall P**: Which contributes extra water, modeled here with a conversion factor b.

The **effective water level (n)** is the sum of these contributions. Flooding occurs when this water level exceeds the local floor elevation. In our case, the domain is divided into two regions (see Fig.5):

1. **Sea – side, with the Sea and the Natural Bathymetry (Seafloor):**
   - Bathymetry extends from x=0 to x=150.
   - The seafloor slopes gently from −20m at x=0 to −15m at x=150.
   - This region is naturally underwater (with sea level defined at z=0).
2. **Engineered Port Floor (Dock Area):**
   - Extends from x=150 to x=300 and y=0 to y=100.
   - It is built up to a constant elevation of 2m.
   - Under normal conditions (initial conditions – Fig.5, where the sea-level is at z=0), this area is dry. Flooding occurs when **n>2m**.

When a storm surge (and additional rainfall) occurs, the effective water level may rise above these thresholds. The extent and depth of flooding in the engineered port area (and over the natural seafloor) can be estimated by comparing **n** with the floor elevation.

General Equations of this problem:
Effective Water Level: $n = n_{tide} + n_{\text{surge}} + bP$ where: • n_{tide} is the astronomical tide level (m). • n_{surge} is the storm surge (m). • P is the rainfall amount (in mm), and **b** is the conversion factor (m of sea-level rise per mm of rainfall).
Flooding Condition and Depth: • At a location (x,y) with a floor elevation z(x,y), flooding occurs if **n>z(x,y)** • The water depth (or flood depth) d(x,y) is then given by: d(x,y) = max (n – z(x,y), 0)
Flooded Area: The total flooded area Af is computed by integrating over the region where the condition is met: $$A_f = \int_{[(x,y):n>z(x,y)]} dxdy$$ This is the general approach for a flooded area, if needed. In our case, where the port is at a stable elevation, we do not need to estimate this (the engineered port floor is a defined rectangular area, so if the entire region is overtopped, the flooded area is simply its area). In other cases, where the boundaries are defined, it can be a simpler area estimation.

Example:

We assume three scenarios of storm surge severity, a mild (e.g. RCP2.6), a moderate (RCP4.5-6.0) and an extreme (RCP8.5). The table below sets indicative values for the parameters, as defined above. The ones changing under each scenario are the $\boldsymbol{n_{\mathbf{surge}}}$ and the $\boldsymbol{P}$ (the coloured cells in each case).

The b parameter is assigned a typical value for small, poorly drained basins[9]. In a confined port area with limited drainage, much of the rainfall might contribute to a rapid water level increase[10]. A common assumption is that about 1 mm of rainfall translates roughly into a 1 mm (or 0.001 m) increase in the local water level[11].

Simple Storm Surge port flooding example

Parameter	Symbol	Values	Units	Notes	Scenario
Astronomical Tide	n_tide	0.4	m	Above the z=0, initial conditions sea-level	Mild (e.g. RCP 2.6)
Storm Surge	n_surge	0.7	m		
Rainfall	P	80	mm	At the location of the port	
Rainfall conversion factor	b	0.001	m/mm	Typical value for small, poorly drained basins (port)	
Rainfall contribution	b*P	0.08	m		
Effective water level	$n = n_{tide} + n_{surge} + bP$	1.18	m		
Flooding	dport(x=150,y)	1.18	m	No flooding (water depth d < z port, 2m). **Difference:**	**-0.82**
Parameter	**Symbol**	**Values**	**Units**	**Notes**	
Astronomical Tide	n_tide	0.4	m	Above the z=0, initial conditions sea-level	Moderate (e.g. RCP 4.5-6.0)
Storm Surge	n_surge	1	m		
Rainfall	P	110	mm	At the location of the port	
Rainfall conversion factor	b	0.001	m/mm	Typical value for small, poorly drained basins (port)	
Rainfall contribution	b*P	0.11	m		
Effective water level	$n = n_{tide} + n_{surge} + bP$	1.51	m		
Flooding	dport(x=150,y)	1.51	m	No flooding (water depth d < z port, 2m). **Difference:**	**-0.49**
Parameter	**Symbol**	**Values**	**Units**	**Notes**	
Astronomical Tide	n_tide	0.4	m	Above the z=0, initial conditions sea-level	Extreme (e.g. RCP 8.5)
Storm Surge	n_surge	1.6	m		
Rainfall	P	150	mm	At the location of the port	
Rainfall conversion factor	b	0.001	m/mm	Typical value for small, poorly drained basins (port)	
Rainfall contribution	b*P	0.15	m		
Effective water level	$n = n_{tide} + n_{surge} + bP$	2.15	m		
Flooding	dport(x=150,y)	2.15	m	Yes, flooding (water depth d > z port, 2m). **Difference:**	**0.15**

