UNIVERSITY OF PADUA

RESIDENCE TIME IN MICRO-TIDAL BASINS

Graduation thesis

A.Y. 2013/2014

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16/04/2014

Summary

1. Introduction

Talking about water quality it is important to know which rules refer; in Italy it is European Directive 2000/60/CE, which was transposed with legislative Decree 3 April 2006 n.152. The most important objectives of this directive are: prevent the qualitative and quantitative deterioration of waters, improve their condition and ensure a sustainable use. For this purpose it is planned to analyse the characteristics of the water bodies, to define reference conditions, and their spatial and temporal evolution, in order to compare the current situation with the recovery objectives required by the regulations.

Studying water quality in tidal basins, elements to be considered are: abundance and variety of biological populations, physical and chemical parameters (ex.: temperature, salinity and nutrients) and morphological conditions (ex.: surface and depth of the basin). Morphological parameters are usually studied with soil analysis, while the other elements are investigated through the analysis of water quality which, usually, uses ecological numerical models.

Ecological models of water quality are useful instruments to evaluate the actual conditions of a natural basin and also to evaluate the effects of some interventions to improve the water exchange capacity; but they have some not negligible limitations.

In natural basins it is necessary to examine the temporal evolution of lots of chemical and biological species and also the interactions between different species. The equations that represent these dynamics can be often conceptualized with a first order kinetic, it means

that the model will be described by a huge number of parameters. These parameters need to be calibrated on the basis of a large number of experimental surveys but, usually, such a number of data is not available and so the calibration of the model can not be performed in a correct way. To overcome this problem we rely to experience and intuition to give a proper value to the parameters. This proceeding often does not ensure a reliable result due to the multiplicity of linkages between chemical and biological species and then because of the difficulty in understanding which are the causes of some problems and which are the effects of the proposed interventions. Another aspect about ecological numerical models to be considered is the computational effort required to obtain a result; it is very high and not always justified by the required level of knowledge and by the time in which results must be obtained.

Considering the difficulties related to the use of ecological models to evaluate water quality and to propose actions aimed to improve the current conditions, it is possible to use some indicators , in particular *hydrodynamic indicators*, instead of ecological models. Their principle advantages are that they are fast and simple to be calculated and that the values they assume can be evaluated on the basis of experience alone and on some specific knowledge; this is due to the fact that these indicators are independent on the interactions between chemical and biological species.

Among the indicators that are proposed in literature, the most widely used to evaluate the water exchange capacity, and then the water quality, are some characteristic times-scale; among them, in this work, *residence time* is considered. This specific time-scale is representative of the water quality because, in a general way, it is the time a parcel takes to exit from a basin. Then the lower the residence time the higher the water exchange and so the easier the water renewal and the removal of the injected pollutants from the water.

The goal of this thesis is to calculate the residence time, starting from a punctual injection of a conservative tracer in the Venice lagoon, using a numerical model that simulates the diffusive processes and then compare the obtained results with those obtained in a previous work in which the residence time was computed with different initial conditions.

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The thesis is subdivided in various chapters; in chapter 2 some definitions of two characteristic times-scale are reported to underline how in literature a lot of definitions are associated to the residence time. Here the 'e-folding residence time' has been considered. In chapter 3 the Venice lagoon is described because all the simulations are carried out in this basin; in chapter 4 the used model and software are described and in chapter 5 the obtained results and the comparison with the other work are reported.

2. Characteristic times-scale in literature

The intrinsic cleaning capacity of lagoons and semi-enclosed basins can be represented by two different types of processes: biogeochemical processes and physical processes. The first concerns all the mechanisms that reduce the active pollutant concentration by modifying its reactivity both by biological and chemical neutralization. The latter includes those processes that neutralize the pollutant effect simply by mechanical removal from the ecological compartment (Rodhe, 1992).

Sedimentation, evaporation, advection and diffusion can be considered the main physical processes that influence the cleaning capacity of a lagoon ecosystem water compartment. Through the advection and diffusion mechanisms, the water mass is transported to the open sea where it is mixed with the sea water. The time spent by each water particle inside the lagoon gives an idea of the efficiency of this physical cleaning process. The determination of the hydrodynamic indicators is thus of major interest in the environmental management of the lagoon basins (Baleo et al., 2001).

If the tide is the main forcing for the water circulation, such as in the Venice lagoon case, the cleaning capacity of the basin is influenced by the characteristic of the tidal exchange. In this situation, the flushing mechanism is produced through repeated exchange of the intertidal water volume between the embayment (the Venice lagoon) and the receiving water body (the Adriatic sea). Water entering the embayment on flood tide fills the intertidal volume until the high water is reached. This new water mixes with the existing water in the embayment and, as the tide falls, the intertidal volume of water discharges out of the embayment on the ebb tide. Some fraction of the discharged water

is lost by exchange and mixing within the receiving water body, the remainder returns to the embayment on the subsequent flow. Not all the water entering on the incoming tide is then 'new water'. Therefore, the tidal flushing and the cleaning capacity depend not only on the tidal range and the basin geometry but also on the effluent water that returns on the subsequent flood tide, the so called return flow (Sanford et al., 1992). Hence in order to investigate the cleaning capacity of the Venice Lagoon the influence of the return flow on the basin flushing dynamic has to be taken into account.

In literature it is possible to find a lot of different characteristic times-scale used to estimate the water quality; in this chapter we are going to consider the *flushing time* and the *residence time* which are useful parameters for the evaluation of the transport capacity of a contaminant within a water body. Residence time is considered a local measure with spatial variation, whereas flushing time is considered a measure of the system level and a unique value for the entire water body (Choi and Lee, 2004).

2.1 Flushing time

The flushing time is an integrative parameter that describes the general exchange characteristics of a water body without identifying the underlying physical processes, the relative importance of those processes, or their spatial distribution (Monsen et al., 2002). The study of this characteristic time is important in the analysis of pollutants in marine environments and it is defined as the time required to replace the polluted water accumulated in a basin with clean water.

In order to calculate the flushing time numerical models, that take into account of how the water gradually comes out from the basin and of the effects of ebb and flow due to tide, are used. This characteristic time-scale can be used to evaluate the water quality with reference, for example, to the de-oxygenation process which is mainly related on the extent of the mixing of the basin water with the sea water, when we are talking about coastal basins. As a result, the risk of eutrophication caused by de-oxygenation of the water is reduced if the planktonic organisms are rapidly removed from the basin, that

is, if there is a good water exchange. So the water quality is higher in basins with lower flushing time.

2.2 Residence time

Residence time is not a well-defined term. In the literature various meanings are associated with this concept. Some authors define it as the time required for a water particle to travel from a location to the boundary of the region (Bolin and Rodhe, 1973; Zimmerman, 1976; Dronkers and Zimmerman, 1982; de Kreeke,1983; Prandle, 1984).In a very similar way residence time is defined as the period during which a water parcel, initially located at the point considered, needs to leave the domain (Soulsby and Tetzlaff, 2008). Then residence time depends on the water parcel location and the estuary definition; thus it has been mainly applied to semi-enclosed aquatic systems such as reservoirs or estuaries where its geographic characteristics establish the limits of the study zone. In other works it is defined as the average time for all the water to remain in the initial domain (Wang et al., 2004). From the first definition the residence time is a local concept and depends on the position of the parcels while from the last definition it is a non-punctual concept averaged on the entire basin.

Cucco and Umgiesser (2006) define residence time as the time required for each element of the domain to replace most of the mass of a conservative tracer, originally released, with new water. To compute it , it is used the mathematical expression given by Takeoka (1984) known as the remnant function.

The conservative tracer, initially released inside the lagoon with a concentration of 100%, is subjected to the action of the tide and the wind forcing that drives it out of and often again inside the basin through the three inlets that connect the Venice lagoon with the Adriatic sea (where the initial concentration of the tracer is 0%). This leads to a decay of its concentration in time. The remnant function *r(x,y,t)* of the concentration is given at each position of the domain as:

$$r(x,y,t) = \frac{C(x,y,t)}{C_0(x,y)}$$

where $C(x, y, t)$ is the concentration at time t of the conservative tracer in the position x,y and $C_0(x, y) = C(x, y, t = 0)$ is its initial value. The residence time τ can then be defined as:

$$\tau = \int_0^\infty r(t)dt$$

And for every position x,y of the domain as:

$$\tau(x, y) = \int_0^\infty r(x, y, t)dt.$$

If the decay of the concentration is exponential, it means $C(t) = C_0 e^{-\alpha t}$, then it is easy to see that substituting this expression in the equation that gives the remnant function and then in that one which gives the residence time, the following result is obtained:

$$\tau(x, y) = \int_0^\infty \frac{C_0 e^{-\alpha t}}{C_0} dt = \frac{1}{\alpha}$$

Which is the time it takes to lower the concentration to 1/e of its initial value (*e-folding residence time*).

On the basis of the previous results it is possible to rewrite the decay law of the concentration in the following manner:

$$C(x, y, t) = C_0(x, y)e^{-t/T_e}$$

where T_e is the time the concentration takes to lower its value to 1/e of the initial one and the other symbols have the usual meaning. In order to verify that T_e is actually the residence time the next equality is imposed:

$$\frac{C(x, y, t)}{C_0(x, y)} = \frac{1}{e}$$

For t=t$_{res}$=e-folding residence time. Now substituting this expression in the previous one you get:

$$\frac{1}{e} = e^{-t_{res}/T_e}$$

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from which you obtain: $t_{res} = T_e$, as it turned.

3. Description of the Venice Lagoon

In this chapter a description of the evolution, the current situation and the future developments of the Venice Lagoon is reported.

The Venice Lagoon has a surface of about 550 km^2 comprised between the Brenta outfall in the south and the Sile outfall in the north. On the landside its boundaries are nowadays defined by human operas rather than natural elements.

From the hydrographic point of view, the Venice lagoon can be divided in three basins that are easily identified by the three inlets of the lagoon, Lido, Malamocco and Chioggia from the north to the south. From a morphological point of view the lagoon is not a continuous and uniform water table but, in each of the three basins, it is characterized by zones always above the water level, salt marshes, mudflats and zones always submerged by water.

3.1 Birth and evolution of a lagoon

The birth of a lagoon is due to the opposition between continental and marine processes. The continental elements are represented by rivers which carry sediments; the closer to the sea the finer the transported sediments; so we pass from gravel to sand, silt and clay moving from upstream to downstream. Marine elements are represented by waves, tides and coastal currents that, in the North of the Adriatic sea are generated by winds

(Bora and Scirocco). So, as already said, the birth of a lagoon is due to the interaction between these elements.

The transported sediments come from Alps that, being quite young mountains, are subjected to an high erosion process. Once rivers reach the sea, the sediments they transport give rise to the outfalls (deltas in our case); on the other hand sediments are also transported by longshore currents of the sea so they deposit not only in deltas but also parallel to the shoreline giving rise to some formations parallel to the shore (*lidi*). Therefore a part of the coast comprised between two deltas tends to become a basin partially isolated from the sea, a lagoon, because of the position of *lidi*, which limit the future lagoon on the seaside. These *lidi* are not continuous formations but they are interrupted by some inlets that are responsible of the water exchange between lagoon and sea.

When the sea is subjected to a sufficiently strong tidal fluctuations, the flow and ebb currents that occur between sea and lagoon maintain the inlets efficient, it means that they are not going to be closed. So a part of the sediments transported by rivers can flow into the sea, cleaning the lagoon from the sediments themselves.

The evolution of a lagoon depends on the relationship between the erosion induced by the marine forces and the sediment deposition due to rivers. Therefore different situations may arise:

- if the sediment transport prevails we have the clogging of the inlets and the accumulation of the solid materials inside the lagoon; then the lagoon becomes a part of the emerged land
- if the sea erosive action prevails, the emerged formations (*lidi*, salt marshes etc.) are going to disappear ; then the lagoon becomes a part of the sea
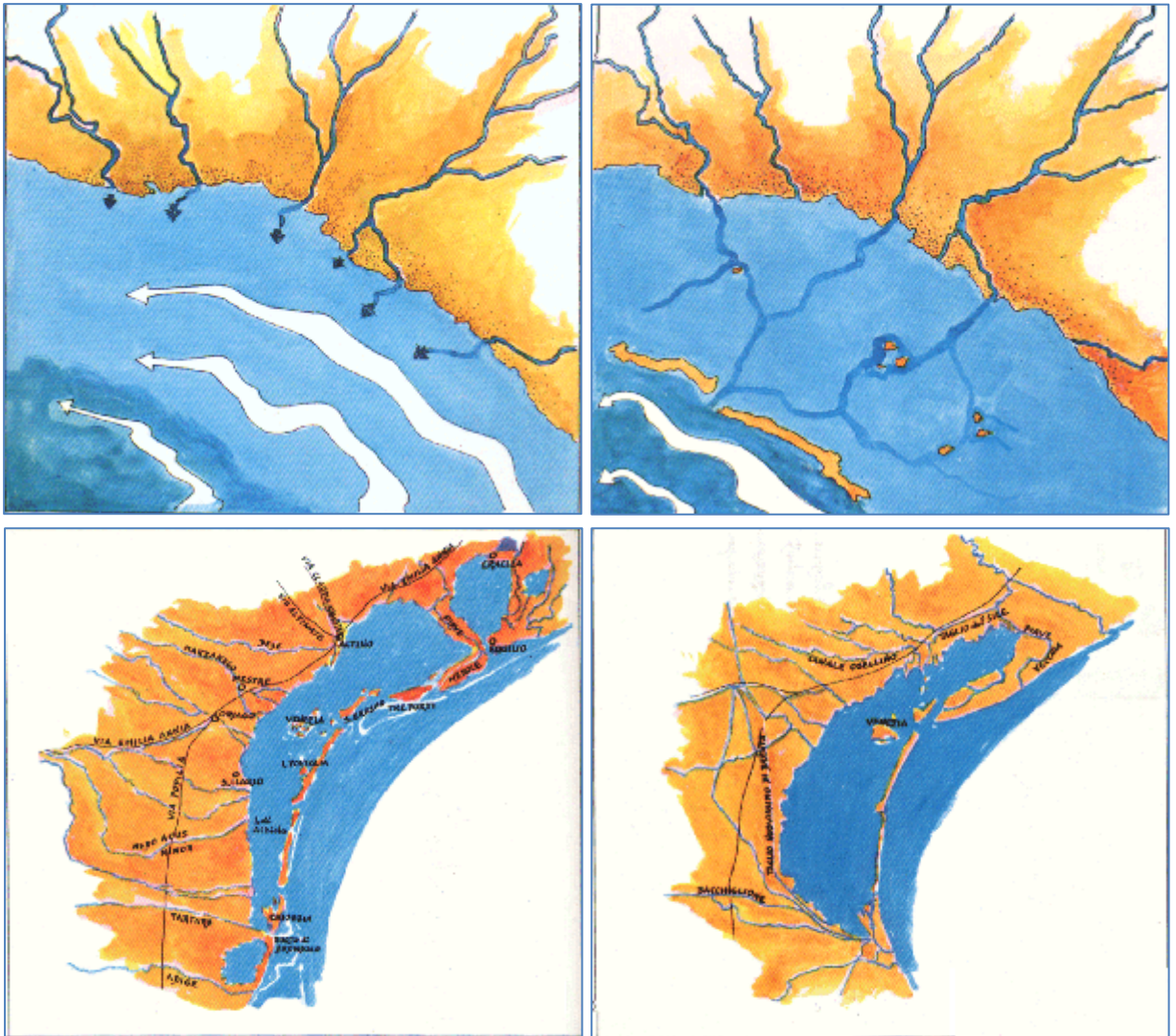- if there is an equilibrium between the two processes (erosion and nourishment) the lagoon survives.

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Figure 3.1: birth and evolution of the Venice Lagoon

3.2 Venice Lagoon

We have already seen how a lagoon born and the continuous opposition of the marine and continental forces that determine its evolution; now a more precise description of the Venice Lagoon is provided.

Figure 3.2: Venice lagoon

3.2.1 Historical evolution of the Venice Lagoon

The Venice Lagoon was born six thousand years ago , after the last glaciation. Deltas of Padana plain rivers went on toward the sea because of their sediment transport, shoreline currents and wave action; the combined action of these elements led to the formation of *lidi* which delimited ponds that took the characteristics of a brackish ecosystem. In 1000 a.d. the area interested by the lagoon was the one comprised between Adige river in the south and Piave river in the north; between them other rivers such as Bacchigione, Brenta, Dese and Sile discharged to the Adriatic sea. At that time

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the lagoon was characterized by eight inlets and considering on one side the nourishment due to the sediments transported by rivers and on the other side the erosion due to the wave and tide action, the first element was the prevailing one.

As just said, the sediment transport was higher than the erosion so the inlets tended to be clogged; to avoid this problem from 1300 a.d. and until recent years a series of hydraulic works with the aim of diversion of rivers were carried out. As a consequence the problem related to the excess of sediment carried to the lagoon by rivers was solved but, on the other hand, a problem related to the possibility of contrast the marine erosion was born. Indeed this is the current trend of the Venice Lagoon: an erosive process that acts together with a subsidence process causing the transformation of the lagoon in a marine environment.

