



On characteristic hydraulic times through hydrodynamic modelling: discussion and application in Patos Lagoon (RS)

ARTICLES doi:10.4136/ambi-agua.2456

Received: 19 Aug. 2019; Accepted: 12 Feb. 2020

Laura Aguilera*^{id}; Ana Lígia Favaro Dos Santos^{id};
Paulo Cesar Colonna Rosman^{id}

Área de Engenharia Costeira. Programa de Engenharia Oceânica. Instituto Alberto Luis Coimbra de Pós Graduação de Engenharia. Universidade Federal do Rio de Janeiro (UFRJ), Centro de Tecnologia, Bloco C, S/N, CEP: 21941-972, Rio de Janeiro, RJ, Brazil. E-mail: analigiafavaro@gmail.com, pccrosman@ufrj.br

*Corresponding author. E-mail: lauraaguilera@oceanica.ufrj.br

ABSTRACT

Although the analyses of characteristic hydraulic times are important diagnostic tools for studying water mass exchanges and identifying areas prone to stagnation that are potentially subjected to eutrophication effects, their concepts and uses are often misinterpreted. This paper compares similarities and differences between widely used characteristic hydraulic times, CHT, known as Residence Time, Times of Water Renewal Rates and Water Age. A proper definition for each of these characteristic hydraulic times is stated to avoid the existing confusion with multiple concepts in the literature. Methodologies to compute these CHT through hydrodynamic modelling systems are presented and, in order to enhance understanding, applied to three idealized cases in steady flow channels: (1) Channel with uniform flow; (2) Channel with a lateral inflow; and (3) Channel with a lateral embayment. Finally, a practical example is discussed by applying the methodologies to the Patos Lagoon (RS). The results for the idealized channel cases are non-intuitive and this theoretical discussion clarifies the interpretation and uses of different timescales and outlines the Water Age as the more versatile and multifunctional timescale if compared to the others addressed here. The results for the Patos Lagoon exemplify the valuable information that CHT can offer for environmental management in natural water bodies.

Keywords: environmental hydrodynamics, hydrodynamic modelling, transport timescales.

Sobre tempos hidráulicos característicos através de modelagem hidrodinâmica computacional: discussão e aplicação à Lagoa dos Patos (RS)

RESUMO

Embora a análise de tempos hidráulicos característicos seja uma ferramenta importante para estudar trocas de massas de água e identificar áreas propensas a estagnação de águas, que são potencialmente vulneráveis a efeitos de eutrofização, seus conceitos e usos são interpretados de forma errada com frequência. Este artigo compara as diferenças e similaridades entre tempos hidráulicos característicos, CHT, amplamente utilizados, tais como: Tempo de Residência, Tempo de Taxas de Renovação e Idade da Água. Definições precisas de cada um



destes tempos característicos são incluídas neste trabalho com o intuito de evitar confusão entre os múltiplos conceitos presentes na literatura. São apresentadas metodologias para o cálculo destes CHT utilizando sistemas de modelagem hidrodinâmica e, a fim de aprimorar o entendimento, aplicadas a três casos idealizados em canais de fluxo constante: (1) Canal com fluxo uniforme; (2) canal com um afluxo lateral; (3) Canal com uma baía lateral. Posteriormente, um exemplo prático é discutido aplicando as metodologias à Lagoa dos Patos (RS). Os resultados para os casos de canais idealizados não são intuitivos. A discussão teórica esclarece a interpretação e os usos dos diferentes tempos característicos e destaca a Idade da Água como o mais versátil e multifuncional, se comparada com os outros CHT abordados neste trabalho. Os resultados da Lagoa dos Patos são um exemplo do grande valor das informações que os CHT oferecem para a gestão ambiental em corpos hídricos naturais.

Palavras-chave: hidrodinâmica ambiental, modelagem hidrodinâmica, tempos hidráulicos característicos.

1. INTRODUCTION

The analysis of characteristic hydraulic times (CHT) has been used as an important diagnostic tool. These analyses are helpful to track the water mass exchange (Monsen *et al.*, 2002), giving us an important knowledge of the hydrodynamics processes that helps water bodies to recover from local pollution. Currently, transport models are the main tool used worldwide to develop CHT analysis (Bacher *et al.*, 2016). One can find numerous examples in the literature of CHT studies on water bodies pressured by the surrounding population or by the presence of industrial activity, that usually present environmental risks.

Du and Shen (2016) studied the Residence Time in the Chesapeake Bay, the largest estuary in the United States and very important for local economy and ecology. Also, Ying *et al.* (2018) and Qi *et al.* (2016) used CHT to study, respectively, the quality of water in deteriorated bays due to anthropogenic influences and deteriorated lakes that face an eutrophication problem. Water timescales analysis has been also developed in important lagoons like the Lagoon of Venice in the northeast of Italy (Viero and Defina, 2016), or reservoirs like Jirau Reservoir which shelters the Jirau hydropower system (Rosman, 2018), on Madeira River in the Brazilian Amazon Region. Port zones have also been investigated using CHT, assisting in harbor environmental management as stated by Grifoll *et al.* (2014), where the authors analyzed the water renewal and mixing of the Barcelona harbor zone in the northwest Mediterranean Sea.

Despite the extensive use of CHT analysis, there is no consensus in definitions, concepts and methodologies. As a result, several definitions of characteristic hydraulic timescales have been published (Bolin and Rodhe, 1973; Zimmerman, 1976; Monsen *et al.*, 2002; Delhez *et al.*, 2014; Cucco and Umgiesser, 2015; Liu *et al.*, 2017; Huguet *et al.*, 2019). There are several concepts that are different from each other but are closely related between them, thus very precise definitions are necessary to obtain correct result interpretations.

The purpose of this study is to contribute towards a consensus for concepts and methodologies to calculate CHT and discuss correct interpretations of the results to stimulate their applications in complex natural water bodies using hydrodynamic computational models. The specific objectives were: (1) compare transport time scales widely used to measure water retention and scalar quantities transported with water, focusing on the similarities and differences between the concepts of Residence Time, Times of Renewal Rates and Water Age; (2) describe and present clearly and accurately the procedures for computing these concepts; (3) calculate Residence Time, Times of Renewal Rates and Water Age applied to idealized cases to identify the influence of inflows and stagnation water areas in these CHT; (4) calculate Residence Time, Times of Renewal Rates and Water Age in a natural water body, specifically

in the Patos Lagoon (RS); and (5) identify challenges in analyzing results of Residence Time, Times of Renewal Rates and Water Age in natural water bodies. It is important to clarify that the objective of presenting CHT results in Patos Lagoon is to discuss correct interpretation of the results for natural water bodies.

2. MATERIALS AND METHODS

We adopted in this work the following definitions: a) Residence Time (R_T): given a domain of interest in a water body with particles positioned at various locations in an initial time, the R_T for each particle is the time it takes to leave the specified domain as it is passively transported by local currents; b) Times of Renewal Rates ($T_{RR\%}$) represents the time it takes to attain a water renewal of X% in different regions of the water body; and, c) the Water Age (W_A) indicates, for a given position of the domain, the average time the water parcels that are in that position remain in the domain of interest as the flow circulates through the domain.

The mathematical models for Residence Time, Times of Renewal Rates and Water Age hereby presented were implemented and applied to three idealized channel cases and a natural water body using SisBaHiA[®], a professional well-tested computational system for hydrodynamic modelling registered by COPPE/UFRJ, <http://www.sisbahia.coppe.ufrj.br/>. This computational system has been successfully used in different projects and scientific research (González-Gorbeña *et al.*, 2015; Peixoto *et al.*, 2017; Rosman, 2018; Silva *et al.*, 2019). Nevertheless, the following methodologies are not restricted to be used with SisBaHiA[®], and can be implemented in any other hydrodynamic numerical model.

In this work, the following SisBaHiA[®] models were adopted for numerical simulations: the Eulerian Transport Model (ETM) to calculate the $T_{RR\%}$ and the W_A ; and the Lagrangian Transport Model (LTM) to calculate the R_T . All transport models were driven by hydrodynamic models included in SisBaHiA[®]. The governing equations for such model adopt a filtering technique approach similar to Large Eddy Simulation to define turbulence stresses (Bedford and Dakhoul, 1982; Smagorinsky, 1963; Leonard, 1975; Aldama, 1985; Rosman, 1987). The spatial discretization is optimized for natural water bodies and uses mostly biquadratic quadrilateral finite elements with nine nodes but can also include quadratic triangular finite elements with six nodes. The spatial discretization is up to fourth order, depending on the mesh irregularity. The temporal discretization uses second order implicit finite differences scheme, mixing Crank-Nicolson (Crank and Nicolson, 1947) and Implicit Factored schemes (Beam and Warming, 1978).

The SisBaHiA[®] ETM and LTM solve the advective-diffusive transport processes with kinetic reactions and adopt filtering techniques to define turbulent diffusivities. The ETM is suitable to simulate the scalar transport of dissolved substances in the water column, like generic substances, contaminants or any order parameter that indicates water quality. The LTM is ideal to simulate the scalar transport of substances that are floating, mixed or occupying only one layer in the water column. Therefore, the LTM model is capable of simulating small-scale clouds of contaminants and plumes. Ample details of SisBaHiA[®] models, equations and numerical schemes are in Rosman (2019).