In the mild scenario, there we have $n_{tide} = 0.4m,\ n_{\mathrm{surge}} = 0.7m,\ and\ P = 80mm$, leading to a sea-level rise of z=1.18m above the initial conditions (z=0). There is no flooding, as this is 0.82m below the 2m-tall port.

In the moderate scenario, there we have $n_{tide} = 0.4m,\ n_{\mathrm{surge}} = 01m,\ and\ P = 110m$, leading to a sea-level rise of z=1.51m above the initial conditions (z=0). There is no flooding, as this is 0.49m below the 2m-tall port.

9 https://ponce.sdsu.edu/Applied_Hydrology_Chow_1988.pdf
10 https://coast.noaa.gov/slr/ & https://www.ipcc.ch/report/ar6/wg1/
11 https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.3803 & https://www.nature.com/articles/ncomms11969 & https://iopscience.iop.org/article/10.1088/1748-9326/7/1/014032

In the extreme scenario, there we have $n_{tide} = 0.4m,\ n_{\text{surge}} = 1.5m,\ and\ P = 150mm$, leading to a sea-level rise of z=2.15m above the initial conditions (z=0). There is flooding, as this is 0.15m above the 2m-tall port.

These scenarios are shown in Fig.6.

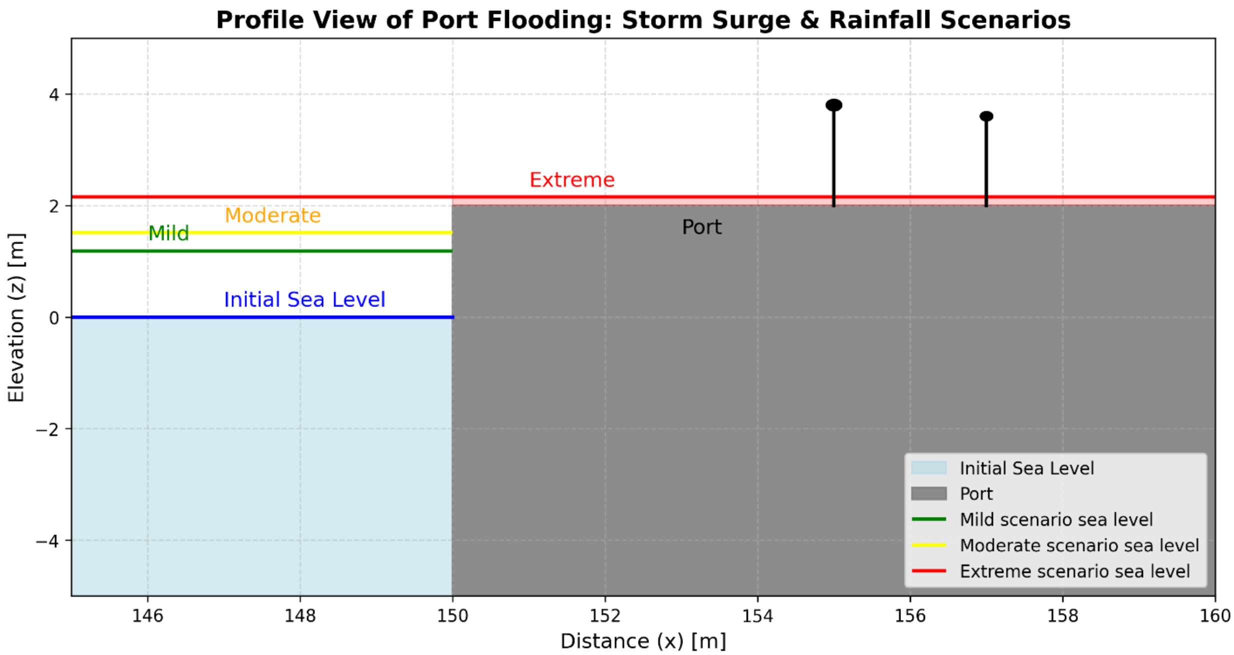

Fig.6: The port flooding under the three examined scenarios, mild (+1.18m, no flooding), moderate (+1.51m, no flooding), and extreme (+2.15m, causing flooding by 0.15m over the port). The figures on the port structure represent a man 1.80m – tall and a woman 1.60m – tall, for comparison purposes of the flooding.

Simple Sea-level rise port flooding example

In our port system, flooding is driven by a combination of a potential tide and a sea-level rise. In this example, the flooding is caused not by a temporary storm surge but by a long-term rise in the baseline sea-level, which is a concern for many areas, as climatic changes might speed up sea-level rises worldwide[12]. Over time, as the water level increases, areas that were once dry, such as the engineered port dock of our example, may become inundated. This sea-level rise is modeled as an annual increment determined by a climatic coefficient[13]. In this case, we have a combination of the following flood drivers:

- **Astronomical Tide $\boldsymbol{n_{tide}}$** : The normal sea level considering the tidal levels and water movements resulting solely from the gravitational forces of the earth, sun, and moon, without any atmospheric influences.