3.2.2 Causes of the morphological evolution of the Venice Lagoon

For some time now the Venice Lagoon is experiencing, in an increasingly apparent way, the negative effects of intense erosion processes, particularly in the central part of its basin within the perimeter formed by the large canals that branch off from the Lido and Malamocco inlets and the manmade channels built to allow to the modern ships the access to the inner ports. As a result of these phenomena the lagoon is losing its original forms, characterized by shallow water and by a bottom innervated by a huge network of channels that, starting from the three inlets, develop themselves through the inner part of the lagoon with more and more minute ramifications. This network of channels brings to the boundaries of the lagoon the beneficial effects of the periodical tides that alternate in the inlets and contributes to the renewal of the water in the basin. Until some decades ago the part of the lagoon closer to its boundaries on the landside, the *dead lagoon*, was characterized by the presence of a lot of salt marshes, that are vegetated zones with an elevation such that they are submerged only during particularly strong high tides. Among the salt marshes, crossed by myriad of small channels, ponds of shallow water are interposed and so an extremely complex morphological fabric is created. This fabric is useful, from an hydrodynamic point of view, to increase the dispersion phenomena and then to promote the water exchange in the most distant

zones from the inlets. These conditions are the conditions that are disappearing. The areas occupied by the salt marshes deeply decreased during the last century because of the joint action of the increased sea level and subsidence of the ground. At the same time the mudflats (*velme*) and the areas near to the canals became deeper and deeper so that today the bottom of the *living lagoon* does not emerge even during strong low tides, the lagoon is becoming a piece of the sea.

Then the hydrodynamic role that the lagoon channels had on controlling the tide propagation in the inner part of the lagoon was deleted by the generalized deepening of the bottom of the water zones, and then the lagoon flow regime has been completely modified.

In the following figure the variation of the bottom depth is represented; colours from yellow to red represent the erosion.
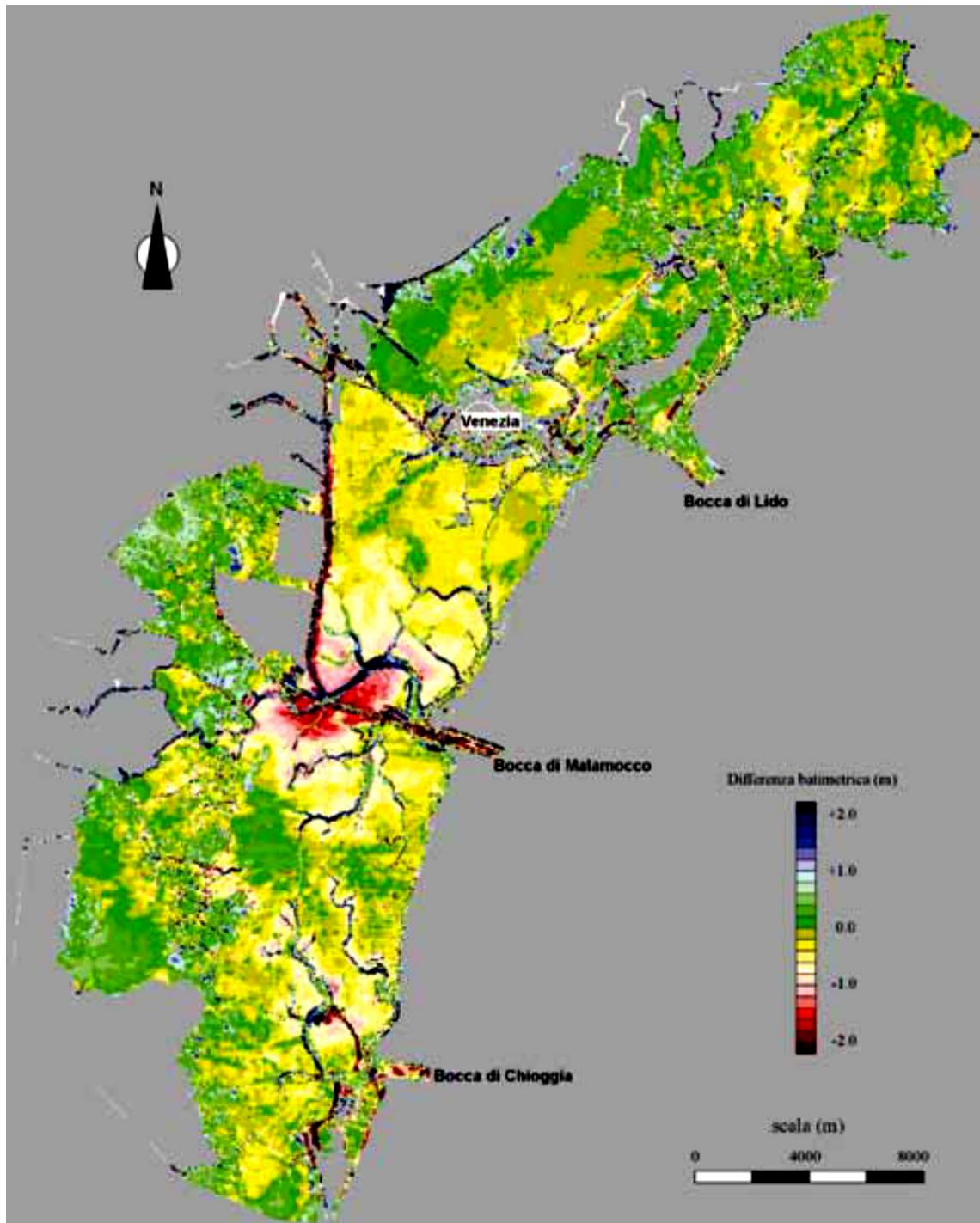
Figure 3.3: variation of the bottom depth in the period between 1970 and 2003 [Icram Rapporto Tecnico,2003]

Then summarizing what has just been said, the evolution of the lagoon is due to natural and human factors that can contribute to increase the morphological phenomena of imbalance or stabilize the system. The current trend of the basin is the erosion of the salt marshes and mudflats and also an increase of the bottom depth of the lagoon; because of these factors the hydrodynamic role of lagoon channels, which controls the

propagation of tides in the inner part of the basin, has been set aside and the flow regime has been modified. Then the Venice Lagoon is becoming a stretch of sea.

Among the natural factors that affect the lagoon equilibrium there are:

- wave motion due to wind, currents and boats
- disappearance of some aquatic plants (*fanarogame)*
- subsidence and eustasy phenomena of the ground

The wave motion increases the erosion processes and, on the other side, it is increased by the deepening of the lagoon bottoms that amplifies the violence of the waves. In fact, once it starts, the erosion process is a self-perpetuating process: the increased depth of the bottom causes an increase of the wave strength that causes an higher erosion.

The disappearance of *fanerogame* due to water pollution deprives the lagoon of a good defence against erosion because these aquatic plants consolidate the bottom with their roots.

The last two phenomena are the eustasy, i.e. the increasing of the average sea level due to the earth climatic changes, and the subsidence, i.e. the lowering of the ground that can be caused by both natural processes and human interventions. The natural subsidence is due to the sediment consolidation under their own weight and, to a lesser extent, to the tectonic movements. The anthropogenic subsidence is, instead, caused by the depressurization of the artesian aquifers because of an excessive extraction of water between 20s and 70s. To overcome this problem the pumping of water was banned and anthropogenic subsidence has stopped but the natural subsidence is still ongoing.

Among the human factors that affect the equilibrium of the lagoon there are:

- river diversions
- the construction of three outer jetties that delimit the channels of the ports
- the adjustment of the water roads and the dredging of canals
- the construction of the industrial pole
- reclamations and fish farms
- MoSE (*Modulo Sperimentale Elettromeccanico*)

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The diversion of rivers was used to avoid the clogging of the lagoon inlets caused by the sediments transported by rivers; on a long term perspective it reaches its goal but on the other hand it causes an increase of the erosion: the eroded material can not be substituted by sediments.

During the XIX and XX centuries some important interventions were carried out: the construction of the armed dams in the three inlets with the aim of directing the tide and deepening the access fairway, the dig of commercial channels (Vittorio Emanuele and Canale dei Petroli) to improve the port and commercial functions of Venice, the construction of the railway and automobile bridges and of the airport, the deepening of the Lido channel to guarantee the access to the port of Venice to bigger ships and many others. These interventions modified the hydrodynamic of the basin so that the port channels reach spontaneously the depth of 9-10 m (Malamocco) and 7-8 m (Lido). The reduction of the lagoon surface is also due to agricultural reclamation and the creation of fish farms.

The last human intervention started in 2003, it concerns the construction of mobile gates in the lagoon inlets in order to protect the lagoon from the high tides with levels larger than 110 cm on the a.s.l. and with a maximum height of 3 m (MoSE). This mobile gates should also avoid the deterioration of the lagoon morphology; so it should be useful to contrast the processes that is transforming the lagoon in a stretch of sea.

All the natural and human phenomena described cause an average increase in the depth of the bottom that in the central lagoon is almost of 1 m (figure 3.3). The hydrodynamic consequences are very relevant: the propagation of the tide in the inner part of the basin is no longer controlled by the dissipative forces which reduce the peaks, but now it is controlled by the inertial forces which tends to amplify the peaks of the tide with respect to the ones we have in the sea.

Then the coastal ecosystem management requires a detailed and updated knowledge of the current hydrodynamic and geomorphological conditions, the processes acting on the system and the balance of the materials exchanged between the sea and the lagoon. Considering the lagoon ecosystems the hydrodynamic has a dominant role both in the geomorphological evolution processes and in the variation of geochemical and biological

characteristics of the suspended and deposited sediments. In addition to the hydrodynamic characteristics of the basin, in the Venice Lagoon the effect of the human activities that directly and indirectly affect the ecosystem have to be considered in the control and management of the lagoon ecosystem.

As a result we can say that for a proper and effective management of the Venice Lagoon it is necessary to know the past and current physical and geomorphological processes and also the hydrodynamic that control their intensity and extent. The equilibrium between the erosive and depositional processes is the main factor to be considered to ensure the survival of the lagoon.

3.2.3 Water pollution

Another problem of the Venice Lagoon, and maybe the most inherent to the subject matter of this thesis, is the pollution of the lagoon waters. The pollution of the lagoon is due to different sources: punctual sources such as industrial and civil discharges of that areas in which there are not treatment plants and sewers and diffuse sources which consider the pollutants that come from the washout of agricultural fields or of the surface of cities after a rain event and the pollution due to the ships and boats. Obviously the lagoon receives water from various rivers, then also the contaminants transported by them and collected in their respective catchment areas reach our basin.

When the pollutants that enter the basin are organic substances or inorganic substances with a fertilising effect, and then substances that contain nitrogen and phosphorous, they produce a direct and an indirect contamination. The primary direct pollution is due to the oxygen consumption caused by the decomposition of the organic matter introduced in the basin, the secondary indirect pollution is due to the fact that the organic substances and nutrients allow an high production of living organic matter (aquatic plants, algae and plankton) that, once it dies, deposits on the bottom of the lagoon causing a new oxygen consumption to decompose it (this second kind of pollution is called *eutrophy*). It may happen, particularly in areas with a low water exchange, that the oxygen concentration in water decreases under the required limit to sustain aquatic

life, then the fish fauna can no longer live in those areas. In some extreme cases not only the fish fauna but also the other living organisms, aquatic plants and algae included, could die because of the lack of dissolved oxygen: these conditions are called *anoxic conditions* and they usually refer to an oxygen content lower than 1 mg/l.

To evaluate the tendency to eutrophication of a basin some hydrodynamic indicators, as an example times-scale, could be used; in fact they are useful to determine the water renewal capacity of the considered basin. The use of these times-scale is also useful to evaluate the effectiveness of proposed interventions to improve the water quality.

In this thesis the residence time in the Venice Lagoon is considered, the higher the residence time, the lower the water exchange in that areas.

4. Description of the used model

In this chapter the instruments used to calculate the residence time in the Venice Lagoon are described.

4.1 Introduction

To analyse the water exchange in the Venice Lagoon it is necessary to know in an accurate and punctual way the hydrodynamic characteristics of the basin when it is subjected to the action of the tide.

In the present work periodic conditions are assumed, it means that always the same tide, repeated over time, is used as system forcing. More complex analysis , that consider real tides, provide more precise but also less meaningful results, because the analysis and the discussion of the results are more complex; in fact if the period of the real tide has an order of magnitude which is comparable with the characteristic time-scale we are considering (e-folding residence time), in some parts of the basin the moment when the tracer is injected has a significant influence on the results. The same reasoning can be done for the wind effect that produces an increase of the mixing intensity processes. So also considering the wind effects the analysis becomes more complex, moreover winter winds are stronger than summer winds so, also in this case, the results depends on the moment of injection of the tracer. Therefore we decided not to consider the wind effect in the calculation of the residence time.

On the basis of the previous assumptions, it results that the considered basin is subjected almost only to the action of the tide, therefore the times-scale are strongly dependent on the mixing processes and then on the diffusion effects. Thus the used model must be able to rightly describe the diffusion process.

The numerical model (**2DEF**) that implements the discrete solution of the system of differential equations governing the problem and that simulates the diffusion processes has been developed by the Department of Civil, Edile and Environmental (ICEA) of the University of Padua.

The hydrodynamic module solves the equations for the long waves in shallow water with a finite elements method. The flow field is discretized in 2D triangular elements associated with 1D linear elements. The flow equations on the horizontal directions x,y , averaged on the vertical direction, are the following ones (D'Alpaos and Defina, 1995; Defina, 2000):

$$\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q_x^2}{Y}\right) + \frac{\partial}{\partial y}\left(\frac{q_x q_y}{Y}\right) - \left(\frac{\partial R_{xx}}{\partial x} + \frac{\partial R_{xy}}{\partial y}\right) + \frac{\tau_{bx}}{\rho} - \frac{\tau_{wx}}{\rho} + gY\frac{\partial h}{\partial x} = 0$$

$$\frac{\partial q_y}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q_x q_y}{Y}\right) + \frac{\partial}{\partial y}\left(\frac{q_y^2}{Y}\right) - \left(\frac{\partial R_{xy}}{\partial x} + \frac{\partial R_{yy}}{\partial y}\right) + \frac{\tau_{by}}{\rho} - \frac{\tau_{wy}}{\rho} + gY\frac{\partial h}{\partial y} = 0$$

$$\eta\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0$$

The symbols used in the equations have the following meanings:

- *h* is the water level
- *(x,y)* are the horizontal spatial coordinates
- *g* is the gravity acceleration
- *ρ* is the fluid density
- *t* is the time
- *q* is the vertical integral of the velocity; q_x and q_y are its components in the x,y directions
- R_{xy} are the turbulent stresses on the horizontal plane

- $\tau_b = (\tau_{bx}, \tau_{by})$ is the shear stress at the bottom and it is expressed as:

$$\frac{\tau_b}{\rho} = gY \left(\frac{|q|}{k_s^2 H^{10/3}} \right) q$$

where k_s is the roughness coefficient given by Strickler.

- $\eta(h) = \frac{1}{2} \left[1 - \mathrm{erf}(\frac{2D}{a_r}) \right]$ is the local fraction of flooded domain, for every time t and in every element

- $Y = \int_{-\infty}^{h} \eta * dz = a_r \left(\eta \frac{D}{a_r} + \frac{1}{4\sqrt{\pi}} e^{-4(\frac{D}{a_r})^2} \right)$ is the volume of water per unit surface, for every time t and in every element

- $H \cong Y + 0.27\sqrt{Y * a_r} * e^{-2Y/a_r}$ is an equivalent water depth , for every time t and in every element

- $erf()$ is the error function

- $D = h - z_b$ is an average depth calculated as the difference between the elevation of the water surface and the bottom elevation

- a_r is the maximum height of the local ground irregularities.

The hydrodynamic model also simulates the transport and the diffusion of a conservative tracer; the equation that describes this phenomenon is:

$$\frac{\partial C}{\partial t} + \frac{q_x}{Y}\frac{\partial C}{\partial x} + \frac{q_y}{Y}\frac{\partial C}{\partial y} - \frac{\partial}{\partial x}\left(D_{xx}\frac{\partial C}{\partial x} + D_{xy}\frac{\partial C}{\partial y} \right) - \frac{\partial}{\partial y}\left(D_{yx}\frac{\partial C}{\partial x} + D_{yy}\frac{\partial C}{\partial y} \right) = f(C)$$

where C is the concentration (averaged on the vertical direction), **D** is the diffusion tensor and $f(C)$ describes the kinetic of the considered substance. In the case of a conservative tracer (that is our case) f(C)=0. In the numerical model we used the diffusion tensor **D** is reduced to the diffusion coefficient D which is calculated in every point of the domain and at every instant by the hydrodynamic module. Considering these simplifications the transport and diffusion equation becomes:

$$\frac{\partial C}{\partial t} + \frac{q_x}{Y}\frac{\partial C}{\partial x} + \frac{q_y}{Y}\frac{\partial C}{\partial y} - D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right) = 0$$

and it is numerically solved with a finite volume method once the properly boundary conditions are defined.