All the simulations carried out in this paper used the Hydrodynamic 2DH Model, where the quantity conservation equations motion and the continuity equation are vertically averaged.

2.1. Residence Time Simulation

The most common characteristic hydraulic time is the Residence Time (R_T). However, this is a term that has different meanings depending on the scientific community or work. The application of computational modelling allows the definition of the R_T as a function varying in space for different hydrodynamic conditions. Although there are many concepts applied to the R_T terminology, most of them considered it as the required time for a particle to traverse a given

domain (Zimmerman, 1976; Monsen *et al.*, 2002; Delhez *et al.*, 2014; Du and Shen, 2016). Bacher *et al.* (2016) presented a review of articles that use hydrodynamic modelling to calculate Residence Time with lagrangian and eulerian approaches. Here, to calculate the R_T within a predefined region of the modelling domain, the LTM receives information directly from the hydrodynamic model. Initially, the predefined domain is filled with neutral particles. The particles represent centroids of water mass parcels inside the domain and therefore, they do not occupy space. The model enumerates and associates every particle with its initial position and release instant. The LTM of R_T considers advective and dispersive processes of particles but does not compute turbulent diffusion of water masses among particles.

The total simulation time is defined to characterize the period of interest, during which the local currents transport all the particles. Whenever a particle exits the predefined domain, its R_T is recorded in its launch position. Hence, at the end of the simulation, the value of the R_T of each particle is registered at the launching position of the particle inside the predefined domain. Particles that remained within the domain until the end of the simulation receive an R_T equal to the duration of the simulation.

2.2. Times of Renewal Rates Simulation

For heterogeneous and varied water bodies, it is better to use the eulerian approach, which permits the analyses of parcels of water at different locations over time. In this approach, the water flux passes through a control volume that is considered an observation point. For this reason, if the goal is to analyze the characteristic time for water renewal, it is recommended that the Times of Renewal Rates ($T_{RR\%}$) be computed directly at different points over time, to obtain the time evolution of the renewal rates at different points of the study domain (Roversi *et al.*, 2016; Rosman, 2018).

Following the usual hierarchy of the models, an ETM that calculates $T_{RR\%}$ receives information directly from a hydrodynamic model. The $T_{RR\%}$ simulation assumes a reference value of Water Renewal Rate, W_{RR} , equal to 0% for the waters that are inside the domain of interest at the initial simulation instant. For renewal purposes, incoming waters, i.e., waters that enter the domain by the open boundaries or through other inflows, such as rivers, have a reference value equal to 100%. As new water with 100% reference value mixes with initial water of 0% reference value an intermediary value is computed, indicating the percentage of mixing at any given point in time.

To represent these two conditions, a generic substance with concentration C is used as a tracer for new water. Consequently, at the beginning of the simulation, all the water enclosed within the domain of interest is considered old and is prescribed with concentration $C = 0$. All new water inflows in the domain after the initial time are considered new water with concentration $C = 100$.

Then, due to the advection, dispersion and diffusive processes, the percentage of fresh or new water in the domain will be directly proportional to this generic substance concentration, varying from 0% to 100%. The values resulting from these simulations represent the percentage of the mixing of new and old waters in each position of interest, delimited by the predefined domain. The W_{RR} will be different at each point of the domain because it depends on the magnitudes of the currents and turbulence in different places and times, as a function of the advective-diffusive transport.

The Times of Renewal Rates, $T_{RR\%}$, are the characteristic hydraulic times associated with the concept of water renewal. It means the necessary time, with respect to the initial modelling time, for a water parcel to reach a specific value of Water Renewal Rate, W_{RR} .

2.3. Water Age Simulation

The Water Age is an extended and very discussed concept in literature with different

methodologies (Deleersnijder *et al.*, 2001; Li and Shen, 2015; Qi *et al.*, 2016; Viero and Defina, 2016; Huguet *et al.*, 2019). Here, the analysis of Water Age allows us to analyze the average time that the water remains in the predefined domain over time. This time is estimated from the decay of an age-marker passive substance present in water. To determine the decay time, a first order decay kinetic reaction of the age-marker substance is mandatory, with a constant rate of $k > 0$ and without other effects of losses and gains of mass.

To conceptualize the calculation, consider a uniform well-mixed volume of water in the whole domain, with initial concentration C_0 for the age-marker substance. Considering a first-order decay kinetics, the time variation of the concentration of the age-marker substance, $C(t)$, is given by Equation 1:

$$\frac{dC}{dt} = -kC \quad (1)$$

Whose analytical solution leads to Equation 2:

$$C(t) = C_0 \exp(-kt) \quad (2)$$

and hence Equation 3:

$$t = \frac{-\ln\left(\frac{C}{C_0}\right)}{k} \quad (3)$$

Once the initial concentration C_0 and a later concentration $C(t)$ are known, the decay time elapsed between the two concentration values defines the W_A at the recorded time of $C(t)$, in respect to the initial condition.

The k unit is the inverse of time and it is easier to understand its magnitude by an equivalent time, like the well-known half-life time denoted as T_{50} . For example, it is more intuitive to understand that every two days a given concentration will be reduced by 50% than to extract this information from a reaction rate of $k = -0.347/day$. Note that $T_{50} = -\frac{\ln(0.5)}{k}$. Another very useful equivalent time is T_{90} , which is the time it takes for a 90% concentration reduction due to decay processes. Note that T_{90} is equivalent to an order of magnitude decay, thence $k = -\frac{\ln(0.1)}{T_{90}}$.

When considering a water body in which new water with $C = C_0$ inflows in multiple points at different times and outflows of water with different decay periods might occur at different points and times, it becomes evident that the C will be a function of space and time. Therefore, the W_A will also be a function varying in space and time. Hence, at a given position and instant, due to turbulent advective-diffusive transport mechanisms, the W_A function value represents an average age for the local water mixture, which is composed of water parcels with different ages, given by Equation 4:

$$W_A(x, y, t) = \frac{-\ln\left(\frac{C(x,y,t)}{C_0}\right)}{k} \quad (4)$$

Regarding the decay kinetics, the value of W_A does not depend on the value of the decay rate k , because the resulting values of C are consonant with k . However, in natural water bodies, with space-time varying flows, different values of k will cause different concentration gradients. In the mass balance equation for the decaying age-marker substance, the turbulent advective-diffusive balancing fluxes depend on the concentration gradients, and due to that, the resulting W_A can differ slightly for different values of the decay rate. For this reason, it is important to prescribe a suitable k value to obtain proper results for water age function $W_A(x, y, t)$.

As the numerical accuracy is limited, the decay constant k must be carefully chosen in terms of the equivalent T_{90} . For every elapsed T_{90} in a simulation, a decay of one order of magnitude occurs, which involves a decimal place. If T_{90} is too large in relation to the duration of the modelling, the decay may be so small that the values of C will be always very close to C_0 . On the other hand, if the given T_{90} is too small in relation to the duration of the modelling, the values of C will approach zero rapidly, the gradients of C will be more pronounced near the inputs and the effects of advective-diffusive balancing fluxes terms will have more influence on the estimation of W_A . Both cases may generate inaccuracy. For best results, suitable values of k should have an equivalent T_{90} between half and double the duration of the simulation.

To calculate the W_A with SisBaHiA[®], the ETM receives information directly from a hydrodynamic model. A primary initial condition $C(x, y, t_0) = C_0 = 1$ is set throughout the domain. Therefore, at the beginning $W_A = 0$, since $\ln(1) = 0$ in all locations. During the simulation time, the new waters that enter the domain by the open boundaries or through other inflows, such as rivers, have age zero and, therefore, must have age-marker substance concentration equal to one, i.e., $C(x_i, y_i, t) = C = 1$.

As the initial waters and the new waters with $W_A = 0$ are mixed and transported in the system domain, the value of C decreases at each point as a function of the decay process. Thus, the value of W_A becomes different at each point because it depends on the magnitude of the currents and the turbulence at each location during the simulation time.

An important consideration about the hydrodynamic models linked with transport models for the analysis of Water Age is that precipitation and evaporation should not be included. These two processes produce a change in the water volume and can lead to distortions in the result of Water Age due to dilution or intensification of the concentration of the age-marker substance used to calculate W_A . In natural systems where it is necessary to include these effects, such as lakes, for example, equivalent lateral flows could be used to incorporate the mass of the reference substance, or infiltration and exfiltration processes.

The total simulation time to analyze Water Age should be enough for the simulation to achieve a dynamic equilibrium. An appropriate duration should be approximately the time required for a renewal of at least 50% of the water of the system that is being modelled. This duration can be estimated doing a previous modelling of $T_{RR\%}$.

2.4. Study Cases

For the idealized tests, three processes were approached using steady flow situations: (a) water exchanges in a uniform channel; (b) the effect of lateral inflows; and (c) the effect of water stagnation areas.