- **Sea-level rise $\boldsymbol{\Delta n_{\mathrm{slr}}}$** : A gradual increase modeled as $\boldsymbol{\Delta n_{\mathrm{slr}} = c \cdot t}$

Where, c is the annual sea-level rise rate (in m/year), and t is the time in years from the baseline (t=0).

The **effective water level n(t)** is the sum of these contributions:

$$\boldsymbol{n(t) = n_{\mathrm{tide}} + c \cdot t}$$

Flooding occurs when this water level exceeds the local floor elevation.

Our geometry remains same as in the previous example:

- The sea-side (z=0m) and the Natural Bathymetry (Seafloor) are same as in the previous example.
- Engineered Port Floor (Dock Area), is the same build-up area to the constant elevation of 2m. Under the normal conditions (initial conditions – Fig.5, where the sea-level is at z=0), this area is dry. However, as n(t) increases due to sea-level rise, once **n(t)>2m**, flooding will occur in the port area.

When a storm surge (and additional rainfall) occurs, the effective water level may rise above these thresholds. The extent and depth of flooding in the engineered port area (and over the natural seafloor) can be estimated by comparing **n** with the floor elevation.

General Equations of this problem:
Effective Water Level: $\boldsymbol{n(t) = n_{tide} + \Delta n_{\mathrm{slr}} = n_{\mathrm{tide}} + c \cdot t}$ where: • $\boldsymbol{n_{tide}}$ is the astronomical tide level (m). • $\boldsymbol{\Delta n_{\mathrm{slr}}}$ is the difference in the sea-level rise (m) from the baseline (t = year 0) until the studied moment (t = studied year). • **c** is the annual sea-level rise rate (in m/year).
Flooding Condition and Depth: • At a location (x,y) with a floor elevation z(x,y), flooding occurs if **n>z(x,y)**, for any year t. • The water depth (or flood depth) d at any year t is expressed by: d(x,y,t) = max [n(t) – z(x,y), 0)

[12] https://www.nature.com/articles/nclimate3325
[13] https://www.nature.com/articles/nclimate2159

Example:

We assume the same three scenarios of sea-level rice pace, a mild (e.g. RCP2.6), a moderate (RCP4.5-6.0) and an extreme (RCP8.5), for a time horizon of t=100 years. The table below sets indicative values for the parameters, as defined above. The one parameter changing under each scenario is the c factor (the coloured cells in each case).