In order to use the numerical model *2DEF* it is necessary to define the physical domain of the calculations (file *.geo*); it consists in a grid made of nodes and triangular elements which reproduces the geometry of the site of interest (Venice Lagoon in our case) with the required accuracy. As well as the physical domain, the model needs the definition of a *.sim* file where the initial and boundary conditions of the problem and the method of calculation are defined. To display and elaborate the results given by the model a specific software (*Incidenze 2.3.6)* is used. With this software it is possible to visualize the boundary and initial conditions of the problem (file *.sim* and *.bup*) and the results of the calculation (file *.out*). The model gives us the results in terms of concentration in time (that is what we need in order to calculate the residence time), but *Incidenze* is able to visualize them only in terms of levels, so these outcomes must be elaborated with another specific software so that they can be displayed using *Incidenze* instead of levels.

In the following paragraphs a more detailed description of the domain, input and output files, used to calculate the spatial and temporal behaviour of the concentration, is provided.

4.2 Computational domain (.geo)

The domain is represented in the .geo file which contains the planimetric description of the Venice lagoon in 2003 (*laguna2003.geo*).

In the domain the geographical and geometrical boundaries of the area of interest and water basins are represented with the most important elements of the landscape, in order to obtain a representation as closer to the reality as possible. To do this we rely on the specific cartography in vector format provided by institutional entities (as an example Carta Tecnica Regionale), or on the results of surveys carried out directly on site.

Then Incidenze discretizes the domain creating a mesh made of mono-dimensional elements (nods) and bi-dimensional elements (triangles) on which the equations that

solve the hydraulic problem are applied. The discretization of the domain is different in its various parts: where an higher accuracy of calculation is required the triangular elements of the mesh are smaller (the average dimension of the triangle side control the discretization step); in this way the optimization of the computational effort required by the model is obtained.

The computational domain that was used is made of 51724 nodes and 98433 triangular elements; it includes the three inlets of the Venice Lagoon (Lido, Malamocco and Chioggia), the coastal and internal part of the lagoon and also a part of the Adriatic Sea. The domain is represented in figure 4.1.

It is possible to observe that the degree of refinement of the mesh is much more stringent for the representation of the inlets (figure 4.2) where the most intense velocity gradients are expected and, therefore, where a more detailed description of the domain is equivalent to a significant improvement in the estimation of the flow characteristics. The degree of refinement of the mesh is rather smaller in the open sea and in the inner part of the basin, where more gradual changes in the flow conditions are expected.

Once the planimetric geometry of the domain is defined, it is necessary to assign to every element of the mesh the values of the parameters that characterize the region; they are:

- bottom elevation (h_f) with respect to the average sea level; it is defined by the mean value of the considered element, it means by the elevation of its center of mass
- the value of the Gauckler-Strickler coefficient (k_s) which takes into account the resistance to the flow due to the roughness of the bottom (the higher k_s the lower the resistance to the flow)
- the maximum height of the local ground irregularities (a_r) that is used to divide the elements of the mesh in emerged and submerged elements; a value of 0.3 has been assigned to this parameter in every triangular element.

In figure 4.3 the values of h_f in the Venice lagoon are represented, they are expressed in meters above the average sea level [m a.s.l.]. The dark red parts represent the emerged areas of the lagoon where the ground has an elevation higher than 0 m a.s.l., these areas

(salt marshes) are flooded only during high tide periods; on the contrary the dark blue parts represent the areas with a bottom elevation lower than -5 m a.s.l. (open sea and main channels of the lagoon).

In figure 4.4 the values of k_s are represented; six different values of k_s have been assigned to the domain elements:

- k_s=40 $\dfrac{m^{1/3}}{s}$ to the sea

- k_s=35 $\dfrac{m^{1/3}}{s}$ to the main channels

- k_s=30.02 $\dfrac{m^{1/3}}{s}$ to the areas near the main channels

- k_s=30 $\dfrac{m^{1/3}}{s}$ to the most of the basin

- k_s=20 $\dfrac{m^{1/3}}{s}$ to the coastal area between Malamocco inlet and Chioggia inlet

- k_s=15 $\dfrac{m^{1/3}}{s}$ to the salt marshes.

Figure 4.1: computational domain
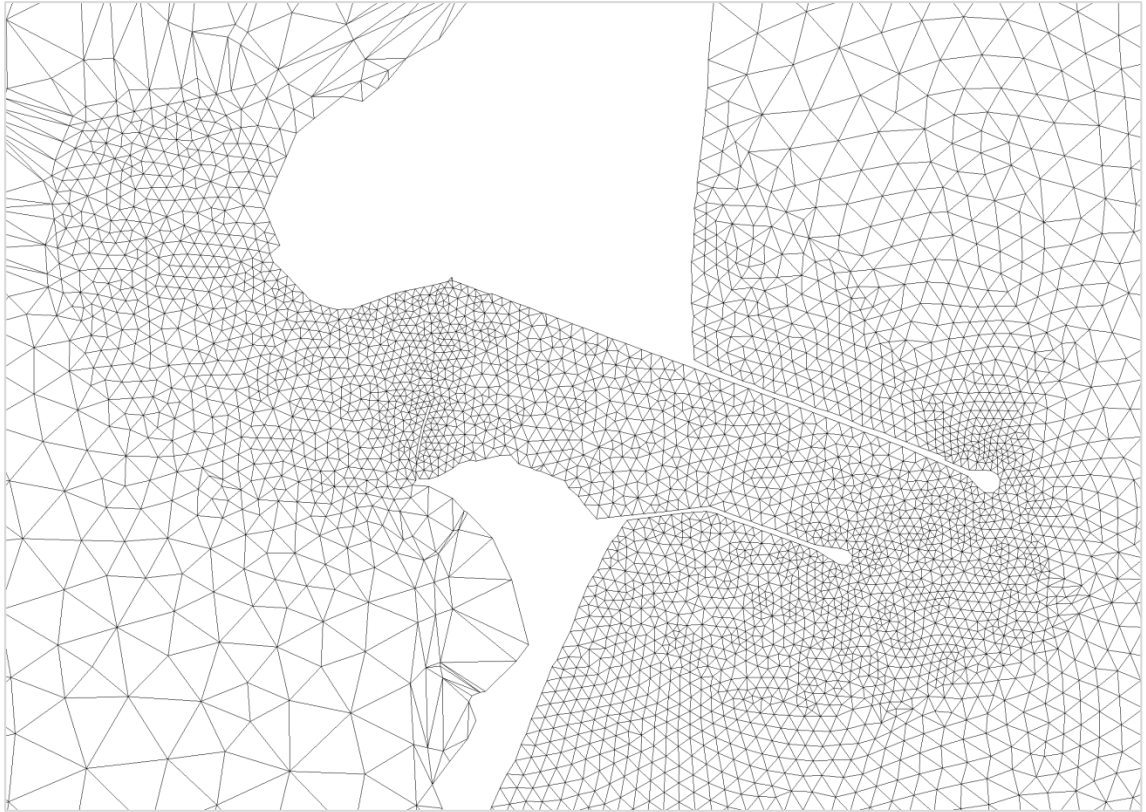
Figure 4.2: refined mesh (Malamocco inlet)
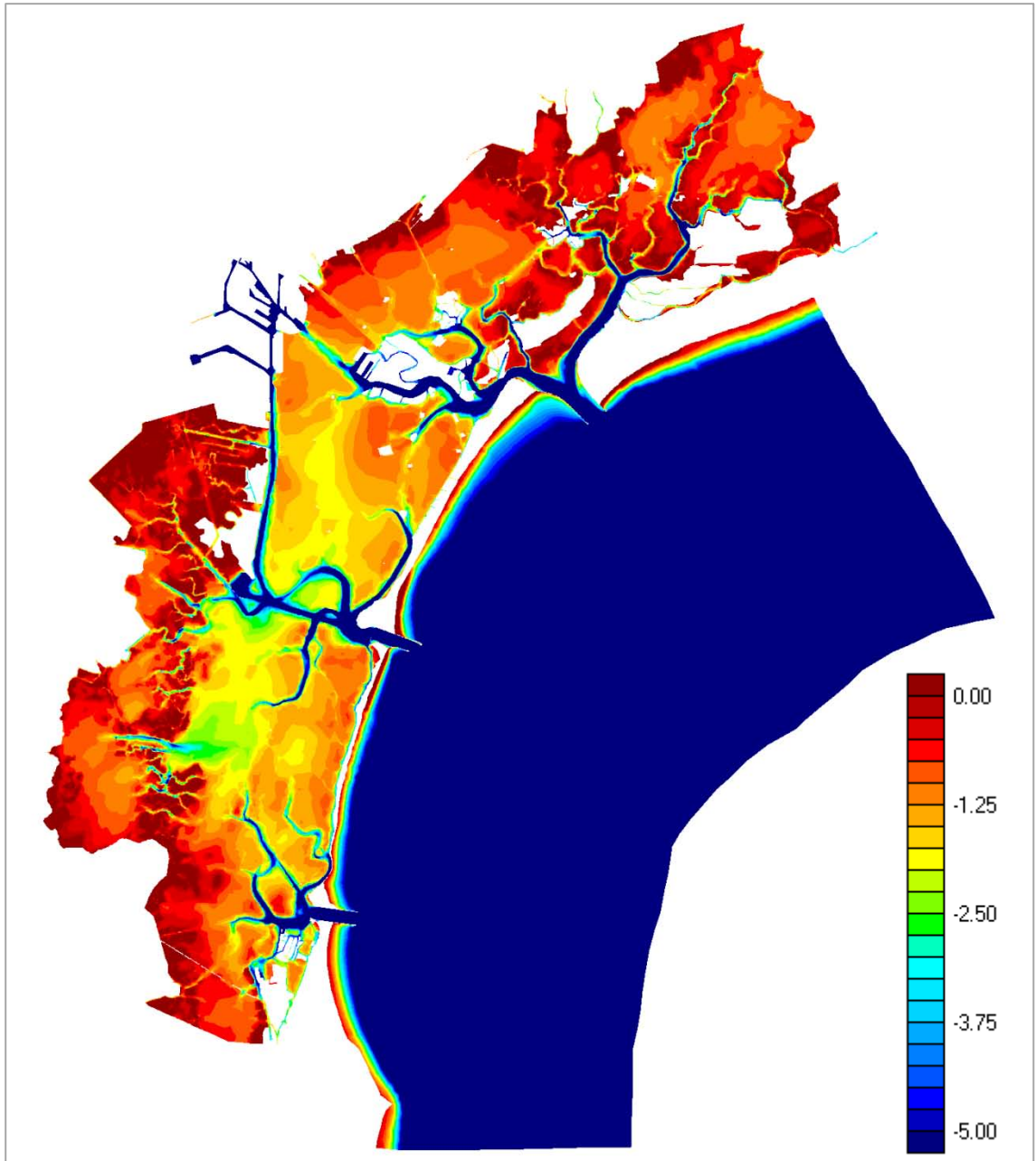
Figure 4.3: bottom elevation expressed in [m a.s.l.]
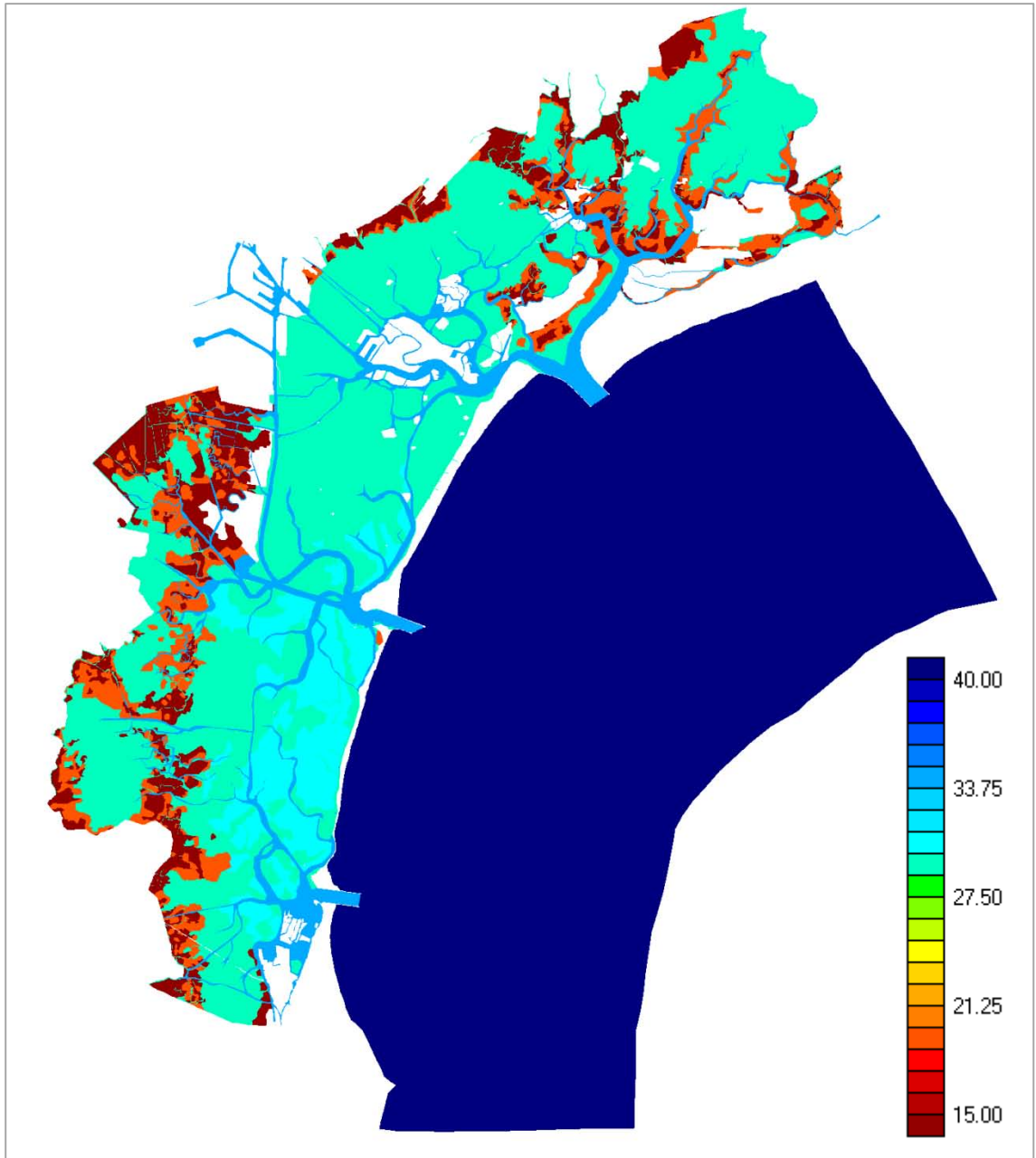
Figure 4.4: Gauckler-Strickler coefficient distribution, expressed in [m$^{(1/3)}$/s]

4.3 Instructions and boundary conditions (.sim)

The .sim file contains the initial and boundary conditions needed by the numerical model; it is a text file which is divided in various sections where the instructions to carry out the simulation are provided. In this paragraph the main sections of the .sim file and the choices made are described.

1. **General data of the simulation**

   In this firs part the duration of the simulation, the computational time step and the time step with which results are printed are provided. All these times are expressed in seconds. In the simulations made the duration was set equal to 345600 s (four days), the computational step to 2 s and the step with which results are printed to 1800 s. Obviously the residence time, that has been calculated for different points of the lagoon, is often higher than four days so every simulation is the sum of many repeated sub-simulations, each one with a duration of four days. The initial conditions of every sub-simulation are the output of the previous one.

   In this section of the .sim file the names of the .geo file, that is the domain of the simulation, and of the .out file, that is the output of the simulation, are required. Finally it is possible to decide if the hydrodynamic has to be calculated in every simulation or not (1/0); in our case the hydrodynamic is considered as a constant so that it is not calculated in every simulation but it is imported from an external file which contains the hydrodynamic of the lagoon.

2. **List of the variables to be printed**

   In this part the parameters that the model has to calculate are chosen; in our case the model calculates water levels, discharges and the nodal concentration due to the diffusion.

3. **Initial conditions**

   In this section we decide if the initial conditions have to be read from a restart file or not (1/0). If yes the name of the .bup file must be indicated; the .bup file contains the information on the situation at the last moment of the previous sub-

simulation. So this .bup file is the output of the previous simulation and the input of the current one.

4. **Tables of time varying data**

   In the first line of this section it is necessary to specify how many tables we are going to enter, then in the second line we have to specify the time step with which the values have to be read by the model, the total number of data contained in the table and the name of the table. Now we can insert the data of the table. This procedure has to be repeated for every table we are going to enter. In this work two tables are considered: the first one is about sea levels and simulate the sinusoidal behaviour of a tide, the second one sets the concentration of the tracer in the sea equal to zero.

5. **Boundary conditions**

   In this section the nodes of the domain on which the boundary conditions about levels are applied are specified. The levels we consider for these nodes are the ones reported in the first table entered in the 'tables of time varying data' section. At first the number of nodes to which the boundary conditions have to be applied is inserted; then a table with three columns is written. In the first column the number of the node is reported, in the second one the number of the table of the previous section to which refer is reported and in the third one an amplification coefficient (set equal to one for every node) is written. The nodes on which these boundary conditions are applied can be seen in figure 4.5 (obtained opening the .sim file with *Incidenze*); they are 105 nodes.