Therefore, to analyze CHT for these cases, three numerical steady flow tests were developed: Test 1 - Channel with uniform flow; Test 2 - Channel with a lateral inflow; and, Test 3 - Channel with a lateral embayment, to represent a stagnant prone zone.

The simple geometry of all tests allows an easy and intuitive interpretation of the results, facilitating the observation of the influence of each variable and, in this case, the physical result of water renewal using the concepts of Residence Time, Times of Renewal Rates and Water Age. All tests employed similar computational domain and mesh discretization, with changes only to include a lateral inflow in Test 2 and a lateral embayment in Test 3. Next sections describe the characteristics of each test, which were modelled using SisBaHiA[®].

For all tests, the respective channel has an equivalent bottom roughness amplitude of 0.02m, which results in Chézy coefficient values $C_h \cong 50\text{m}^{1/2}/\text{s}$.

Test 1. Channel with uniform flow

This test considers a straight channel with 10km extension and 600m width. The initial conditions were a predefined water level gradient and homogeneous water column, $H = 2\text{m}$. At

the upstream boundary, there is an inflow of $Q_1=300\text{m}^3/\text{s}$ uniformly distributed, and at the downstream boundary the water level is given as -0.125m . The channel's bathymetry has a slope to result in a uniform and steady flow in the channel, with a depth averaged velocity of $0.25\text{m}/\text{s}$. Figure 1 schematizes Test 1, whose domain was discretized with a quadratic finite element mesh with 300 quadrilateral elements of $200\text{m} \times 100\text{m}$, v. Figure 2.

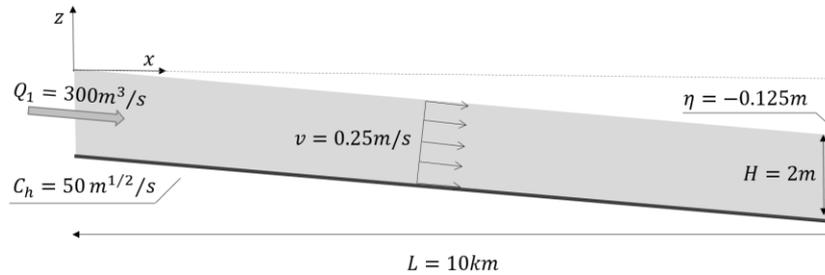


Figure 1. Idealized modelled channel scheme for Test 1.

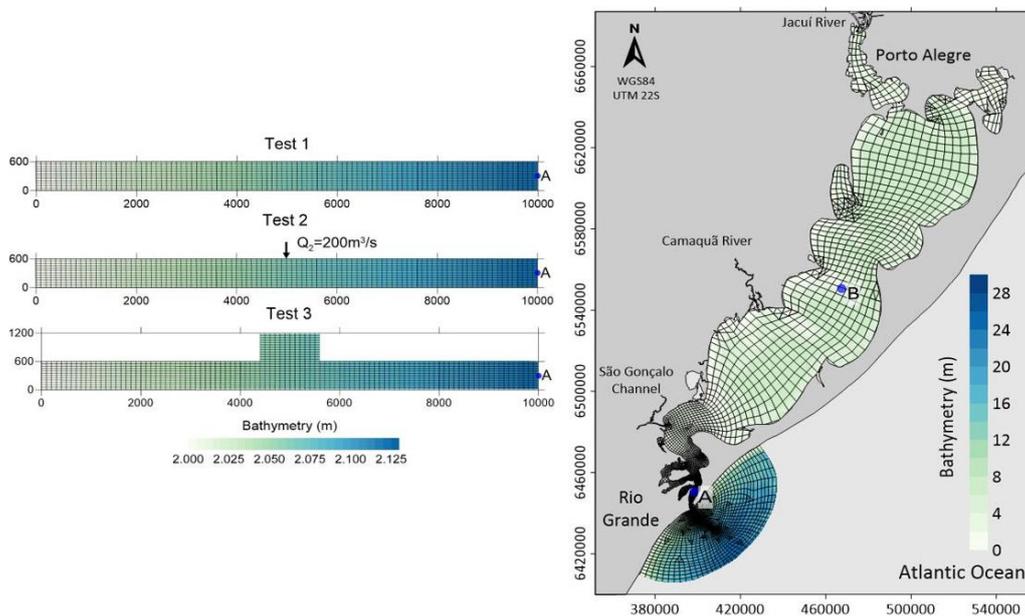


Figure 2. Left: Modelling domain of the channel for Test 1 to Test 3 with the finite element mesh, bathymetry, and the position of Station A used to present the results. Axes represent local coordinates in metres. In the figure, the elements are shown with internal lines connecting the 9 nodes of each element. Right: Modelling domain of Patos Lagoon with the finite element mesh, bathymetry, and the position of stations A-B used to present the results. Axis in UTM coordinates (WGS84, 22S).

Test 2. Channel with a lateral inflow

Test 2 was carried out with the same modelling domain and the same initial conditions used in Test 1. To simulate a lateral inflow on the mainstream, a constant inflow of $Q_2=200\text{m}^3/\text{s}$ was introduced in the center of the left margin of the channel, as shown in Figure 2. The resulting velocity field for this test is steady and varied along the channel.

Test 3. Channel with a lateral embayment

Test 3 considers the same channel with a 10km extension and a 600m width but has a lateral embayment in the center of the channel, with a width of 600m and a length of 1000m. Figure 2 presents the discretized domain, with a quadratic mesh of 336 quadrilateral finite elements of $200\text{m} \times 100\text{m}$. The initial conditions were the same as those established in Test 1, with a constant and spatially distributed discharge of $Q_1=300\text{m}^3/\text{s}$ upstream, the water level

fixed at -0.125m at the downstream boundary. The resulting velocity field is steady and varied along the channel.

For all the idealized tests, the total simulation time was 24h. For Test 1, the travel time along the channel is approximately 11h but the total simulation time was extended to 24h because Test 3 requires even longer to fully renovate. It is worth mentioning that for all the idealized tests the time step of the hydrodynamic model was 60s, with a maximum Courant number of 6.5. To compute the R_T with the LTM for all the idealized tests, the entire domain was filled with neutral particles one-metre apart from each other.

Patos Lagoon study case

Patos Lagoon is located in the state of Rio Grande do Sul, Brazil, and extends from latitudes 29.99° S to 32.20° S with mean longitude of 51.40° W , Figure 3. It is the largest choked coastal lagoon in the world (Kjerfve, 1986), with over 300km in length and an average width of 40km, its surface covers about 10360km^2 . The lagoon receives waters from an approximately 200000km^2 drainage basin (Seeliger *et al.*, 1997). Socioeconomic activities such as agriculture and extensive livestock farming have been developed around the lagoon (Fernandes, 2001).

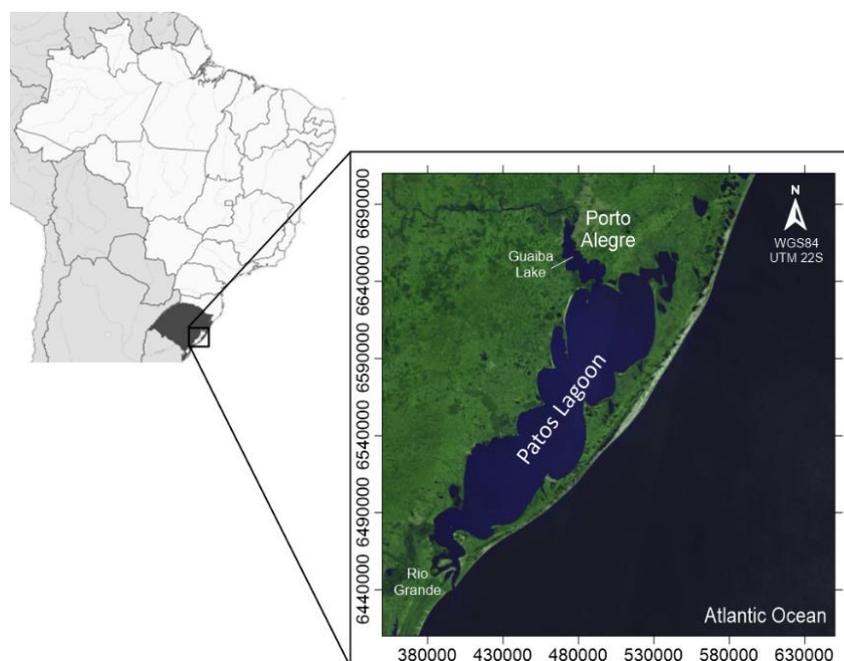


Figure 3. Localization and satellite view of Patos Lagoon (Lansat 8 OLI, 2016).

The Lagoon is connected to the ocean through a channel located at its southern end, the Rio Grande Channel (Marques *et al.*, 2009). The Port of Rio Grande, the second most important port in Brazil for the development of Brazilian international trade (Rio Grande do Sul, 2019), is near the mouth of the lagoon at the Atlantic Ocean. Patos Lagoon is navigable by vessels from the mouth to Guaíba Lake, northwest of the lagoon (Martelo *et al.*, 2019). The so-called Guaíba Lake is the main source of fresh water supply to the metropolitan area of Porto Alegre, the State capital, with a population of about 4.3 million inhabitants (Bendati *et al.*, 2000). Studies of hydraulic timescales could characterize areas prone to stagnation and indicate critical measurement points for quality monitoring programs. The delimitation of zones whose waters are mostly renewed by riverine or tidal flows are some of the relevant results that could be extracted from the modelling of CHT in Patos Lagoon.