The c parameter is assigned typical values of projected sea-level rises for different scenarios, ranging from 1cm/year (mild) to 1.5cm/year (moderate) and to 1.8cm/year (extreme).

Simple Sea-level rise port flooding example					
Parameter	**Symbol**	**Values**	**Units**	**Notes**	**Scenario**
Astronomical Tide	n_tide	0.5	m	Above the z=0, initial conditions sea-level	Mild (e.g. RCP 2.6)
Sea-Level annual rate	c	0.01	m	Typical value of 1 cm per year	
Time Elapsed	t	100	years	Baseline t=0	
Sea-level rise in t=100	Δn_slr	1	m		
Effective water level	n(t=100)	1.5	m	At the port location	
Flooding, t=100	dport(x=150,y)	1.5	m	No flooding (water depth d < z port, 2m). **Difference:**	**-0.5**
Parameter	**Symbol**	**Values**	**Units**	**Notes**	Moderate (e.g. RCP 4.5 - 6.0)
Astronomical Tide	n_tide	0.5	m	Above the z=0, initial conditions sea-level	
Sea-Level annual rate	c	0.015	m	Typical value of 1.5 cm per year	
Time Elapsed	t	100	years	Baseline t=0	
Sea-level rise in t=100	Δn_slr	1.5	m		
Effective water level	n(t=100)	2	m	At the port location	
Flooding	dport(x=150,y)	2	m	Marginal flooding (d = z port, 2m). **Difference:**	**0**
Parameter	**Symbol**	**Values**	**Units**	**Notes**	Extreme (e.g. RCP 8.5)
Astronomical Tide	n_tide	0.5	m	Above the z=0, initial conditions sea-level	
Sea-Level annual rate	c	0.018	m	Typical value of 1.8 cm per year	
Time Elapsed	t	100	years	Baseline t=0	
Sea-level rise in t=100	Δn_slr	1.8	m		
Effective water level	n(t=100)	2.3	m	At the port location	
Flooding	dport(x=150,y)	2.3	m	Yes, flooding (water depth d > z port, 2m). **Difference:**	**0.3**

In the mild scenario, there we have $n_{tide} = 0.5m \; and \; c = 0.01m$, leading to a sea-level rise of z=1.5m above the initial conditions (z=0). There is no flooding, as this is 0.5m below the 2m-tall port, in t=100.

In the moderate scenario, there we have $n_{tide} = 0.5m \; and \; c = 0.015m$, leading to a sea-level rise of z=2m above the initial conditions (z=0). This reaches exactly the level of the 2m-tall port, in t=100, making it unsuitable for further operation.

In the extreme scenario, there we have $n_{tide} = 0.5m \; and \; c = 0.018m$, leading to a sea-level rise of z=2.3m above the initial conditions (z=0). There is flooding, as this is 0.30m above the 2m-tall port in t=100, making it unsuitable for further operation.

These scenarios are shown in Fig.7.

