



Coastal Inundation Under Climate Change

User manual

Plugin for QGIS 3.44 and later

Plugin created by Daniel Ibarra Marinas, Facultad de Ingeniería y Ciencias, Universidad Autónoma de Tamaulipas, to model coastal inundation under sea level rise scenarios.

daniel.ibarra@uat.edu.mx

ORCID: [0000-0003-3683-4456](https://orcid.org/0000-0003-3683-4456)

[ResearchGate](https://www.researchgate.net/profile/Daniel-Ibarra-Marinas)

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1. What the plugin does

Plugin created by Daniel Ibarra Marinas, Facultad de Ingeniería y Ciencias, Universidad Autónoma de Tamaulipas, to model coastal inundation under sea level rise scenarios. For each scenario it raises the sea level over a digital elevation model (DEM) and marks as flooded only the pixels that lie below the new level **and** connect to the sea through pixels that are also below it. Low areas behind a dune, a dyke or any higher ground are not flooded: they are stored in a separate layer as disconnected low areas.

It also takes into account the uncertainty of the DEM and of the sea level projection. Instead of a single flooded area, it gives three: a lower band, a central band and an upper band, so you can see which areas flood even when the error goes against flooding, and which ones only flood when it goes in favour.

What it does not do

It is a static threshold model with connectivity. It does not simulate erosion or changes in the shape of the coast, waves, storm surge, tidal dynamics, drainage, groundwater or the failure of defences. The sea level rise is an input: the plugin does not compute projections.

2. Requirements and installation

- QGIS 3.44 or later. The plugin is declared compatible with QGIS 4, but it has not been tested there yet.
- numpy and GDAL, which come with QGIS.
- scipy is recommended. With scipy the connectivity step is fast; without it, the plugin uses a slower pure Python method and tells you so in the log.

Installation

- 1 In QGIS, open **Plugins > Manage and Install Plugins**.
- 2 Go to **Install from ZIP** and select CoastalInundation_Under_ClimateChange_v0.5.4.zip.
- 3 Click **Install Plugin**.
- 4 Open the **Processing Toolbox**. The tool is in the group **Coastal Inundation Under Climate Change**.

To update, install the new zip over the old one. There is no need to uninstall first.

3. Preparing your data

The DEM

- It must be a raster file that GDAL can read (GeoTIFF, for example).
- Its coordinate reference system must be projected and in metres (UTM, for example). Geographic coordinates are not accepted.
- It must be north-up. Rotated rasters are not accepted.
- The DEM heights, the base level and the sea level rise must all refer to the same vertical datum. The plugin warns you if the CRS does not declare a vertical datum, but it cannot check it for you.

NoData and sea points

Many coastal DEMs (for example, lidar from national agencies) leave the sea as NoData. The parameter **NoData handling** decides what to do with it:



- **NoData connected to a sea point is sea** (default). You can click directly on the sea, even if it is NoData. The water spreads from that NoData into the valid pixels below the level. Sea NoData is not counted as flooded area and stays NoData in the depth raster.
- **Barrier**. NoData blocks the water. The sea point must then fall on a valid pixel below the level.
- **Also NoData touching the raster edge is sea**. Useful when the sea reaches the DEM in several places not connected to each other. Use it with care: with lidar tiles, NoData on the edge may be land outside the survey, and water would come in from the land side.

With the default option, inland NoData gaps connected to the sea NoData (a lagoon without lidar returns, for example) also count as sea. Other NoData gaps still block the water. If the sea reaches areas that are only connected through valid pixels above the level, use a points layer and put one point in each area.

Size and memory

The whole raster is loaded into memory, at roughly 30 bytes per pixel. The plugin shows the estimate in the log and warns you above 4 GB. If you run out of memory, clip the DEM to the coastal strip or resample it.

Uncertainty values

The DEM vertical RMSE usually comes from the accuracy report of the data provider or from your own validation with ground control points. If the report also gives the mean error (bias), enter it: lidar under vegetation is often biased upwards. For the projection you can give either a standard deviation σ in metres or, better, a low and a high percentile per scenario (17/83 or 5/95), which keeps the asymmetry of the projections. If you do not know them, leave them at 0: the plugin will then give only the central result.

4. Parameters

Labels appear in English and Spanish in the tool window. The table uses the English part.