The computation of CHT to Patos Lagoon serves as a guide for applications and results interpretations for other studies. Patos Lagoon was chosen to compute CHT for the following reasons:

- Seasonal changes significantly modify its hydrodynamic circulation, due to changing winds, river discharges and storm surges;
- It has a connection with the sea and, therefore, a tidal influence area;
- There are important economic and industrial activities in its basin;
- In terms of CHT, there are just a few studies related to Residence Time of the lagoon, in a traditional way, which differs significantly from what we present ahead (Moller, 1996; Fernandes, 2001).

The adopted modelling domain of Patos Lagoon, shown in Figure 2, and the hydrodynamic model for the Patos Lagoon is the same as that which was calibrated and validated for the hydro-sedimentological analysis concerning the National Dredging Plan of the National Secretary of Ports, of the Brazilian Federal Government (COPPETEC, 2015).

The modelling domain of Patos Lagoon includes all the lagoon and vicinal coastal areas. It has a variable depth distribution, with an average of 6m, making the lagoon a very shallow water body, tending to be vertically well-mixed. The entrance channel is about 22km long, 2km wide and approximately 12m deep. The main port terminals are in this channel, in which the water column can be vertically stratified by saline intrusion. Bathymetry data, derives from nautical charts of the Directorate of Hydrography and Navigation of the Brazilian Navy, and other available data from surveys in the channels, and it is referred to mean sea level at Rio Grande Port. The sediment characterization of the Patos Lagoon and the most distant areas of the navigation channels is predominantly silty, with fractions of sand and clay (Toldo Jr. *et al.*, 2005). In the port areas, available sediment data from surveys were used (DNIT, 2007; FURG, 2008). The discretization of the domain used 1982 quadratic finite elements, containing 8149 calculation nodes. In Figure 2, the mesh grid is shown with internal lines connecting the 9 nodes of each quadrangular element and the 6 nodes of each triangular element.

For a better characterization of the hydrodynamics and water renewal, this study considers two seasonal scenarios: a Summer/Dry scenario and a Winter/Wet scenario, from 12/21/2010 to 03/20/2011 and 06/21/2011 to 09/23/2011, respectively. For both scenarios, the modelling includes effects of astronomical tides and storm surges, the main tributary rivers and local winds. Due to the importance of waves generated by local winds in Patos Lagoon, the hydrodynamic model was coupled with the wave generation model. Storm surge effects in the mean water level were obtained from averaging daily measurements. The astronomical tide levels, generated from the main harmonic constants of a tidal station, were also considered despite their minor influence on the hydrodynamic regime. Both stations were located at the end of the Rio Grande Channel. The NCEP Reanalysis Model (Kistler *et al.*, 2002) provided the wind data used in this modelling, for 25 points distributed along the modelling area at a resolution of 0.5°. For the period covered, the northeast quadrant winds are predominant, and the highest velocities were 16m/s. When cold fronts hit the study area, winds of the southwest quadrant were observed. These events generate a set-up and set-down mechanism of oscillation with the nodal line in the mid lagoon area. This oscillation has the same period of the passages of frontal systems for this region, 3 to 10 days, which occurs more frequently in winter. Figure 4 shows the sea level boundary condition and the wind regime for the two scenarios.

The modelling considers the inflows of the three main tributaries: daily flow data from ANA (2015) for Jacuí River and Camaquã River, and a mean annual value for São Gonçalo Channel (Bordas *et al.*, 1984; Hartman and Harkot, 1990; Vaz *et al.*, 2006). Jacuí River is the

river with higher discharge seasonal changes; it has a maximum discharge approximately of $1600\text{m}^3/\text{s}$ for the Dry scenario and $16000\text{m}^3/\text{s}$ for the Wet scenario.

For the simulation of CHT in Patos Lagoon, the total simulation time was 3 months for each scenario, the time step of the hydrodynamic model was 100s, with a maximum Courant number of 26. To compute the RT with the LTM for the Patos Lagoon simulation, the entire domain was filled with around 13100 neutral particles, no more than 1000m apart.

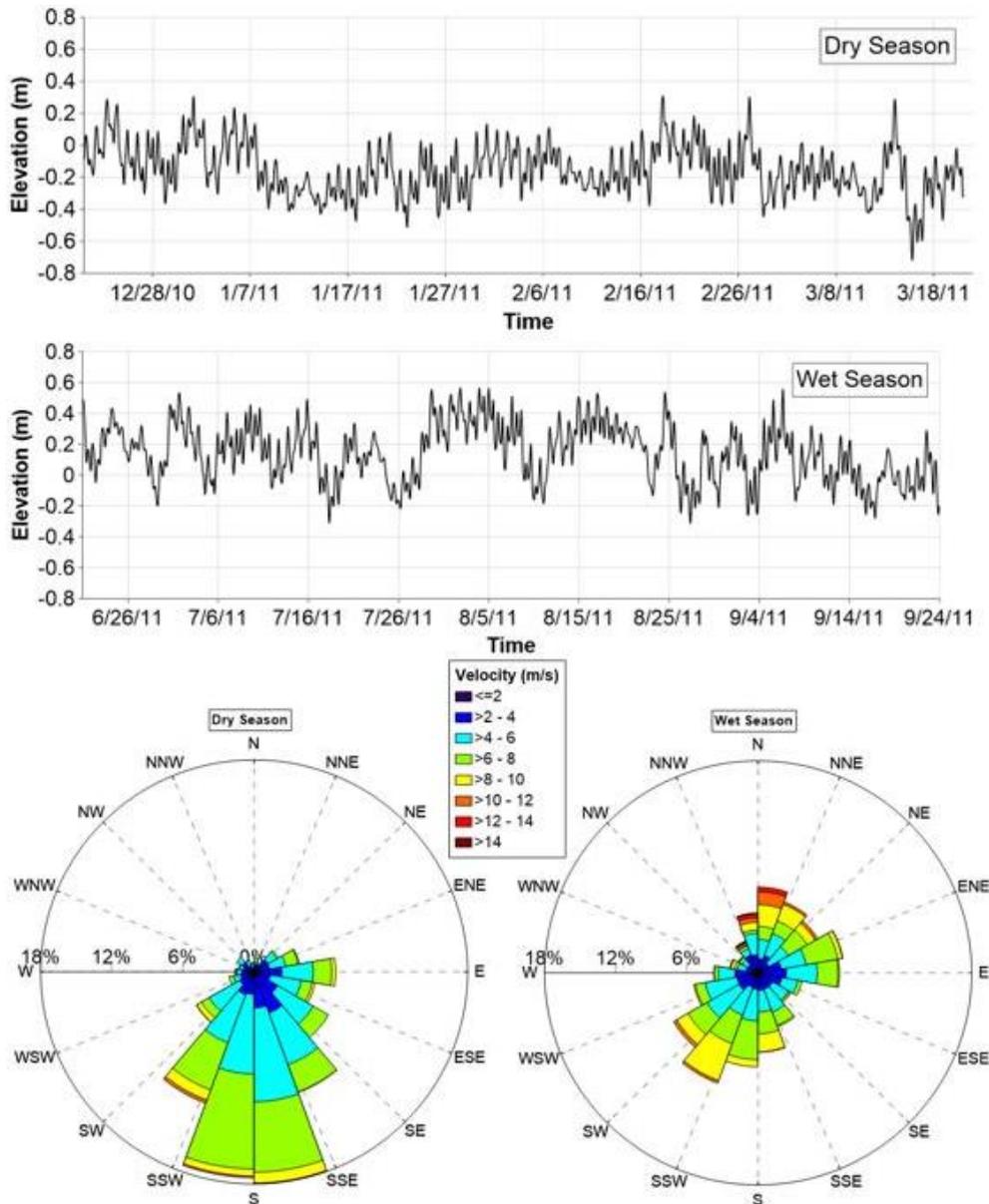


Figure 4. Sea level boundary condition and wind regime for Dry and Wet Season scenarios.

3. RESULTS AND DISCUSSION

3.1. Residence Time

Figure 5 shows the isolines maps for the three idealized tests at the end of the RT simulation. At the end of the simulation, the particles that have not left the channel have a R_T value of 24h. As it can be seen, the R_T presents different values along the channel. For all cases, as expected, next to the open boundary the water R_T is minimum. For Test 1 and Test 2, the

water in the upstream of the channel has the maximum R_T . For Test 3 the maximum R_T is within the lateral stagnant embayment.

Comparing Test 1 and Test 2, the influence of the lateral inflow is noticeable. The lateral inflow imparts a faster flow in the downstream half of the channel, resulting in a R_T lower at such half of the channel in Test 2 if compared to Test 1. The lateral inflow creates a backwater upstream of the confluence, which hinders the flow, making the R_T higher in the upstream half of the channel if compared to Test 1. This is a relevant aspect, because when planning a monitoring campaign, it is important to consider relevant inflows entering the mainstream.