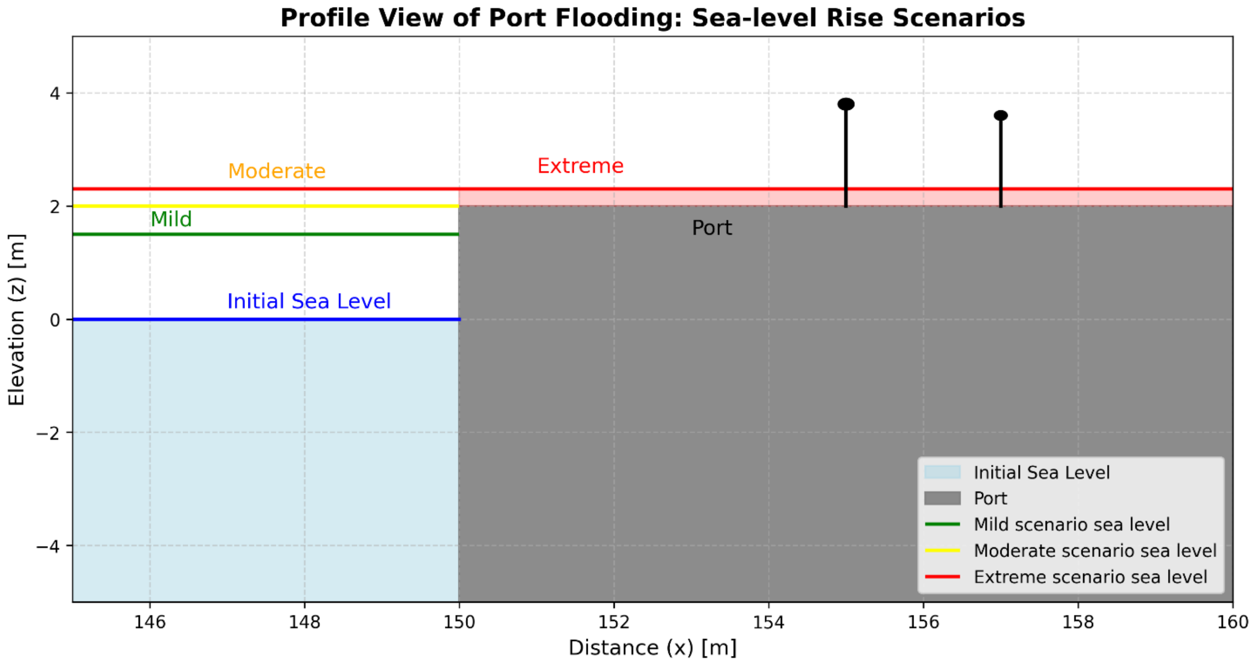

Fig.7: The port flooding under the three examined scenarios, mild (+1.5m, no flooding), moderate (+2m, marginal flooding), and extreme (+2.3m, causing flooding by 0.30m over the port). The figures on the port structure represent a man 1.80m – tall and a woman 1.60m – tall, for comparison purposes of the flooding.

Simple combination example: Sea-level rise and a Storm Surge causing port flooding

In reality, coastal flooding can be exacerbated by the combination of gradual sea-level rise (due to climate change) and short-term extreme events (such as storm surges)[14]. As the baseline sea level increases over time, a given storm surge can result in much higher water levels relative to the engineered port floor[15]. This means that the same storm can become far more catastrophic under future climate conditions[16].

- **Astronomical Tide $\boldsymbol{n_{tide}}$**: Same as in the previous examples, for the time t.
- **Storm Surge $\boldsymbol{n_{\mathrm{surge}}}$** : The additional water elevation due to a storm, at the time t.
- **Rainfall P**: Which contributes extra water, modeled here with a conversion factor **b** (m of sea-level rise per mm of rainfall).
- **Sea-level rise $\boldsymbol{\Delta n_{\mathrm{slr}}}$** : A gradual increase modeled as $\boldsymbol{\Delta n_{\mathrm{slr}} = c \cdot t}$
  where, c is the annual sea-level rise rate (in m/year), and t is the time in years from the baseline (t=0).
- We set **t=30 years as the examined time-horizon**, in this example, in order to showcase how these risks might make a port non-usable in the short-term.

Our geometry remains same as in the previous examples, with the sea-side (z=0m) and the Natural Bathymetry (Seafloor) being same as in the previous examples.

The Engineered Port Floor (Dock Area), is the same build-up area to the constant elevation of 2m. Under the normal conditions (initial conditions – Fig.5, where the sea-level is at z=0), this area is dry. However, as n(t) increases due to sea-level rise or if there is a storm surge further raising the water level, then if the effective water level **n(t)>2m**, flooding will occur in the port area.

