2014 - 2020 Interreg V-A
Italy - Croatia CBC Programme
Call for proposal 2019 Strategic

MARLESS (MARine Litter cross-border awarenESS and innovation actions)

Priority Axis: Environment and cultural heritage; Specific objective: 3.3 - Improve the environmental quality conditions of the sea and coastal area by use of sustainable and innovative technologies and approaches

3.3.2 Model of dispersion of floating waste

Model features and implementation PART 2-3

Activity 3.3

WP 3

Version: FINAL
Distribution: PUBLIC
Date: 31/01/2023

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PROJECT MARLESS

Work Package:	WP3 Monitoring optimization
Activity:	Activity 3.3 Marine litter hot spots identification
WP Leader:	PP2
Deliverable:	D3.3.2 Model of dispersion of floating waste

Version:	Final	Date:	31/01/2023
Type:	Report		
Availability:	Public		
Responsible Partner:	PP2		
Involved Partner	ARPA FVG		
Editor:	ARPA FVG		
Contributors:	/		

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Model of dispersion of floating waste

Activity Deliverable (3.3.2)
PART 2-3
Model features and implementation

WP3
Activity 3.3

Introduction

The deliverable D3.3.2 is composed by three parts; the first describes the process followed to identify the numerical model that is used for simulating the dispersion of floating waste. The second part deals with the model implementation while the third focuses on the model features; both those parts are presented in this document.

In this document the model of dispersion of floating waste chosen for the deliverable 3.3.2 is presented. In the first part the GNOME model is treated in detail with an introduction of the model features, a discussion on the model implementation and, finally, a presentation of some preliminary tests.

In the second part the PyGNOME model is presented with a brief tutorial on how to install the model and a presentation of some issues and tests. In the final part of the document a summary of the results obtained are shown.

General NOAA Operational Modeling Environment (GNOME)

In the PART 1 of this document the GNOME and the PyGNOME models have been considered as the most suitable candidates to achieve the MARLESS objectives.

In the following sections the GNOME model is presented with an overview of its features and the results of some tests.

Dispersion model features

GNOME is a simulation system designed for the modeling of pollutant trajectories in the marine environment.

It is a two-dimensional in space Eulerian/Lagrangian model in which vertically isolated layered systems can be modeled.

Inputs to GNOME include maps, bathymetry, numerical circulation models, location and type of the spilled substance, oceanographic and meteorological observations and other environmental data.

For currents, GNOME recognizes finite element, rectangular, and curvilinear grid circulation models in both American Standard Code for Information Interchange (ASCII) and Network Common Data Form (NetCDF) file formats. Finite element models may have either the velocities on the triangles or on the nodes. Both steady state and time-dependent circulation models are supported.

For winds, GNOME accepts constant time series or regular grid time-dependent model. Both NetCDF and ASCII formats are supported for wind model data.

The output consists of graphics, movies, and data files for post-processing.

The model has been extensively tested and verified and it contains an easy-to-use graphical user interface.

It is designed with two user modes: for novice (the *standard mode*) and for more sophisticated users (the *diagnostic mode*):

- **Standard mode**: with the standard mode regions are modeled with Location Files, that consists of pre-packaged map, tide, and current data where the parameter values are predetermined. The user has to download the location file corresponding to his region of interest (from http://response.restoration.noaa.gov/gnomelocationfiles) and he is guided to set the wind speed, direction, and spill information through dialogue boxes. For the location files the CATS (Current Analysis for Trajectory Simulations) hydrodynamic model is used: a 2-D depth-averaged steady-state finite element circulation model. It generates constant patterns that are made time dependent by connecting them with a time-series. The patterns are on a triangle grid that allows a good matching with shoreline and a higher resolution near the shore.
- **Diagnostic mode**: in diagnostic mode the user controls the inputs, so it is required a good knowledge in oceanography and modeling to set up input data and to interpret the results. It is possible to build a complete model including shorelines, currents, winds, and spill distribution.

In the following sections some characteristics of this model are going to be treated in detail.

Movers

Movers represent the physics that causes the movement of the pollutant parcel in the water (for example currents, winds, and diffusion). There are two categories of movers: the *universal movers* that apply everywhere and consist of wind and diffusion; all the other movers that apply only to the map to which they are attached. The overall movement is calculated adding together the velocity components from all the movers (currents, wind, diffusion, and any other) at each time-step using a forward Euler scheme (a 1st-order Runge-Kutta method).

The calculation of the total movement is a simple vector addition of the displacement of a given pollutant particle by each mover over the time-step. In the model setup, each mover can be marked active, and so used in the model calculation, or inactive at any given time.

In GNOME, each particle is treated as a Lagrangian element and carries with it its latitude and longitude coordinates and other properties at each given time. The DAG (Directional Acyclic Graph) tree algorithm identifies in what grid cell each particle is in, so that the closest velocity node can be identified and the element advanced in space by that velocity.

Regarding the **current movers**, GNOME accepts either time-dependent or steady-state current patterns; the latter are usually driven by time-dependent tide files.

The model accepts model data on rectangular, curvilinear, and triangular grids from various models to use as currents. For rectangular grids the model allows the velocities to be at the centre of the grid boxes or at the nodes: in either case it uses the same value throughout a grid box and does not interpolate. For curvilinear grids the model divides each grid box into two triangles and assumes that the velocity for both triangles is at the lower-left corner of the grid box. For triangular grids,

CATS outputs velocities at the centres and there is no interpolation. Instead, if an imported model has velocities at the nodes, the values are interpolated.

All the time-dependent currents are interpolated linearly in time and the model has an option to extrapolate time-dependent currents with the first and last times in the file.

The uncertainty values can be set for any current patterns.

As far as the **wind movers** are concerned, there are different ones allowed: constant, time dependent, and time/space dependent. The first two can either be loaded through a wind dialog box or from a file in the On-Scene Spill Model (OSSM) wind file format, in which the files contain date, time, speed, and direction information and the units are selected when the files are loaded. The spatially varying winds must be loaded via ASCII file or NetCDF format file. The time-dependent wind is interpolated using a Hermite polynomial fit and the spatially dependent wind is interpolated linearly in time, but not interpolated in space. It can either be on a regular or a curvilinear grid.

The **component mover** is a wind-driven current. This mover can have one or two current patterns, which must be in the form of CATS currents scaled by a constant or time-dependent wind. The current components can be scaled linearly by wind speed or by the square of wind speed (i.e. wind stress). The current pattern can also be scaled by a time-average of past wind values: if no historical winds are available or the wind record is insufficient to satisfy the selected time over which to average, the model can be set to extrapolate and will use whatever wind is available until enough data are accumulated.

The **diffusion mover** represents the random spreading and it is performed by a simple random walk with a square unit probability. The random walk is based on the diffusion value that is set in the model and that represents the horizontal eddy diffusivity in the water, so it is treated as a stochastic process. Gravitational and surface tension effects are ignored, as these are only important during the first moments of a spill and the complex representation of sub-grid diffusion and spreading effects are ignored.

In GNOME, the displacement ($\Delta x, \Delta y$) is calculated from the input diffusion coefficient, and at each diffusion time-step a dx and dy displacements are chosen randomly from a uniform distribution of floating point numbers between -1 and 1: the result is a distribution of points spread throughout square.

The **evaporation** is treated by a simplistic 3-phase evaporation algorithm where the pollutant is considered as a three-component substance with independent half-lives. The pollutant type selected for the spill determines the parameters chosen for the weathering simulation and there is evaporation if the oil type requires it; in particular if the Lagrangian element mass is zero after weathering, it is marked as evaporated. This mover can be used only for oil spill and not for marine litter.

Trajectories and windage

The model provides two trajectory solutions: a *best estimate* (or forecast) trajectory, and a *minimum regret* (or uncertainty) trajectory.

The "best estimate" solution shows the model result with all of the input data assumed to be correct. Instead, the "minimum regret" solution displays the trajectory that incorporates the uncertainties, since models, observations and forecasts are rarely perfect.

Each trajectory is represented by a Lagrangian element, which is a statistically independent piece of the modelled pollutant. The "best estimate" trajectory is represented by black points and the "minimum regret" by red ones. According to NOAA, the chance of a spill remaining in the area covered by the red splits is in the order of 90 %, provided that a correct degree of uncertainty is used.

The **windage** expresses how large the ocean surface winds can directly drag the litter in addition to the advection of ocean currents, and it is generally classified into low (1% of the wind speed, this is the case of fishing nets, bottles floating below the ocean surface, which are not directly affected by winds), moderate (2%-3% of wind speed, this is the case of capped plastic bottles partially filled with water, shoes that are affected by both the ocean surface currents and winds), and high (greater than 4% of the wind speed, this is the case of Styrofoam, empty plastic bottles, and fishing buoys with low density that float on the surface of the water and are primarily driven by winds) [1].

Thus, this parameter is typically about 1%-4% of the wind speed based on analytical derivation and empirical observation. This range is used as default in GNOME with a uniform distribution, the model picks a random number within the user-selected range of windage values for each particle and moves it according to that number at each time-step. This random uniform spreading happens only in the direction of the wind.

Since the model should behave the same when the time-step is changed as much as possible, it accepts a range of windage percentages and a persistence time-step moving the elements accordingly to get the desired amount of spreading. The persistence time indicates how long until the random value is reset. There are two options: 15 minutes (the default) used for modeling something which windage will increase or decrease with time, something being pushed below the surface by waves, then floating back up to the surface; infinite persistence, used for modeling heavier floating objects in which the particles may have a different windage, but will maintain that difference indefinitely. The windage is a property that applies to any wind mover that the user sets up.

The amount of spreading due to the wind is given by the following equation:

$$\frac{d\sigma^2}{dt} = S(t)$$

(1)

Where σ^2 is the variance of the element location, S(t) is a spreading parameter that is a function of time, as the wind velocity is a function of time. For a constant wind, the variance of the particles grows linearly in time, the same as diffusion with a constant diffusion coefficient:

$$\sigma^2 = St$$

(2)

With the algorithm used, at any given time-step the resulting spreading by wind is given by the following equation:

$$S = \frac{\Delta W^2 U^2 \Delta t}{3}$$

(3)

Where ΔW is the range of the windage parameters, and U is the wind velocity at that time-step. The degree of spreading is a function of both the wind speed (which it should be) and the time-step, which it should not. Experiments with GNOME have demonstrated that the spreading does, indeed, vary with time-step.

If we explain the physics as above, imagining that any given particle is moved from the surface, and travels at a slower speed for a while, and then moves back up, and travels at a faster speed, the time-step is the persistence of this process. That is, the amount of time a given particle spends traveling at a given velocity. Imaging the extremes:

1) infinite persistence would have each particle moving at a different speed, and keeping that speed the entire time, resulting in a lot of spreading, and
2) infinitely short persistence would have each particle varying its speed constantly between the extremes, resulting in all the particles moving at the mean velocity, resulting in no spreading.

It has been decided at a GNOME development meeting that this was a "bad thing", and that it should be fixed. As much as possible, a model should behave the same when the time-step is changed.

A uniform distribution at each time step gives the resulting spreading coefficient:

$$S = \frac{\Delta x^2}{3\Delta t}$$

(4)

where Δx is the range of distances over which the elements are distributed. This is computed by multiplying the windage by the wind speed, resulting in Eq. (3).

If the reference windage is defined as being from A to B times the wind speed, with a persistence of Δt_0, we have:

$$\Delta W_0 = B_0 - A_0$$

and the mean windage:

$$\overline{W_0} = \frac{B_0 + A_0}{2}.$$

From Eq. (3) we want S to be constant, so we can compute the values for a given time-step from:

$$\frac{\Delta W^2 U^2 \Delta t}{3} = \frac{\Delta W_0^2 U^2 \Delta t_0}{3}$$

(5)

And:

$$\overline{W} = \overline{W_0}$$

(6)

Thus, the range of windage values is a function of the square root of the ratio of the reference time-step to the actual time-step:

$$\Delta W = \Delta W_0 \sqrt{\frac{\Delta t_0}{\Delta t}}$$

(7)

and then the minimum windage, A, and the maximum windage, B, are as follows:

$$A = \overline{W} - \frac{\Delta W}{2}$$

(8)

$$B = \overline{W} - \frac{\Delta W}{2}$$

(9)

If we use the new A and B in the same code as before, all should be well.

Beaching and refloating

At each time-step GNOME checks the map to see whether the new particles positions are on land or in water. The **beaching** algorithm checks the entire line on the bitmap between the old point and the new one and beaches the particles at the first land box it hits. The location in the water right before the land is reached is stored in such a way to use as a starting point when a particle is re-floated. If the "prevent land jumping" box is not checked a simplified algorithm looks at whether the new point is in water or on land and ignores the path the particle took. Interaction of the pollutant with sediment and biota is not modelled.

Half-life is a parameter which empirically describes the adhesiveness of the litter, typically oil, to the shoreline. It summarized different parameters (such as substrate porosity, the presence or absence of vegetation, the inherent stickiness of the oil and other physical properties and processes of the environment). It represents the number of hours in which half of the oil on a given shoreline is expected to be removed if there is an offshore wind or diffusive transport and sea level is at the same level, or higher, than the level of the oil when it was beached. This parameter allows **refloating** of oil after it has impacted a given shoreline. The refloated half-life is one hour by default: if the

value is higher the oil will stick to the shoreline longer, while for very small values the oil refloats instantly.

The probability of refloating of a Lagrangian element, is defined as:

$$p = 1 - \exp\left(\frac{-t\,ln(2)}{refloat\ prameter}\right)$$

Where t is the time interval of integration in hours and the refloat parameter is the half-life refloating parameter expressed in hours.

The refloating for an individual Lagrangian element is determined by choosing a random number on the interval (0,1): if the random number is less than the probability of refloating the element is refloated. When an element is refloated, it is placed at its last water position before beaching.

This parameter can be used also for marine litter, in the following sections an analysis of this parameter is presented in detail.

Uncertainty

To consider an **uncertainty** solution the box under the *include minimum regret* should be checked, this option creates a second set of Lagrangian elements that moves under the influence of the active movers.

For the diffusion mover the random step is increased as the square root of the uncertainty factor.

The various current and wind movers have parameters for *start-time* and *duration* of the uncertainty. The start-time indicates the hour into the model run that the wind becomes uncertain. The duration indicates how long an element will have that uncertainty value, before having it randomly reset.

The current patterns uncertainty, including component mover patterns, is parametrized by four factors that are the percentage of the given velocity; they are considered for the parallel and normal directions and for the forward and backward directions. Moreover, the CATS currents also have an eddy diffusivity uncertainty parameter that simulates eddy mixing processes dominant during slack water. The current uncertainty outputs are the displacements over one time-step in the x and y directions: for velocities greater than 10^{-6} m/s all the four factors and the eddy diffusivity parameter are calculated; instead, for velocities lower than 10^{-6} m/s only the eddy diffusivity parameter is considered.

For the wind mover, the uncertainty is considered for the speed scale (i.e. the uncertainty in the wind speed) and for the angle scale (i.e. the uncertainty in the wind direction).

The wind uncertainty outputs are displacements over one time-step in the x and y directions and are calculated only in the wind velocity is greater than 10^{-6} m/s. The uncertainty is log-normal in speed, as the forecasts in general over-predict the winds, and Gaussian in angle. The standard deviations for speed and angle are updated at every time-step. There is also a maximum angle scale of 60°.

In the following sections the dispersion model implementation and some preliminary tests are going to be presented for the GNOME desktop interface.

Dispersion model implementation

The latest version of GNOME can be downloaded from the site https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/response-tools/gnome.html. For example on a Windows PC, once you downloaded the installation program, double-click the *GnomeSetup.exe* file icon, and follow the directions you will see on the screen. Below, the preliminary tests are going to be presented.

Preliminary tests

Some preliminary tests are performed in order to understand how the windage works and how the simulations change with the addition of a universal mover. In addition, a simulation in backward mode is performed.

With and without the universal mover diffusion

In the following figures the model settings, the wind and current mover data (taken from the FIRESPILL project http://interreg.c3hpc.exact-lab.it/FIRESPILL/gnome_inputs/gnome_inputs.html), the spill information and the windage settings are shown.

Maps
- **North_Adriatic**
  - Refloat half life: 1 hr
  - ☐ Show Land / Water Map
  - **Movers**
    - **Wind File: CRMA-WRF_AlpeAdria_20210907_00+72h.nc**
      - ■ Active
      - ☐ Show Grid
      - ☐ Show Velocities (@ 1 in = 10 m/s)
      - Start Time: September 07, 2021 00:00
      - End Time: September 10, 2021 05:00
      - **Uncertainty**
        - Start Time: 0.00 hours
        - Duration: 3.00 hr
        - Speed Scale: 2.00
        - Angle Scale: 0.40
    - **Currents: "roms_20210907_00+72h.nc"**
      - ■ Active
      - ☐ Show Grid
      - ■ Show Velocities (@ 1 in = 1 m/s) at 0 m
      - Multiplicative Scalar: 0.01
      - Start Time: September 07, 2021 00:00
      - End Time: September 10, 2021 00:00
      - **Uncertainty**
        - Along Current: 50 %
        - Cross Current: 25 %
        - Start Time: 0 hours
        - Duration: 24 hours

Model Settings
- Start time: September 07, 2021 00:00
- Duration: 72 hours
- Computational time step: 0.25 hr
- ■ Include the Minimum Regret solution (RED SPLOTS on screen)
- ☐ Show Currents
- ■ Prevent Land Jumping
- ☐ Run Backwards

Spill Information

Spill Name: _____   ☐ Bottom Spill   z: 0   m

Pollutant: non-weathering ▾   # Splots: 1000   Windage

Amount Released: 5   m**3 ▾

Release start
September ▾ 7 2021 ▾   Lat: Deg: 45   Min: 7.17   North ▾
Start Time: 0 : 0   Long: Deg: 13   Min: 35.82   East ▾
(24-hour)

☐ Different end release time   ☐ Different end release position

No Dispersants ▾
○ decimal degrees
● degrees/minutes
○ degrees/minutes/seconds

OK   Cancel   Help...

Windage Settings

Settings

Persistence: 15 minutes ▾

Windage: 1 to 4 %

OK   Cancel   Help...

In the following section the results obtained without diffusion are presented with a test perfromed with the change of the windage parameters, since without diffusion there is not the additional random spreading.

Without diffusion
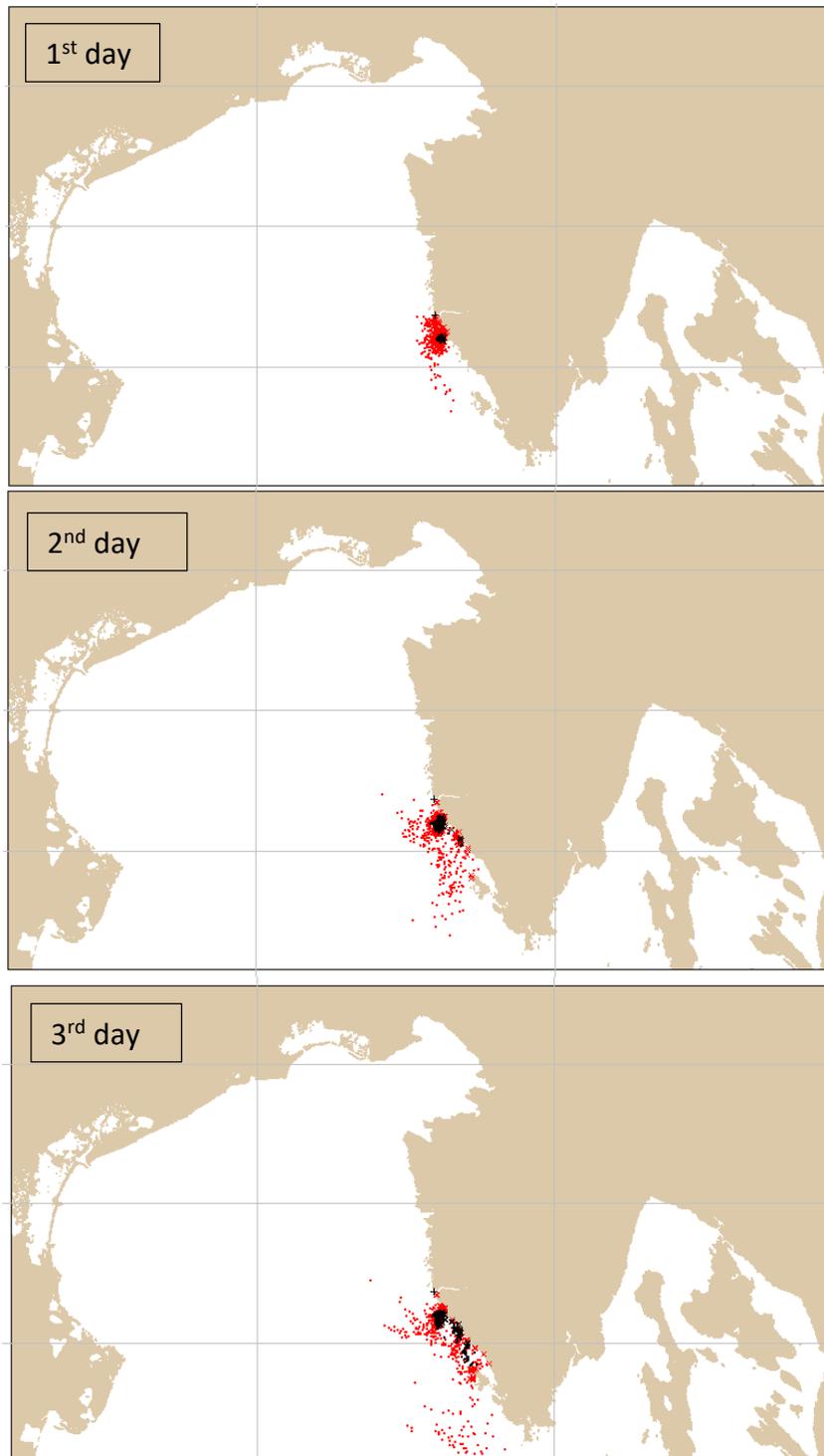
Figure 1: first, second and third day of simulation without the diffusion mover.