6. **Data about transport and diffusion**

   In this section it is specified if we want to calculate the diffusion (1/0) and the name of the .out file.

7. **Data about wind, data about infiltration, data about solid transport and data about wave actions**

   The model is also able to calculate these phenomena, but in this work they are not considered.
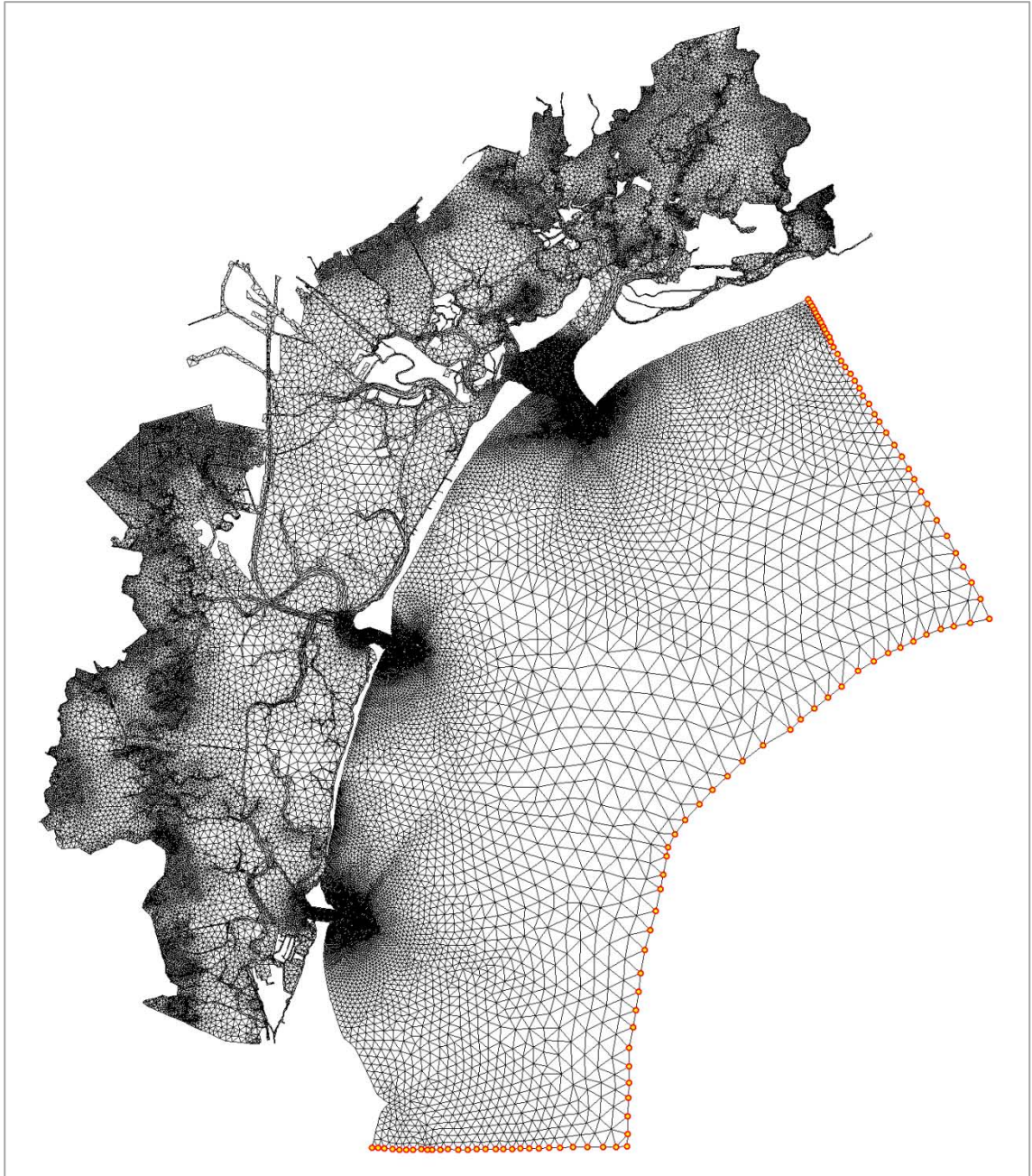
Figure 4.5: nodes of the domain on which boundary conditions are applied

4.4 Results of the simulation (.out)

The .out files are the files produced by the model on the basis of the instructions, initial and boundary conditions that have been set in the .sim file. These files can be visualized with *Incidenze* once the .geo file (*laguna2003.geo*) has been opened; the problem is that with *Incidenze* it is possible to display only levels on time while, to calculate the residence time, we are interested on the behaviour of concentration on time.

To overcome this problem a specific software (*concentrazioni.exe*) is used; it substitutes the levels with the concentrations computed by the numerical model. Then the .out file provided by the model is the input file of *concentrazioni* which gives, as a result, another .out file that, once it is opened with *Incidenze*, allow to visualize the behaviour of the concentration on time instead of levels.

So it is possible to display the behaviour of concentration on time with *Incidenze* but only for the duration of a sub-simulation (four days) because we can not open more than one .out file at the same time. In order to obtain the continuous trend on time of the concentration in the chosen nodes of the domain, the *fort.666* file can be used. This text file is another output file of the numerical model and it contains the mass of tracer in the lagoon and in the open sea for every time step of the sub-simulation. Then we can import these values on a spreadsheet (for example *Excel*) and put the various sub-simulation one after the other in order to obtain the continuous trend of concentration on time. We must pay attention to delete the first raw of the *fort.666* file of the current sub-simulation or the last one of the previous sub-simulation because they are identical. Once the continuous trend of the concentration in time is known we can estimate the residence time. The moment in which the ratio between C and C_0 goes below the value 1/e can be considered the residence time of a parcel initially posed in the chosen point.

The results of the simulations carried out in the Venice lagoon are presented in the following chapter.

5. Residence time in Venice Lagoon

In this chapter the results obtained with the application of the model to the Venice Lagoon are reported; moreover a comparison between these results and the ones obtained in a previous work is considered.

5.1 Description of the used procedure

To calculate the residence time, various simulations in different points of the domain were carried out. In this thesis a punctual injection of the tracer is considered and then the residence time of the conservative tracer in the lagoon due to a mass injection in that point is calculated. From a practical point of view the following procedure was adopted:

1. At first the point in which the tracer is inserted is chosen and with a specific software (*tabella_C_assegnata.exe*) a table corresponding to the initial condition of the simulation about the concentration is obtained (*for125.dat* file). This table contain a value of the concentration of the tracer for every node of the domain at the initial moment of the simulation (t=0) so it contains 51724 values. They are all zero a part one that is 1000 (the value of the initial concentration I choose for the injection point);

2. The table contained in the *for125.dat* file is then copied in the *esempio.bup* file which now contains the initial conditions about concentration, water levels and

discharges in the nodes of the domain at t=0. So *esempio.bup* is the restart file we choose in the .sim file in the first sub-simulation of every point;

3. Now using the *2DEF model* three output file are obtained: *prova.out* that can be visualized using *Incidenze* once the concentrations are substituted to the levels using a specific software, as already described in the previous chapter; *2DEFtmp.out* that is used as restart file, and so as initial conditions, for the sub-simulations after the first one for every considered node and *fort.666* that is a data file we import in Excel to obtain the continuous behaviour of the concentration on time. In this last file the mass of tracer in the lagoon and in the sea and the time steps at which they are calculated are reported in three different columns for the decided time step (1800 s in our case).
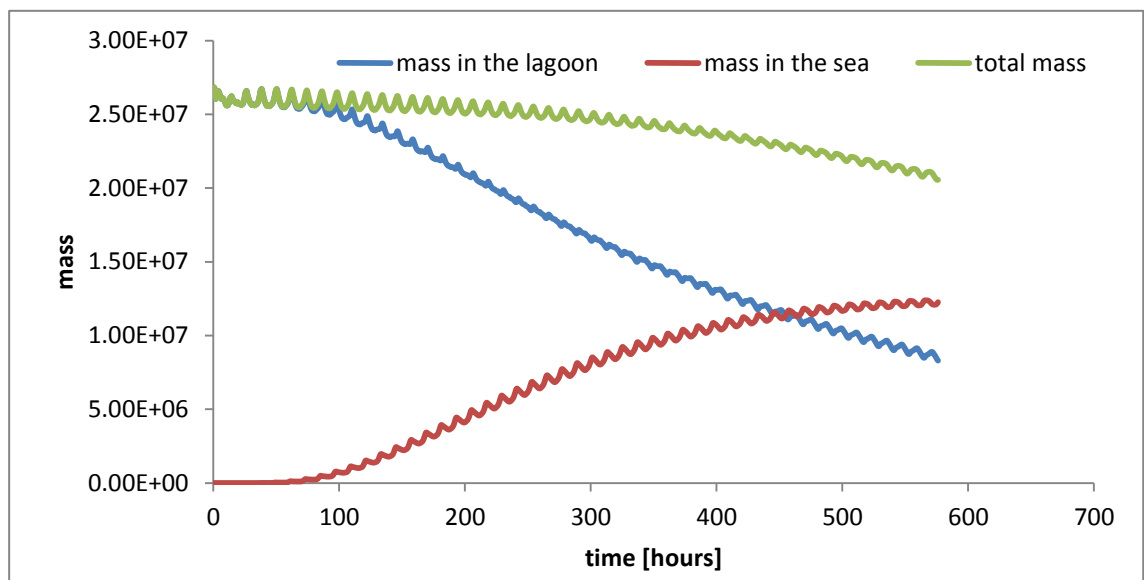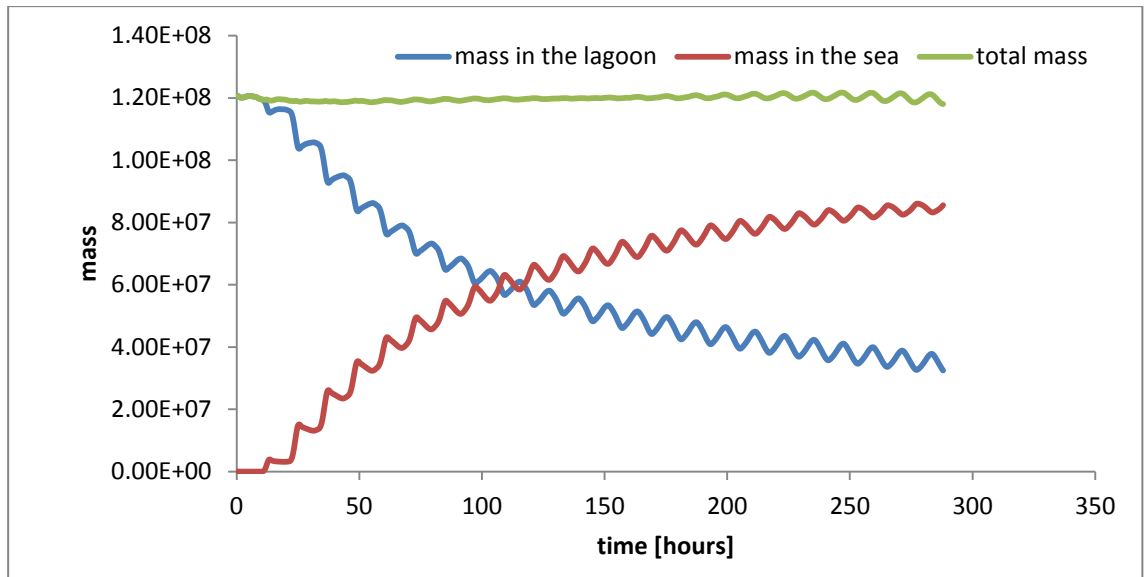
Figure 5.1: examples of the fort.666 files of various consecutive sub-simulations visualized with excel

It is possible to see that the total mass sometime is constant with time while other times it decreases on time and this is symptomatic of the fact that the boundaries of the sea in the domain (*laguna2003.geo*) are not impermeable so some mass can be lost. To calculate the residence time, actually the 'e-folding residence time', we need to elaborate the data contained in the *fort.666* file to obtain the ratio between the current mean concentration C in the lagoon and the initial concentration C_0.
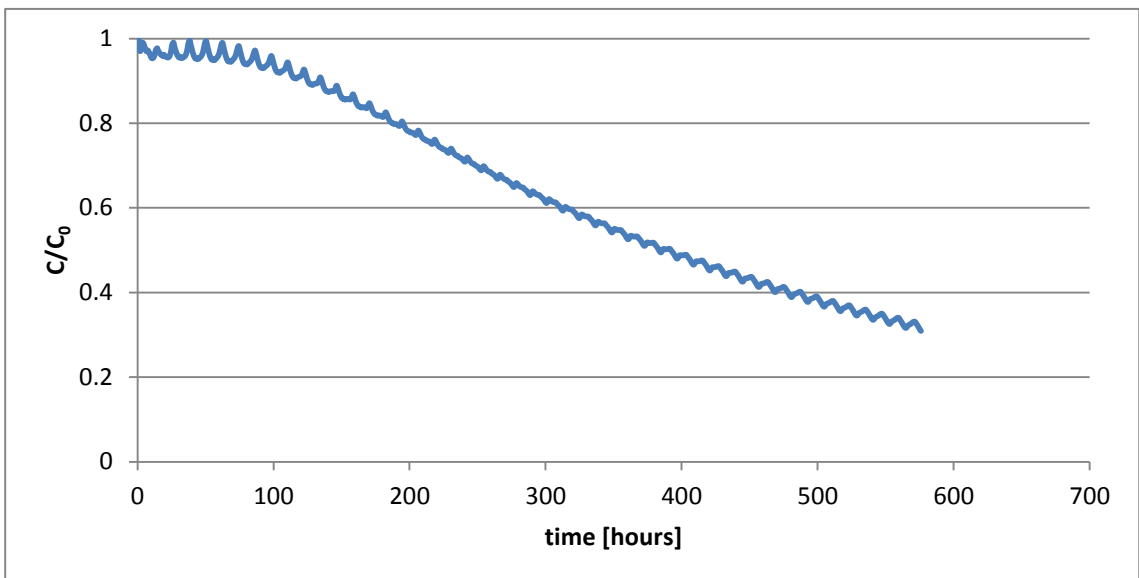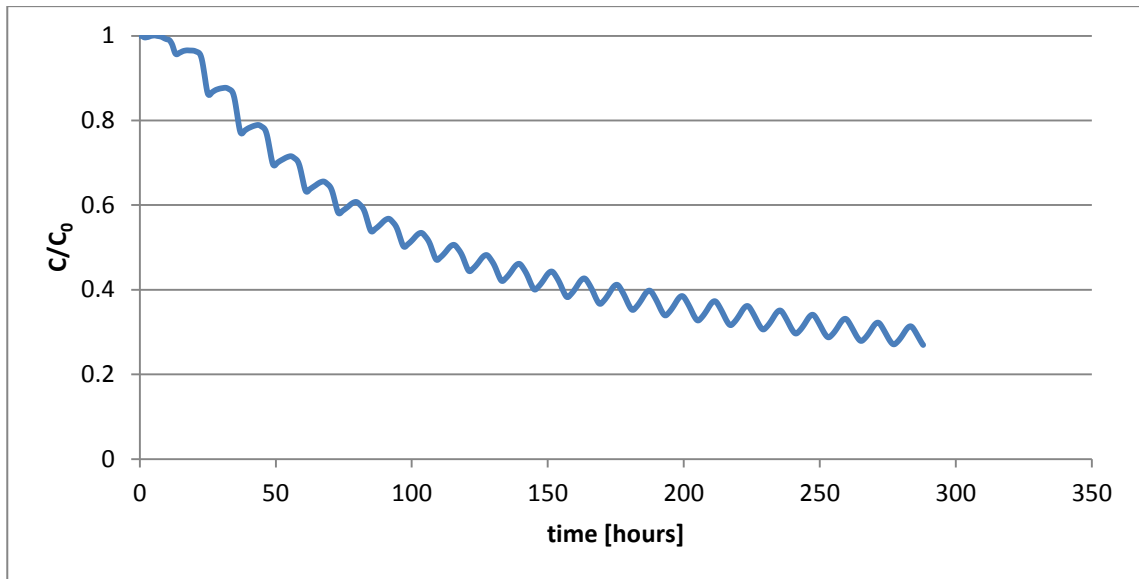
Figure 5.2: examples of the C/C$_0$ behaviour in the lagoon for simulations of 288 and 576 hours