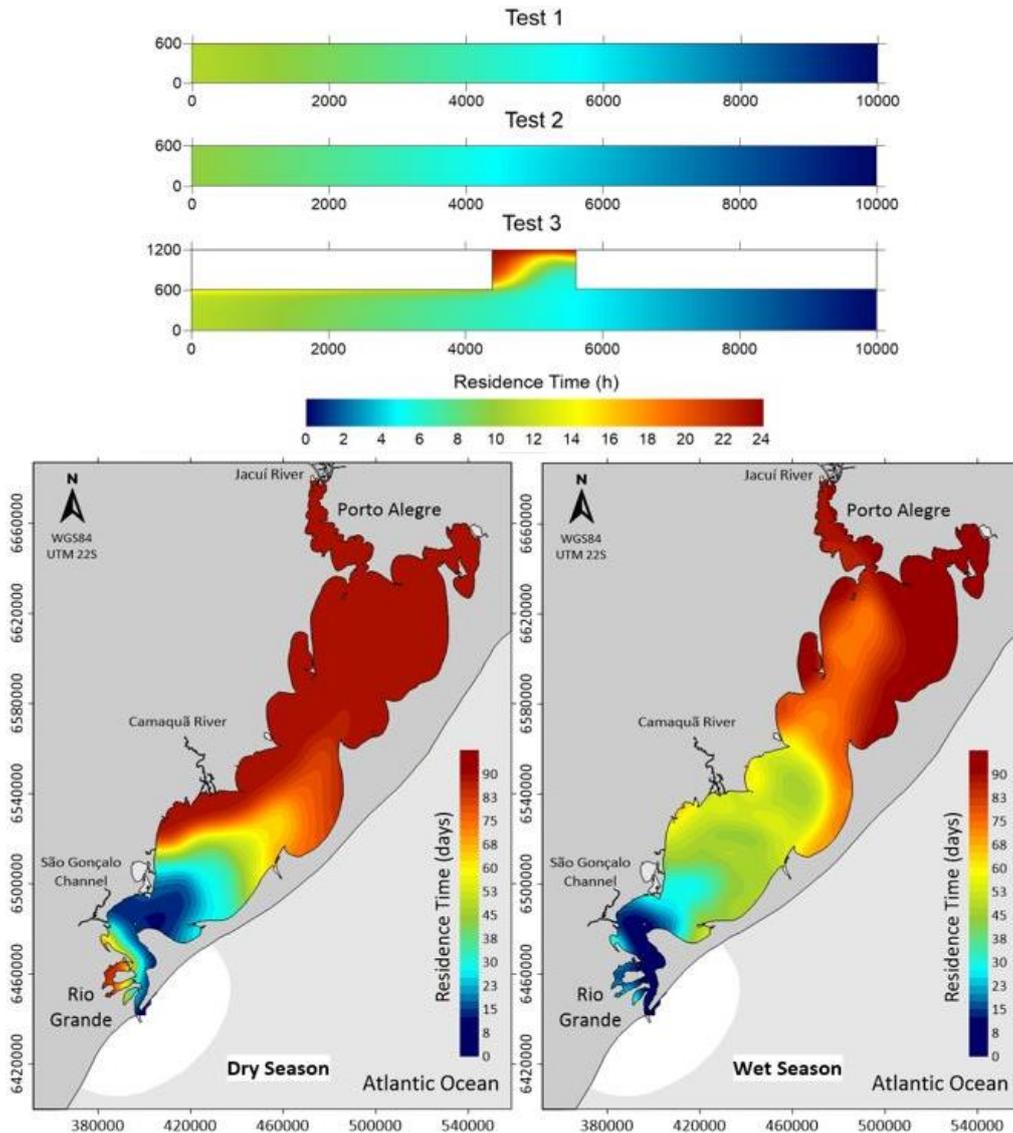


Figure 5. Above: Maps of isolines of Residence Time, for the end of the 24h simulation for Test 1 to Test 3. Below: Maps of isolines of Residence Time for the end of the three-month simulation for the Dry and Wet scenarios in Patos Lagoon.

In Test 3, the left margin upstream of the lateral embayment presents values of R_T higher than the right. This happens because particles flowing in the left margin are tapped in the lateral embayment. These particles are retained in the stagnation area and require more time to leave the channel. In the lateral embayment yet, particles remain trapped in this region during the 24h of simulation, so the $R_T = 24h$. The R_T analysis shows that stagnation areas in relatively low flows, like the one presented in the idealized channel, can confine water. In nature, this represents regions with low water renovation that are prone to trophic processes. In the case of

Test 3, results showed particles retained at the stagnation area during the whole simulation time. This is not a completely realistic situation compared with eddy areas in natural flows, where diffusive processes would cause mixing with water parcels outside of the eddy area.

The results of Patos Lagoon in Figure 5, at the final time of the R_T simulation for the Dry and Wet season scenarios, show that the particles that did not exit the lagoon after the 90-day simulation period got a R_T value of 90 days. For both scenarios, the northern region has a higher R_T than the rest of the lagoon, but the isolines maps show relevant seasonal differences.

For the Dry scenario, all the particles that were at the initial time in the north region do not leave the lagoon after 90 days. For the Wet scenario, the R_T value decreases from 90 days to approximately 70 days in the northwest region. As stated in the idealized channel Test 2, river discharge is not represented in R_T simulations as new water entering the modelling domain. Although, the influence of significantly higher values of Jacuí River discharges during the wet season are noticeable. The stronger velocities induced by Jacuí River allow the particles of the northwest region to reach the middle lagoon area. In the middle of the lagoon, the influence of frontal systems forces the entrance of sea water, increasing the magnitude of the velocities and allowing the particles located in the southern areas to exit the lagoon through the Rio Grande Channel. Smaller river discharges that have no relevant influence on the hydrodynamics, such as the Camaquã River, do not influence significantly the final result of R_T .

Tidal influence is observed comparing the Dry and Wet R_T results in the saline intrusion area. For Dry scenario, when river discharges of Jacuí River are smaller, tidal entrance is not restrained and the isolines of $R_T < 20$ days are located in a more internal zone of the lagoon. The preferential flow course is on the right of Rio Grande Channel and, consequently, the R_T of the little estuarine arms located at the left of the channel is higher. For the Wet scenario, Jacuí higher discharges imply stronger opposition to tidal entrance and, therefore, values of $R_T < 20$ days are limited to a narrower estuarine area. In this scenario, the difficulty of tidal flow to enter the lagoon induces the flow to pass through the estuarine channels, reducing the R_T in this area if compared to the Dry scenario.

In the northwest region, for both scenarios, R_T is 90 days. This means that the particles that were initially in that region remain in the lagoon domain. However, from R_T results, one cannot know to where those particles were transported. Even though, if particles are retained in this natural embayment, the result would not be a completely realistic situation in eddy areas in natural flows, where diffusive processes would cause mixing with water parcels outside of the eddy area. Since a particle represents the centroid of a water mass distribution, it is important to remember that lagrangian modelling of R_T considers advective and dispersive processes of particles but does not compute turbulent diffusion of water masses among particles. Therefore, in heterogeneous water bodies such as the Patos Lagoon, particles transported just by advective and dispersive processes could result in nonrealistic mixing situations, due to the lack of proper turbulent diffusion.

3.2. Times of Renewal Rates

To present the results of the Times of Renewal Rates models, Figure 6 shows isolines maps of renewal rate at a specific $T_{RR\%}$. For this study and the idealized cases, the time of $T_{R50\%}$ at the downstream station A, v. Figure 2 was chosen. A $T_{R50\%}$ at Station A is the time when 50% of the water at A entered the modelling domain after the initial simulation time. Consequently, the other 50% is from waters that were already in the channel at the initial time, but certainly not in the same place as Station A.

For the idealized cases, Figure 6 shows that the isolines of Renewal Rate, for the time of $T_{R50\%}$ at Station A, for Test 1 and Test 2 are very similar, but the effects of the lateral inflow in Test 2 are noticeable. For Test 1, water renewal is homogeneous along the channel section at Station A. For Test 2, due to the lateral inflow, the Renewal Rate along the section of Station

A varies from 45% in the right margin of the channel to 80% in the left margin. For Test 3, the isolines show that a plume of water with lower Renewal Rates exits the lateral embayment and arrives at the end of the channel producing a variation of Renewal Rate from 10% to 60% across the channel section of Station A.