Windage: 1-4% (infinite persistence); after 3 days
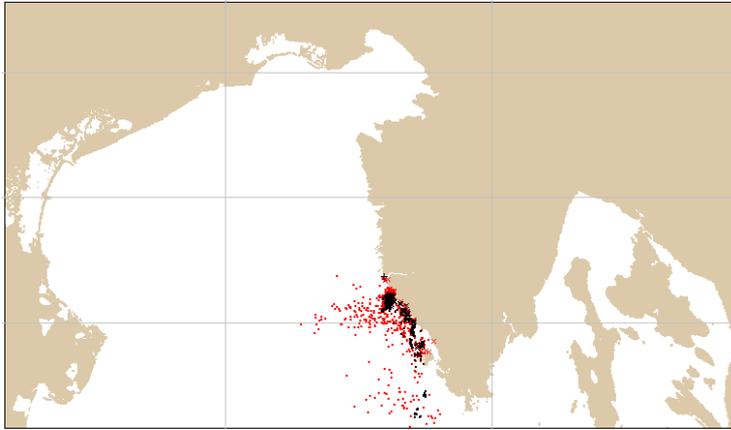
Lower windage: 1% (15 minute of persistence): after 3 days
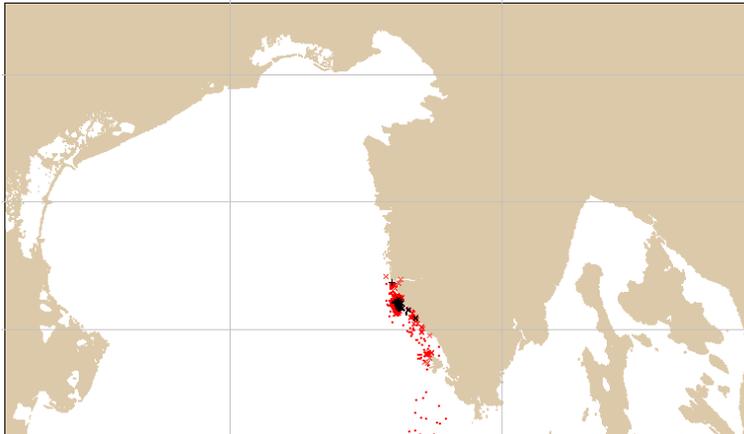
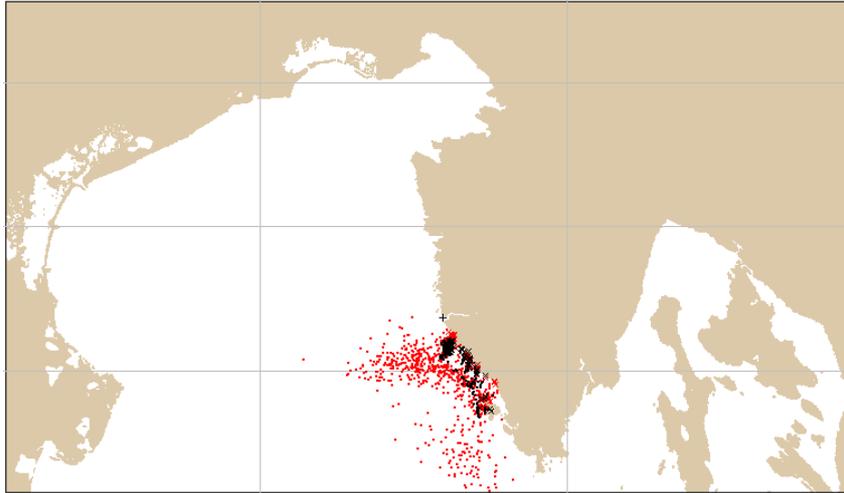## Moderate windage: 2-3% (15 minutes of persistence); after 3 days
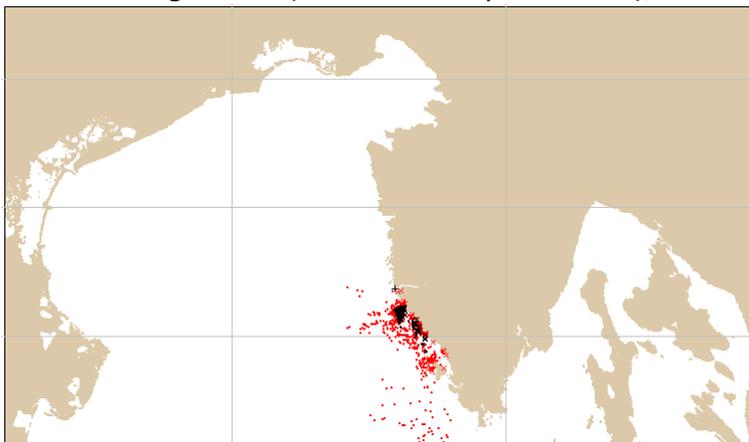
Figure 2: results of the third day of simulation with different windage values.

The results above show that with higher values of windage the Lagrangian elements are more spread along the wind direction.

High windage: 4% (15 minutes of persistence); after 3 h

High windage: 4% (infinite persistence); after 3 h
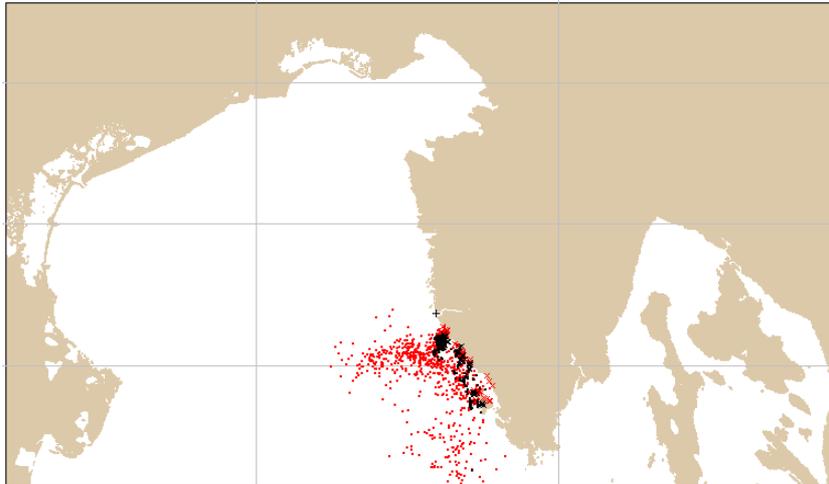
Figure 3: results obtained fixing the windage value and changing the persistence

As the windage value is fixed, we expect that the results will be the same. The results present some differences since the Lagrangian elements are approaching the beach and the refloating process is parametrized with the generation of a random number.

With diffusion

In the following section the results obtained with the universal mover diffusion are shown.

```
▼ Universal Movers
  ▼ Random: "Diffusion"
    ▉ Active
      10000 cm**2/sec
      Uncertainty factor: 2
```

The diffusion value is chosen in such a way to consider marine litter, as can be seen in this research [2].
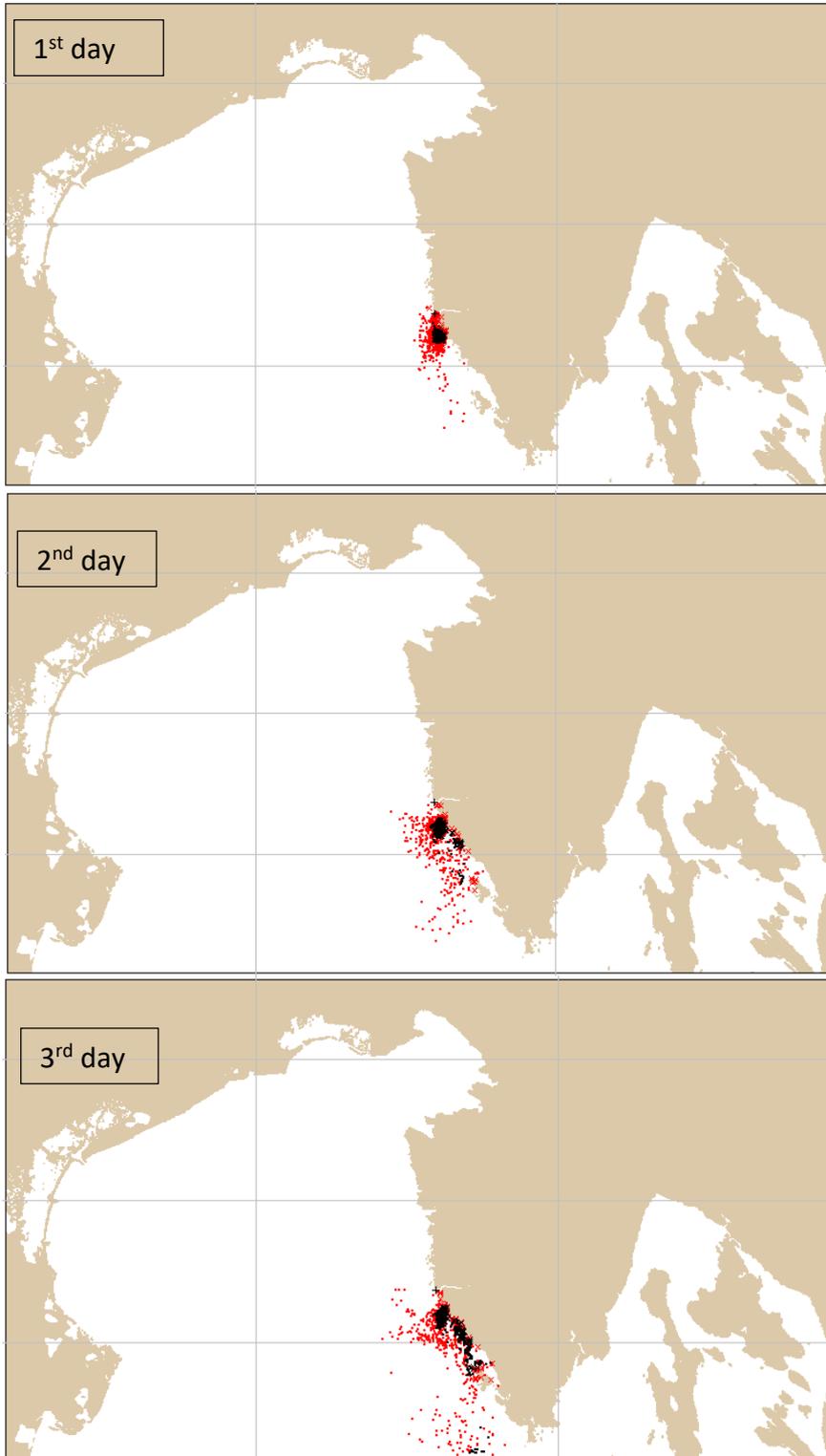
Figure 4: first, second and third day of simulation with the diffusion mover

The results obtained with the addition of the diffusion show that the Lagrangian elements are more spread in respect to the results obtained without this mover.

In the following figure a test with different uncertainty factors is shown.
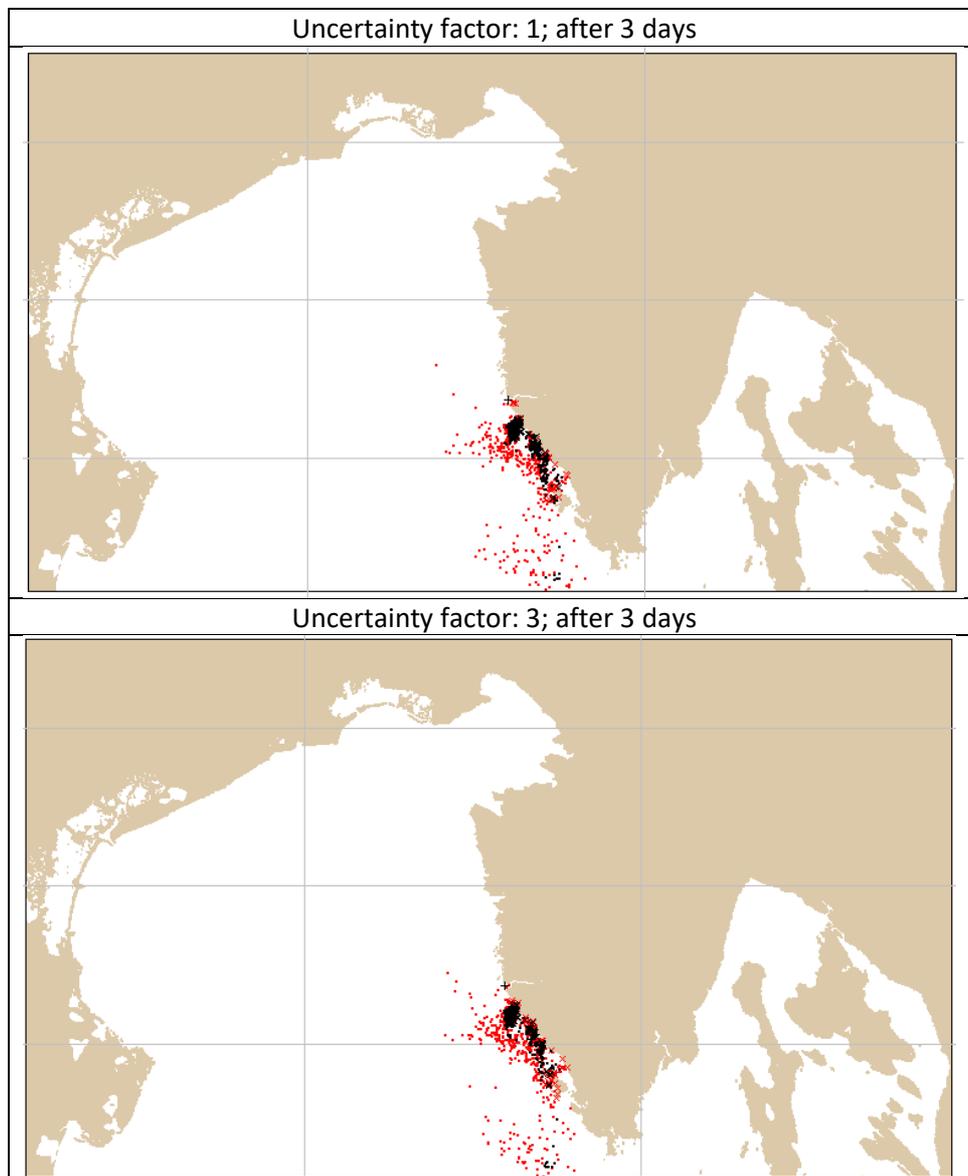
Figure 5: results of the test with different uncertainty factors.

Since the random diffusion step is increased as the square root of the uncertainty factor, the first value (uncertainty factor equal to 1) stands for no uncertainty. Regarding the above results, with higher uncertainty factors the diffusion is greater, as expected.

Hindcast

In this test, the dispersion simulation is performed in backward mode, with the selection of the setting: *Run Backwards*. The following figures show the settings and the results.

▼ **Maps**
  ▼ North_Adriatic
    Refloat half life: 1 hr
    ☐ Show Land / Water Map
    ▼ Movers
      ▼ Wind File: CRMA-WRF_AlpeAdria_20210907_00+72h.nc
        ■ Active
        ☐ Show Grid
        ☐ Show Velocities (@ 1 in = 10 m/s)
        Start Time: September 07, 2021 00:00
        End Time: September 10, 2021 05:00
        ▼ Uncertainty
          Start Time: 0.00 hours
          Duration: 3.00 hr
          Speed Scale: 2.00
          Angle Scale: 0.40
      ▼ Currents: "roms_20210907_00+72h.nc"
        ■ Active
        ☐ Show Grid
        ☐ Show Velocities (@ 1 in = 1 m/s) at 0 m
        Multiplicative Scalar: 0.01
        Start Time: September 07, 2021 00:00
        End Time: September 10, 2021 00:00
        ▼ Uncertainty
          Along Current: 50 %
          Cross Current: 25 %
          Start Time: 0 hours
          Duration: 24 hours

▼ **Model Settings**
  Start time: September 07, 2021 00:00
  Duration: 48 hours
  Computational time step: 0.25 hr
  ■ Include the Minimum Regret
    solution (RED SPLOTS on screen)
  ☐ Show Currents
  ■ Prevent Land Jumping
  ■ Run Backwards
▼ **Universal Movers**
  ▼ Random: "Diffusion"
    ■ Active
      10000 cm**2/sec
      Uncertainty factor: 2

To better analyse the backward trajectories mode a test is performed taking the Isonzo river's mouth as source for the forward trajectories and two different beaches, on the east and west part of this source, as source points for the backward trajectories: this test is shown in the following section.

Test: forward trajectory from the Isonzo river and backward trajectories from Fossalon and Marina Nova beaches

In this test, the forward trajectory from the Isonzo river's mouth (first figure above) is performed for different days considering three days of simulation, using the wind and current movers from the

FIRESPILL project (available daily from this link http://interreg.c3hpc.exact-lab.it/FIRESPILL/gnome_inputs/gnome_inputs.html). Using the same movers, two backward trajectories are considered for 3 days of simulation, from the Fossalon and the Marina Nova beaches (second and third figure respectively), in order to understand if the marine litter coming from the Isonzo river will deposit on these beaches. For every simulation the windage is taken with a persistence of 15 minutes and with a range of values from 1% to 4%. An additional mover is added: the random diffusion as universal mover with a coefficient of 10000 cm^2/s and an uncertainty factor of 2.

Figure 6: Isonzo river's mouth
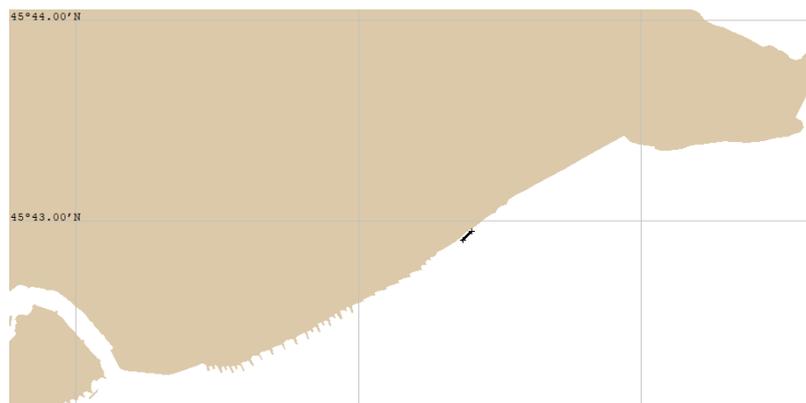
Figure 7: Fossalon beach
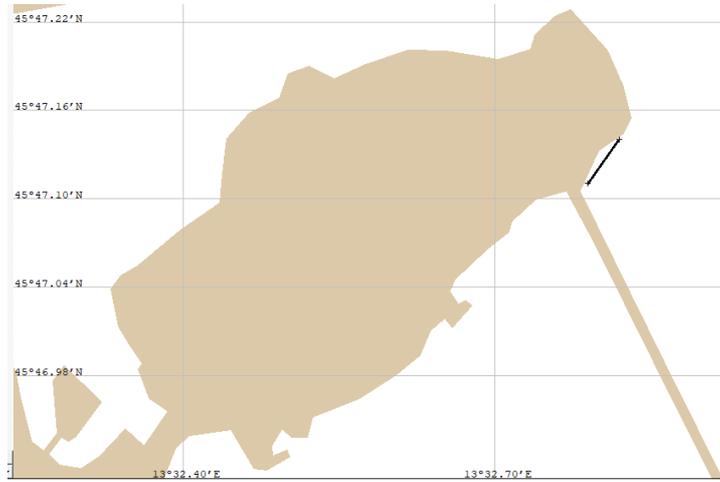
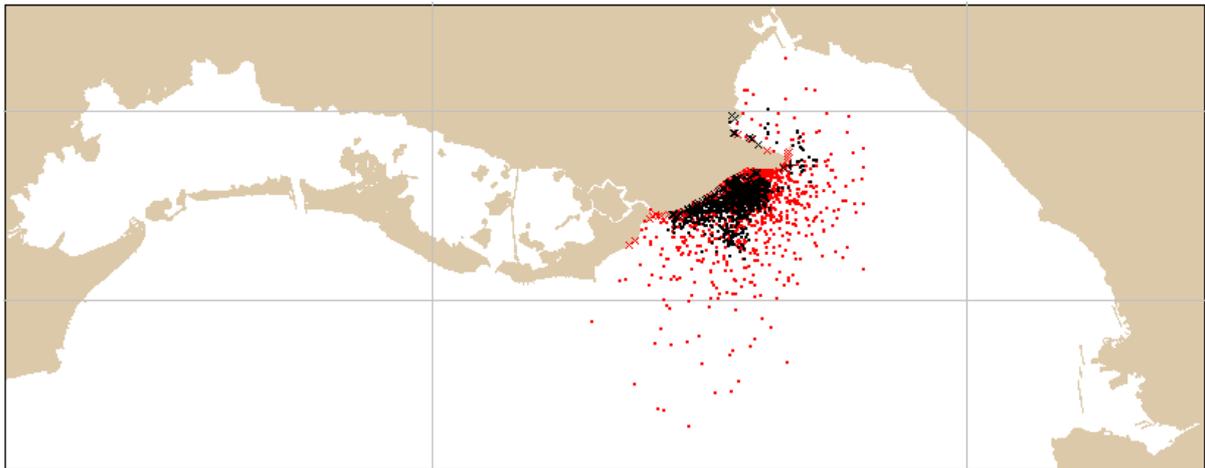*Figure 8: Marina Nova beach*