The **effective water level n(t)** is the sum of all these contributions:

$$\boldsymbol{n(t) = n_{\mathrm{tide}}(t) + n_{\mathrm{surge}}(t) + bP(t) + c \cdot t}$$

Flooding occurs when this water level exceeds the local floor elevation. So:

$$if\ n(t) < 2m, \qquad no\ flooding$$

$$if\ n(t) \geq 2m, \qquad flooding$$

The extent and depth of flooding in the engineered port area (and over the natural seafloor) can be estimated by comparing **n** with the floor elevation, as in the previous examples.

[14] https://www.sciencedirect.com/science/article/abs/pii/S0959378008000447
[15] https://iopscience.iop.org/article/10.1088/1748-9326/7/1/014032/meta
[16] https://link.springer.com/article/10.1007/s10584-009-9790-0

Example:

We assume the same three scenarios of sea-level rice pace and a storm surge taking place at a certain point of the year t: a mild (e.g. RCP2.6), a moderate (RCP4.5-6.0) and an extreme (RCP8.5), for a time horizon of t=30 years. The table below sets indicative values for the parameters, as defined above. The ones changing under each scenario are the coloured cells in each case.

The b parameter is assigned a typical value for small, poorly drained basins, following the same values as in the first example above. The c parameter is assigned typical values of projected sea-level rises for different scenarios, same as the second example above. All parameters were assigned the same typical values as in the previous examples per scenario, while the **time horizon t was set to 30years**, in order to emphasize the short-term potential risk of those combined hazards.

Simple Storm Surge & Sea-level rise combination, port flooding example

Parameter	Symbol	Values	Units	Notes	Scenario
Astronomical Tide	n_tide	0.5	m	Above the z=0, initial conditions sea-level	
Storm Surge	n_surge	0.7	m	Assuming this storm at the t=30	
Rainfall	P	80	mm	At the location of the port	
Rainfall conversion factor	b	0.001	m/mm	Typical value for small, poorly drained basins (port)	Mild (e.g. RCP 2.6)
Rainfall contribution	b*P	0.08	m		
Sea-Level annual rate	c	0.01	m	Typical value of 1 cm per year	
Time Elapsed	t	30	years	Baseline t=0	
Sea-level rise in t=100	Δn_slr	0.3	m		
Effective water level	n(t=30)	1.58	m	Tide + Storm surge + Rainfall contr. + Sea-level rise	
Flooding	dport(x=150,y)	1.58	m	No flooding (water depth d < z port, 2m). **Difference:**	**-0.42**
Parameter	**Symbol**	**Values**	**Units**	**Notes**	**Scenario**
Astronomical Tide	n_tide	0.5	m	Above the z=0, initial conditions sea-level	
Storm Surge	n_surge	1	m	Assuming this storm at the t=30	
Rainfall	P	110	mm	At the location of the port	
Rainfall conversion factor	b	0.001	m/mm	Typical value for small, poorly drained basins (port)	Moderate (e.g. RCP 4.5 - 6.0)
Rainfall contribution	b*P	0.11	m		
Sea-Level annual rate	c	0.015	m	Typical value of 1.5cm per year	
Time Elapsed	t	30	years	Baseline t=0	
Sea-level rise in t=100	Δn_slr	0.45	m		
Effective water level	n(t=30)	2.06	m	Tide + Storm surge + Rainfall contr. + Sea-level rise	
Flooding	dport(x=150,y)	2.06	m	Yes, flooding (water depth d > z port, 2m). **Difference:**	**0.06**
Parameter	**Symbol**	**Values**	**Units**	**Notes**	**Scenario**
Astronomical Tide	n_tide	0.5	m	Above the z=0, initial conditions sea-level	
Storm Surge	n_surge	1.6	m	Assuming this storm at the t=30	
Rainfall	P	150	mm	At the location of the port	
Rainfall conversion factor	b	0.001	m/mm	Typical value for small, poorly drained basins (port)	Extreme (e.g. RCP 8.5)
Rainfall contribution	b*P	0.15	m		
Sea-Level annual rate	c	0.018	m	Typical value of 1.8cm per year	
Time Elapsed	t	30	years	Baseline t=0	
Sea-level rise in t=100	Δn_slr	0.54	m		
Effective water level	n(t=30)	2.79	m	Tide + Storm surge + Rainfall contr. + Sea-level rise	
Flooding	dport(x=150,y)	2.79	m	Yes, flooding (water depth d > z port, 2m). **Difference:**	**0.79**