Parameter	What it is	Default
Coastal DEM (CRS in metres)	The elevation raster.	Required
Band	Raster band with the heights.	1
Sea point (click on the map)	Click the ... button of the field and then click on the sea in the map.	Optional
Sea points layer	A point layer with one or more sea points. You need the sea point, the layer or both.	Optional
NoData handling	Barrier, NoData connected to a sea point is sea, or also NoData on the raster edge is sea. See section 3.	Connected NoData is sea
Sea level rise scenarios	One or more values in metres separated by ';'. Decimal point or comma, for example: 0.5; 1; 2. With percentiles, these are the medians.	1
The rise you enter is...	Relative : the value already includes vertical land motion. Absolute : it does not, and you can add subsidence below.	Relative
Base level	Level added to the rise, above the DEM vertical datum. For example, the high tide level.	0
Base level raster	Optional surface that replaces the uniform base level where it has data, for example a high tide surface along a long coast. Resampled (bilinear) to the DEM grid.	Optional
Uniform subsidence	Absolute rise only. Metres, positive means sinking. It is subtracted from the DEM.	0



Parameter	What it is	Default
Subsidence raster	Absolute rise only. Resampled (bilinear) to the DEM grid. Where it has no data, subsidence 0 is used and the log says in what percentage of the DEM.	Optional
DEM vertical RMSE	Vertical error of the DEM, in metres.	0
DEM vertical bias	Mean error of the DEM, in metres. Positive if the DEM is too high. It cannot be larger than the RMSE.	0
Projection σ	Standard deviation of the sea level rise, in metres. Only with Symmetric σ .	0
Projection uncertainty given as	Symmetric σ or Percentiles (asymmetric).	Symmetric σ
Percentile pair	17 / 83 or 5 / 95. Only with percentiles.	17 / 83
Low and high percentile per scenario	One value per scenario, in metres, separated by ';', in the same order as the scenarios. Only with percentiles.	Empty
Band factor k (advanced)	Width of the bands in units of σ . With Percentiles it still sets the bands (quantiles $1 - \Phi(k)$ and $\Phi(k)$ of the sum). With 17/83 and a large k (1.96, for example), most of the upper band comes from extrapolating beyond P83: use 5/95 if you raise k.	1.28
Connectivity (advanced)	4 neighbours (only through pixel sides) or 8 neighbours (also through corners).	4
[pending] parameters	Land use, class field, barriers and water passages. Visible but not used yet.	
Output folder	Where the results are written.	Required

The tool will not run if you choose a relative rise and also enter subsidence, because the land sinking would be counted twice.

5. How it works

Flooding with connectivity

For each scenario the plugin computes the level as base level plus rise. If the rise is absolute, it first subtracts the subsidence from the DEM. Then it takes every pixel below that level and keeps only the groups of pixels that touch a sea point. The rest are disconnected low areas.

With 4 neighbours the water only passes through pixel sides. With 8 neighbours it also passes through corners, which can let water leak diagonally across thin barriers such as walls or narrow dunes. That is why 4 neighbours is the default.

Uncertainty bands

The RMSE mixes bias and random error: $RMSE^2 = bias^2 + \sigma^2$. The plugin subtracts the bias from the DEM and uses $\sigma_{DEM} = \sqrt{RMSE^2 - bias^2}$. The total error is $\sigma = \sqrt{\sigma_{DEM}^2 + \sigma_{projection}^2}$, assuming both errors are independent. The flooding is computed three times: at level $-k\sigma$ (lower band), at the central level and at level $+k\sigma$ (upper band).

With $k = 1.28$ and normal, unbiased errors, the probability of a pixel being under water is:

Band	Probability of being under water
lower	$\geq 90 \%$
central	about 50 % to 90 % (exact value at the central level in the log and statistics)
upper (floods only here)	10 % to 50 %

Percentiles instead of σ

Sea level projections are usually skewed towards high values: the upper tail is longer than the lower one. A symmetric σ may then underestimate the upper band, which is where it matters most. With **Percentiles**, you enter the median of each scenario and a low and a high percentile. The plugin treats the projection as two half-normals joined at the median, with 50 % of the mass on each side and one σ per side fitted to your percentiles. This reproduces your median and percentiles exactly. It is not the classical split normal (two-piece normal), whose junction is the mode and whose density is continuous; here the density has a jump at the median. The plugin then adds the DEM error numerically and takes the lower and upper band levels from the percentiles of that sum. The bands become asymmetric.

The central level stays at the **median of the projection**, not at the median of the sum. That way the central map does not change with the DEM or its RMSE, and it can be compared with published tables. The price is that, with a skewed projection, the probability exactly at the central level is a little above 50 %. The plugin computes it and writes it to the log and to the statistics table (prob_at_central).