Day 09/09/2021

Forward trajectory

Figure 9: forward trajectory from Isonzo river's mouth. Picture of the last time step after 3 days of simulation.
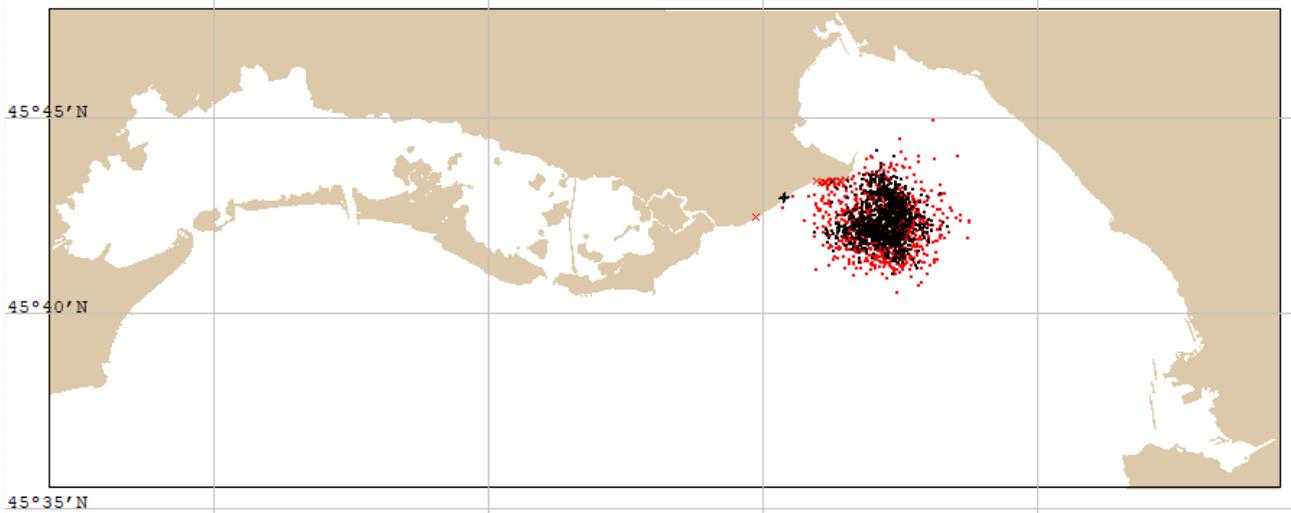
Figure 10: backward trajectory from Fossalon beach. Picture of the last time step after 3 days of simulation.
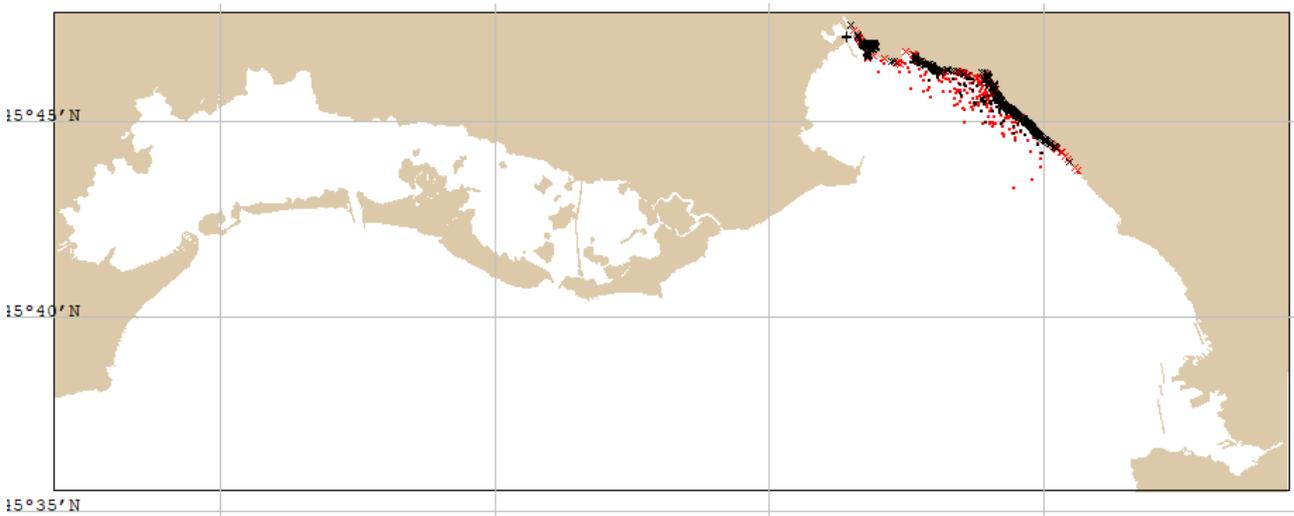

Figure 11: backward trajectory from Marina Nova beach. Picture of the last time step after 3 days of simulation.

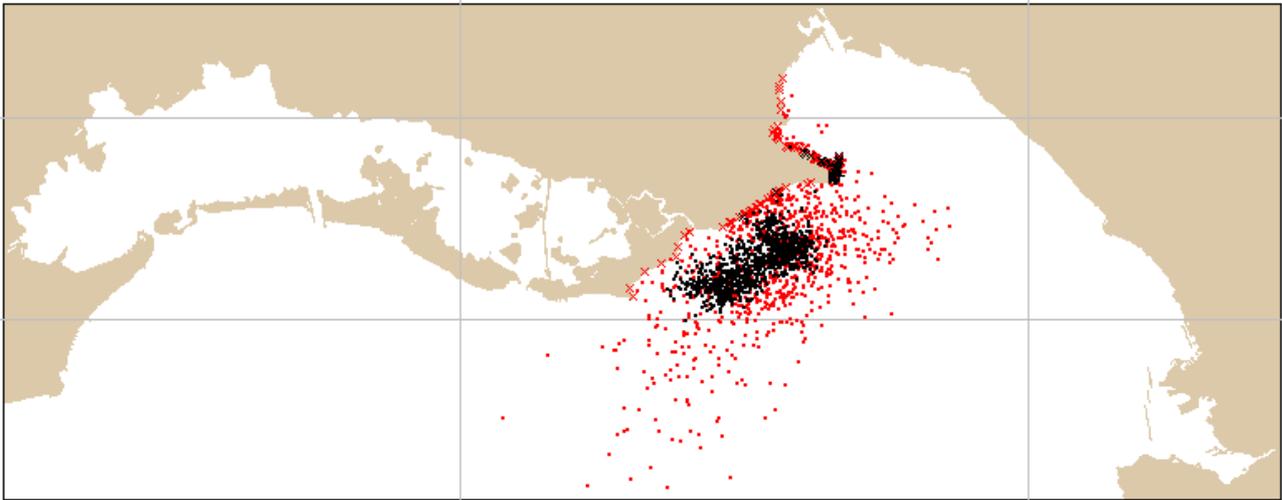Day 10/09/2021

Forward trajectory

Figure 12: forward trajectory from Isonzo river's mouth. Picture of the last time step after 3 days of simulation.
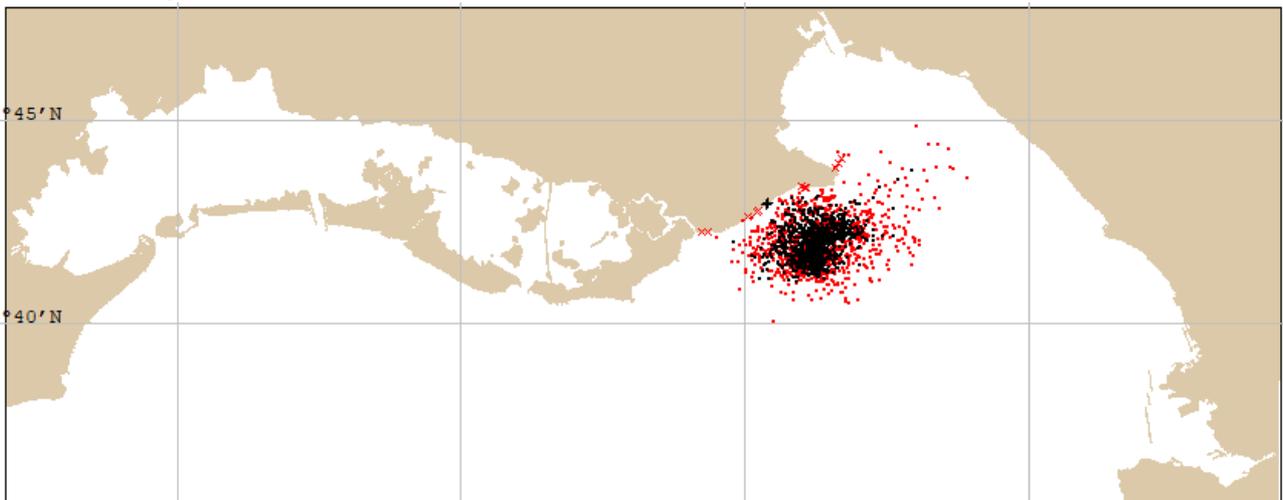
Backward trajectories

Figure 13: backward trajectory from Fossalon beach. Picture of the last time step after 3 days of simulation.

Figure 14: backward trajectory from Marina Nova beach. Picture of the last time step after 3 days of simulation.
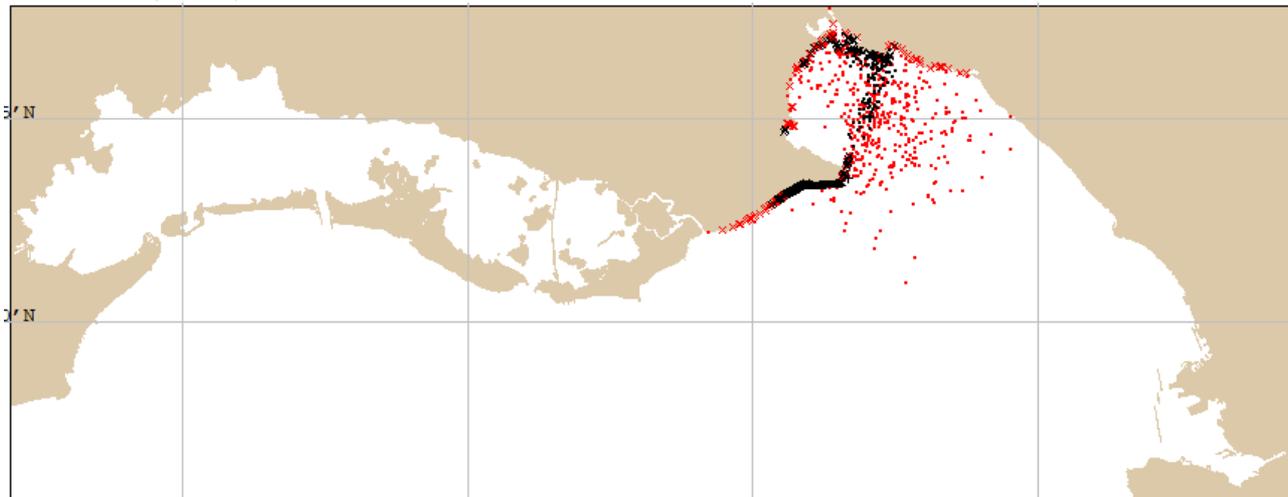
Day 13/09/2021

Forward trajectory

Figure 15: forward trajectory from Isonzo river's mouth. Picture of the last time step after 3 days of simulation.
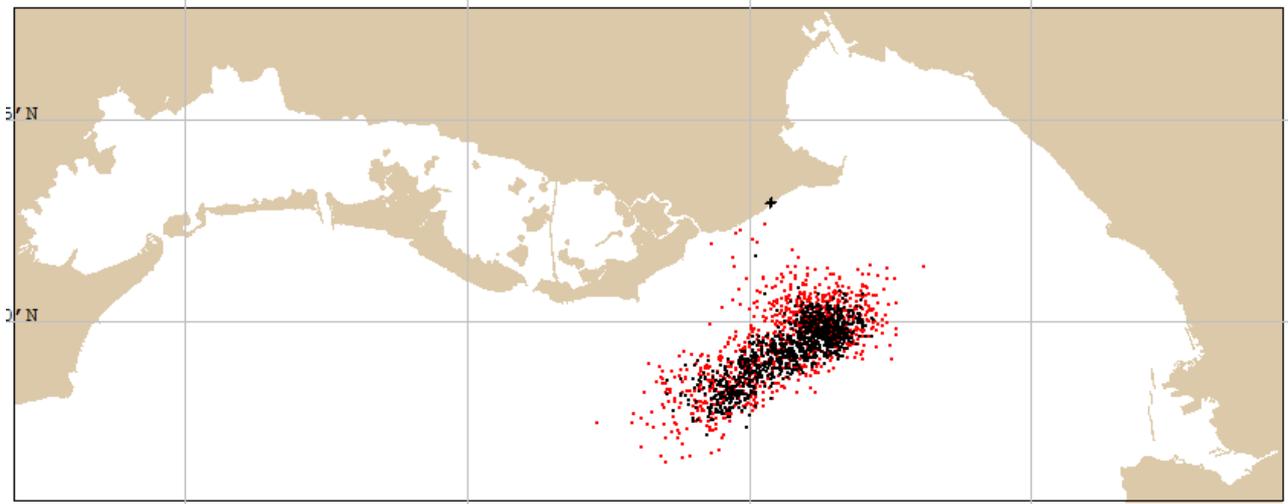
Backward trajectories

Figure 16: backward trajectory from Fossalon beach. Picture of the last time step after 3 days of simulation.
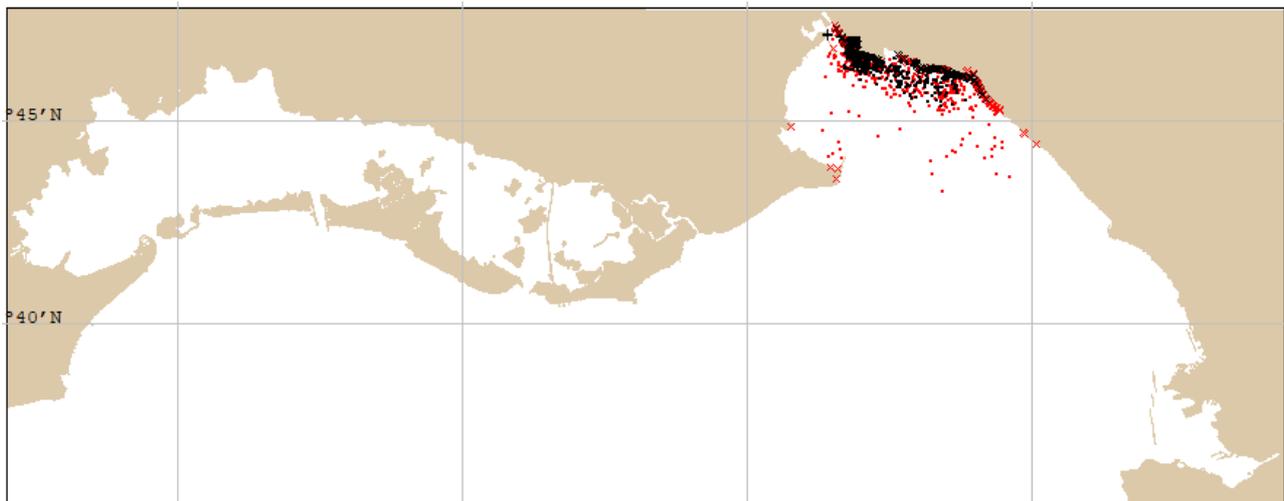

Figure 17: backward trajectory from Marina Nova beach. Picture of the last time step after 3 days of simulation.
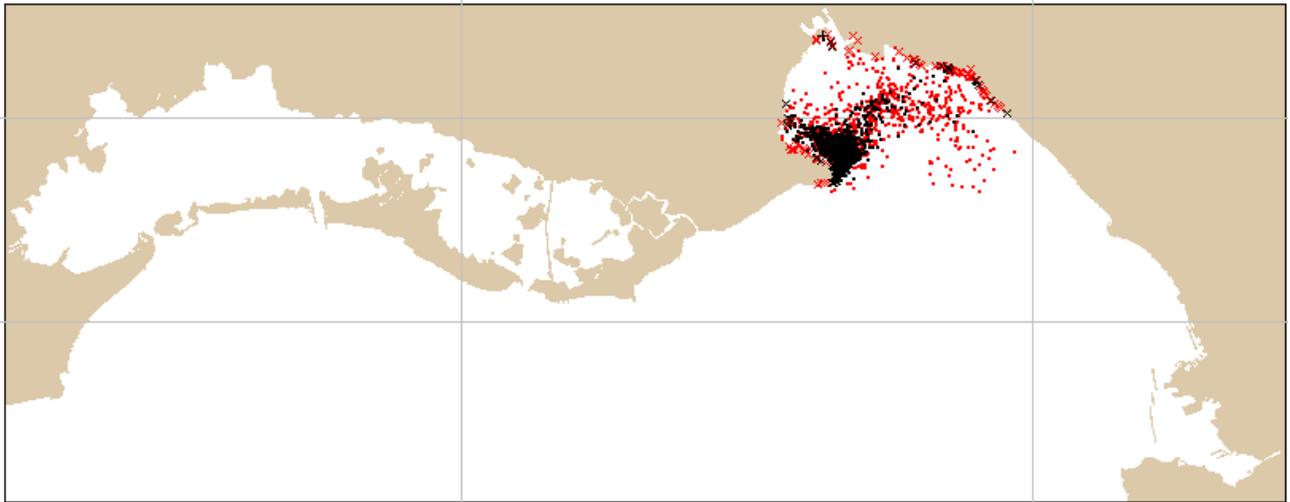
Figure 18: backward trajectory from Marina Nova beach, in this case it is considered the beach on the west part of the pier/breakwater. Picture of the last time step after 3 days of simulation.

Day 14/09/2021

Forward trajectory

Figure 19: forward trajectory from Isonzo river's mouth. Picture of the last time step after 3 days of simulation.

Figure 20: backward trajectory from Fossalon beach. Picture of the last time step after 3 days of simulation.

Figure 21: backward trajectory from Marina Nova beach. Picture of the last time step after 3 days of simulation.

Day 15/09/2021

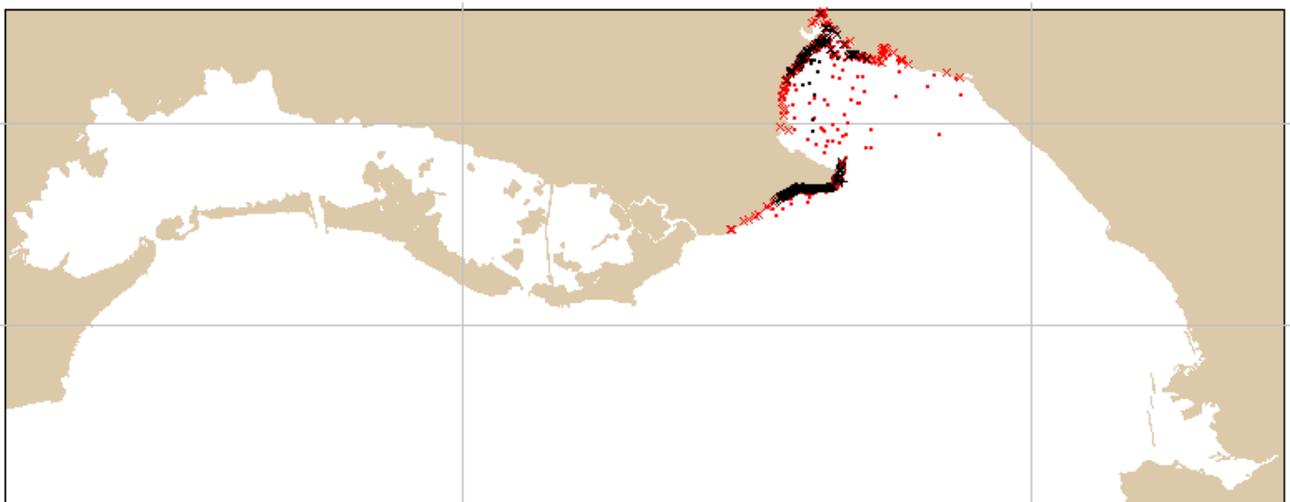### Forward trajectory

Figure 22: forward trajectory from Isonzo river's mouth. Picture of the last time step after 3 days of simulation.
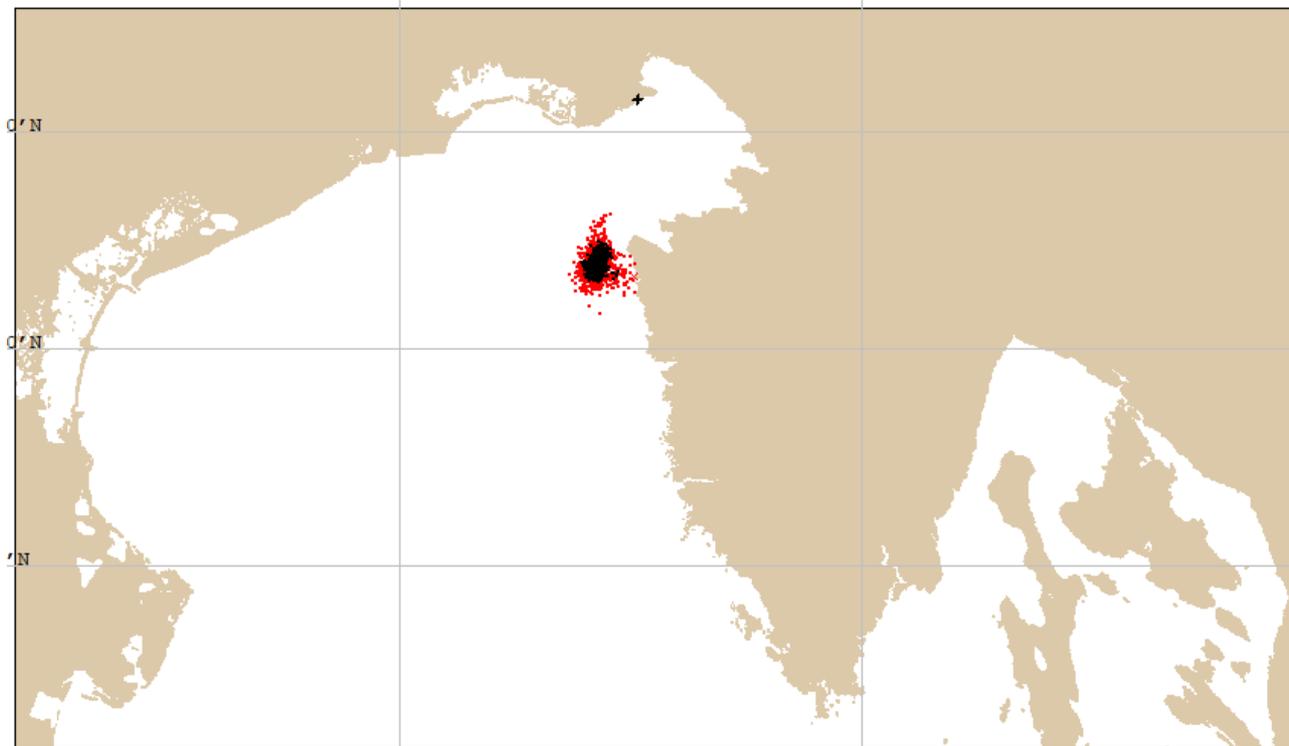
Backward trajectories