To eliminate the fluctuations caused by the tides we consider the average value of the ratio C/C$_0$ every twelve hours and we assign this value to the sixth hour of every interval. The obtained result is the following one:
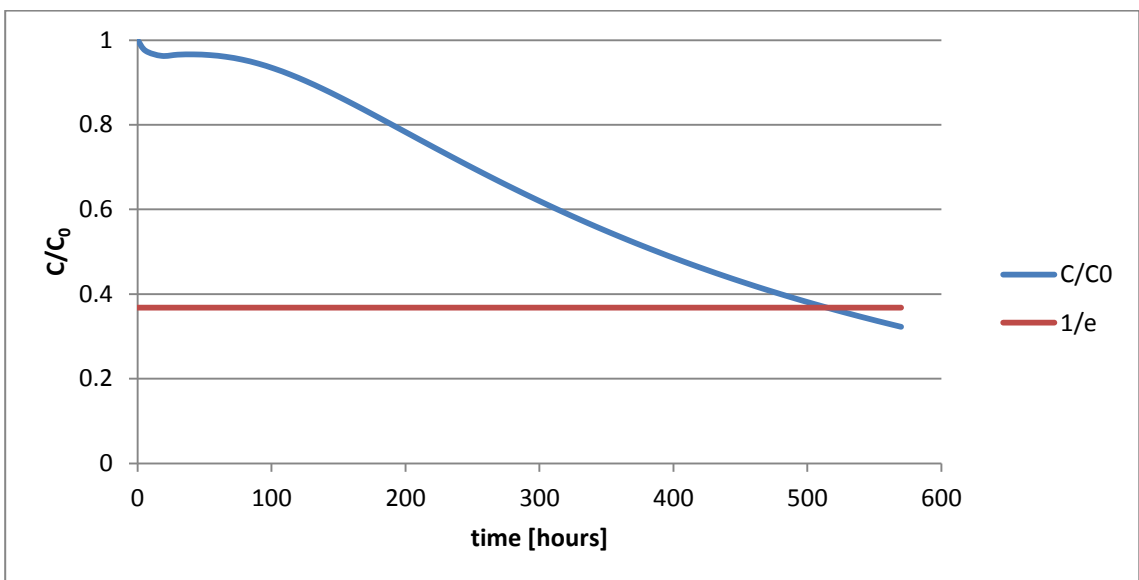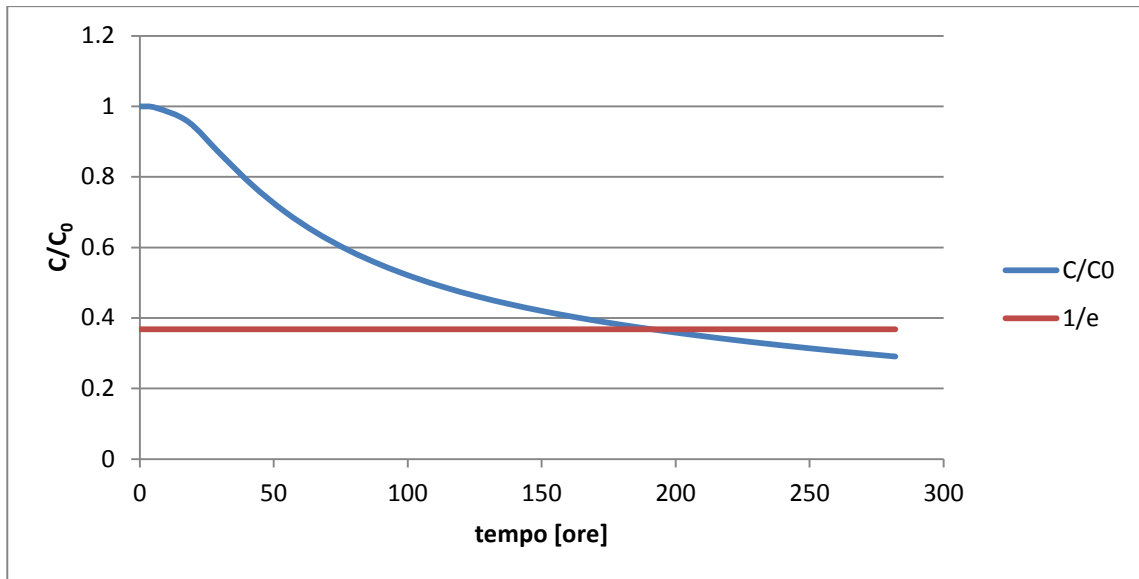
Figure 5.3: examples of the C/C$_0$ behaviour in the lagoon considering values averaged on the tides for the previous simulations

The 'e-folding residence time' is obtained considering the point in which the C/C$_0$ and 1/e lines assume the same value. The described procedure was repeated for many nodes of the domain and some results are shown in the next paragraphs;

4. The results of every simulation can also be visualized with *Incidenze* in order to understand how the mixing processes act. The behaviour of concentration in time for one of the node considered in the previous examples is reported in figure 5.4. It is possible to see that at t=0 days the tracer is present only in the injection node, while in the following days it diffuses through the lagoon and the sea. The

red zones are the areas with an higher concentration of the tracer while the dark blue ones are the areas with a concentration equal to zero. At the beginning of the simulation it is possible to see an expansion of the red zone in the lagoon but after some time, because of the mixing process of the lagoon and sea water due to the tides, the concentration in the basin starts to decrease. The points that are more distant from the inlets are those in which the tracer remains longer and then they are those in which the passage from red to blue takes more time to happen. From a theoretical point of view if we extend the simulation for a very long time (some months) the concentration of the conservative tracer in the lagoon will tend to zero.
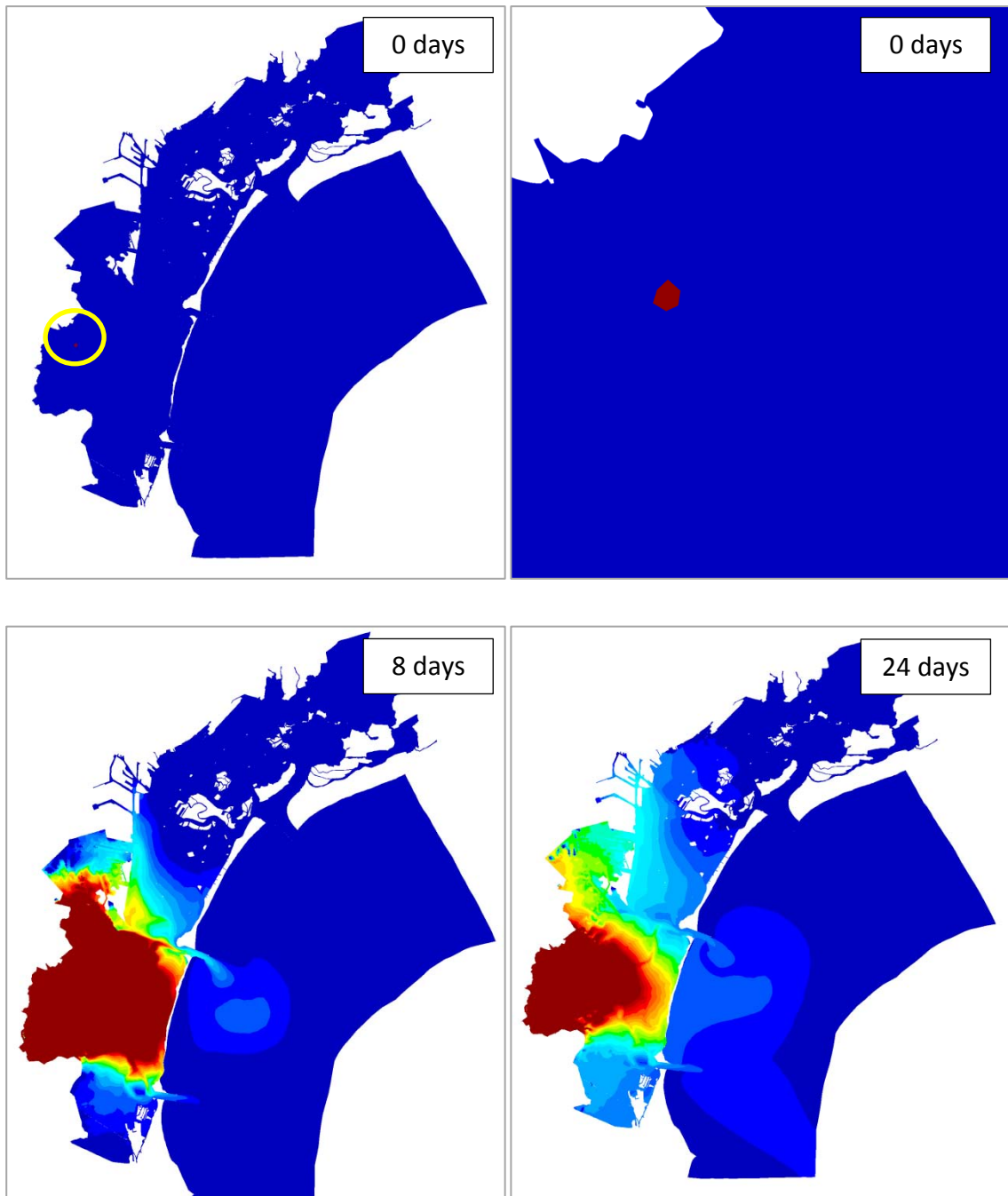
Figure 5.4: behaviour of the concentration in time visualized with _Incidenze_ at different moments

5.2 Injection nodes for the simulations

In the following figure the points in which the mass is injected in the various simulations to calculate the residence time are reported. I try to choose the nodes in such a way to sample all the parts of the lagoon; in this way it is possible to see the difference we have injecting the mass in nodes that are closer to the inlets or in those one that are more

distant from them (obviously an higher residence time is expected if we inject the mass in the latter points). Another aspect I consider in the choice of the nodes is that they need to have a depth such that they do not emerge during the various tides.
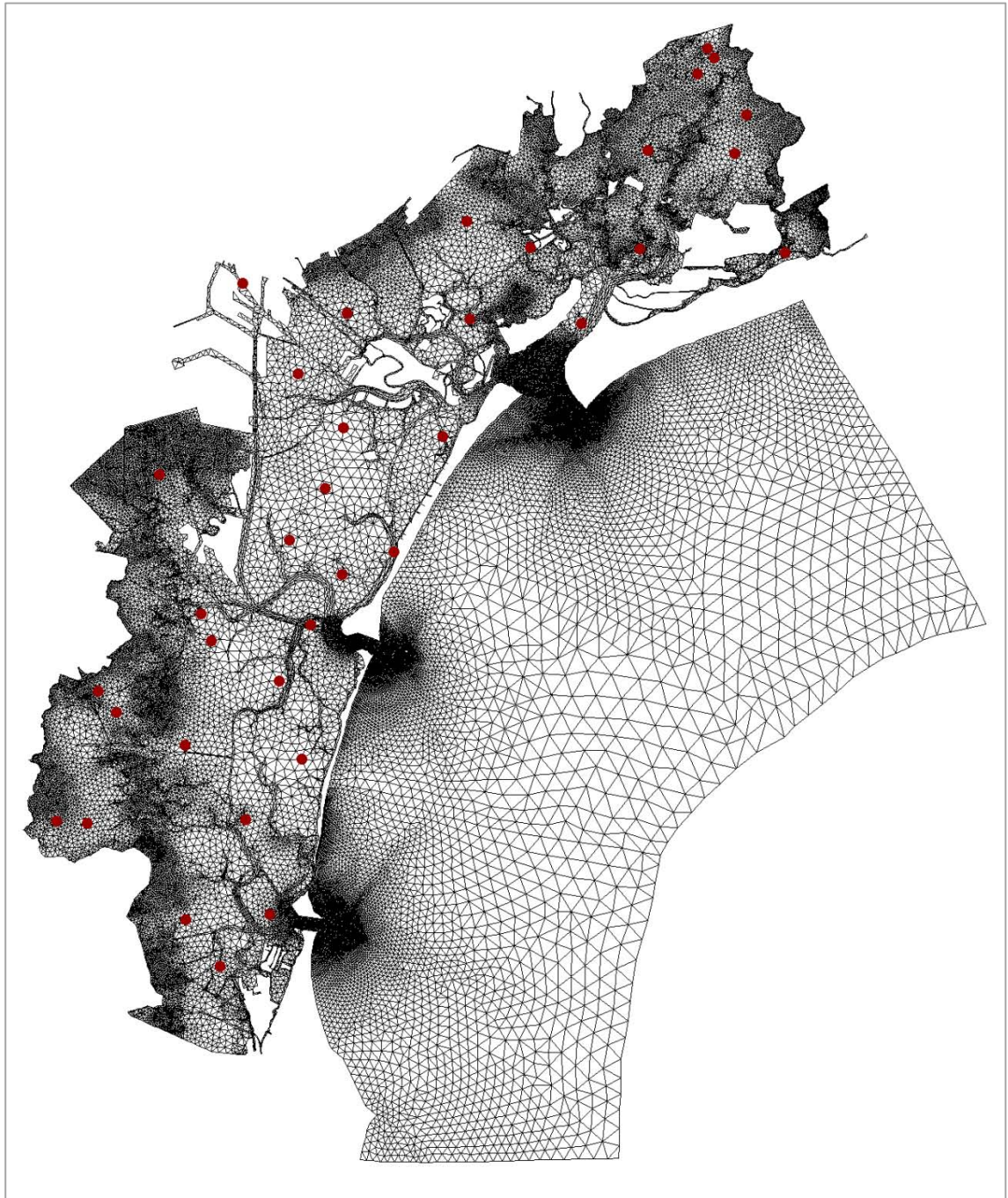
Figure 5.5: injection nodes

5.3 Results of some representative nodes

In this paragraph the results obtained in some representative nodes, chosen between those reported in figure 5.5, are shown. The chosen nodes are reported in the following figure:
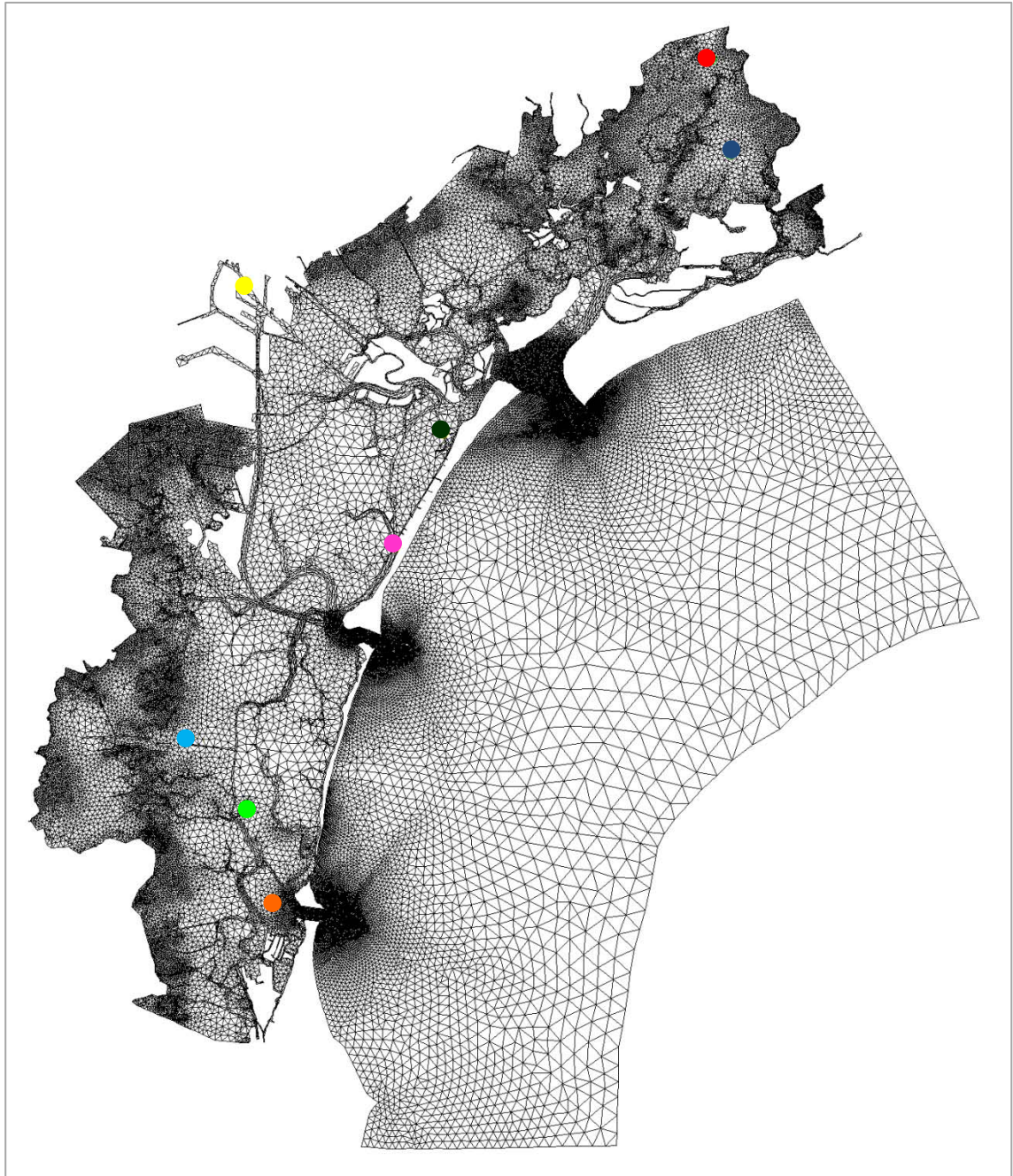
Figure 5.6: nodes of which the results are reported