These are per-pixel values. They ignore connectivity and the spatial correlation of the DEM error, so they are indicative. A uniform bias is also a simplification: under vegetation the bias changes with land cover. Gesch (2009) is a reference for accounting for DEM vertical uncertainty in sea level rise mapping.

Reference: Gesch, D.B., 2009. Analysis of lidar elevation data for improved identification and delineation of lands vulnerable to sea-level rise. *Journal of Coastal Research*, SI 53, 49–58.

<https://doi.org/10.2112/SI53-006.1>

If σ or k is 0, there are no bands and everything flooded is labelled central.

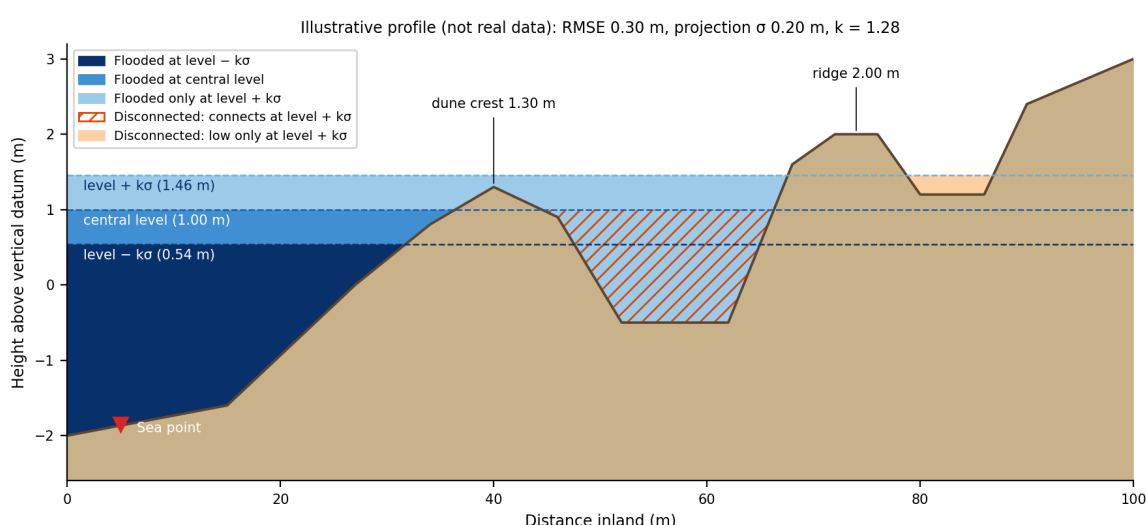


Figure 1. Illustrative profile (invented values) showing the three bands and the two kinds of disconnected low areas.

In Figure 1, the depression behind the dune is below the central level but the dune crest (1.30 m) stops the water. At level + $k\sigma$ (1.46 m) the water passes over the crest, so the depression is classed as *connects at upper*. The small hollow on the right only goes below the level at level + $k\sigma$, and the 2 m ridge keeps it isolated even then.



6. Outputs

Everything is written to the output folder. Each scenario gets a tag with its rise: 1_00m for 1.00 m, 0_50m for 0.50 m. If inundation.gpkg already exists, it is overwritten (the log says so). All layers are loaded into the project when the tool finishes, already styled. File, layer and field names are in English whatever the QGIS language, so the GeoPackage is the same for everyone.

File or layer	Content
depth_<tag>.tif + .qml	Water depth at the central level (level minus ground height), in metres. NoData = -9999. Blue ramp with transparency, from 0 to the 98th percentile of the depth.
inundation.gpkg > flood_<tag>	Flooded polygons. Field band: first band in which the pixel floods. Fields value, rise_m, level_m, area_m2.
inundation.gpkg > disconnected_<tag>	Low disconnected areas. Field status.
statistics	One row per scenario: areas in m ² for each class, flood_total_central_m2 (lower + central), σ , DEM σ , k, percentiles, band offsets below and above the central level, and prob_at_central.
metadata	Every setting of the run: DEM, CRS, vertical datum, scenarios, rise type, base level, subsidence, RMSE, σ , k, connectivity, author, date and version.

Classes

Layer and field	Value	Meaning
flood > band	lower	Floods already at level - $k\sigma$. Darkest blue.
flood > band	central	Floods at the central level.
flood > band	upper	Floods only at level + $k\sigma$. Lightest blue.
disconnected > status	connects_at_upper	Below the central level and isolated, but the water reaches it at level + $k\sigma$. These are the places where a dune or a dyke is right at the limit.
disconnected > status	isolated	Below the central level and still isolated at level + $k\sigma$.
disconnected > status	low_only_at_upper	Only below the level at level + $k\sigma$, and isolated.