In the mild scenario, there we have $n_{tide} = 0.5m, n_{\text{surge}} = 0.7m,\ P = 80mm, and\ c = 0.01m$, leading to a sea-level rise of z=1.58m above the initial conditions (z=0). There is no flooding, as this is 0.42m below the 2m-tall port, in t=30.

In the moderate scenario, there we have $n_{tide} = 0.5m, n_{\text{surge}} = 1m,\ P = 110mm, and\ c = 0.015m$, leading to a sea-level rise of z=2.06m above the initial conditions (z=0). There is flooding, as this is 0.06m above the 2m-tall port in t=30, making it unsuitable for further operation.

In the extreme scenario, there we have $n_{tide} = 0.5m, n_{\text{surge}} = 1.6m,\ P = 150mm, and\ c = 0.018m$, leading to a sea-level rise of z=2.79m above the initial conditions (z=0). There is flooding, as this is 0.79m above the 2m-tall port in t=30, making it unsuitable for further operation.

These scenarios are shown in Fig.8.

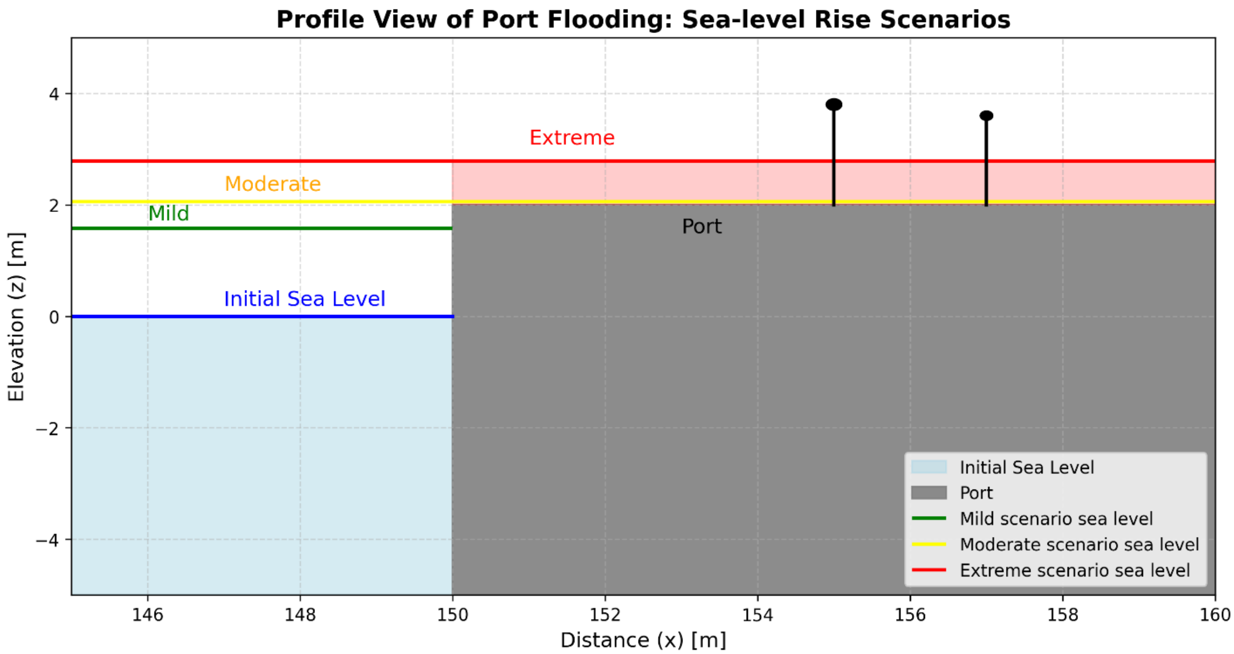

Fig.8: The port flooding under the three examined scenarios, mild (+1.58m, no flooding), moderate (+2.06m, causing flooding by 0.06m over the port flooding), and extreme (+2.79m, causing flooding by 0.79m over the port). The figures on the port structure represent a man 1.80m – tall and a woman 1.60m – tall, for comparison purposes of the flooding.

These examples refer to only a few cases of port flooding. In reality there can be more causes, like the ones mentioned in the beginning (tides, storm surges, rainfalls, sea-level rise, wave overtopping), so there can be many more combinations that might cause a flood.