For everyone of these nodes the continuous behaviour of the ratio C/C_0 and a semi-logarithmic graph ($\ln[C/C_0]$ vs time) are reported. In fact, knowing that the ratio C/C_0 is defined by the relation:

$$\frac{C}{C_0} = e^{-t/T_e}$$

We can apply the logarithm, then we obtain:

$$\ln\left(\frac{C}{C_0}\right) = -\frac{t}{T_e}$$

Which is a straight line; so in the semi-logarithmic chart we have to obtain a straight line (more or less). In particular when t=T_e, that is the time the concentration takes to lower its value to 1/e, the result is:

$$\ln\left(\frac{C}{C_0}\right) = -1$$

In this way it is easier to recognize the residence time.
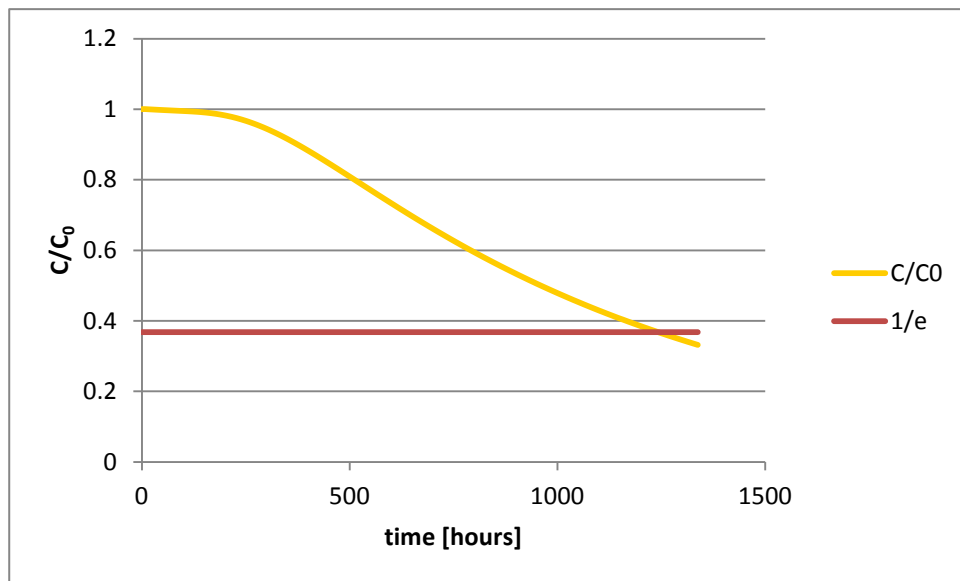
5.3.1 Node 26159 (red one)
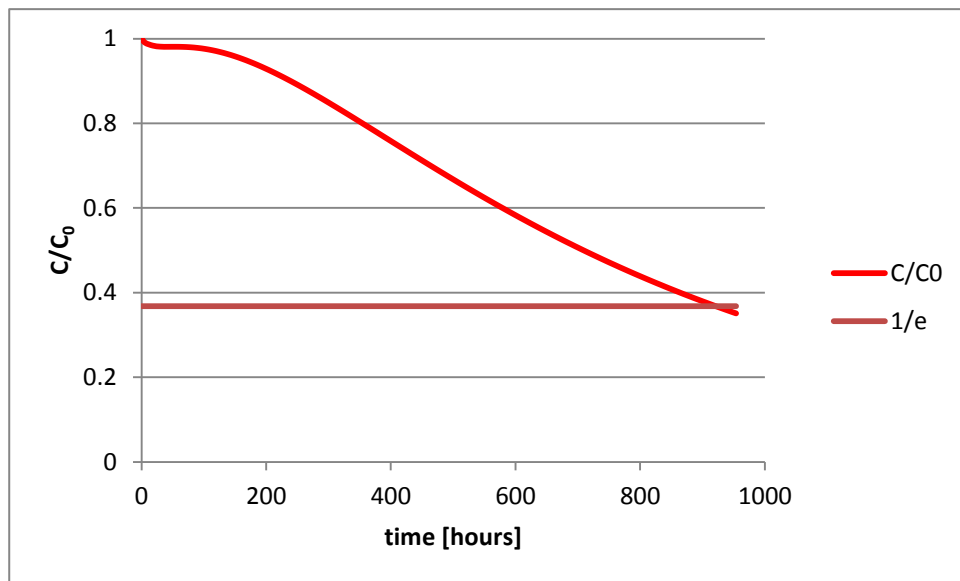
Figure 5.7: behaviour of C/C$_0$ when we inject the tracer in node 26159
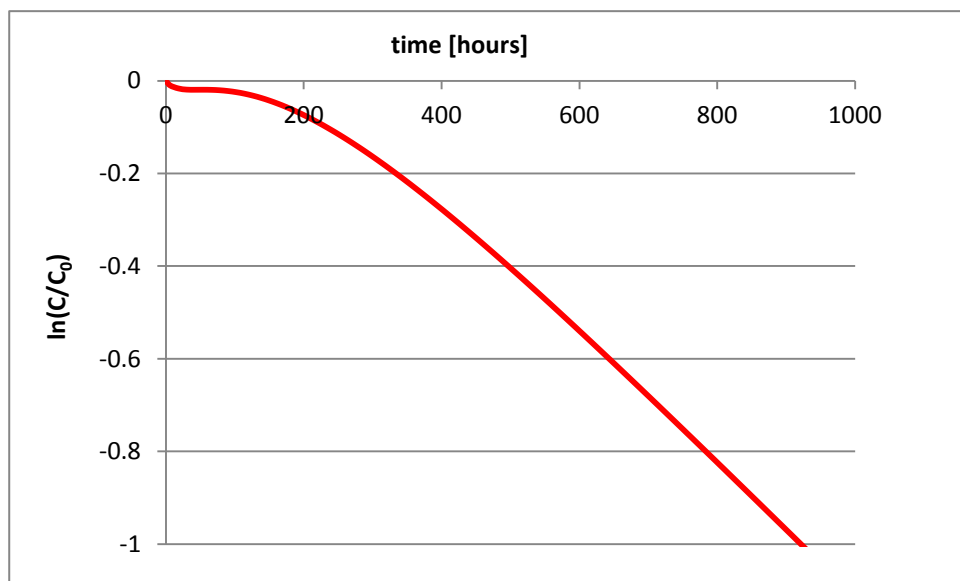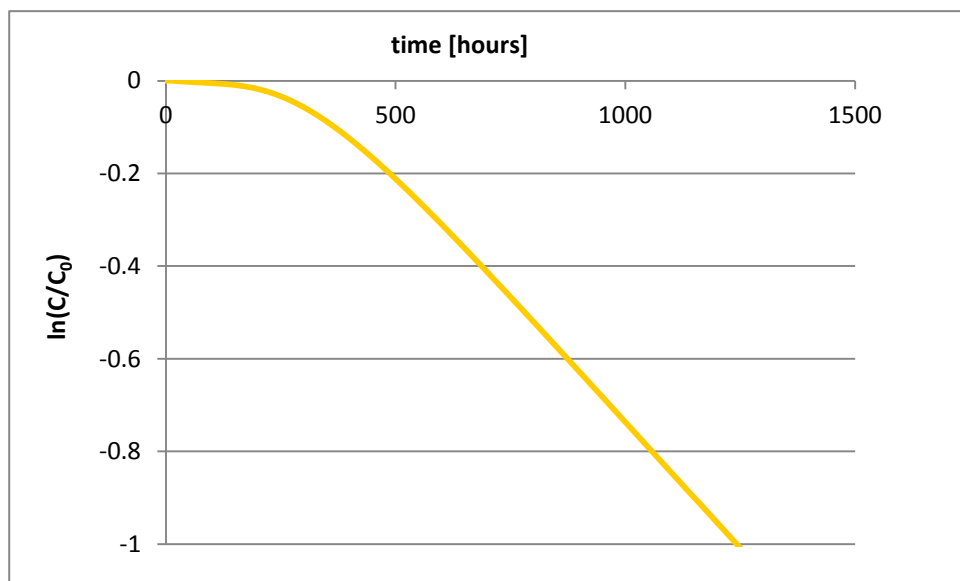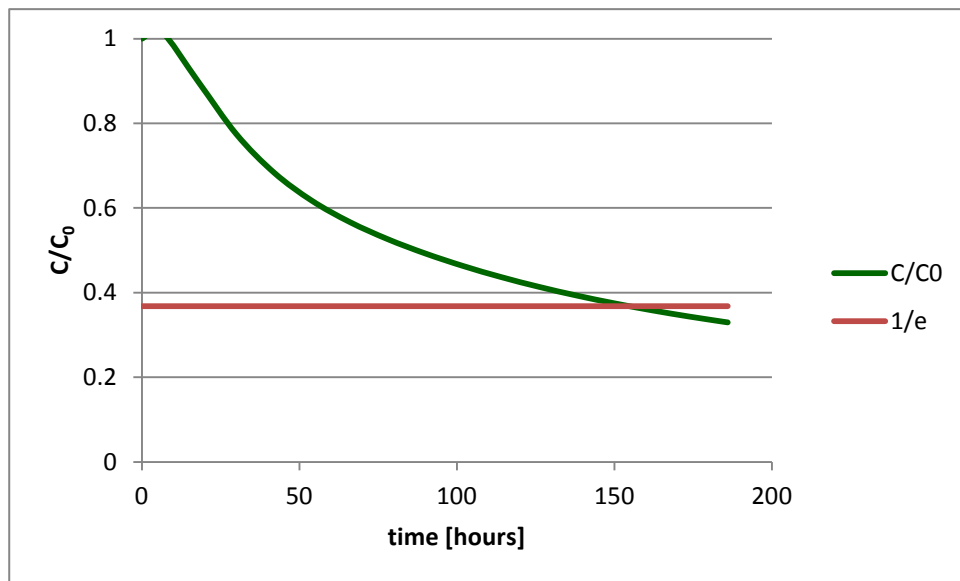

Figure 5.8: residence time when we inject the mass in node 26159

Injecting the mass in this node the residence time is equal to 930 hours that are 38.75 days.

5.3.2 Node 22325 (dark blue one)
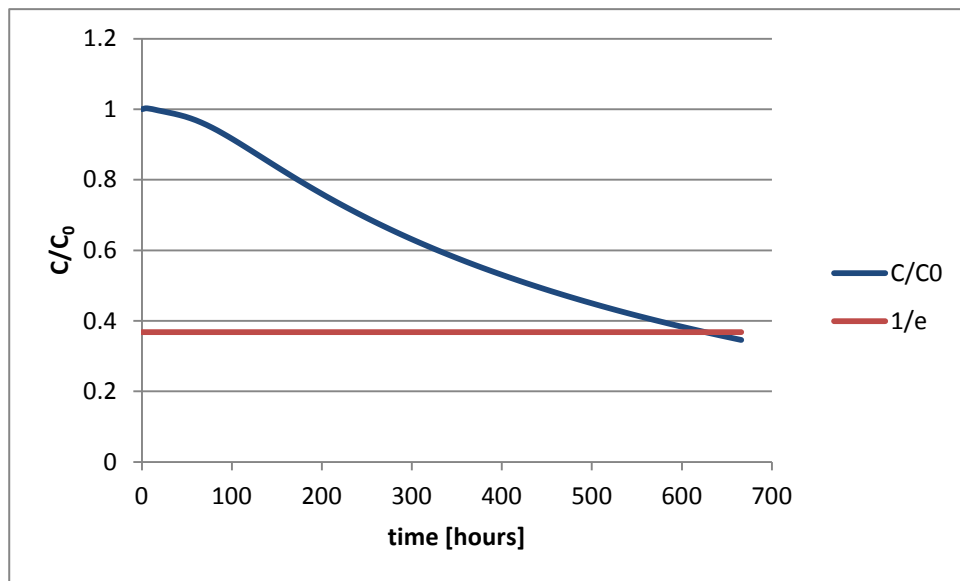
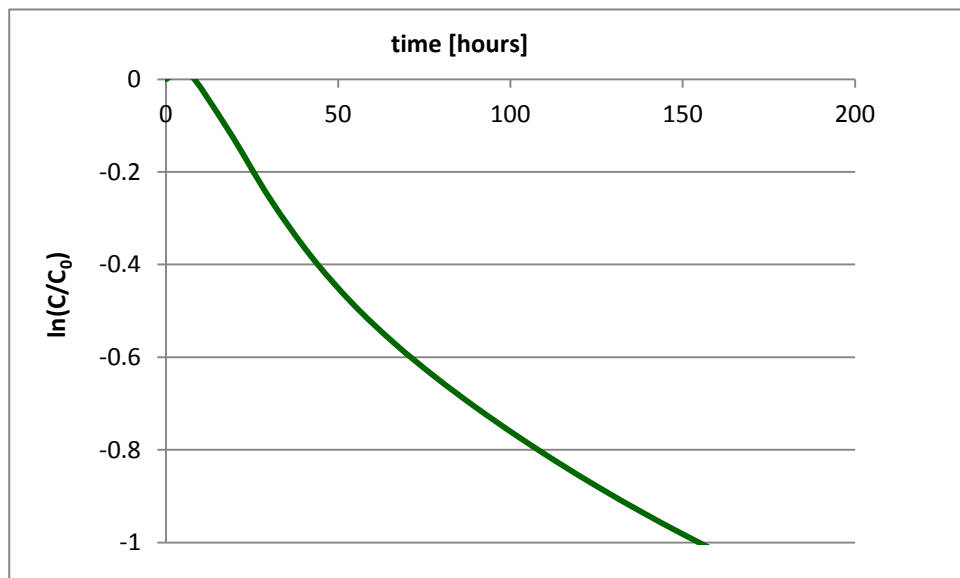Figure 5.9: behaviour of C/C_0 when we inject the tracer in node 22325
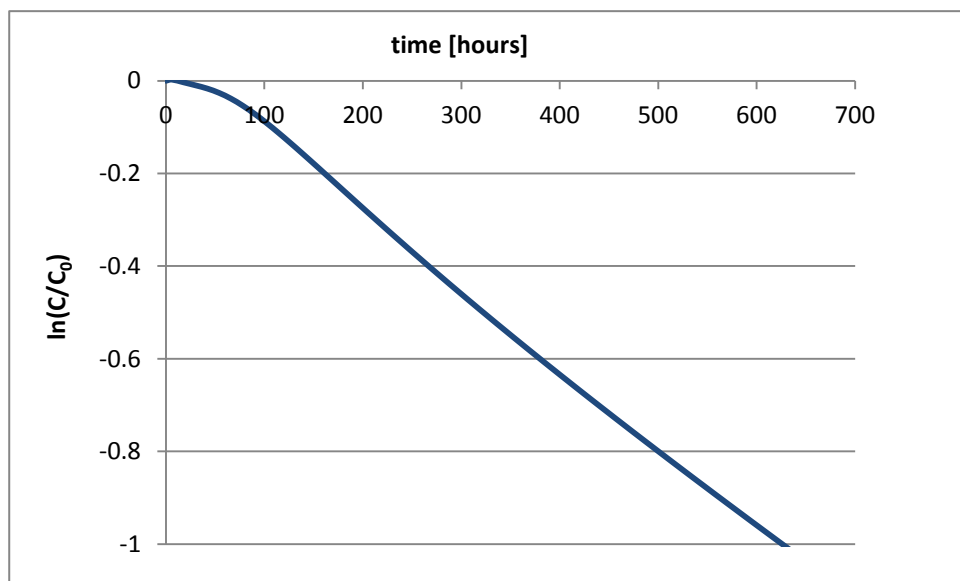
Figure 5.10: residence time when we inject the mass in node 22325

Injecting the mass in this node the residence time is equal to 630 hours that are 26.25 days.

5.3.3 Node 15831 (yellow one)

Figure 5.11: behaviour of C/C$_0$ when we inject the tracer in node 15831

Figure 5.12: residence time when we inject the mass in node 15831

Injecting the mass in this node the residence time is equal to 1254 hours that are 52.25 days.

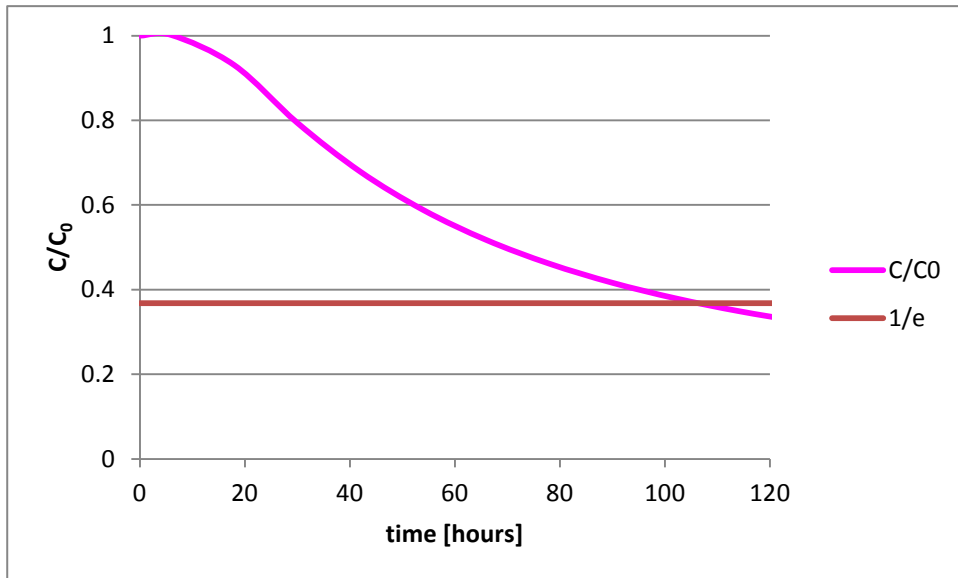### 5.3.4 Node 12566 (dark green one)

Figure 5.13: behaviour of C/C$_0$ when we inject the tracer in node 12566

Figure 5.14: residence time when we inject the mass in node 12566

Injecting the mass in this node the residence time is equal to 162 hours that are 6.75 days. In this case a small error can be seen: the ratio between C and C$_0$ is higher than 1 for a very small interval of time (and thus its logarithm is higher than 0); this has no physical meaning and probably is due to some computational errors.