Figure 23: backward trajectory from Fossalon beach. Picture of the last time step after 3 days of simulation.
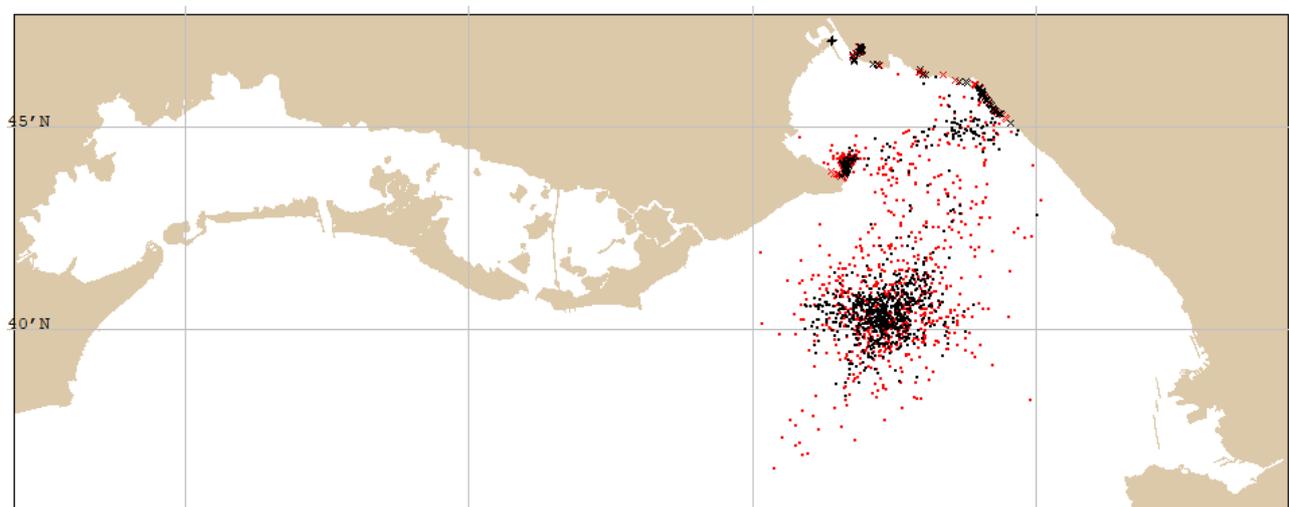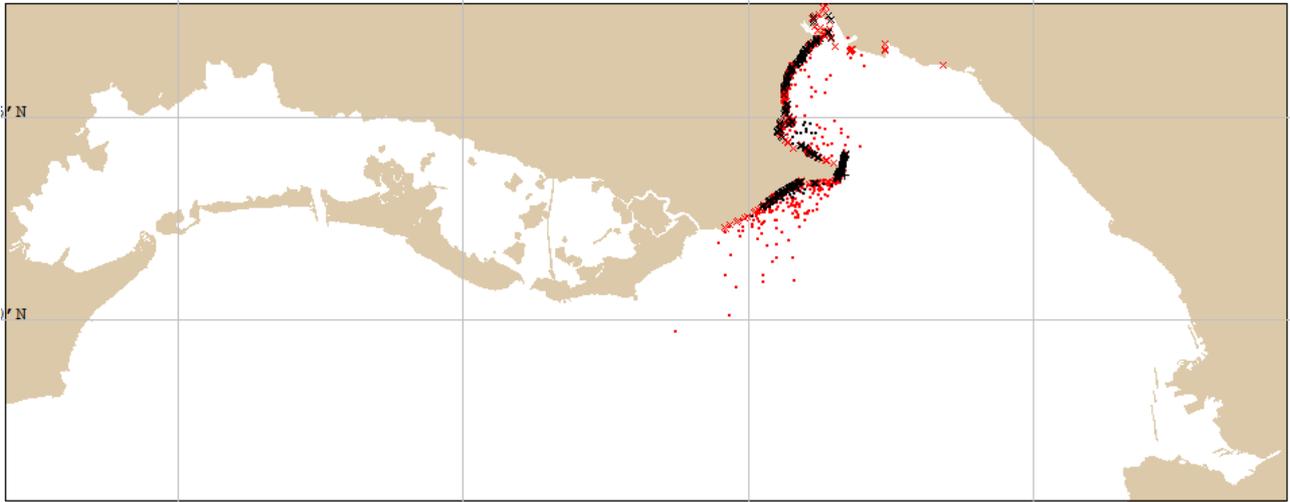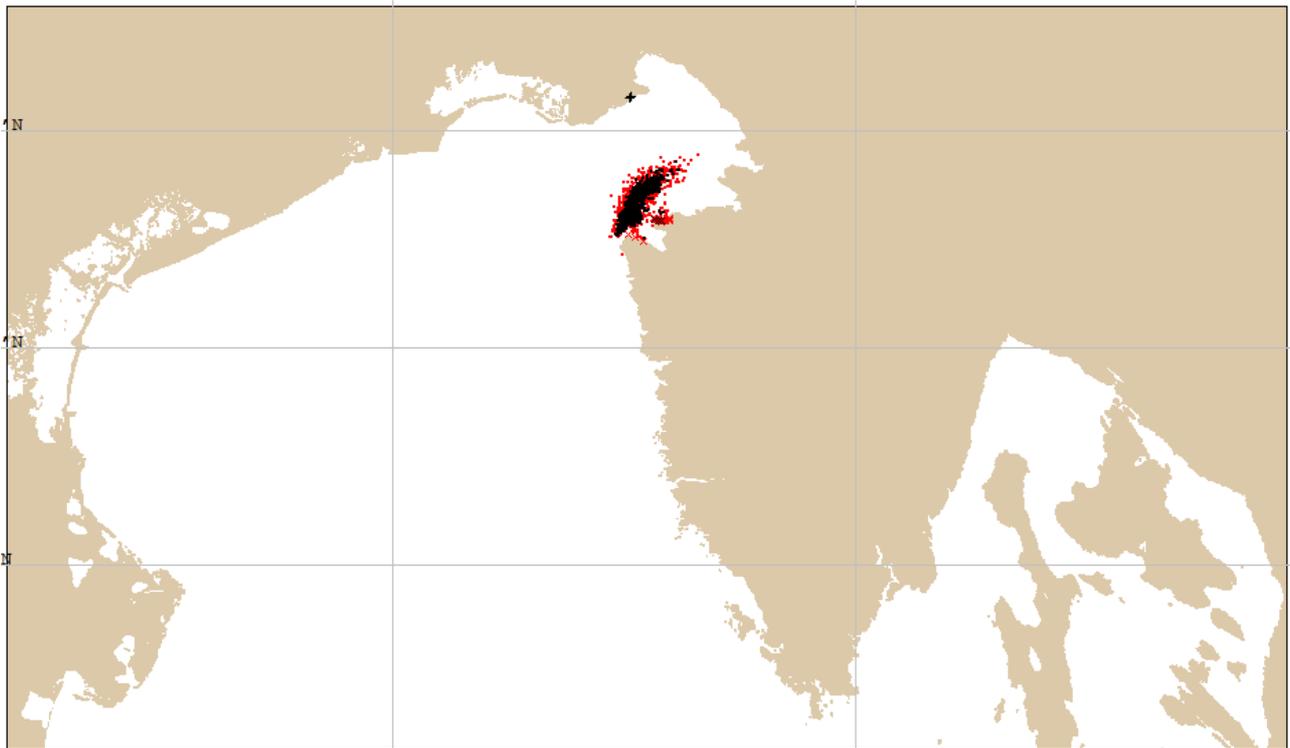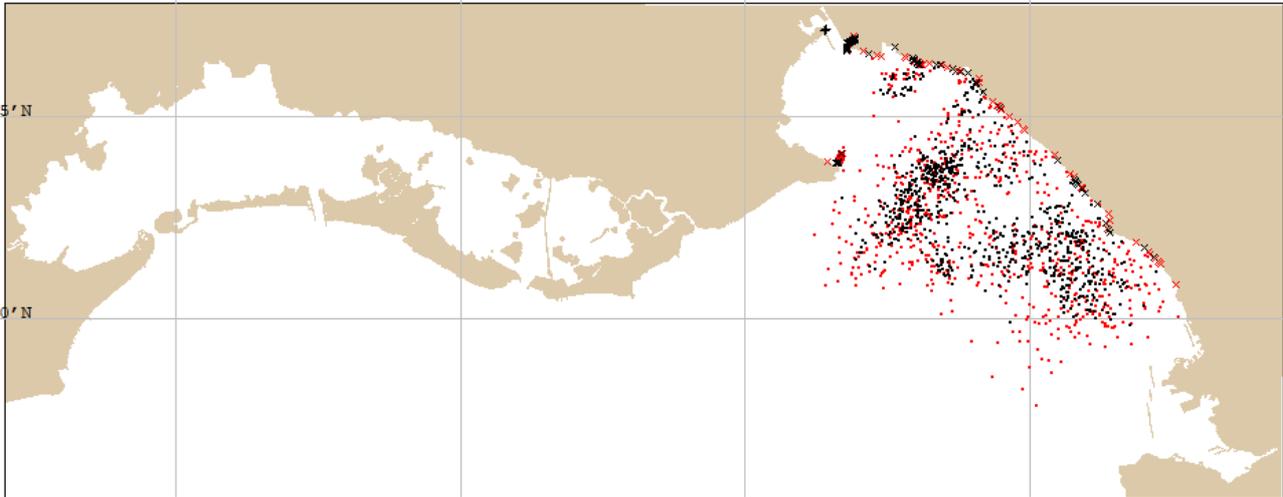
Figure 24: backward trajectory from Marina Nova beach. Picture of the last time step after 3 days of simulation.

Discussion of the results

Considering the day 09/09/2021, the forward trajectory simulation from the Isonzo river's mouth shows that the marine litter dispersion is going to be deposit on the Fossalon beach. Regarding the backward trajectory simulation from this beach, it proved that part of the deposited marine litters came from the Isonzo river. On contrary, the deposited marine litters on the Marina Nova beach are not arriving from the Isonzo river.

As far as the day 10/09/2021 is concerned, the forward trajectory simulation from the Isonzo river shows that a little part of the marine litters is beached on the Fossalon beach and it is not on the Marina Nova beach. Looking to the backward trajectory simulation from the Fossalon beach, the litters are not coming from the Isonzo river; regarding the Marina Nova backward trajectory simulation, the litters are coming from some eastward sources.

Considering the day 13/09/2021, the Isonzo river forward trajectory simulation shows that the litters are going to be deposited on the Fossalon beach and on the Marina Nova one; regarding the backward trajectories simulations only the one from the Marina Nova beach on the west part of the backwater come in part from the Isonzo's mouth.

Looking to the day 14/09/2021, the forward trajectory simulation shows that the marine litters are going to be beached on both the beaches, but considering both the backward trajectories simulations the litters are not coming from this river.

As regards the day 15/09/2021, the forward trajectory simulation shows that the marine litters are going to be deposited on the considered beaches, but the respective backward trajectories simulations don't show the litters coming from the Isonzo river.

For every considered day, a backward simulation is performed also for the Marina Nova beach on the west part of the breakwater. In general, the results of the simulations are similar to the one performed for the Marina Nova beach in Figure 8; only for the 14/09/2021 the result was different.

For two backward trajectories simulations from the Fossalon beach it was necessary to consider a bigger domain (the North Adriatic Sea instead of the Friuli Venezia Giulia domain).

Below, a test on the dimension of the output files is presented.

Test: file dimension

With the following test, different number of Lagrangian elements has been set in order to get more knowledge about the dimension of the NetCDF output files. Two simulation are considered: the one with a starting point near the map boundaries; the one with a starting point far from the domain limits. The results are shown in the following table:

	netCDF file dimension	
Number of elements	*Off domain – forward trajectory*	*Forward trajectory*
10^3 splots	9037 KB	9037 KB
10^4 splots	90318 KB	90318 KB

As it can be seen, the files with 10^4 splots have a dimension one order of magnitude higher with respect to the files with 10^3 splots.
Regarding the simulations with starting point near the boundaries, although a significant amount of particle left the domain during the simulation, the file dimension does not change and the consume of time is almost the same.

In order to perform annual massive simulations it is suitable the use of the PyGNOME model, in order to take advantage of the model with the power of the high performance computing. On the following section, the PyGNOME model is presented.

PyGNOME

PyGNOME is a set of python bindings (and utilities) to the General NOAA Operational Modeling Environment (GNOME). It can be used to write your own scripts to set up and run scenarios. It can also be modified to include alternative algorithms or customized transport processes.

Dispersion model features and implementation

PyGNOME consists of compiled C++ code (libgnome), compiled Cython code (*.pyx files), and compiled Python extensions. It can be installed either from source, in which case an appropriate compiler is needed, or from binaries provided by NOAA.
Since there are many dependencies that can be hard to build, the easiest way is to use the conda package manager.

The model has been installed in the C3HPC cluster. Below, the steps necessary to install the model are shown for the Linux environment:

1. Install Anaconda's Miniconda following the steps at https://conda.io/docs/user-guide/install/ selecting the Python-3 version.

2. Once you have conda set up, you can compile and install PyGNOME. PyGNOME is not currently available as a conda package, as it is under active development, and many users will need access to the source code. You will need the files from the PyGNOME sources available here: https://github.com/NOAA-ORR-ERD/PyGnome

   You can or download a zip file of all the sources and unpack it, or you can clone the git repository. If you clone the repository, you will be able to update the code with the latest version with a simple command, rather than having to re-download the whole package.

   To be able to clone, you will need a git client: it should be available from your package manager doing:

   apt_get install git

   Once you have the client the following command will create a PyGNOME directory with all the code in it:

   git clone https://github.com/NOAA-ORR-ERD/PyGnome.git

3. The conda packages required by PyGNOME are listed in the file *conda_requirements.txt* in the top directory of the project. Once you have the source code, you can create an environment for PyGNOME:

   conda create -n gnome --file conda_requirements.txt

   This will create an environment called "gnome" with Python itself and everything that it needs to run. If you get an error about a particular package not being able to be installed, then conda will not install any of the packages in the file. If however, a package of that particular version is missing, you can try to edit the conda_requirements.txt file and comment out the offending package by putting a "#" at the start of the line:

   ...
   scipy>=0.17
   py_gd>=0.1.5
   # libgd>=2.2.2
   gsw>=3.0.3
   ...

   That will disable that particular package, and hopefully everything else will install.

4. Then activate the newly created environment:

   conda activate gnome

   To verify the correct installation of the model, it is necessary to run some tests as:

   cd PyGnome/py_gnome/tests/unit_tests
   py.test

   and if those pass, you can run the following command to do some more tests:

   py.test --runslow

In the following sections some issues and some tests are going to be presented.

Issues, tests and consideration on the data analysis

First issues

1. We have to copy the current and wind NetCDF data in the directory where we run the model: problem solved.
2. The temporal resolution for current and wind data is 1 hour. The current data starts at 00:00 while the wind one at 00:30. This creates problems for the choice of the model time step: with time step of 1 minutes there is no problem, while with a time step of 15 and 30 minutes an error occurs:

```
ERROR -   movers - line:369 - No available data in the time interval that is being modeled
     Model time: 2018-01-02 00:00:00
     Data available from 2018-01-01 00:30:00 to 2018-01-01 23:30:00
     Mover: currentfiles.txt of type <class 'gnome.movers.current_movers.GridCurrentMover'>
     Error: CyGridCurrentMover returned an error: -1
Time outside of interval being modeledTraceback (most recent call last):
  File "/lustre/arpa/farrisc/PyGnome/py_gnome/gnome/movers/movers.py", line 353, in
prepare_for_model_step
    self.mover.prepare_for_model_step(seconds,
  File "gnome/cy_gnome/cy_mover.pyx", line 96, in
gnome.cy_gnome.cy_mover.CyMover.prepare_for_model_step
OSError: CyGridCurrentMover returned an error: -1

During handling of the above exception, another exception occurred:

Traceback (most recent call last):
  File "first_gnome_test.py", line 216, in <module>
    main()
  File "first_gnome_test.py", line 204, in main
    model.full_run()
  File "/lustre/arpa/farrisc/PyGnome/py_gnome/gnome/model.py", line 1153, in full_run
    results = self.step()
  File "/lustre/arpa/farrisc/PyGnome/py_gnome/gnome/model.py", line 1075, in step
    self.setup_time_step()
  File "/lustre/arpa/farrisc/PyGnome/py_gnome/gnome/model.py", line 852, in setup_time_step
    m.prepare_for_model_step(sc, self.time_step, self.model_time)
```

File "/lustre/arpa/farrisc/PyGnome/py_gnome/gnome/movers/movers.py", line 370, in prepare_for_model_step
    raise RuntimeError(msg)
RuntimeError: No available data in the time interval that is being modeled
    Model time: 2018-01-02 00:00:00
    Data available from 2018-01-01 00:30:00 to 2018-01-01 23:30:00
    Mover: currentfiles.txt of type <class 'gnome.movers.current_movers.GridCurrentMover'>
    Error: CyGridCurrentMover returned an error: -1
ERROR -   movers - line:369 - No available data in the time interval that is being modeled
    Model time: 2018-01-01 23:45:00
    Data available from 2018-01-01 00:30:00 to 2018-01-01 23:30:00
    Mover: currentfiles.txt of type <class 'gnome.movers.current_movers.GridCurrentMover'>
    Error: CyGridCurrentMover returned an error: -1
Time outside of interval being modeledTraceback (most recent call last):
  File "/lustre/arpa/farrisc/PyGnome/py_gnome/gnome/movers/movers.py", line 353, in prepare_for_model_step
    self.mover.prepare_for_model_step(seconds,
  File "gnome/cy_gnome/cy_mover.pyx", line 96, in gnome.cy_gnome.cy_mover.CyMover.prepare_for_model_step
OSError: CyGridCurrentMover returned an error: -1

During handling of the above exception, another exception occurred:

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  File "/lustre/arpa/farrisc/PyGnome/py_gnome/gnome/model.py", line 1153, in full_run
    results = self.step()
  File "/lustre/arpa/farrisc/PyGnome/py_gnome/gnome/model.py", line 1075, in step
    self.setup_time_step()
  File "/lustre/arpa/farrisc/PyGnome/py_gnome/gnome/model.py", line 852, in setup_time_step
    m.prepare_for_model_step(sc, self.time_step, self.model_time)
  File "/lustre/arpa/farrisc/PyGnome/py_gnome/gnome/movers/movers.py", line 370, in prepare_for_model_step
    raise RuntimeError(msg)
RuntimeError: No available data in the time interval that is being modeled
    Model time: 2018-01-01 23:45:00
    Data available from 2018-01-01 00:30:00 to 2018-01-01 23:30:00

> Mover: currentfiles.txt of type <class 'gnome.movers.current_movers.GridCurrentMover'>
> Error: CyGridCurrentMover returned an error: -1

Problem 2: solved. The duration time has to be changed to 23 hours because the current data starts at 00:30 and ends at 23:30. But in this way we are losing the time step at 00:00.

3. There is no way to set a release repetition with a different time step from the one set for the simulation. For example it is not possible to set a dt of integration of 15 minutes and implement a release of a number of particles every one minute. It is only possible to set the number of particle per time step.

4. To set the number of particle for time step (i.e. a delayed release and repeated release) you can use the object PointLineRelease in which you can set the parameter '**num_per_timestep** – fixed number of LEs released at each timestep'. Although this object is shown in an example in the documentation an error occur:

> Traceback (most recent call last):
>   File "first.py", line 216, in <module>
>   main()
>   File "first.py", line 199, in main
>   model = make_model()
>   File "first.py", line 172, in make_model
>   spill = gs.PointLineRelease(num_elements=10,#*60*72,
> AttributeError: module 'gnome.scripting' has no attribute 'PointLineRelease'

```python
import gnome.scripting as gs
from datetime import datetime, timedelta
start_time = datetime(2015, 1, 1, 0, 0)
model = gs.Model(start_time=start_time,
            duration=timedelta(days=3),
            time_step=60 * 15, #seconds
            )
release = gs.PointLineRelease(release_time=start_time,start_position=(-144,48.5,0),num_elements=1000)
spill = gs.Spill(release=release)
model.spills += spill
```

Test with multiple files

With the current and wind files we have performed 2 days of simulation deselecting each mover in every simulation in order to see if the model is reading correctly the NetCDF files. Moreover we added the random mover diffusion and the same check is performed in order to see if it works properly.

Simulation for 1 month

We performed one simulation with current and wind data of one month, in particular January 2018, with a dt of integration of 15 minutes and a data backup of one hour. The release is continuous from the Isonzo river's mouth: it starts from 10 particles and continue to release 10 particles every 15 minutes. The mover diffusion is implemented with a diffusion coefficient of 10^4 cm^2/sec.

Then, the NetCDF output file has been post processed in order to save for every time step the particles that are found in two polygonal areas that represent the beaches of Fossalon and Marina Nova. The polygons are chosen with a width of 150 m in order to take account of the spatial resolution.

Simulation for more months

The same simulation proposed for one month is performed for more months: in particular, for the period that goes from the 25th of November 2017 to the 7th of August 2018. In this case the continuous release is of one particle every 15 minutes, with a total number of particles at the end of the simulation of 24488.