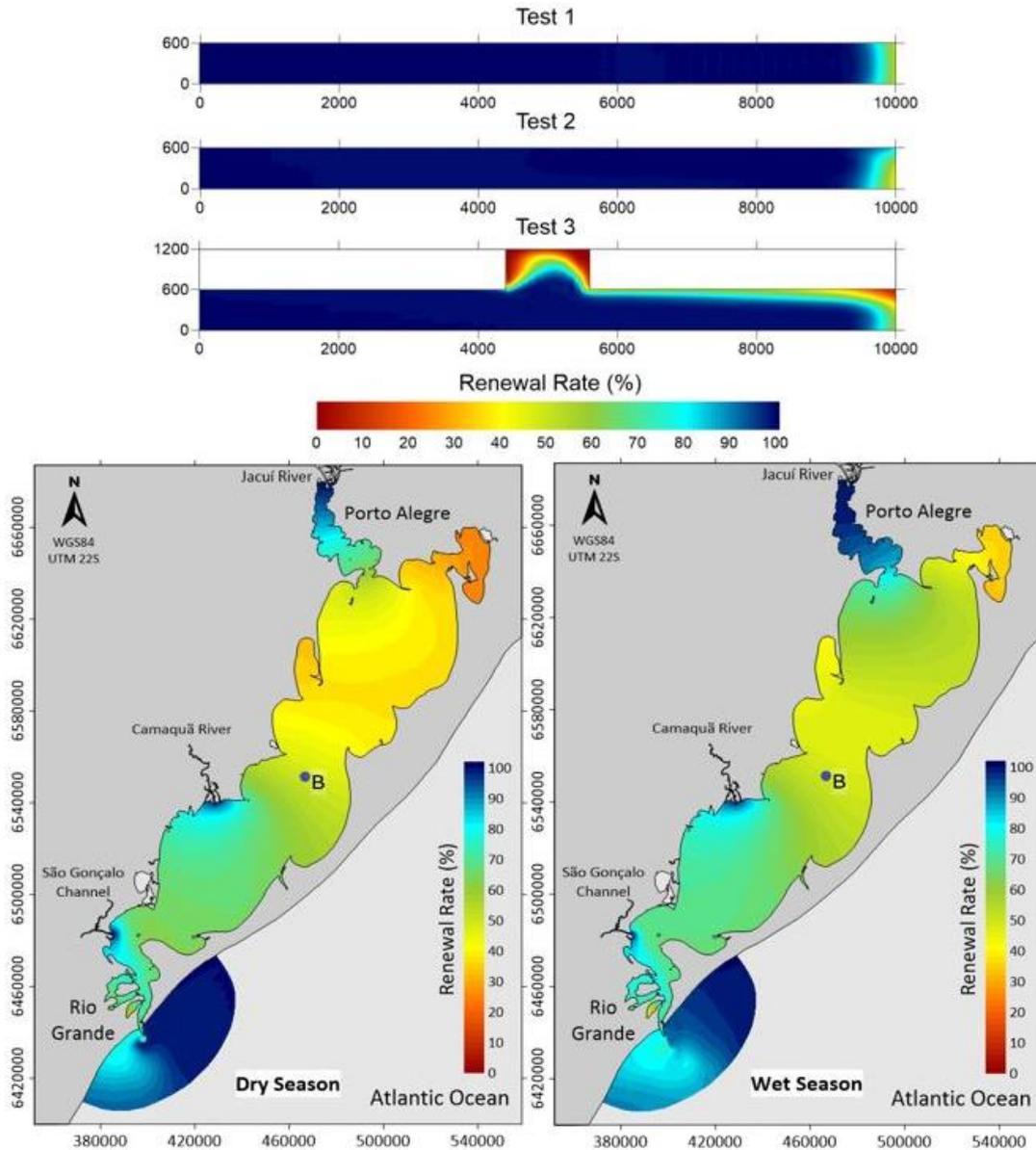


Figure 6. Above: Map of isolines at the time $T_{R50\%}$ at the center of the outflow section of the channel, Station A, for Test1 ($T_{R50\%} = 11.1h$), Test 2 ($T_{R50\%} = 9.8h$), and Test3 ($T_{R50\%} = 11.4h$). Below: Map of isolines at the time $T_{R50\%}$ at the center of the lagoon, Station B, for the Dry scenario ($T_{R50\%} = 41$ days), and the Wet scenario ($T_{R50\%} = 39$ days).

For the Patos Lagoon case, Figure 7 represents the isolines maps of renewal rate at the specific $T_{R50\%}$ in station B located in the middle of the lagoon, as depicted in Figure 2. The higher discharge of Jacuí River in the Wet scenario is responsible for almost 100% of water renewal of Guaíba Lake, the embayment that receives this affluent. Jacuí River is also responsible for the greater water renovation of the north half of the lagoon, 20% higher for the Wet scenario if compared with Dry scenario. Observing the results of the natural northeast embayment for both scenarios, the influence of higher Jacuí River discharges accelerates water renewal up to $T_{R50\%} = 40$ days approximately. From this result, one can conclude that water

parcels that initially were in this embayment at the beginning of the simulation, were mixed with more renovated waters that come from Jacuí River. This information, which cannot be derived from the R_T results, is important for management and monitoring decisions.

The saline intrusion region does not present relevant seasonal changes. Water renewal in this area occurs due to tidal and storm surge effects and water 100% renovated discharges of the two main river tributaries of this region. Notice that the isoline of more than 90% renovated near São Gonçalo Channel is more far away from the mouth of the channel in the Dry scenario than in the Wet scenario. This is the case because the intense discharge of Jacuí River blocks the flow of São Gonçalo Channel during the Wet scenario.

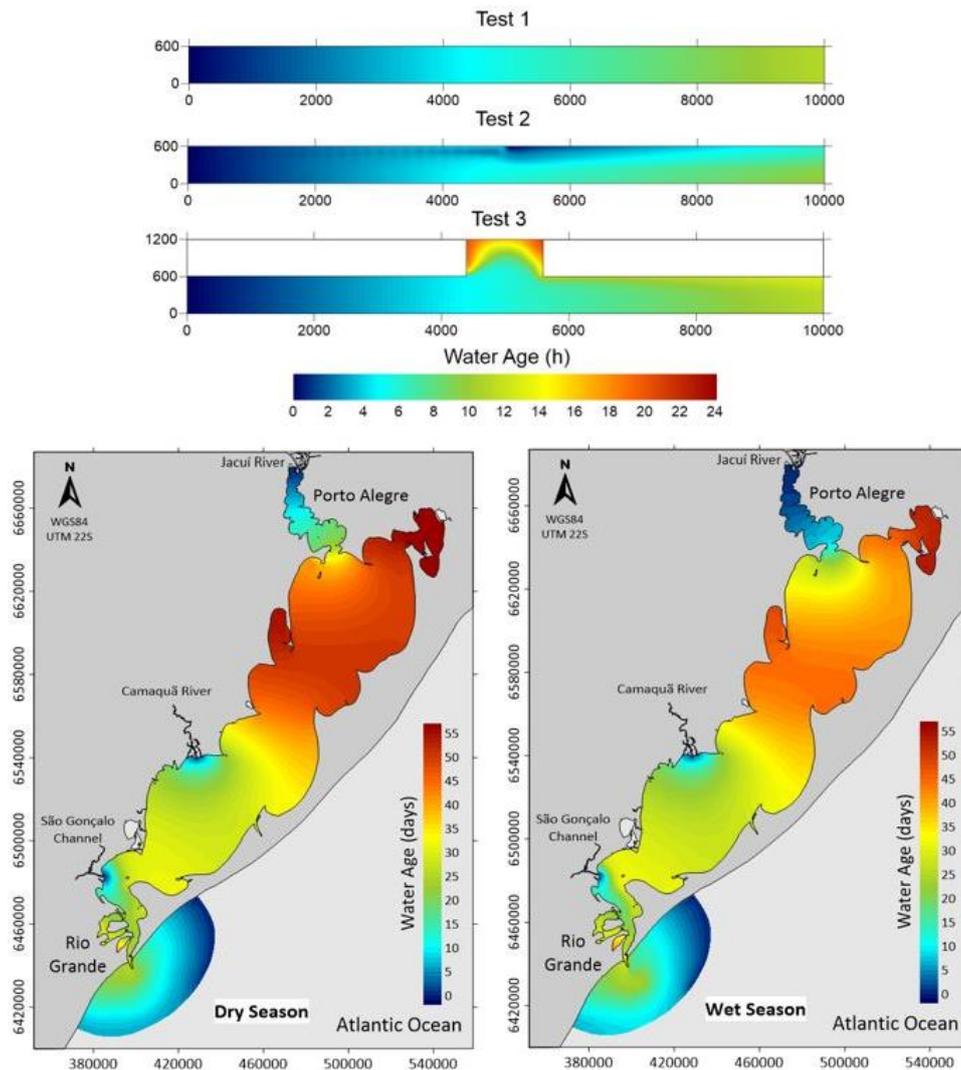


Figure 7. Above: Map of isolines of Water Age at the end of the 24h simulation for Test 1 to Test 3. Below: Map of isolines of Water Age at the end of the three-month simulation for the Dry and Wet scenarios in Patos Lagoon.

3.3. Water Age

During the Water Age simulation, as hydrodynamic circulation progresses, parcels of newer waters are mixed with older ones. Advection, diffusion and decay processes continue varying W_A in space and time, so the value of W_A becomes varied and variable.