With Percentiles, level - $k\sigma$ and level + $k\sigma$ in this table and in Figure 1 stand for the offsets of each band below and above the central level, which are different (band_lower_offset_m and band_upper_offset_m in the statistics table).

Areas are computed as number of pixels times pixel area. Within each table the classes are exclusive, but the two tables overlap: every connects_at_upper pixel is also counted in flood_upper. Do not add flooded and disconnected areas together.

If you use a base level raster, the field level_m is empty, because the level changes from pixel to pixel.

7. Step by step

- 1 Load the DEM in QGIS and check its CRS (metres) and its vertical datum.
- 2 Open the tool from the Processing Toolbox.
- 3 Choose the DEM and the band.
- 4 Mark the sea point on the map, or choose a points layer.
- 5 Choose the **NoData handling**. If your DEM leaves the sea as NoData, keep the default (NoData connected to a sea point is sea).



- 6 Write the scenarios, for example 0.5; 1; 2.
- 7 Choose whether the rise is relative or absolute, and add subsidence only if it is absolute.
- 8 Set the base level (or a base level raster), the DEM RMSE and the DEM bias.
- 9 Give the projection uncertainty: a σ , or better the low and high percentile of each scenario.
- 10 Choose the output folder and click **Run**.
- 11 Read the **Log** tab: it shows the level of each scenario, the flooded area and any warning.
- 12 Review the loaded layers, starting with the connects_at_upper areas.

8. Messages and what to do

Messages appear in English or Spanish depending on the QGIS language.

Message (short)	What it means and what to do
The DEM CRS is not in metres	Reproject the DEM to a projected CRS in metres.
The DEM is rotated	Reproject it to a north-up grid.
The DEM declares no vertical datum	Warning only. Make sure the DEM, the base level and the rise use the same datum.
No sea point is on sea NoData or on a valid pixel below the central level	Default NoData option. Your points are on valid pixels above the level. Click on the sea itself (NoData or water pixels).
No sea point is on a valid pixel below the central level (Barrier option)	Points on NoData do not count with Barrier. Choose NoData connected to a sea point is sea, or move the point to a valid pixel below the level.
Nothing floods: no valid pixel below the level connects to the sea	The sea point is fine, but no land or water pixel with a value below the level touches the sea. Check the level, the datum and whether the coastline pixels have values.
The lower band ... is empty	No valid pixel below level – $k\sigma$ connects to the sea. It is normal with large σ or a steep coast. With the Barrier option it can also mean the point is too high.
... sea point(s) fall outside the DEM	Those points are ignored. Check their position and CRS.
Warning: very large raster	Clip the DEM to the coastal strip or resample it.
You marked a relative rise and also entered subsidence	Set subsidence to 0 or choose Absolute.
The bias cannot be larger than the RMSE	Check both values in the accuracy report.
There must be one low and one high percentile per scenario	Write as many percentiles as scenarios, in the same order.
Each scenario needs low percentile $\leq$ median $\leq$ high percentile	Check the order of the values.
... sea point(s) fall on NoData, which is set as a barrier	Choose NoData connected to a sea point is sea.
NoData touching the raster edge is treated as sea	Warning only. Check that the edge NoData is sea.
The base level raster has no data in ...	The uniform base level is used there.
Connectivity engine: pure Python (slow)	scipy is not available. The result is the same, only slower.
Could not open ... to save its style	The layer is fine but will appear without the plugin style.

9. Limitations



- Static model: the coast does not change and there is no erosion, sediment transport or morphological response.
- No waves, storm surge, tidal dynamics, drainage, groundwater or failure of defences.
- Only what is in the DEM counts. Walls, dykes or culverts narrower than a pixel may be lost or may block water that in reality passes.
- The bands assume normal and independent errors. The probabilities are indicative.
- With Symmetric σ , the upper band may be underestimated because projections are skewed. Use Percentiles when you have them. With Percentiles, the tails beyond the given values are an extrapolation of the two half-normals; 5/95 reduces that extrapolation compared with 17/83.
- Sea NoData is identified by connection to a sea point (or to the raster edge). Inland NoData gaps connected to it count as sea; other gaps block the water.

10. Version and pending work

This manual describes version 0.5.4. Planned for later versions: statistics by land use, barriers and water passages, a bias raster by land cover, an event mode with waves, and a Monte Carlo treatment of the DEM error with spatial correlation.

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Contact: daniel.ibarra@uat.edu.mx · ORCID: [0000-0003-3683-4456](https://orcid.org/0000-0003-3683-4456) · [ResearchGate](#)

Code, releases and bug reports: [GitHub](#).

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