The evaluation of the number of beached particles in the beaches of Fossalon and Marina Nova is performed. In the following figures the results are shown:
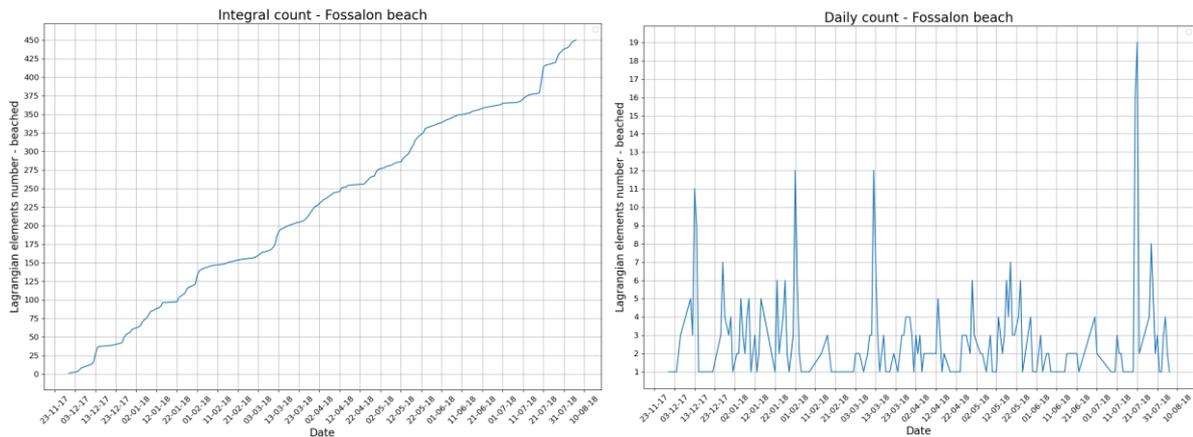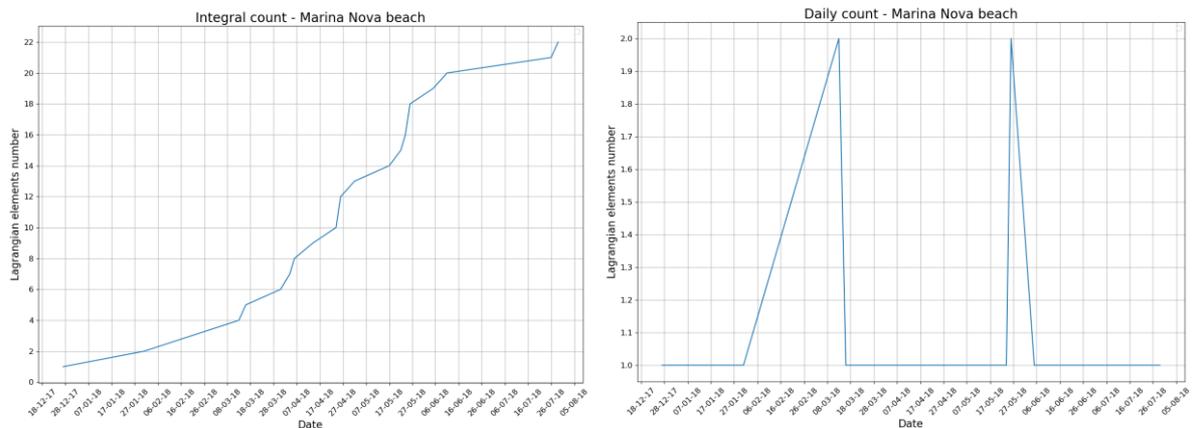
On the top and the bottom left part the integral count of the particles crossing the polygons of Fossalon and Marina Nova beaches is shown. Regarding the Fossalon's plot the number of particles crossing the polygon is the same as the number of beached particles; in particular, the plot shows that the 2% of the total amount of released particles is beached. Regarding the Marina Nova one, it can be seen that the total number of particles that have crossed the polygon is only the 0.09% in respect to the total amount, this is because a breakwater protects this beach.

On the top and the bottom right part the daily count of the particle crossing the polygons of Fossalon and Marina Nova beaches is shown. This plots show how the particles go in and go out from the polygons. In particular, for the Fossalon's plot, since the particles are beached, it can be seen the refloating behaviour.

Spatial resolution of beached Lagrangian elements

Evaluating the plots that show the beached (in red) and not beached (in blue) Lagrangian elements over a map, we found that the beached particles stay one over the other following a specific grid pattern with about a spacing of 200 m. In order to understand if this grid pattern was dependent from some parameters (in particular the time interval of integration, Δt, and the time interval of data backup, Δtb), we decided to perform different tests keeping the refloat halflife parameter fixed (48 hours). The source of release is the Isonzo river's mouth, the release is continuous and the simulations are performed for the month of February 2018. The beach in study is Fossalon and the particular time steps of the plots is the 4th of February 2018 at 1:30UTC.

The following plots are going to show the results:

Δt = 10 min – Δtb = 60 min

Δt = 5 min – Δtb = 30 min

Δt = 5 min – Δtb = 60 min
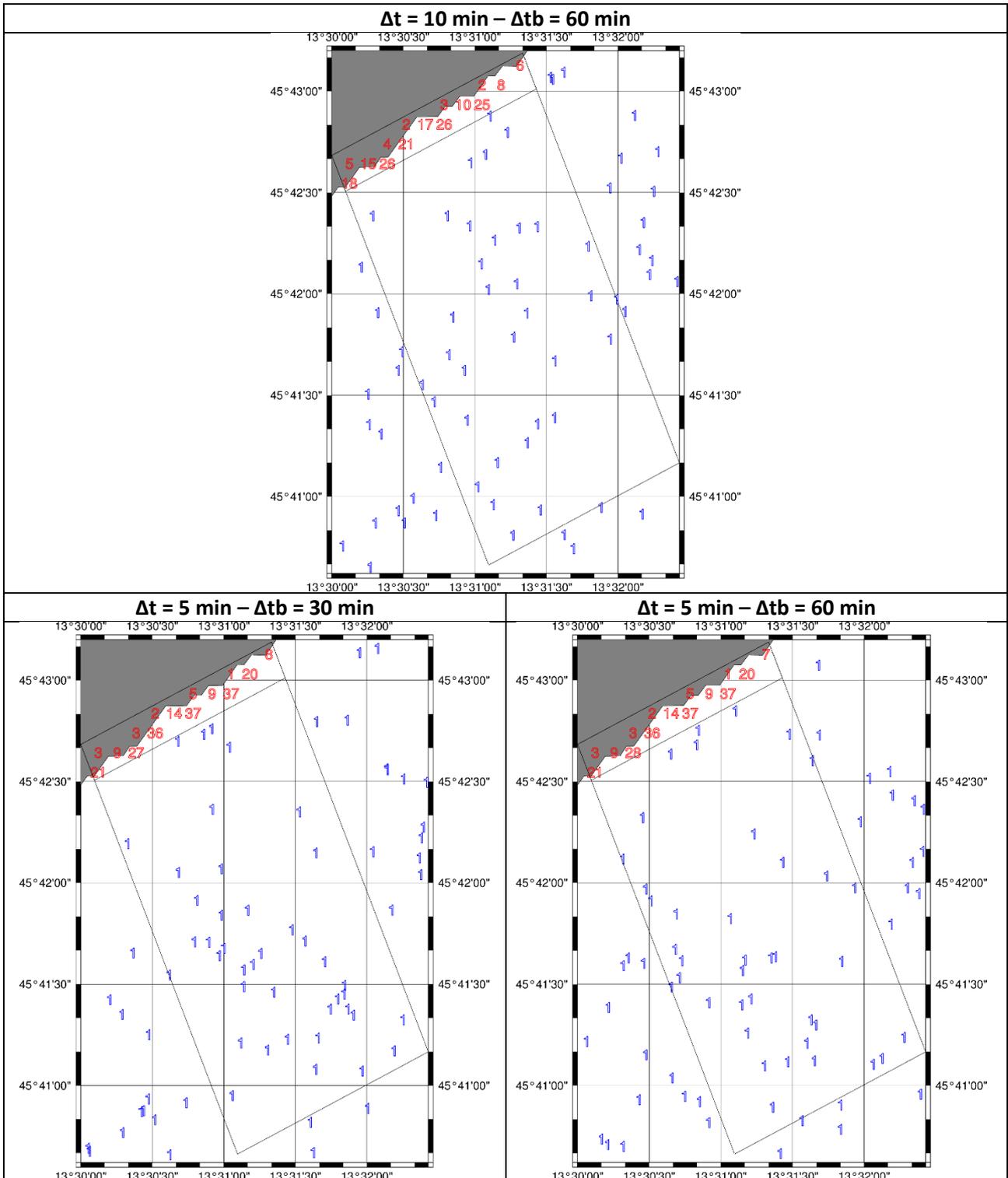
As it can be inferred from the plots above, the grid in which the particles beach is not dependent from the parameters but it is a spatial resolution inherent to the model.

Choice of the polygon representing the beach in study

After having analysed the plots of beached (in red) and not beached particles (in blue) on a map, we understood that the polygon to choose is dependent from the spatial resolution of the model near the coastlines.

Considering the beach of Fossalon for the following examples, if we chose the real extension of the beach (the first two plots), the count of the beached particle would have been underestimated since the polygon extension is lower than the spatial resolution of the model. For this reason we decide to take a wider polygon (about 3 km x 350 m: the one that contains the red beached particles in the third plot) as representative for the beach in study. The wider polygon, that contains both red and blue particles and has a dimension of about 3 km x 4 km, is then used for the statistical analysis.
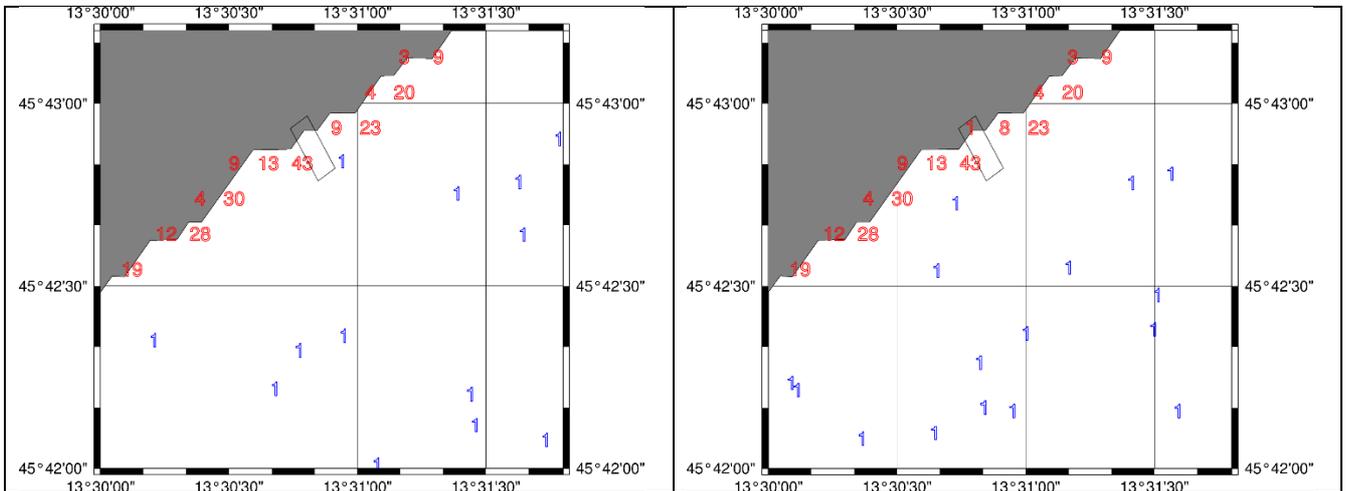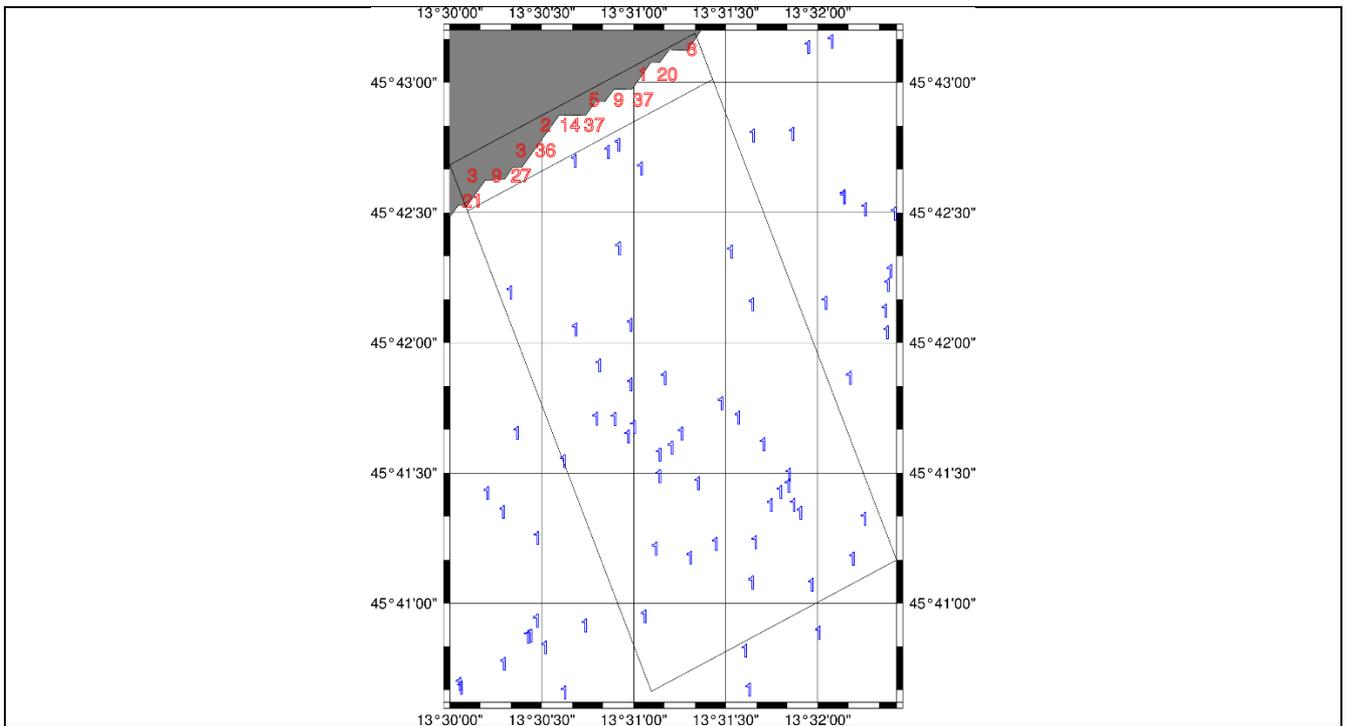
Statistical analysis

The analysis can be performed for yearly, seasonal or monthly simulation. For all of the simulation durations, the analysis starts from a daily statistics summarized in the following points:

Daily analysis

- Hourly count of the particles that are beached inside a polygon (that represents a specific beach) and of the particles that are not beached.
- Make some statistical analysis for each day:
    1. determine the minimum and the maximum number of beached/not beached particles
    2. determine the mean and the median of beached/not beached particles
    3. determine the ratio between the beached particles and the total number of beached and not beached particles inside the bigger polygon (shown in the previous plots)

- Determine the permanence for all the particles classified as 'beached':
    1. considering each specific Lagrangian element, the maximum time of its permanence as beached during the day is saved
    2. looking to the maximum hours of permanence of all the particles, the daily minimum, maximum, median and mean are saved.

All of this data are going to be saved in an ASCII file as a base for all the possible statistical analysis that one can subsequently perform.

Below a scheme for an analysis for a not specific interval of time is proposed. This interval of time can be a year, a season or more months in general; below a monthly analysis in presented.

Monthly analysis

- Determine the minimum and the maximum number of beached/not beached particles in each month considering the minimum/maximum of the daily results present in the ASCII file
- determine the mean of beached/not beached particles in each month calculating the average of the daily mean results that are in the ASCII file
- determine the median of beached/not beached particles in each month calculating the median of the daily mean results found in the ASCII file
- determine the annual or seasonal average time of permanence of each particle as beached starting from the monthly average time of permanence saved in the ASCII file

Refloat halflife parameter test

The refloat halflife parameter fixes the probability of resuspension for each marine litter, the random number generated explained in the section 'Beaching and refloating' above is not dependent from the marine litter type, so the permanence characteristics of a specific object and the beach type are summarized with this parameter.

This parameter is defined for each marine litter type that you would simulate and the beach type in which you attend the litter to be beached. Once you choose the refloat halflife parameter, you should adjust the windage range considering that bigger object are more subjected to the wind advection.

A test is performed considering a duration of one month (the same for all the simulations) with a continuous release of 10 particles per hour from the Isonzo river's mouth changing for each simulation the half-life parameter. The parameters chosen are: 1, 2, 4, 8, 12, 24, 48, 72, 96, 120 and 192 hours; for each simulation the 'Daily analysis' presented in the section above is performed for the beach of Fossalon.

The first 5 days of simulation are removed in order to consider an environment dirty enough.

The maximum, mean and median in hours of the permanence of particles as beached is shown in the following table and in the following plots:

Half-life (hours)	1	2	4	8	12	24	48	72	96	120	192
Max (hours)	41	63	88	185	273	450	814	814	814	814	814
Mean (hours)	6.56	10.40	17.72	32.54	46.09	84.21	139.68	183.04	227.31	240.83	290.72

Median (hours)	5	8	13	25	37	64.5	104	142	194	200	234
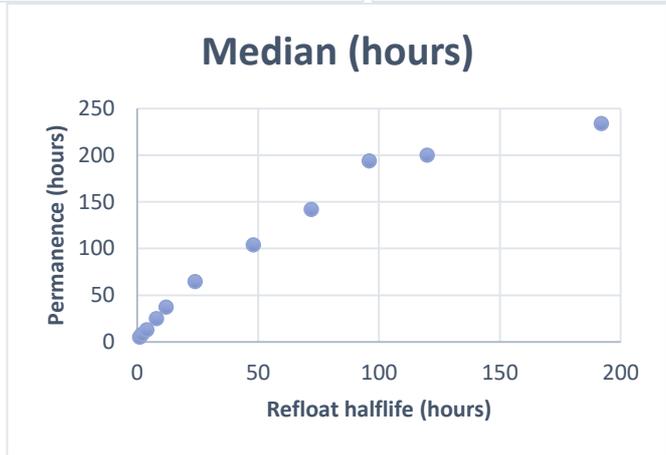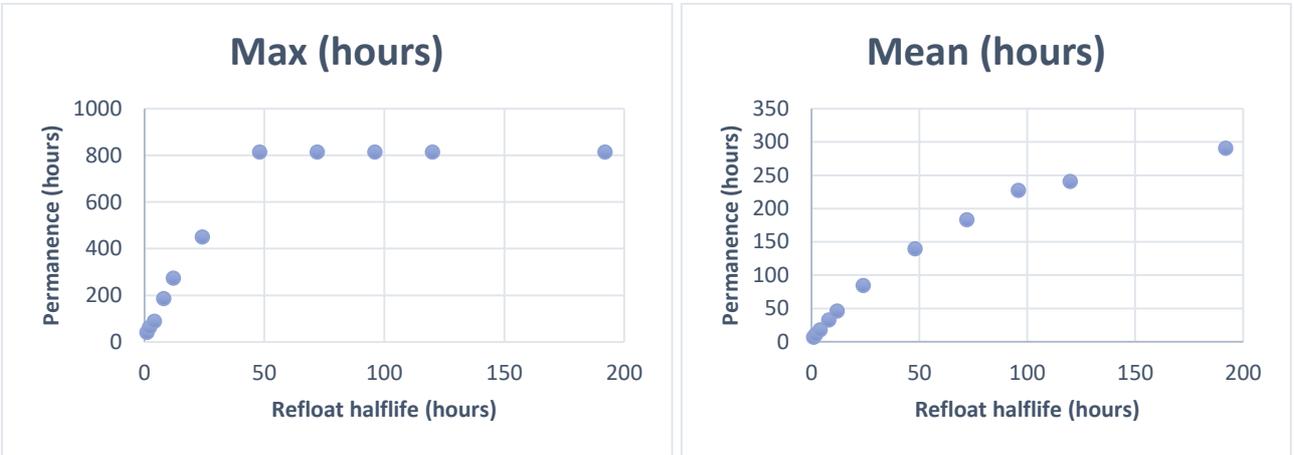
The first of the following two plots shows the total number of beached particles in the Fossalon beach in function of the time for all the half-life parameters chosen, while the second one, in function of the time, shows the ratio between the total number of beached particles and the number of the particle circulating in the area souring the beach, as shown in the two polygons in the figures in the section 'Spatial resolution of beached Lagrangian elements', for all the half-life parameters considered.