Figure 7 presents the W_A spatial results at the end of 24h of simulation for the idealized cases. For each case, these results represent the average age of the water mixture at each point. As the inflows enter on the channels with $W_A = 0$, the water parcels next to them, with $W_A > 0$,

are mixed and renewed rapidly, decreasing the resulting W_A of the mixture. This is noticed at the left of Figure 7, at the beginning of the channel for the three tests and at the center for Test 2 case, where there is an additional lateral inflow. The influence of the lateral inflow is noticed in the results of Test 2, where there are newer waters at the right margin of the channel. This analysis, together with those previously presented for Test 2 in the R_T and $T_{RR\%}$ sections, shows the importance of properly considering inflows in characteristic hydraulic time analyses in natural water bodies where rivers have a significant influence. At the final time of the simulation, where equilibrium is reached, both embayment margins present approximately values of $W_A=20h$. For the modelling cases addressed here, the equilibrium is static because the flux is steady. The W_A simulation considers the diffusion processes, so the water mixing is better represented in the results than in the Residence Time analyses.

The Patos Lagoon maps of Figure 7 present the W_A spatial results at the end of the three-month simulation for each scenario. The results show clearly the influence of river inflows in the northern part, and the influence of tides in the southern part. This limit is clear in the 32-day isoline in the central part of the lagoon for W_A results. For both scenarios, as observed in Test 2 for the idealized channel, as the river inflows reach the lagoon with $W_A = 0$, they mixed with water parcels with $W_A > 0$ and renewed rapidly the surrounding areas. The water renewal is, therefore, highly related to the river discharge.

Seasonal changes of Jacuí River discharges modifies W_A in the northwest of the Patos Lagoon from 45 days for Dry scenario, to 35 days for the Wet scenario. As pointed out in the previous results, in the northeast of the lagoon there is a natural embayment that hinders water renewal. Water parcels positioned in this area did not mixed easily with the surrounding water parcels. This information is evident observing the Wet scenario results, since W_A is 50 days in the embayment area and 37 days outside it.

In the southern half of the lagoon, water renewal is more influenced by tidal effects. Comparing the results of W_A in this region, there are no relevant differences between the two seasonal scenarios. Therefore, one could say that the most important seasonal differences in Water Age are mainly ruled by the seasonal Jacuí River discharge variations.

In natural flows, there is no static equilibrium as occurs in steady flows. The equilibrium is dynamic, and, after enough time of simulation, the water age fluctuates around a value depending on the fluctuations of the main hydrodynamic forcing effects, such as tides or river flows fluctuations, for example. After three months of simulation for both scenarios, only the south of the lagoon and the Jacuí River region reached the dynamic equilibrium. The north and the northeast of the lagoon did not reach it, meaning that these areas would achieve higher values that 55 days of W_A at their dynamic equilibrium, which makes this area especially vulnerable to eutrophication effects. Consequently, this region of Patos Lagoon must be monitored as it is more vulnerable to trophic processes.

4. CONCLUSIONS

The results presented in this paper showed that, even in idealized situations with simple domains and controlled flux alterations, non-intuitive results for CHT arise. Therefore, a clear understanding of the concepts regarding different CHT, and the methodologies adopted to compute each case are of paramount importance. When considering the same idealized test, even though the Residence Time, the Times to Renewal Rates and the Water Age analyses represented the same hydrodynamics conditions, the isolines results are visually quite different for each case. These different results conform to the definitions of each concept and the methodology used to compute them. However, if the result interpretation is addressed careless or without a good understanding of the concepts and methodologies behind the characteristic hydraulic times, it could lead to wrong conclusions due to mistaken interpretations. Identifying

correctly the regions with lower W_{RR} and higher W_A and R_T is important because they indicate likely stagnant areas potentially vulnerable to eutrophication effects. This explains the importance of presenting the idealized channel results and discussions included in this paper before presenting the CHT results for Patos Lagoon.

A discussion about lagrangian and eulerian approaches to compute characteristic hydraulic times has also been addressed. The application of the CHT modelling in Patos Lagoon, a heterogeneous water body, the traditional concept of Residence Time, even using the lagrangian approach that allows R_T varying in space and time, showed that it is not ideal. The methodology adopted here considered neutral particles, which do not represent diffusion processes that is important in stagnation areas. The eulerian approach at the applied CHT model proved to be a better option since diffusivity is considered. If the objective is to analyze the time it takes for a given point of the modelling domain to reach a certain water renewal, it is recommended to use the Times of Renewal Rates. However, if the objective is to analyze for how long, on average, the waters remain in the predefined domain over time, it is recommended to apply the Water Age concept presented here.

The Water Age concept proved to be a versatile and multifunctional characteristic hydraulic time in the idealized tests and in Patos Lagoon. A good understanding of the concept and computation of W_A allows, depending on the characteristics of the case, an estimation of the Travel Time, Residence Time or Time of 50% of Renewal Rate of Waters of a region. Monitoring campaign decisions such as the number of sampling sites or the sampling time should be made after Water Age analyses, to see stagnation areas where relevant biogeochemical processes could occur. After analyzing the W_A results for Patos Lagoon, the north and northeast areas were highlighted as the areas where quality monitoring is more needed. These results are useful to make decisions that could save funds in monitoring campaigns. Therefore, the use of W_A as the characteristic hydraulic time is recommended rather than the other concepts addressed here. However, it has been also presented that each CHT gives diverse information, related to its own CHT definition and computation methodology, about the processes involved in water renewal. Consequently, for a better understanding of renewal processes in natural water bodies, it would be recommended that more than one CHT be analyzed.

Finally, this study contributed to clarify widely used CHT concepts that have been frequently used without a unified definition in the literature, leading to misleading interpretations. The results presented here for Residence Time, Times to Renewal Rates and Water Age for simple and intuitive hydrodynamics conditions helped to describe the meaning and the correct interpretation of the results associated with the idealized tests and Patos Lagoon.

The results presented for the CHT analysis in Patos Lagoon exemplifies the useful information that can be extracted from CHT analysis and the advantages of using CHT as a prerequisite for the development of water quality monitoring campaigns in natural water bodies. Thus, this work intends to serve as a guide for future application and results interpretation of these concepts in environmental management and monitoring programs.

For a more precise characterization of the R_T , T_{RR} and W_A in Patos Lagoon, a revision and actualization of the environmental data used for the modelling must be done, in addition to a calibration and validation process using water level and/or current data measured at different points of the lagoon.

5. ACKNOWLEDGES

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001; and by the COPPETEC Foundation.

6. REFERENCES

- ALDAMA, A. A. **Theory and applications of two- and three-scale filtering approaches for turbulent flow simulation**. 1985. Ph.D. (Thesis) - Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, 1985.
- ANA. **Website**. 2015. Available at: <https://www.ana.gov.br/>. Access: Jan. 2020.
- BACHER, C.; FILGUEIRA, R.; GUYONDET, T. Probabilistic approach of water residence time and connectivity using Markov chains with application to tidal embayments. **Journal of Marine Systems**, v. 153, p. 25–41, 2016. <https://doi.org/10.1016/j.jmarsys.2015.09.002>
- BEAM, R. M.; WARMING, R. F. An Implicit Factored Scheme for the Compressible Navier-Stokes Equations. **AIAA Journal**, v. 16, n. 4, p. 393–402, 1978. <https://doi.org/10.2514/3.60901>
- BEDFORD, K.; DAKHOUL, Y. Applying LES Turbulence Modeling to Open Channel Flow. *In: APPLYING RESEARCH TO HYDRAULIC PRACTICE*, 17-20 Aug. 1982, Jackson, Mississippi. **Proceedings**[...] Jackson: ASCE, 1982.
- BENDATI, M. M.; SCHWARZBACH, M. S. R.; MAIZONAVE, C. R. M.; ALMEIDA, L. B.; BRINGHENTI, M. L. Avaliação Da Qualidade Da Água Do Lago Guaíba (Rio Grande Do Sul, Brasil) Como Suporte Para a Gestão Da Bacia Hidrográfica. *In: CONGRESSO INTERAMERICANO DE ENGENHARIA SANITÁRIA E AMBIENTAL*, 27., 2000, Porto Alegre. **Anais**[...] Porto Alegre: ABES, 2000.
- BOLIN, B.; RODHE, H. A note on the concepts of age distribution and transit time in natural reservoirs. **Tellus**, v. 25, n. 1, p. 58–62, 1973. <https://doi.org/10.1111/j.2153-3490.1973.tb01594.x>
- BORDAS, M. P.; CASALAS, A. B.; SILVEIRA, GONÇALVEZ, M. **Circulação e dispersão em sistemas costeiros e oceânicos. Caso da Lagoa dos Patos**. Relatório Técnico. Porto Alegre: IPH/UFRGS, 1984.
- COPPETEC. **Projeto 16861: Modelo matemático aprimorado de quantificação de assoreamento dos acessos aquaviários nos portos contemplados - Porto de Rio Grande - RS**. Rio de Janeiro, 2015.
- CRANK, J.; NICOLSON, P. A practical method for numerical evaluation of solutions of partial differential equations of the heat-conduction type. **Advances in Computational Mathematics**, v. 6, n. 2, p. 207–226, 1947. <https://doi.org/10.1017/S0305004100023197>
- CUCCO, A.; UMGIESSER, G. The Trapping Index: How to integrate the Eulerian and the Lagrangian approach for the computation of the transport time scales of semi-enclosed basins. **Marine Pollution Bulletin**, v. 98, n. 1–2, p. 210–220, 2015. <https://doi.org/10.1016/j.marpolbul.2015.06.048>
- DELEERSNIJDER, E.; CAMPIN, J. M.; DELHEZ, E. J. M. The concept of age in marine modelling I. Theory and preliminary model results. **Journal of Marine Systems**, v. 28, n. 3–4, p. 229–267, 2001. [https://doi.org/10.1016/S0924-7963\(01\)00026-4](https://doi.org/10.1016/S0924-7963(01)00026-4)
- DELHEZ, É. J. M.; DE BRYE, B.; DE BRAUWERE, A.; DELEERSNIJDER, É. Residence time vs influence time. **Journal of Marine Systems**, v. 132, p. 185–195, 2014. <https://doi.org/10.1016/j.jmarsys.2013.12.005>