5.3.5 Node 10283 (pink one)

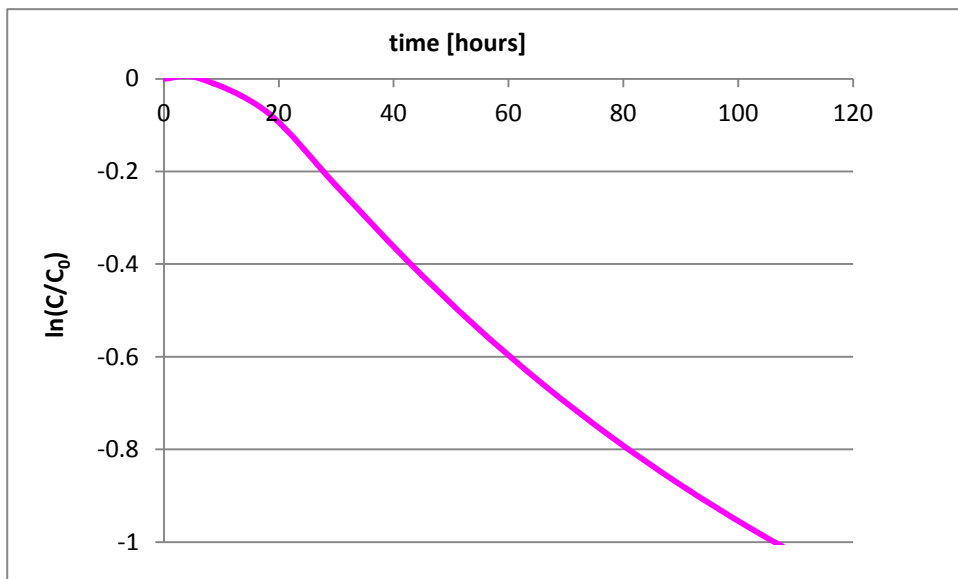**Figure 5.15: behaviour of C/C$_0$ when we inject the tracer in node 10283**

Figure 5.16: residence time when we inject the mass in node 10283

Injecting the mass in this node the residence time is equal to 114 hours that are 4.75 days.
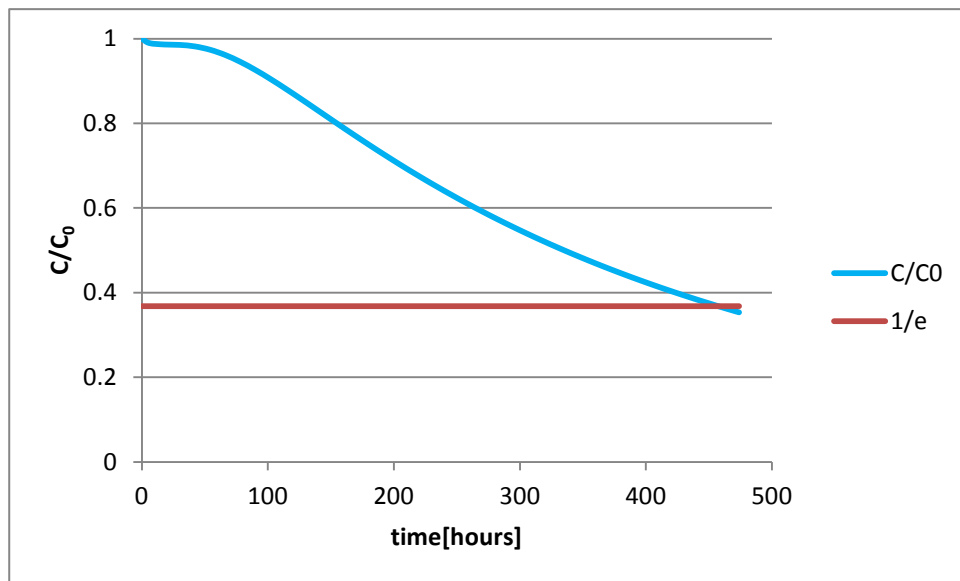
5.3.6 Node 23048 (light blue one)

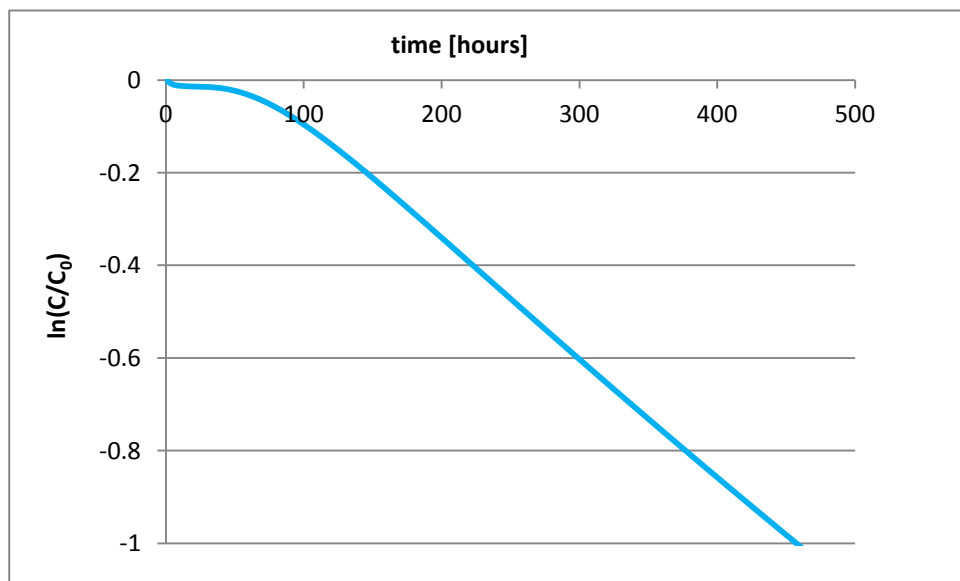**Figure 5.17: behaviour of C/C$_0$ when we inject the tracer in node 23048**

Figure 5.18: residence time when we inject the mass in node 23048

Injecting the mass in this node the residence time is equal to 462 hours that are 19.25 days.
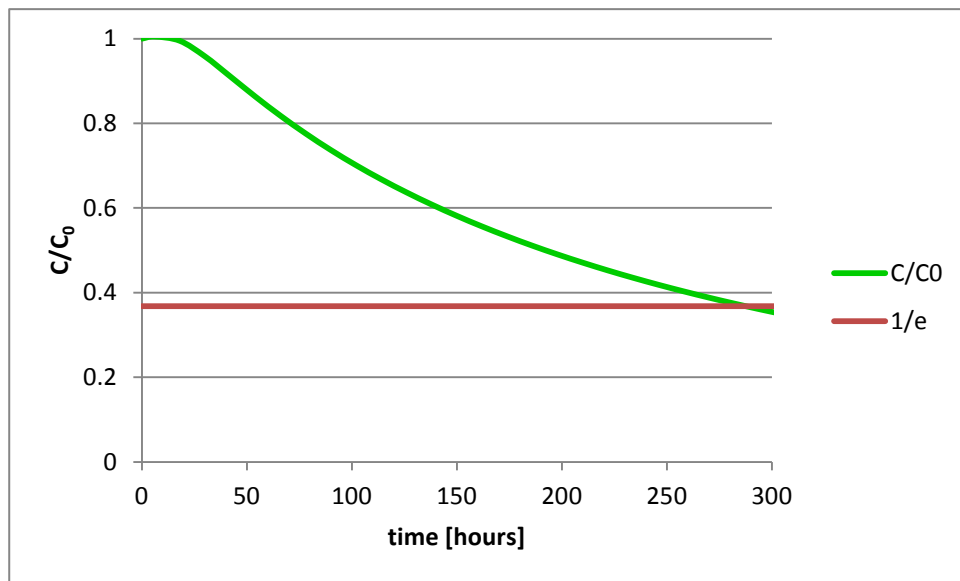
5.3.7 Node 23951 (green one)

Figure 5.19: behaviour of C/C$_0$ when we inject the tracer in node 23951

Figure 5.20: residence time when we inject the mass in node 23951

Injecting the mass in this node the residence time is equal to 294 hours that are 12.25 days.

5.3.8 Node 25187 (orange one)

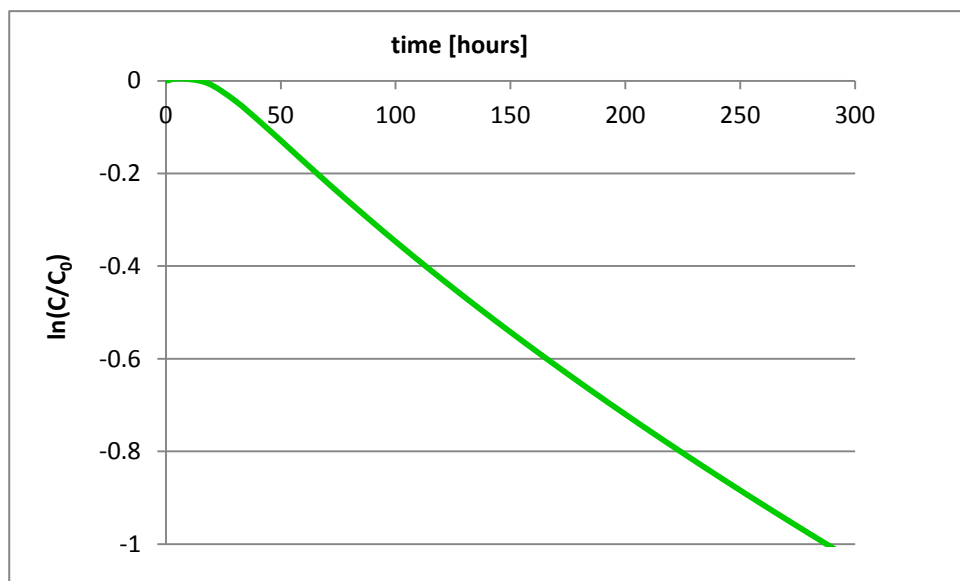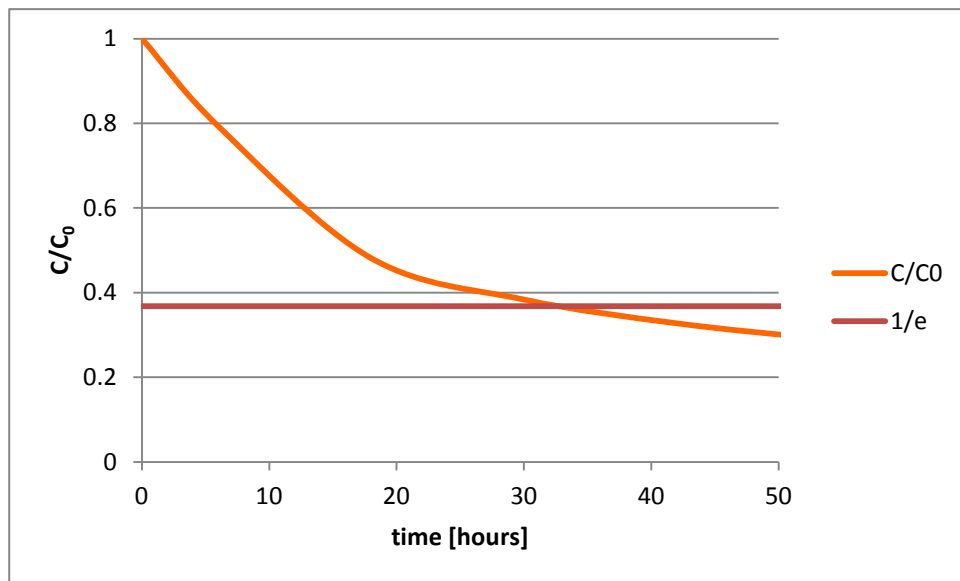**Figure 5.21: behaviour of C/C$_0$ when we inject the tracer in node 25187**
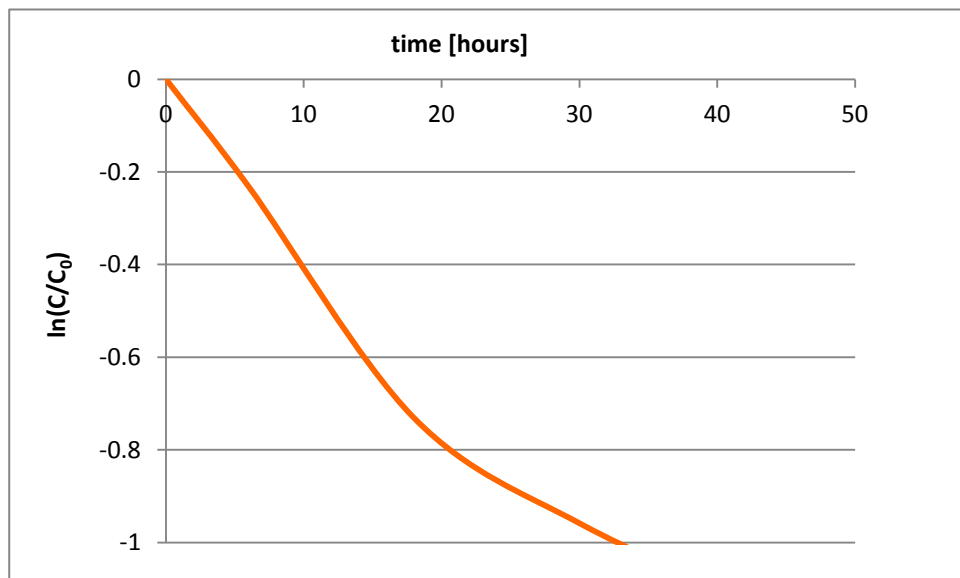

Figure 5.22: residence time when we inject the mass in node 25187

Injecting the mass in this node the residence time is equal to 32 hours that are 1.33 days.

Now the results of these nodes are reported in the same chart to compare them.
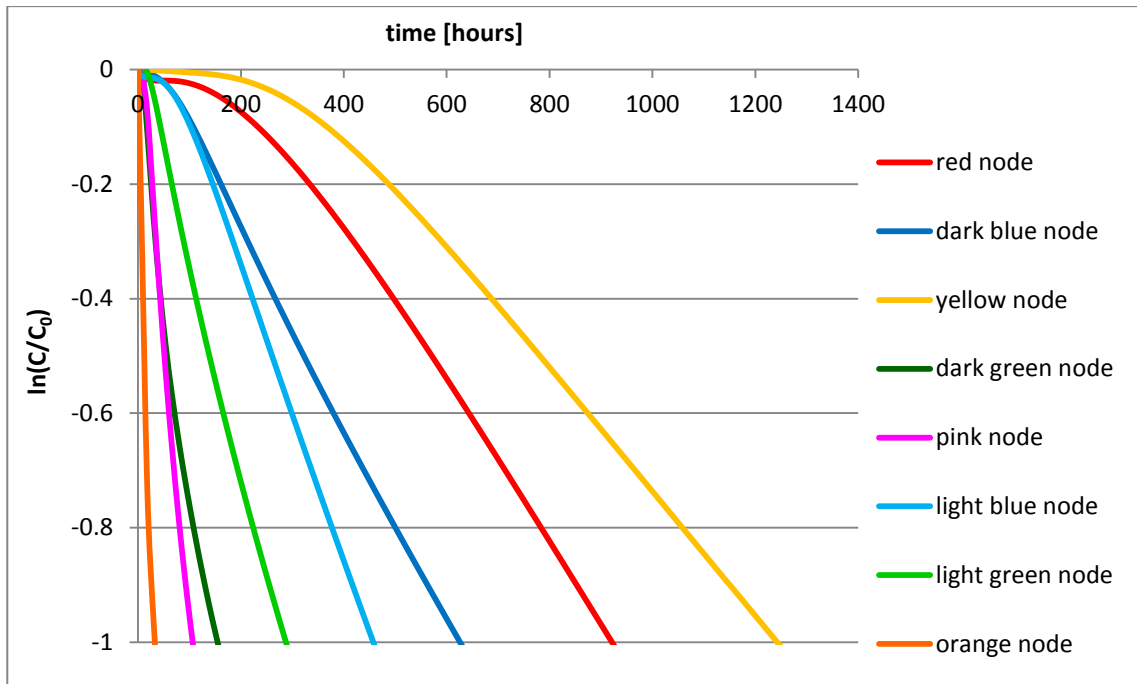
Figure 5.23: comparison between the residence time calculated injecting the tracer in different nodes

It is possible to see that the curves in the semi-logarithmic graph have a rectilinear behaviour, so the theoretical assumption that we have previously done find a good confirmation in the practical applications. The inclination of the straight lines indicates the velocity with which the concentration in the lagoon decreases, as expected, for the nodes closer to the inlets, the ratio C/C_0 reaches the value of $1/e$ much more quickly than the more distant nodes (see figure 5.6). As a consequence the residence time is higher for the latter nodes and lower for the former ones, in fact the residence time increases as the inclination of the lines decreases. Considering all the analysed points the maximum calculated residence time is about 52 days.