Total number of beached particles with different refloat halflife parameter in hours
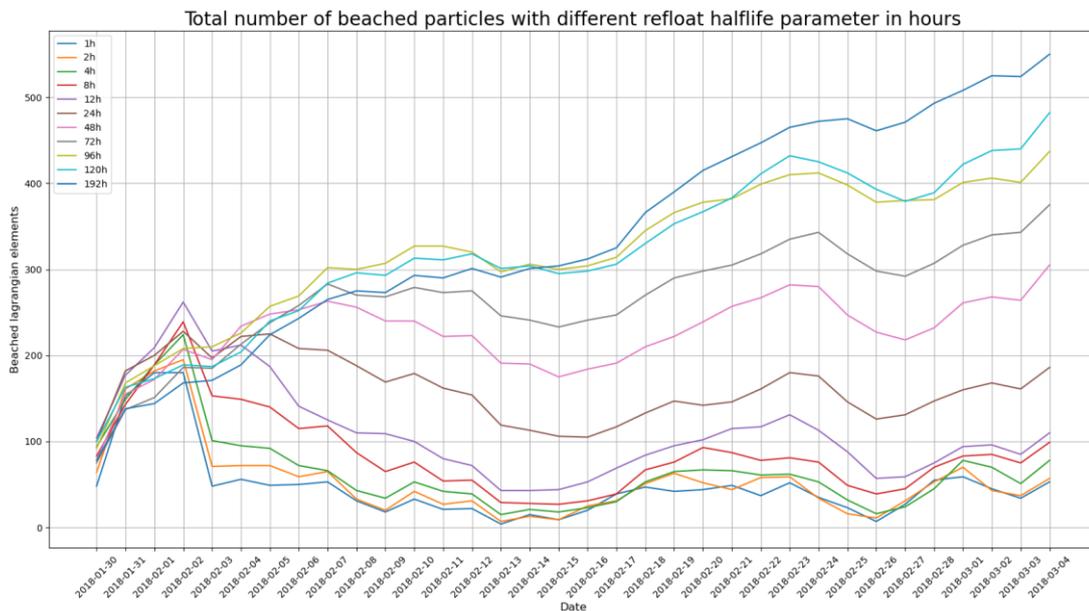
Ratio of the total number of beached particles over the total number of particles in the beach zone with different refloat halflife parameter in h
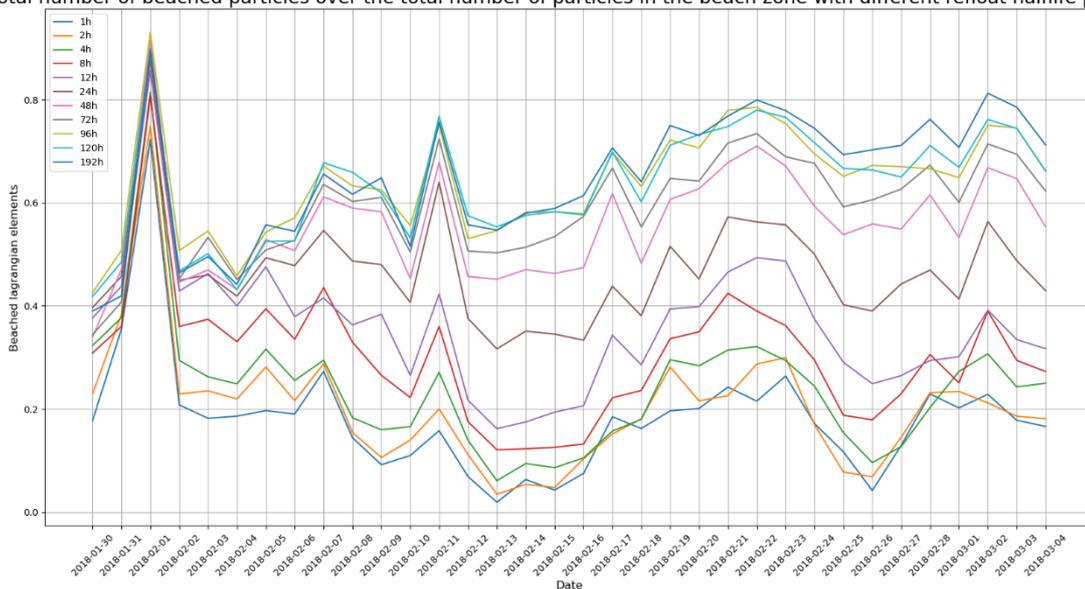
As it can been seen for the results, the number of beached particles grows with the increase of the half-life parameter. The maximum of permanence reaches a plateau when refloat half-life ≥ 48 hours, this means that the maximum hours of permanence of particles as beached is the entire duration of the simulation.

Test time with the same parameters (refloat: 76 days, dt: 10 minutes, number of released particles: 10 per hour)

A time test is performed to evaluate the consume of time varying the duration of the simulation.

- Monthly simulation: about 20 minutes of consume of time.
- 3 months simulation: about 4 hours of consume of time.
- 6 months simulation: about 28 hours of consume of time.

Horizontal diffusion

The horizontal diffusion coefficient is studied in different researchs.

In this research [2] the coefficient of the diffusion is set to 1 m^2/s and treats the global basins.

In these researches, [3] and [4] the coefficient of the diffusion is set to 10 m^2/s: the first one treats the Mediterranean Sea, the second one the global basins.

Refloat half-life parameter and windage for different kind of marine litter

Different kind of marine litter can be simulated coordinating the setting of two parameters: the refloat half-life parameter and the windage (both already presented in the sections above).

Some tests are performed with three different half-life parameters in the northern Adriatic basin: 76 days, i.e. the resuspension timescale obtained for the Mediterranean with analysis of GPS trajectories of drifter buoys [5]; 150 days and 273 days considering the resuspension timescale of plastic debris with different size found in this research [4]. No variation of the beach type are implemented and the windage is selected randomly from a range of 1%-4% of the wind speed. The Lagrangian elements are released from 16 sources (see Table 2) (harbours, rivers, city near the shorelines) using the PyGNOME utilities; the release is continuous with 10 particles per hour for a temporal duration of 9 months.

So, in total there are 48 simulations, for each source all the three refloat parameters have been set. The point with more accumulation of Lagrangian elements are studied and some evaluations are made in order to select beaches to be analysed with the satellite analysis. Only the areas with less antropical material and with less vegetation coverage are taken (see Table 1**Errore. L'origine riferimento non è stata trovata.**): one near the Reno river mouth, one near the Tagliamento river mouth, one near the Grado lagoon mouth (Banco d'Orio beach), one near the Marano lagoon mouth (Isola della Marinetta beach).

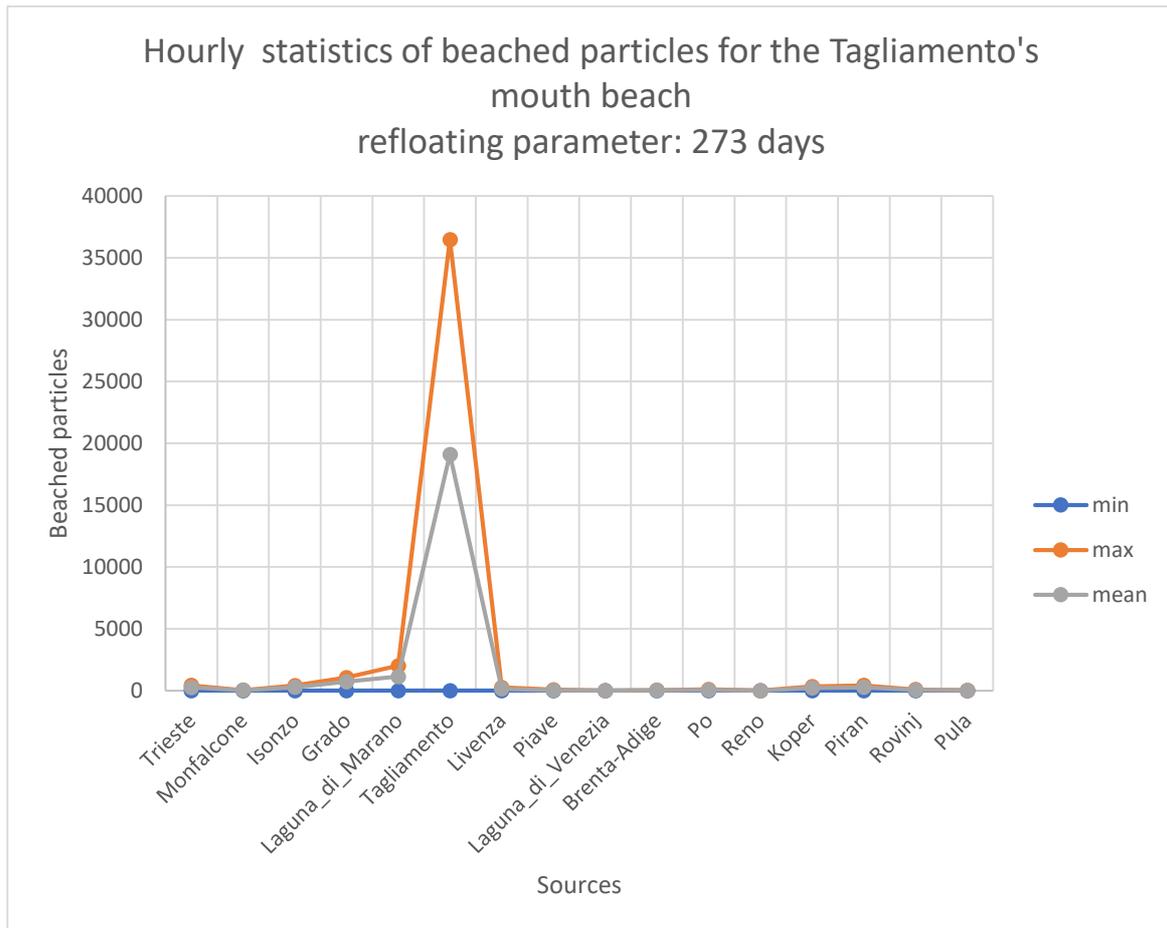| Location	Count
Tagliamento river mouth beaches	82087
Reno river mouth beaches	20428
Isola della marinetta's beach	11248
Banco d'Orio beach	7917

Table 1 Location with the greatest amount of accumulation of beached marine litter.
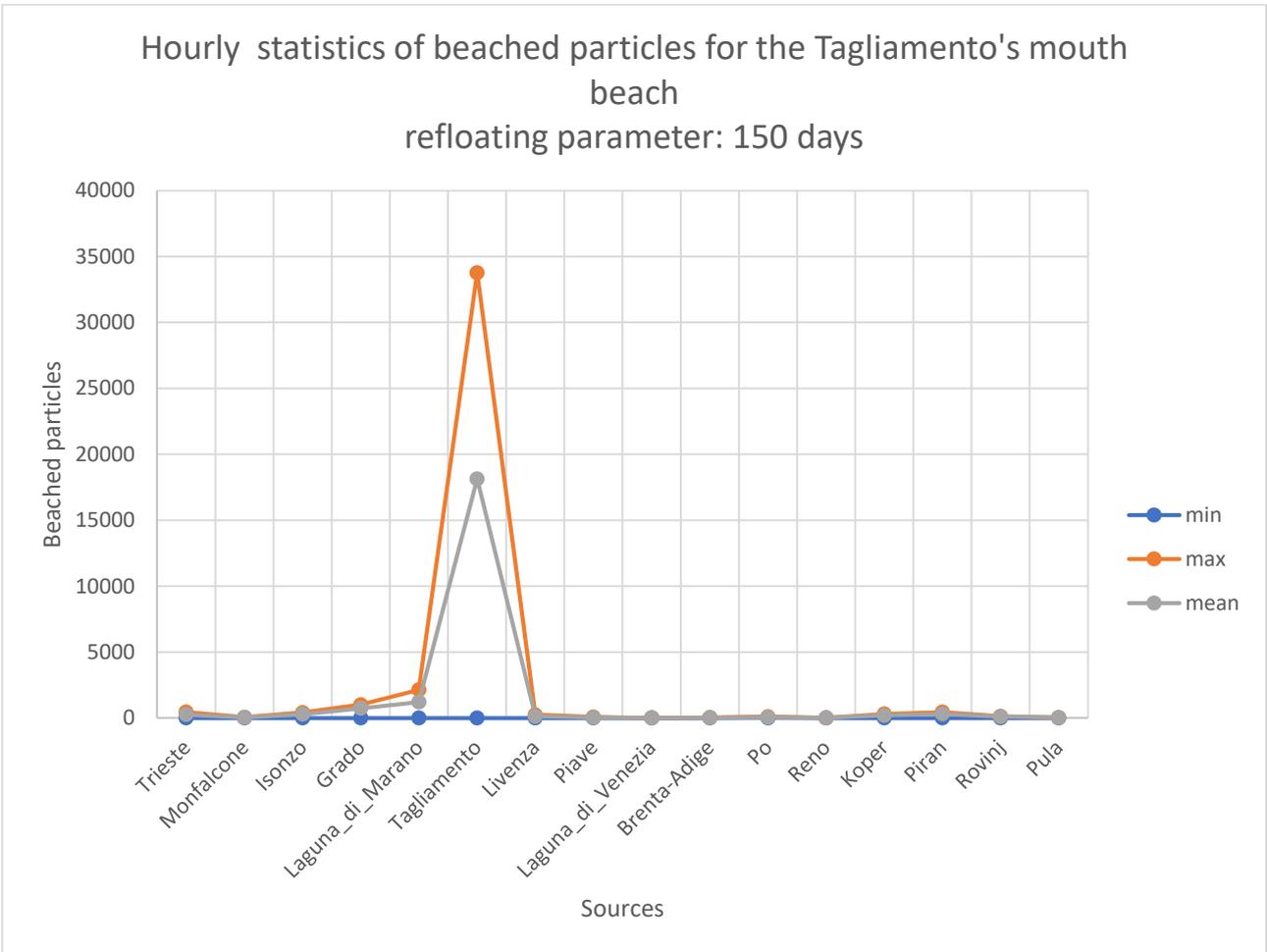
For each of these study areas, considering the different half-life parameters (76 days, 150 days and 273 days), a statistical analysis is performed: the count of beached elements is computed hour by hour, then, for each day, the minimum, maximum and median values of this count are computed. Finally for each source the absolute minimum, the absolute maximum and the absolute mean values are calculated; these results represent the hourly statistic for each area and for each half-life parameter. The daily statistics is performed computing the minimum, maximum, median, mean values of the median results for each day together with the 5% and the 95% percentiles.

The median of the median values for each day is used to compute the contribution of each source in the accumulation of beached material.

These results for each half-life parameter are then put together and the percentage of contribution of all the marine litter type are considered.
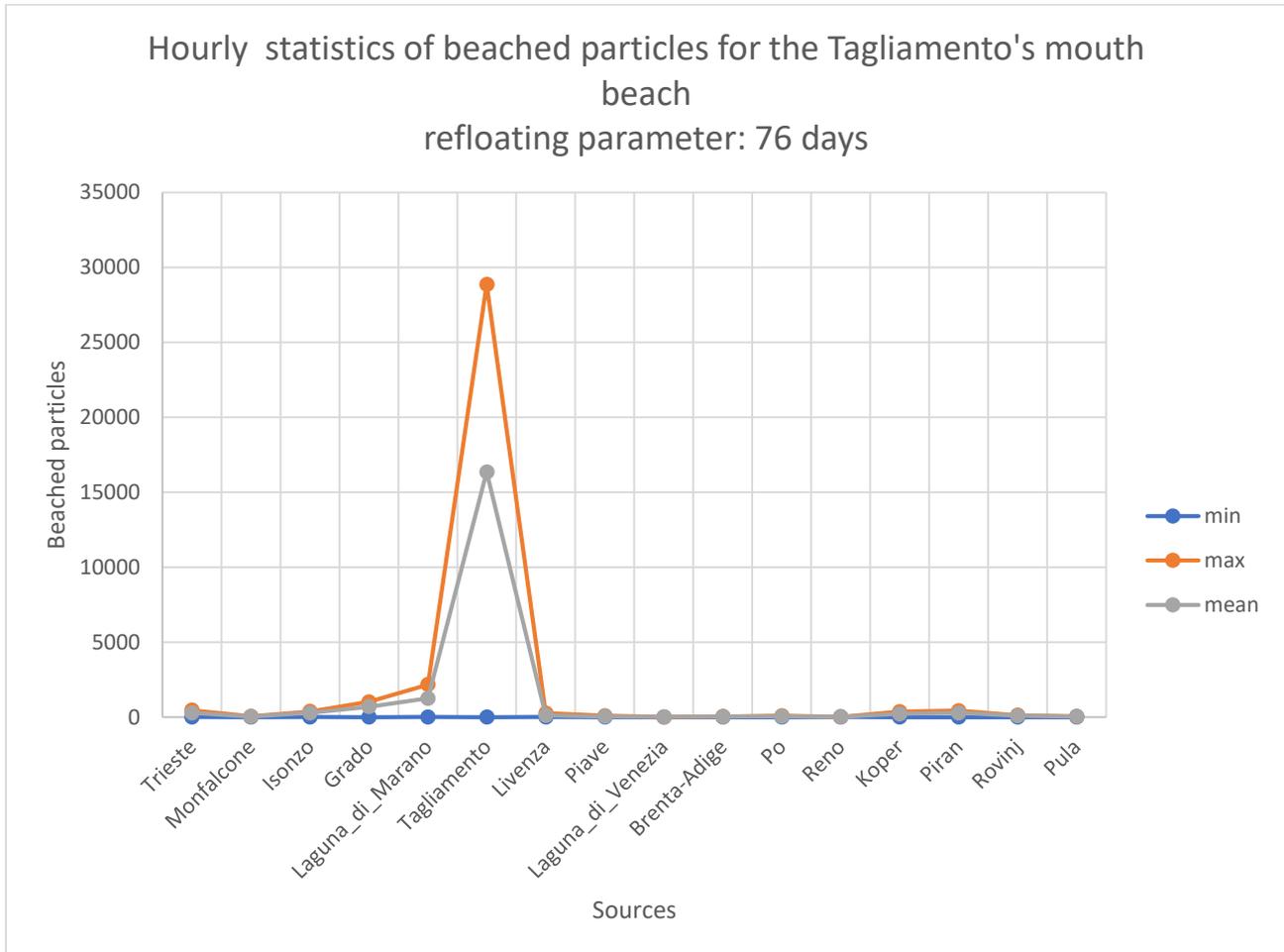
Source	Contribution (%)			
	Banco D'Orio	Isola della Marinetta	Tagliamento mouth	Reno mouth
Trieste	5.44	3.66	1.10	1.23
Monfalcone	0.08	0.07	0.20	0.04
Isonzo	2.80	3.77	1.20	1.80
Grado	69.79	6.27	3.38	2.81
Laguna di Marano	0.88	74.31	5.59	1.01
Tagliamento	1.13	1.68	84.94	1.07
Livenza	0.15	1.06	0.61	1.62
Piave	0.01	0.04	0.13	1.45
Laguna di Venezia	0.01	0.01	0.01	0.26
Brenta-Adige	0.48	0.53	0.12	0.27
Po	0.53	0.09	0.21	2.97
Reno	0.08	0.55	0.05	82.30
Koper	5.88	2.11	0.81	1.34
Piran	8.79	3.29	1.06	1.05
Rovinj	2.97	1.85	0.44	0.30
Pula	0.98	0.73	0.15	0.48

Table 2 Contribution on the accumulation of each source considering all the refloat half-life parameters.

Considering one single beach (the Tagliamento one) and the hourly statistics of beached particles of the different refloat half-life parameters, we can notice that a higher refloat parameter returns a higher amount of beached particles, as expected. Thus, from now, since the choice of this parameter affects only this aspect, the next simulations will be performed only with a refloat parameter of 273 days, the worst possible case to study.

Hourly statistics of beached particles for the Tagliamento's mouth beach
refloating parameter: 273 days

Hourly statistics of beached particles for the Tagliamento's mouth beach
refloating parameter: 150 days

Hourly statistics of beached particles for the Tagliamento's mouth beach
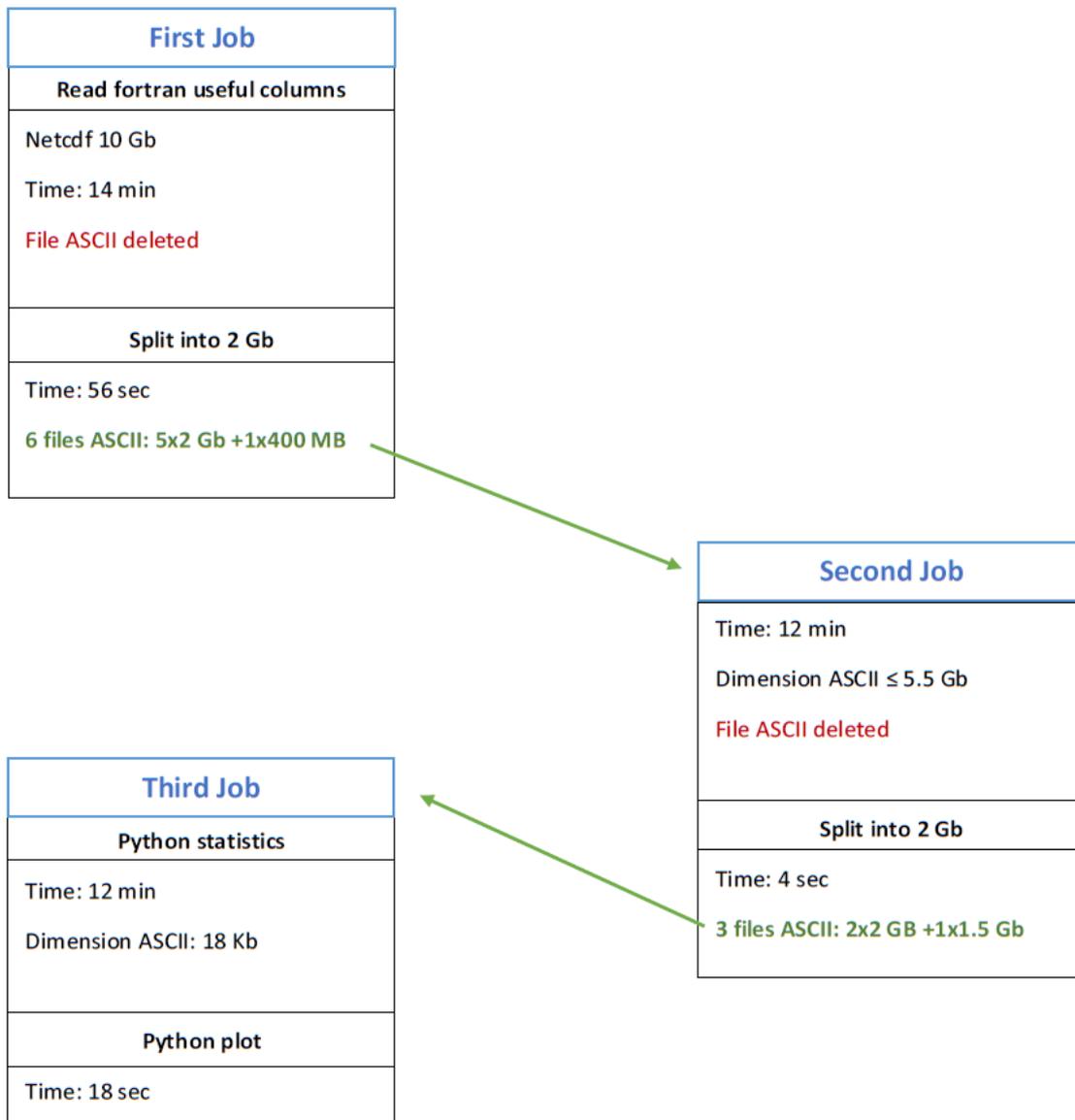refloating parameter: 76 days

Scheme of the new post processing codes: time needed and file dimensions

In order to reduce the consume of time and the dimension of the output file a study of efficiency is performed. The following explanation shows the most efficient way to trait the analysis.