SENSITIVITY ANALYSIS

Sensitivity analysis is a technique used to understand how changes in input variables affect the output of a model or system. It helps identify which variables have the most impact, allowing us to see how small adjustments can lead to significant changes in results. This is especially useful in decision-making.

We tested the sensitivity of the main model's parameters, in the 3rd combinative example, which is the completer case.

The parameters examined are: Astronomical Tide, Storm Surge, Rainfall and Sea-Level annual rise rate (Fig.9).

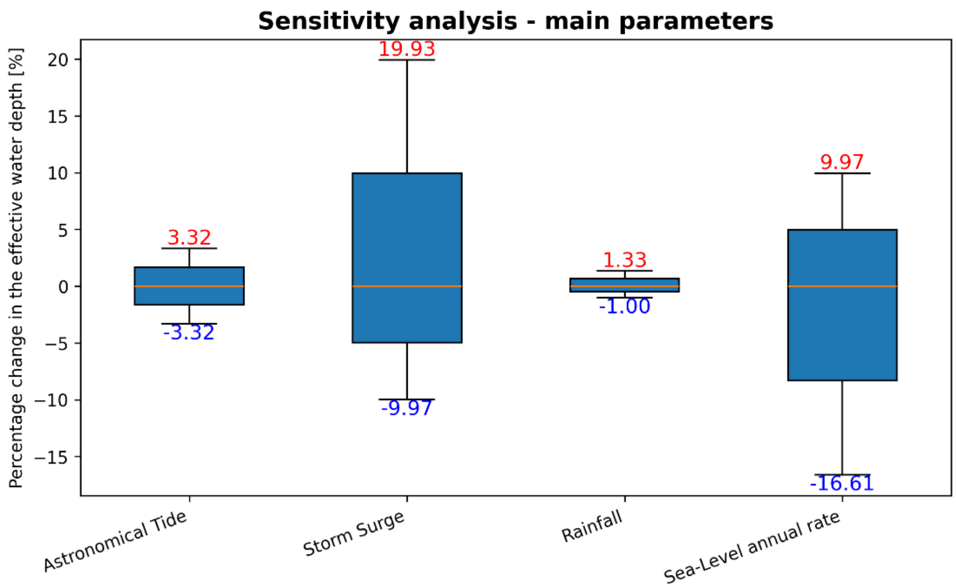

Fig.9: The sensitivity results on how each parameter affects the effective water depth (by the percentage changes compared to the moderate scenario).

The indicative values used for this example, indicate that:

- Storm Surge has the most substantial effect, with changes reaching nearly 20%, highlighting its critical role in determining flood depth. This suggests storm surges are a primary driver of coastal flooding.
- Sea-level annual rise rate follows with approximately 17%, suggesting that rising sea levels contribute significantly to flooding.
- Astronomical tides have a relatively small impact, with changes of ±3.32%, suggesting it contributes to variations but not as significantly as other factors.
- Rainfall has the least influence, with variations between -1.00% and 1.33%, indicating that direct precipitation has a minor effect on flood levels compared to other variables.