Sometimes it may happen that injecting the conservative tracer in nodes that are, from a geographical point of view, more distant from the inlets with respect to other analysed nodes, we obtain a residence time that is lower than the one we calculated for other nodes that are geographically closer to the inlets. This fact can be explained considering that these points are more distant from the inlets from a geographical point of view but they are closer from an hydraulic point of view because they belong to the channels of the lagoon and then, there, the velocity of the water exchange between the lagoon and the sea is higher.

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5.4 Comparison with a previous work

In this paragraph the results of this thesis are compared with the results obtained in a previous work where the residence time was calculated with a different procedure.

In this work the residence time was calculated considering the punctual injection of a specific concentration of a conservative tracer in some nodes of the lagoon; in every simulation the tracer was entered in only one node and then the behaviour of the mean concentration in the lagoon was evaluated. Then in every simulation a different residence time was obtained because the injection nodes were different. Some of the results of this approach are reported in the previous paragraph.

In another work the residence time was calculated considering a diffused injection of a specific concentration of the tracer, in other word the same initial concentration of the tracer was assigned to every node of the lagoon. The results that was obtained are reported in figure 5.24.

In an a priori analysis it was thought that the two methods have to provide different results because the initial conditions are very different. This hypothesis is based on the fact that if we calculate the residence time in the same node with the two different approaches, in the case of the diffused injection, the mass of the tracer that is removed by the mixing process is, in some extent, replaced by the mass entered at the beginning of the simulation in the other nodes and then the residence time should be higher for this approach. In the following graphs it is possible to see if this hypothesis is confirmed or not.
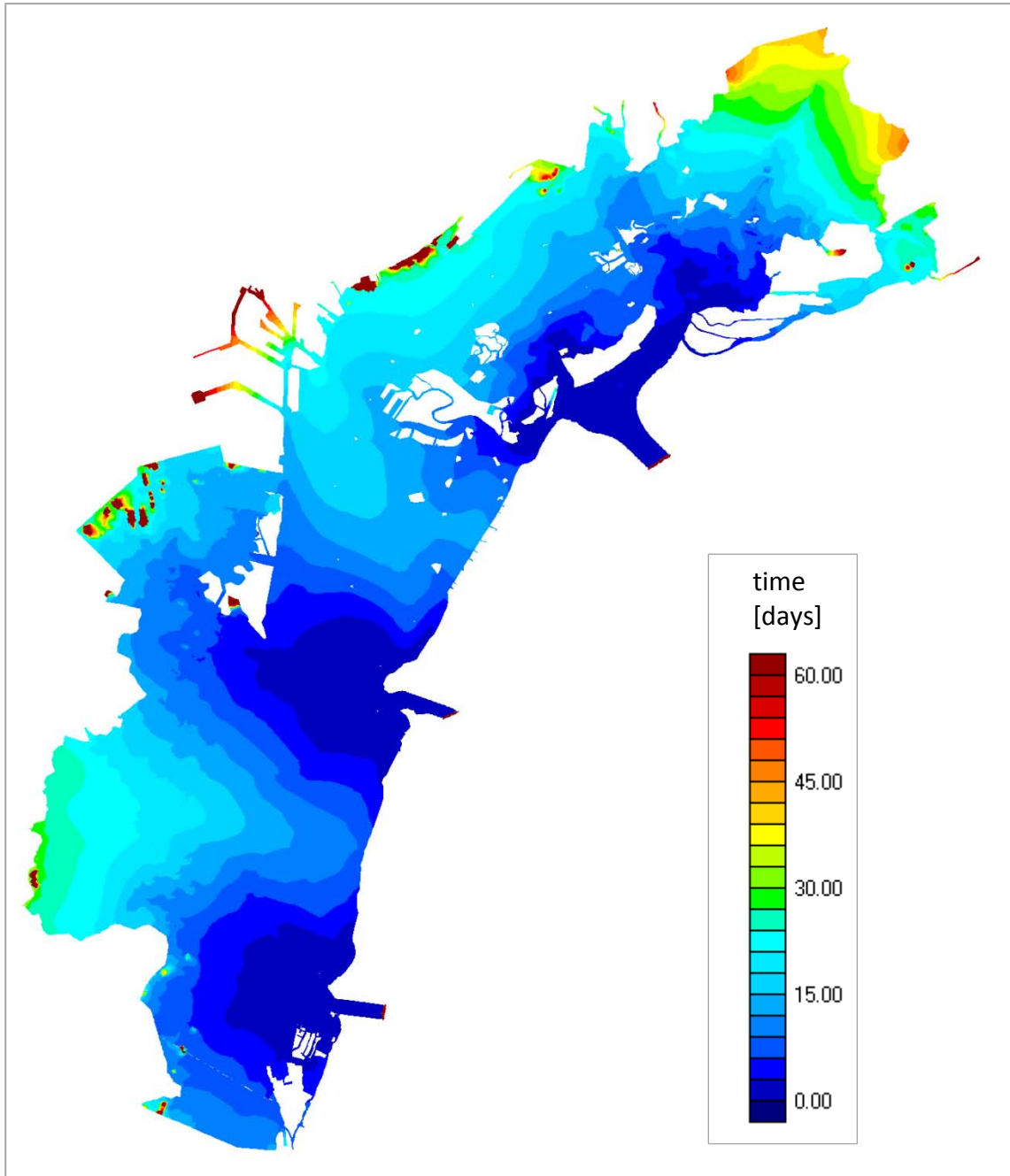
Figure 5.24: residence time with a diffused injection

The residence time calculated with this method in the nodes I analyse (figure 5.5) has been considered in order to compare these values with those I obtained with the punctual injection of the conservative tracer. The results of the comparison are reported in the following graph:
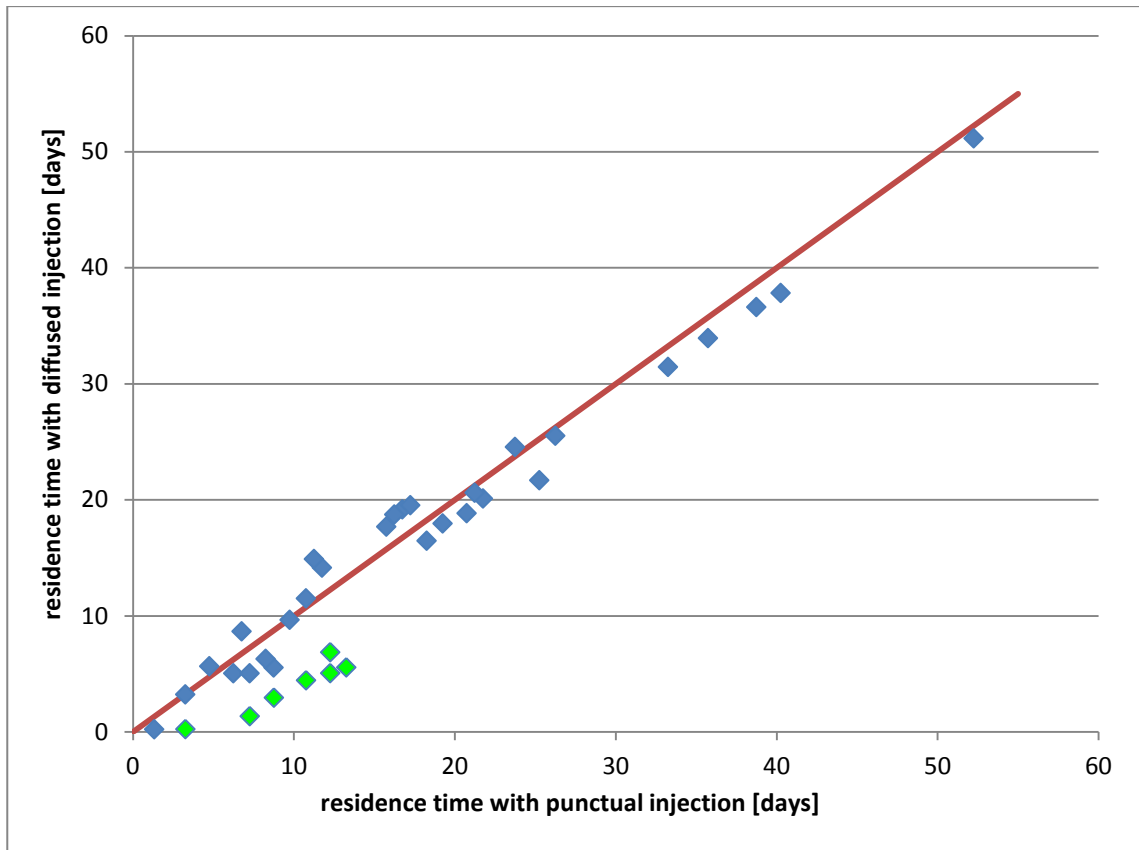
Figure 5.25: comparison between residence time calculated with two different approaches

We can see that, in contrast to what was expected a priori, there is a good correlation between the two different methods with which the residence time was calculated (the results are well distributed along a straight lane inclined of 45 degrees with respect to the horizontal axis) for almost all the considered nodes, even if for residence times higher than 30 days it is possible to note that the residence time with punctual injection is always a little bit higher that the other one. On the contrary if we look at the green points in figure 5.25 it is possible to say that for those nodes the residence time calculated with the two approaches are very different. The results of the two methods for these points are reported in the following table:

node	T_e punctual injection	T_e diffused injection
23951	12.25	6.871
22065	8.75	2.955
16292	10.75	4.452
14695	7.25	1.360
8998	3.25	0.244
22438	12.25	5.069

Table 5.1: residence time [days] with two different approaches

In my opinion (see figure 5.26) these nodes are those one that are very close to the main channels of the Venice lagoon but that do not belong to them. Maybe the fact that in these nodes the residence time calculated with a punctual injection of the tracer is higher than the residence time calculated, for the same nodes, with a diffused injection, can be explained considering the role of the tide. At the beginning of every simulation we have that the water flows from the sea to the lagoon so the mass of the injected tracer moves away from the inlets and this phenomenon is particularly evident in the nodes near the channels because here the tide has a stronger effect because it is not yet damped. Moreover this particular effect of the tide is more effective when we consider a punctual injection of the tracer because in this case all the entered mass is moved away from the inlets by the tide while, if we consider a distributed injection, the mass moved away in the considered nodes is replaced by the mass that comes from the near nodes and then the effect of the initial tide that is entering the lagoon is less effective. To prove this hypothesis further researches should be carried out.
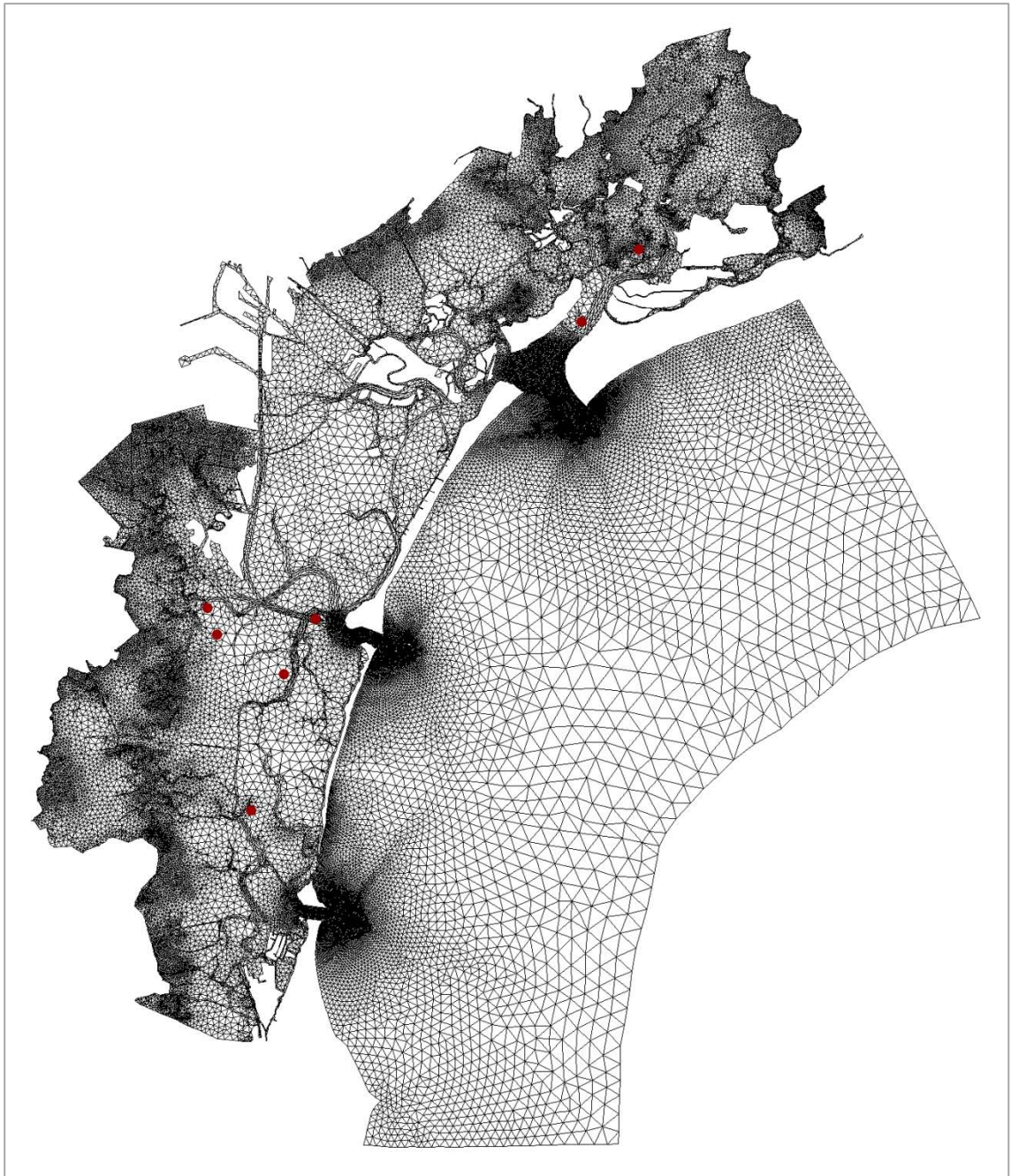
Figure 5.26: nodes in which the two approaches gives different results

6. Conclusions

The Venice Lagoon is an environment that is continuously changing and, from an environmental and water quality point of view, its conditions are gradually getting worse because of the various pollution sources which affect the lagoon. In order to correctly evaluate its water quality and assess the impact of the proposed interventions to improve its conditions, it is necessary to have some effective tools. The ecological models need an high computational effort, depends on a lot of parameters and they are very difficult to be calibrated, so they are not reliable tools. For these reasons we can rely on hydrodynamic indicators, in particular on some characteristic times-scale, to analyse the water quality and to assess the effects of the interventions proposed to improve the water quality in the lagoon. They have the advantage, with respect to the ecological models, of being fast and easy to be calculated and they give results easy to be understood.

Then it is possible to say that the analysis of the times-scale with two dimensional models led to reliable results but also that these results can be used in the field of the water quality analysis and to evaluate, on the basis of some specific knowledge, the effectiveness of the proposed interventions to improve the health of natural sites, such as the Venice lagoon.

In this thesis the residence time of a conservative tracer in the Venice Lagoon, considering a punctual injection of the tracer itself, has been calculated. Actually the 'e-folding residence time' has been calculated: in fact we consider as residence time the

moment in which the ratio between the current mean concentration in the lagoon C and the initial concentration C_0 becomes equal to 1/e. The goal of this thesis is, once the residence time has been calculated for various points of the basin, to compare the obtained results with those obtained in a previous work where the residence time was computed starting from a diffused injection of the conservative tracer.

The analysis was carried out with a finite elements hydrodynamic model that simulates the diffusive processes; from the obtained results it was possible to assess the extent of mixing in different zones of the basin. A greater mixing indicates a greater water exchange and this means a faster decay of the C/C_0 ratio and so a lower residence time. The simulations were carried out in many nodes of the domain and, as it has been hypothesised, the points that are hydraulically more distant from the inlets are those one for which the residence time is higher. The higher residence time that was obtained is of 52.25 days, while, even if we consider the nodes that are very close to the inlets, the residence time does not decrease below about 1 day.

From the comparison of the residence time calculated with the two different methods (punctual and diffused injection of the tracer) it is possible to say that, for the greater part of the analysed nodes, the two approaches provide results that are very similar one with the other, in contrast to what was expected a priori. Instead for the nodes closer to the main channels of the lagoon the residence time computed with the punctual injection method results much more greater than the one calculated with the other approach. This difference in the obtained values could be due to the fact that, at the beginning of every simulation, the water flows from the sea into the lagoon moving the injected mass away from the inlets and causing an increase of the residence time, as explained in chapter 5.

To conclude it is possible to state that there is a good correlation between the values of the residence time calculated with the two different methods, though further simulations and analysis must be carried out to explain the reasons of the differences for the nodes near to the main channels.

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