As the NetCDF simulation output file is of about 10 Gb, the first job executes 2 different steps. The first one is to compile the read Fortran code, in which only the data necessary for the beaching algorithms are written in an ASCII file (particle id, time, latitude, longitude and particle count); the time needed to execute this step is of about 14 minutes, this has to be performed only one time per simulation. In the second step, with a bash command line script, the previous output file is spitted into 2 Gb files, the time needed is of about 2 minutes and the final files are 6: 5 with a dimension of 5 Gb and 1 with a dimension of 400 Mb. The output of the read code and of the second step are deleted in order to not occupy too much space in the cluster.

The second job has 2 steps. The first one is a Python script that takes the splitted files and performed a polygon masking, i.e, the polygon represent a specific beach and the code takes only the particles that are found inside that polygon. This code takes about 12 minutes to be executed and the output file has a dimension of about 5.5 Gb. Since for this test we have taken the worst case, i.e., the beach exactly near the source of release, this dimension represents an upper extreme. The second step is a split into 2 Gb command, it takes less than 10 seconds and produces 3 files: 2 with a dimension of 2 Gb and one with a dimension of 1.5 Gb.

The third job computes and plot the statistics, the overall consume of time is of 12 minutes and the ASCII generated file has a dimension of 18 Kb (the statistics calculated is shown in the section 'Simulations results and summaries'). With this optimization, we passed from a consume of 165 hours to a consume of about 37 minutes.

First Job

Read fortran useful columns

Netcdf 10 Gb

Time: 14 min

File ASCII deleted

Split into 2 Gb

Time: 56 sec

6 files ASCII: 5x2 Gb +1x400 MB

Second Job

Time: 12 min

Dimension ASCII ≤ 5.5 Gb

File ASCII deleted

Split into 2 Gb

Time: 4 sec

3 files ASCII: 2x2 GB +1x1.5 Gb

Third Job

Python statistics

Time: 12 min

Dimension ASCII: 18 Kb

Python plot

Time: 18 sec

Annual simulations

The change of the continuous release of LEs from 10 to 5 particles per hour and the change of the dt of integration from 10 minutes to 15 minute, have allowed to perform a complete annual simulation in 74 hours.

Backward trajectories

Although the documentation presents the possibility to implement the backwards runs, inside the model the relative algorithm is not usable since there is a message in which it is written that these

settings are under development. The backward trajectories are going to be considered in details in the deliverable D3.3.4, with another software.

Coast classification

Although the documentation present the possibility to implement the possibility to set the information about the coast type classification, there were no visible way to implement it. We contacted the NOAA PyGNOME developers, here the answer is reported: '*In theory yes it's possible to do that but the code to do so doesn't exist yet, nor has it been designed yet.*'.

Coastal classification type

The coastal classification work is important in order to know in which places the beaching is possible and in which ones it is not. This will help in the construction of the probability maps of accumulation. For the Italian coast we found a shape-file of the line coast of the 2020, which is very accurate and with high spatial resolution: there is the distinction of natural and artificial coasts (i.e., harbours or other human made structures) and other useful information. The natural coasts are divided into low and high ones, and there is the lithological classification (sandy and sandy with rock beaches, rocky beaches, pebbled and pebbled with rocks beaches).

This file can be downloaded in this site: https ://sinacloud.isprambiente.it/portal/apps/sites/#/coste/pages/dati
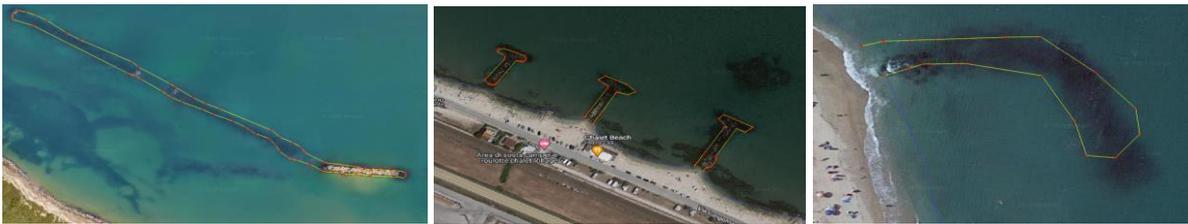

No possibility of beaching

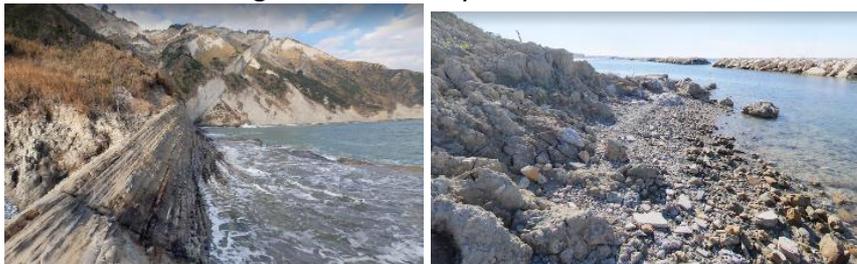Starting from this classification, the places in which the beaching is not possible are:

1. the engineering structures: for example, arbours, structures on rivers' mouth
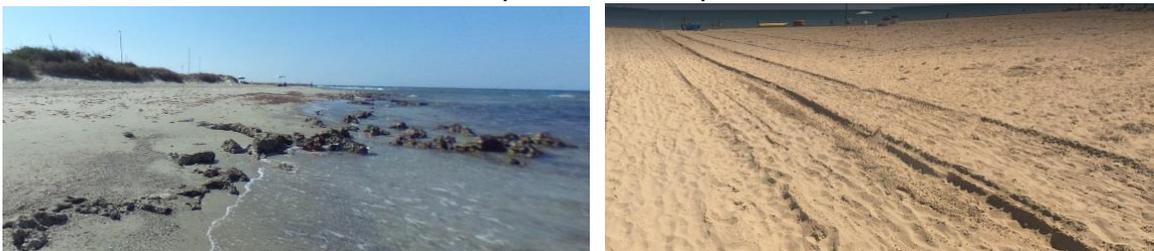
2. the coastal defence works

3. the natural coast classified as high and low rocky beach

Possibility of beaching

The places in which the beaching is possible are:

1. the natural coast classified as low- sandy and low-sandy with rocks beach

2. the natural coast classified as low-pebbled and low-pebbled with rocks beach

The sandy beaches have a higher probability of beaching in respect of the pebbled ones.

In conclusion, the coast type classification is going to be used as a postprocessing step, in order to be able to reject or not the simulations results.

Simulations results and summaries

In this section the simulation results are going to be presented: firstly, the study of the accumulation points of marine litter along the Adriatic Sea's coasts and then the study of the beached marine litter along some MARLESS monitored beaches.

In the second part, a comparison between the results obtained with high resolution currents, from the Shyfem model, and the Copernicus currents is shown.

In the third part, the macroareas of accumulation are presented for each Italian Region.

The statistical analysis on the beaches is performed for every considered source; here below you can see the variables considered:

- Contribute in the accumulation of each source in %: how much each source contributes on the accumulation of marine litter on the beach in study.
- First date of accumulation: first date in which beached particles are found.
- Last date of accumulation: last date in which beached particles are found.
- Beached particle at the end of the simulation: number of beached particles in the last date of the simulation.
- hourly_min(min): absolute minimum value of beached particles in an hour.
- hourly_max(max): absolute maximum value of beached particles in an hour.
- hourly_mean(mean): mean value of beached particles in an hour.
- daily_min(median): daily minimum of the median of beached particles.
- daily_max(median): daily maximum of the median of beached particles.
- daily_mean(median): daily mean of the median of beached particles.
- daily_median(median): daily median of the median of beached particles.
- 5th percentile: 5th percentile of the median of beached particles.
- 95th percentile: 95th percentile of the median of beached particles.

Study of the accumulation points of Marine Litter along the Adriatic sea's coasts
Study of the major accumulation points

Since October 2022 the sources considered are the ones shown in the map and in the list below. They are mainly in the Italian coast and are harbours, rivers' mouths and industries that are along the shoreline. Considering the sources in the northern Adriatic Sea, going eastwards to westwards (from the harbour of Pola to the river of Reno), the simulations have a duration of 9 months with a release of 10 LEs per hour and a dt of integration of 10 minutes. For all the other sources, the simulations have a duration of about 1 year (360 days), with a release of 5 LEs per hour and a dt of integration of 15 minutes.

Figure 25 On the left the map of the sources it is shown in red points. On the right the list of the sources and four of the major accumulation are shown.

Considering all the simulations together, 4 of the major points of accumulation have been studied, they are indicated with a yellow rectangle in the map above and in the list below the sources list.

Here below, the top 3 sources that contributes the most on the accumulation of marine litter on the different beaches are shown.

Beaches near Reno's mouth	Top 3 sources and their contribute in %	
	Source	Percentage continute
	Reno river	78%
	Po river	3%
	Grado lagoon	2%

Beaches near Chienti's mouth	Top 3 sources and their contribute in %	
	Source	Percentage continute
	Chienti river	89%
	Civitanova Marche's harbour	6%
	Potenza river	2%

Beaches near Biferno's mouth	Top 3 sources and their contribute in %	
	Source	Percentage continute
	Biferno river	80%
	Termoli's harbour	11%
	Vasto's harbour	2%

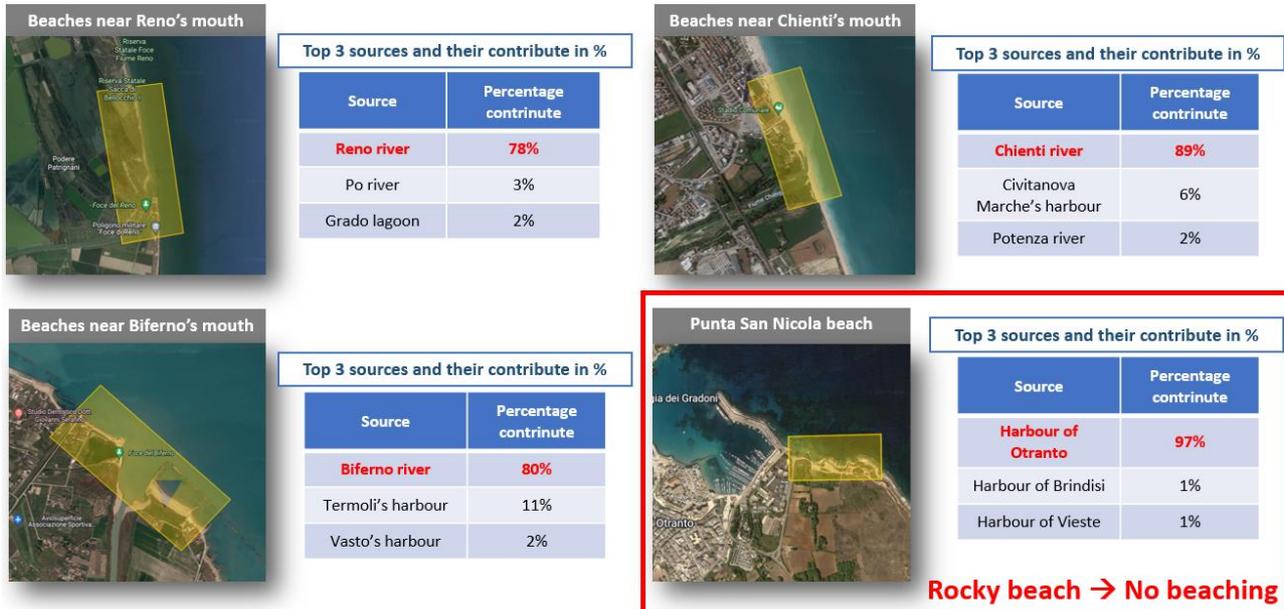| Punta San Nicola beach	Top 3 sources and their contribute in %	
	Source	Percentage continute
	Harbour of Otranto	97%
	Harbour of Brindisi	1%
	Harbour of Vieste	1%

Rocky beach → No beaching

Figure 26 The four major accumulation points are shown in the maps: on top left the beaches near the Reno's mouth, on top right the beaches near the Chienti's mouth, on bottom left the beaches near the Biferno's mouth and on bottom right the Punta San Nicola beach. The top 3 sources that contribute the most on the accumulation are shown in the tables with their percentage contribute.

Considering the first 3 points of accumulation (i.e., the beaches near the rivers' mouths) on the first place there is the nearest river as expected. Considering the last one beach, the Punta San Nicola beach, the first place is occupied by the Otranto's harbour that is near the beach in study, but this beach is classified as rocky beach so, unlike the other 3 that are sandy beaches, the beaching is not possible. This shows you the importance of the classification of the coasts, since it allows to understand if some simulation accumulation results have to be rejected or not.

Study of the beached ML along some MARLESS monitored beaches

In this section the top 3 sources that contributes the most on the accumulation of marine litter on 2 of the MARLESS monitored beaches are shown.

The first one is Grado Pineta beach, on the left you can see the nearest sources in red points, the yellow rectangle indicating the beach in study, and in green points the top 3 sources that contribute the most. On the right, the table shows the top 3 sources and their percentage contribute.
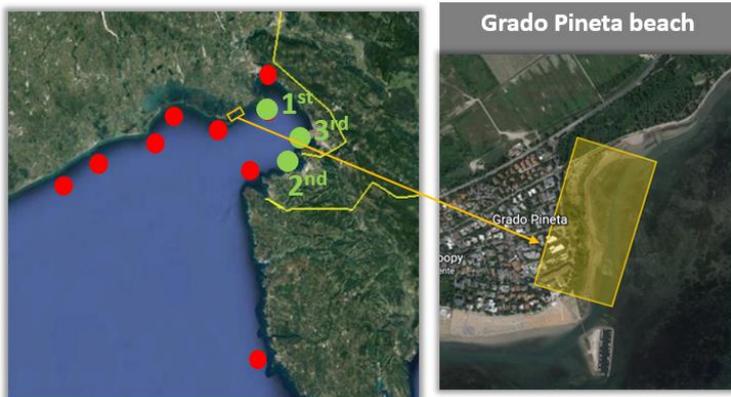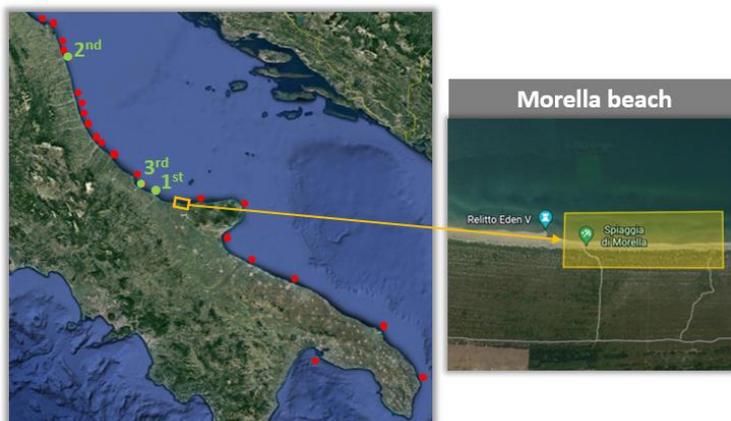
Top 3 sources and their contribute in %	
Source	**Percentage continute**
Isonzo river	**66%**
Koper's harbour	14%
Trieste's harbour	11%

Figure 27 Grado Pineta beach it is shown in the map. On the left the map with the nearest sources (in red points) and the top 3 sources that contribute the most (in green points) are shown. The top 3 sources that contribute the most on the accumulation are shown in the tables with their percentage contribute.

On the first place, there is the Isonzo river with a contribution of the 66%, on the second place with a contribution of the 14% there is the Koper's harbour and on the third place the Trieste's harbour with a contribution of the 11%. All the top 3 sources are close to the studied beach.

The second considered beach is the Morella beach (Bosco Isola Lesina), on the left you can see the nearest sources in red points, the yellow rectangle indicating the beach in study, and in green points the top 3 sources that contribute the most. On the right, the table shows the top 3 sources and their percentage contribute.

Top 3 sources and their contribute in %	
Source	**Percentage continute**
Biferno river	**11%**
Chienti river	9%
Termoli's harbour	9%

Figure 28 Morella beach (Bosco Isola Lesina) it is shown in the map. On the left the map with the nearest sources (in red points) and the top 3 sources that contribute the most (in green points) are shown. The top 3 sources that contribute the most on the accumulation are shown in the tables with their percentage contribute.

On the first place there is the Biferno river with a contribution of 11%, on the second place there is the Chienti river with a contribution of 9% and on the third place with a contribution of the 9% there is the Termoli's harbour. The first and the third sources are close to the studied beach, but the second one is farther. The overall contribution is almost the same, around the 10%, so there is no predominant source that pollutes this beach.

Comparison of the results obtained for high and low resolution currents

In this section the results of the study conducted on high and low resolution currents are shown.

In the below plots, on the left you can see the plot of the high resolution currents (obtained from Shyfem model), they cover mainly the Friuli Venezia Giulia Region, and have a spatial resolution that goes from 10 m inside the lagoon (the zoom on the top left) and 4 km in open sea. On the right, you can see the plot of the low resolution currents (from the Copernicus Marine Service), they cover the entire Adriatic Sea and have a regular spatial resolution of 4 km.
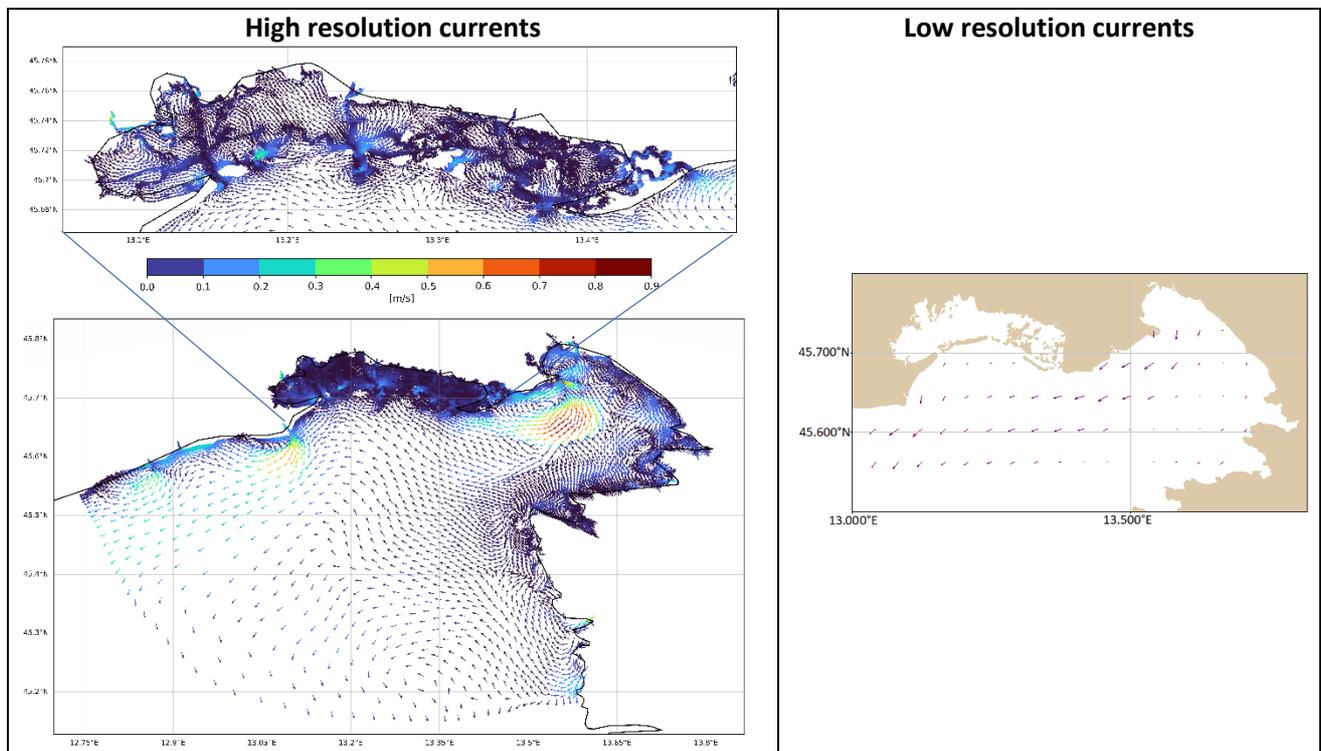

Figure 29 On the left the high resolution currents are shown, on top the zoom of the lagoon it is displayed. On the right the low resolution currents are shown.

One of the advantage to use high resolution currents it's the better spatial resolution on the distribution of the beaches elements, as you can see from the image below: the beached elements for high resolution currents, shown in blue, are distributed every 20 meters, while the ones for low resolution currents, in red, every 200 meters.

Figure 30 Scheme of the distribution of the beached elements for high resolution currents (in blue) and for low resolution currents (in red).

To compare the results between the high and low resolution currents simulations, the sources in orange (shown in the following image) are considered (they goes from the Livenza river to Pirano's harbour). The contribution on the accumulation on the beaches indicated by the yellow squares is calculated for every source.
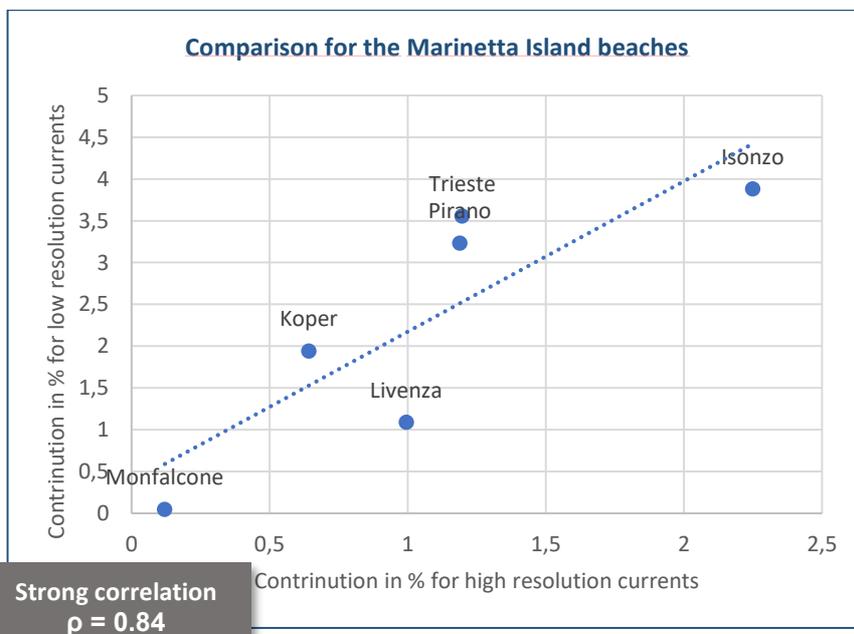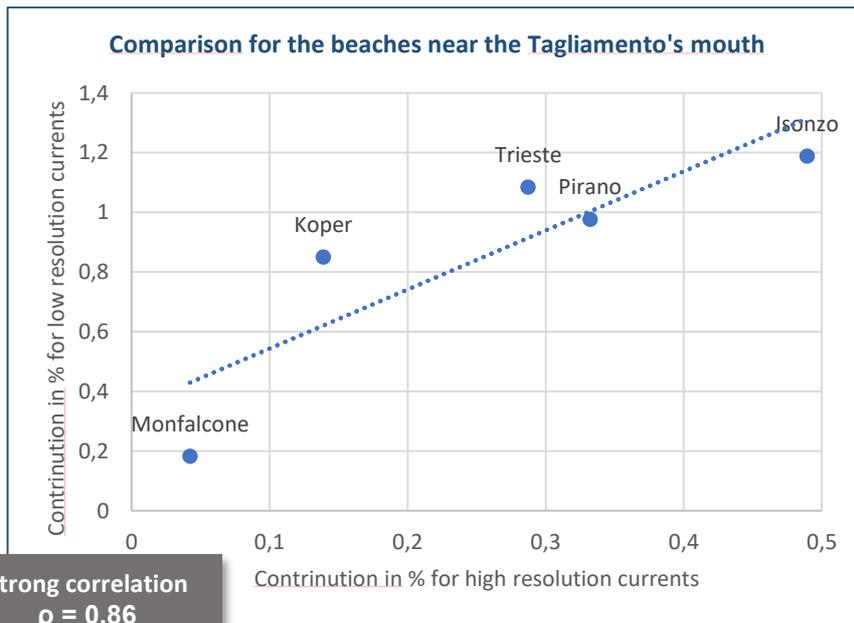

Figure 31 On the left the list of the sources considered for this study, on the right the map with the sources indicated by orange points and with the beaches studied indicated by yellow rectangles.

The contribution of only the sources that are far more than 20 km from the beaches has been considered; the comparison between high and low resolution currents for each beach is shown in

the plots below. As it can be noticed from the Pearson Correlation Coefficient the results are strongly correlated.

So, it can be deduced that the accumulation results are comparable using high or low resolution currents for sources far from the beaches, however, for the sources near the beaches is recommendable to consider high resolution currents.
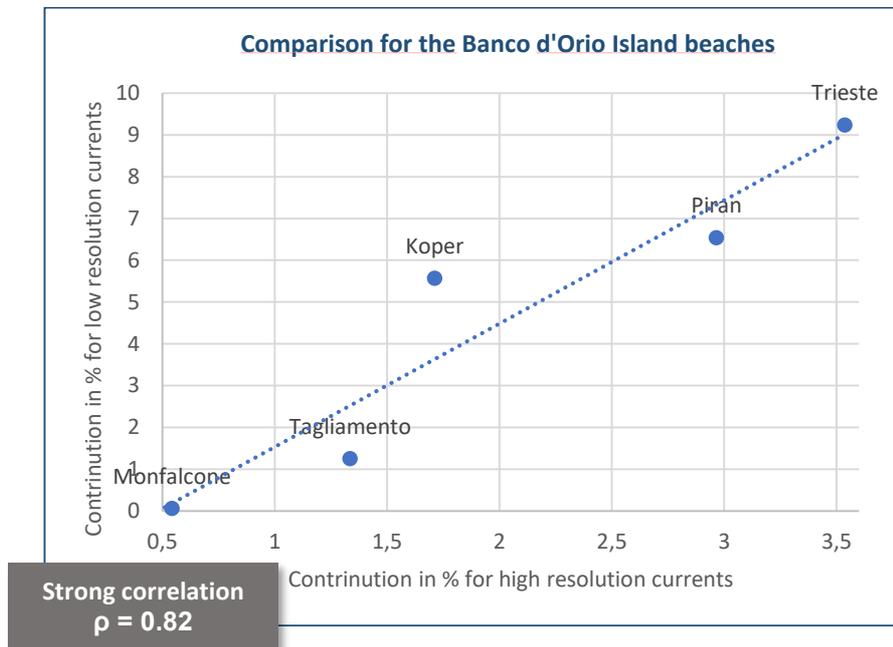

Comparison for the beaches near the Tagliamento's mouth

Strong correlation
ρ = 0.86

**Comparison for the Marinetta Island beaches**

Strong correlation
ρ = 0.84

Figure 32 Plots of the contribution comparisons between high and low resolution currents for every beach considering only the sources (the blue points) farther more than 20 km from the studied beach. The first one is the comparison for the beaches near the Tagliamento's mouth, the second one for the beaches in the Marinetta Island beaches, the last one for the Banco d'Orio Island beaches. For every plot it's shown the linear regression line (the blue dotted line) and the Pearson Correlation Coefficient (ρ).

Macro areas of accumulation

The macro areas of accumulation are calculated considered only an amount of more than 500 beached elements accumulated in the same position. Then, the coastlines are subdivided into polygons of 10 km of length and the elements inside are counted. For every Italian region the percentage contribute is calculated in order to find the macro areas of accumulation. It has to be taken in mind that these results are obtained considering all the sources as equally polluting; so, the results don't indicate if a source pollutes more than one another.
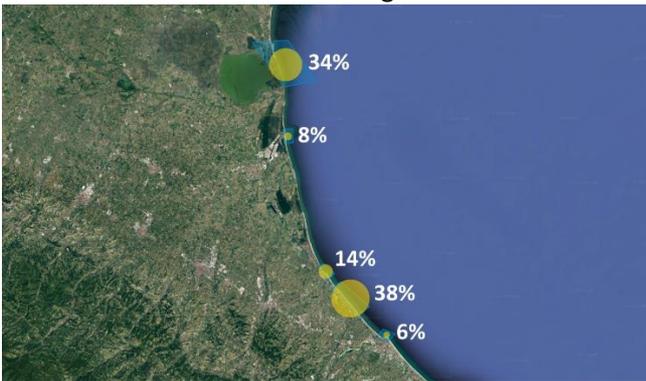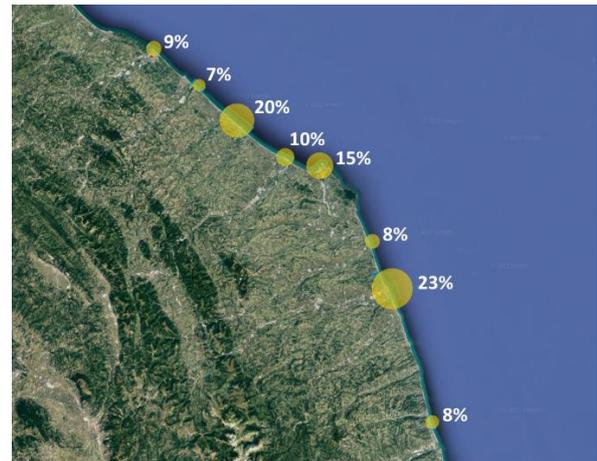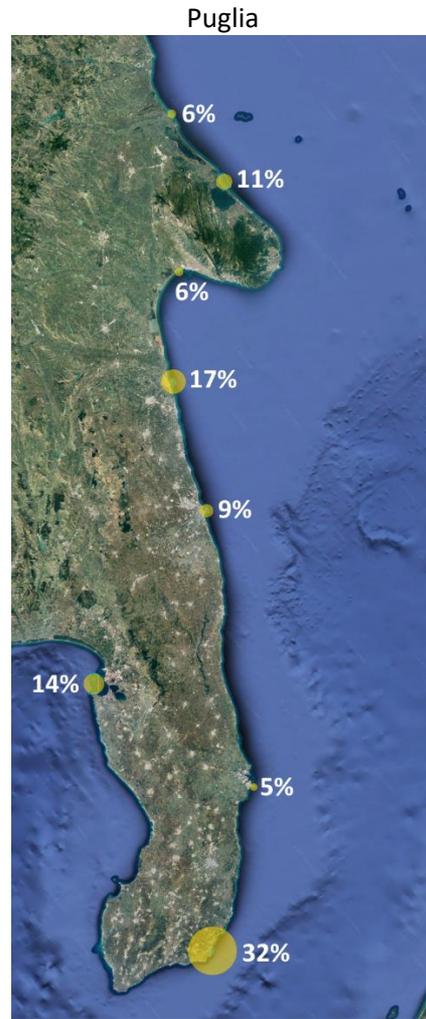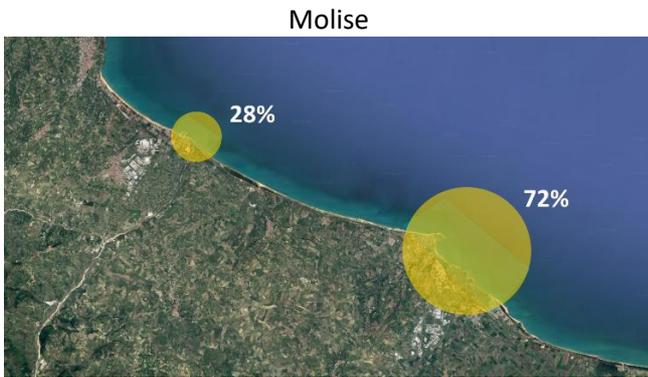
Friuli Venezia Giulia

Veneto

Emilia-Romagna

Marche

Abruzzo

Molise

Puglia
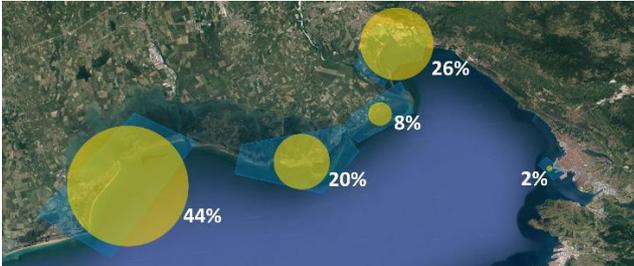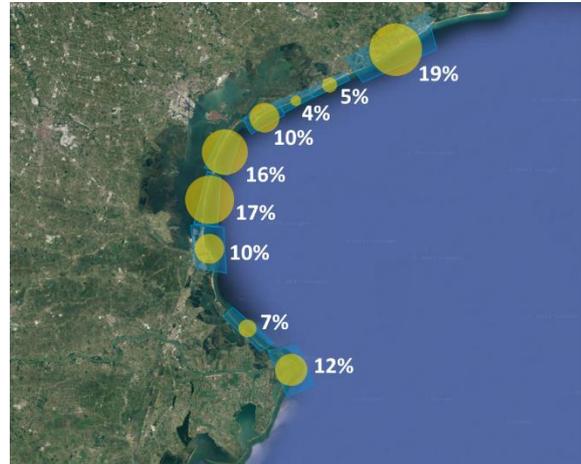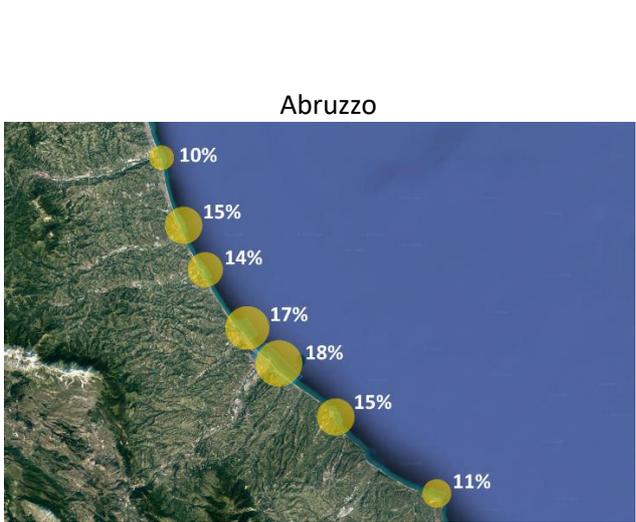
Conclusions

Due to the large amount of information available from simulations and therein analyses, the main results are organized in digital form. In the work in progress they are available in the following website: http://interreg.c3hpc.exact-lab.it/MARLESS/ or in the set of folders and subfolders attached to this document.

The following image shows the homepage of the website; the part relative to this work is the 'Numerical simulations'.
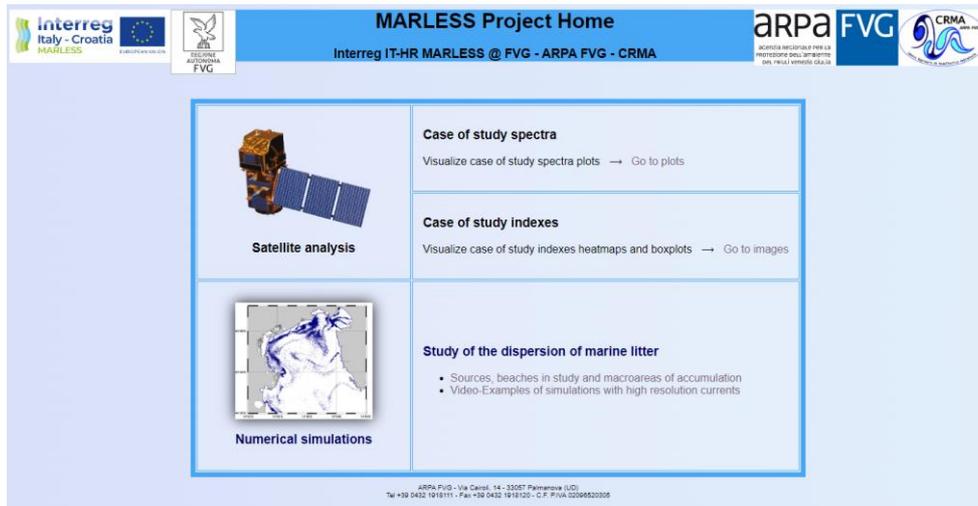
Figure 33 Homepage

On the link 'Sources, beaches in study and macroareas of accumulation' you can find two maps with the sources and the beaches studied since now. Then there is a table with the list of beaches studied an interactive map in which by clicking on the region of interest you see the results relative to that region.
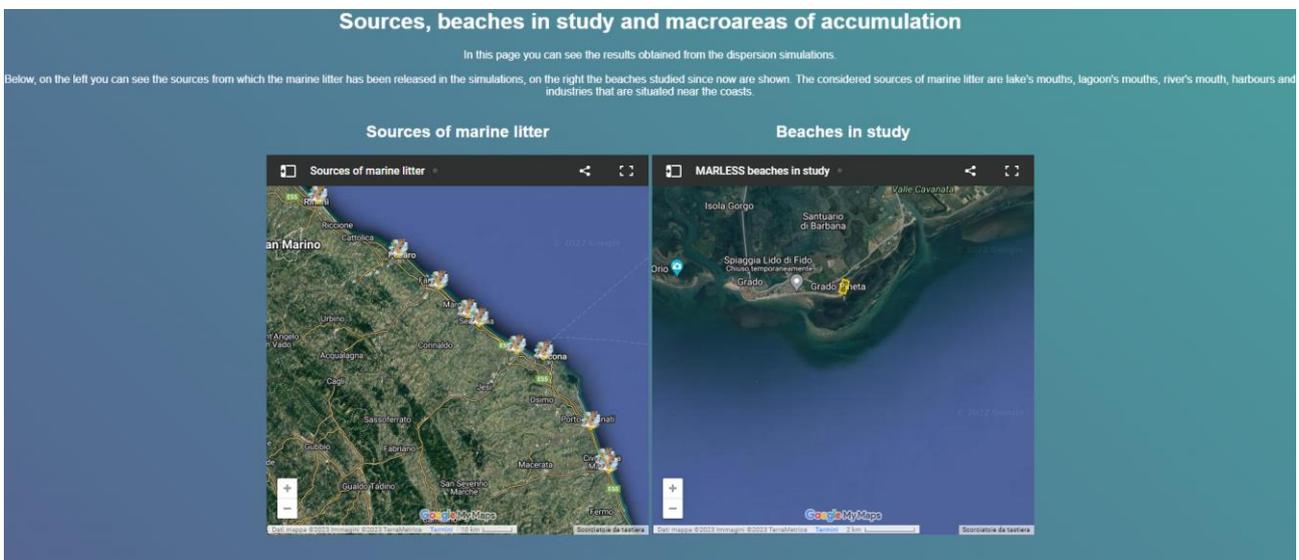

Figure 34 Maps with the sources and the beaches studied since now

List of beaches in study

The following list shows the beaches studied for every region. Click on the beach of interest to see the statistical results obtained.

Friuli Venezia Giulia	Veneto	Emilia-Romagna	Marche	Abruzzo	Molise	Puglia	Croatia
• Grado Pineta beach	• Isola Verde beach	• Riccione beach				• Soleluna Lido beach	• Općina Umag beach • Trstenik beach

Interactive map

Click on the region of interest to see the results obtained: you will see the list of beaches in study and the macro area of accumulation of waste for each region.

Interreg IT-HR

Others

For example, clicking on the Puglia Region you will see the following page with the list of the studied beaches, divided in 'MARLESS monitored beaches' and 'Other beaches', and the macro area of accumulation of that region.
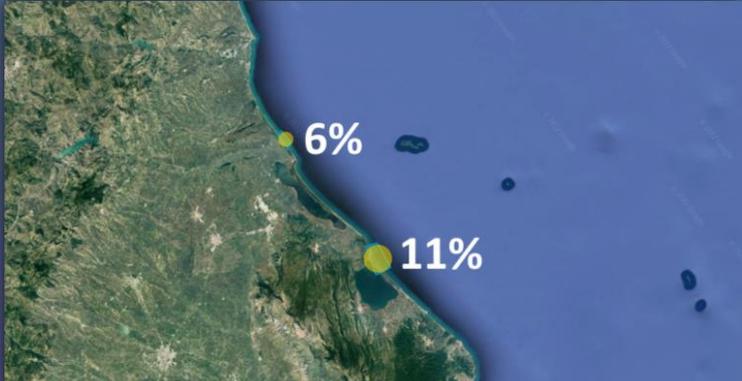

If you click on a specific beach you will open a page with all the statistical analysis conducted for that beach, you can see an example on the following image.
These html pages are also available in the attached folder *D3.3.2.tar*.

Statistical analysis for 360 days of simulations

Source: source from which particles are released.
Contribute in the accoumulation of each source in %: how much each soruce contributes on the accumulation of marine litter on the beach in study.

- from 100% to 60%
- from 59% to 5%
- from 4% to 1%

First date of accumulation: first date in which beached particles are found.
Last date of accumulation: last date in which beached particles are found.
Refloating parameter (days): refloat halflife parameters expressed in days. It is the number of hours in which half of the pollutant on a given shoreline is expected to be removed (if the value is higher than the defalut (1 hour) the pollutant will stick to the shoreline longer, while for very small values.
Beached particle at the end of the simulation: number of beacehd particles in the last date of the simulation.
hourly_min(min): absolute minimum value of beached particles in an hour.
hourly_max(max): absolute maximum value of beached particles in an hour.
hourly_mean(mean): mean value of beached particles in an hour.
daily_min(median): daily minimum of the median of beached particles.
daily_max(median): daily maximum of the median of beached particles.
daily_mean(median): daily mean of the median of beached particles.
daily_median(median): daily median of the median of beached particles.
5th percentile: 5th percentile of the median of beached particles.
95th percentile: 95th percentile of the median of beached particles.

Soleluna Lido

Source	Contribute in the accoumulation of each source in %	First date of accumulation	Last date of accumulation	Refloating parameter (days)	Beached particle at the end of the simulation	hourly_min(min)	hourly_max(max)	hourly_mean(mean)	daily_min(median
Brindisi's harbour	20.08	28/11/2017	18/11/2018	273	131	1	131	58.13	2.0
Vieste's habrour	15.57	30/05/2018	18/11/2018	273	41	1	45	33.09	4.0
Otranto's harbour	6.15	24/02/2018	18/11/2018	273	20	1	20	16.38	5.5
Manfredonia's harbour	5.33	29/05/2018	18/11/2018	273	14	3	14	12.11	3.0
Boiana river 2	5.33	18/06/2018	18/11/2018	273	44	1	44	18.09	1.0
Varano lake	4.92	30/05/2018	18/11/2018	273	11	1	14	10.52	1.0
Barletta's harbour	4.92	11/02/2018	18/11/2018	273	13	1	18	12.82	1.0
Boiana river 1	3.69	19/06/2018	18/11/2018	273	40	1	40	15.16	1.0
Erzen river	3.28	18/06/2018	18/11/2018	273	23	1	23	10.89	3.0
Bari's harbour	2.46	23/12/2017	18/11/2018	273	19	1	19	8.97	1.0
Mat river	2.46	19/06/2018	18/11/2018	273	15	1	15	8.99	4.0
Semam river	2.46	18/06/2018	18/11/2018	273	10	1	10	5.83	1.0
MBM's harbour	2.05	18/06/2018	18/11/2018	273	27	2	27	10.84	3.0
Tronto river	1.64	18/06/2018	18/11/2018	273	4	2	4	4.00	4.0
Biferno river	1.64	18/06/2018	18/11/2018	273	3	1	4	3.87	1.0
Ishem river	1.64	18/06/2018	18/11/2018	273	7	1	7	4.35	1.0

References

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[5] M. L. A. Kaandorp , H. A. Dijkstra and E. van Sebille , *Closing the Mediterranean marine floating plastic mass budget: inverse modeling of sources and sinks,* 2020.