- DNIT. **EIA-RIMA para obras de dragagem de aprofundamento do Canal de Acesso ao Porto de Rio Grande - Volume II - Caracterização do meio físico**. Rio Grande do Sul, 2007.
- DU, J.; SHEN, J. Water residence time in Chesapeake Bay for 1980–2012. **Journal of Marine Systems**, v. 164, p. 101–111, 2016.
- FERNANDES, E. H. L. **Modelling the Hydrodynamics of the Patos Lagoon, Brazil**. PhD (Thesis) - Faculty of Science and Technology, University of Plymouth, Plymouth, 2001.
- FURG. **Relatório das Sondagens Geológicas para o EIA/RIMA - Dragagem de aprofundamento dos canais de acesso e bacias de evolução do Porto Novo (RS) e Porto de São José do Norte**. Rio Grande do Sul, 2008.
- GONZÁLEZ-GORBEÑA, E.; ROSMAN, P. C. C.; QASSIM, R. Y. **Journal of Ocean Engineering and Marine Energy**, v. 1, n. 4, p. 421–433, 2015. <https://doi.org/10.1007/s40722-015-0031-5>
- GRIFOLL, M.; JORDÀ, G.; ESPINO, M. Surface water renewal and mixing mechanisms in a semi-enclosed microtidal domain. The Barcelona harbour case. **Journal of Sea Research**, v. 90, p. 54–63, 2014. <https://doi.org/10.1016/j.seares.2014.02.007>
- HARTMANN, C.; HARKOT, P. F. C. Influência do Canal de São Gonçalo no aporte de sedimentos para o estuário da Laguna dos Patos - RS. **Revista Brasileira de Geociências**, v. 20, p. 329–332, 1990.
- HUGUET, J.-R.; BRENON, I.; COULOMBIER, T. Characterisation of the Water Renewal in a Macro-Tidal Marina Using Several Transport Timescales. **Water**, v. 11, n. 10, p. 2050, 2019. <https://doi.org/10.3390/w11102050>
- KISTLER, R. COLLINS, W.; SAHA, S.; WHITE, G.; WOOLLEN, J.; KALNAY, E.; CHELLIAH, M.; EBISUZAKI, W.; KANAMITSU, M.; KOUSKY, V.; VAN DEN DOOL, H.; JENNE, R.; FIORINO, M. The NCEP–NCAR 50–Year Reanalysis: Monthly Means CD–ROM and Documentation. **Bulletin of the American Meteorological Society**, v. 82, n. 2, p. 247–267, 2002.
- KJERFVE, B. Comparative Oceanography of Coastal Lagoons. **Marine Biology and Coastal Research**, p. 63–81, 1986. <https://doi.org/10.1016/B978-0-12-761890-6.50009-5>
- LEONARD, A. Energy cascade in large-eddy simulations of turbulent fluid flows. **Advances in Geophysics**, v. 18, part A, p. 237–248, 1975. [https://doi.org/10.1016/S0065-2687\(08\)60464-1](https://doi.org/10.1016/S0065-2687(08)60464-1)
- LI, X.; SHEN, Y. Numerical simulation of the impacts of water level variation on water age in Dahuofang Reservoir. **Frontiers of Earth Science**, v. 9, n. 2, p. 209–224, 2015. <https://doi.org/10.1007/s11707-014-0460-9>
- LIU, R. *et al.* Numerical Study on the Influences of Hydrodynamic Factors on Water Age in the Liao River Estuary, China. **Journal of Coastal Research**, v. 80, p. 98–107, 2017. <https://doi.org/10.2112/SI80-014.1>
- MARQUES, W. C. FERNANDES, I. O.; MONTEIRO, M. H.; MOLLER, O. O. Numerical modeling of the Patos Lagoon coastal plume, Brazil. **Continental Shelf Research**, v. 29, n. 3, p. 556–571, 2009. <https://doi.org/10.1016/j.csr.2008.09.022>

- MARTELO, A. F.; TROMBETTA, T.B.; LOPES, B.V.; MARQUES, W.C.; MÖLLER, O. O. Impacts of dredging on the hydro morphodynamics of the Patos Lagoon estuary, southern Brazil. **Ocean Engineering**, v. 188, p. 106325, 2019. <https://doi.org/10.1016/j.oceaneng.2019.106325>
- MOLLER, O. O. **Hydrodynamique de la Lagune dos Patos (30° S, Bresil)**. [S.l.]: L'Universite Bordeaux I, 1996.
- MONSEN, N. E.; CLOERN, J. E.; LUCAS, L. V.; MONISMITH, S. G. A comment on the use of flushing time, residence time, and age as transport time scales. **Limnology and Oceanography**, v. 47, n. 5, p. 1545–1553, 2002.
- PEIXOTO, R. DOS S.; ROSMAN, P. C. C.; VINZON, S. B. A morphodynamic model for cohesive sediments transport. **RBRH**, v. 22, 2017. <https://doi.org/10.1590/2318-0331.0217170066>
- QI, H.; LU, J.; CHEN, X. SAUVAGE, S.; SANCHES-PÉREZ, J. M. Water age prediction and its potential impacts on water quality using a hydrodynamic model for Poyang Lake, China. **Environmental Science and Pollution Research**, v. 23, n. 13, p. 13327–13341, 2016.
- RIO GRANDE DO SUL. **Portos do Rio Grande do Sul**. 2019. Available at: <http://www.portosrs.com.br/site/index.php>. Access: Jan. 2020.
- ROSMAN, P. C. C. **Modeling Shallow Water Bodies Via Filtering Techniques**. [S.l.]: MIT, 1987.
- ROSMAN, P. C. C. Characteristic Hydraulic Times of the Jirau Hydropower Reservoir on the Madeira River – Brazilian Amazon Region. In: SILVA, R. C. V.; TUCCI, C. E. M.; SCOTT, C. A. (Eds.). **Water and Climate - Modeling in large basins**. [S.l.] Brazilian Water Resources Association, 2018. p. 95–132.
- ROSMAN, P. C. C. **Referência Técnica do SisBaHiA®**. Rio de Janeiro: Fundação Coppetec; COPPE, 2019.
- ROVERSI, F.; ROSMAN, P. C. C.; HARARI, J. Water renewal analysis of the Santos Estuarine System using computational modeling. **Revista Ambiente & Água**, v. 11, n. 3, p. 566–585, 2016. <http://dx.doi.org/10.4136/ambi-agua.1770>
- SEELIGER, U.; ODEBRECHT, C.; CASTELLO, J. P. (Eds.). **Subtropical Convergence Environments**. The Coast and Sea in the Southwestern Atlantic. Rio Grande: Springer, 1997.
- SILVA, R. A. G.; GALLO, M. N.; ROSMAN, P. C. C.; NOGUEIRA, I. C. M. Tidal inlet short-term morphodynamics analysed through the tidal prism longshore sediment transport ratio criterion. **Geomorphology**, v. 351, 2019. <https://doi.org/10.1016/j.geomorph.2019.106918>
- SMAGORINSKY, J. General Circulation Experiments with the Primitive Equations. I. The basic experiment. **Monthly Weather Review**, v. 91, 1963. [https://doi.org/10.1175/1520-0493\(1963\)091%3C0099:GCEWTP%3E2.3.CO;2](https://doi.org/10.1175/1520-0493(1963)091%3C0099:GCEWTP%3E2.3.CO;2)
- TOLDO JR., E. E.; DILLENBURG, S. R.; CORRÊA, I. C. S.; ALEMIDA, L. E. S. B.; WESCHENFELDER, J. Sedimentação na Lagoa dos Patos e os Impactos Ambientais. In: CONGRESSO DA ASSOCIAÇÃO BRASILEIRA DE ESTUDOS DO QUATERNÁRIO, 16., 2017, Bertioga. **Anais[...]** Guarapari: ABEQUA, 2005.

- VAZ, A. C.; MÖLLER JR., O. O.; DE ALMEIDA., T. L. Análise quantitativa da descarga dos rios afluentes da Lagoa dos Patos. **Atlântica**, v. 28, n. 1, p. 13–23, 2006.
- VIERO, D. P.; DEFINA, A. Water age, exposure time, and local flushing time in semi-enclosed, tidal basins with negligible freshwater inflow. **Journal of Marine Systems**, v. 156, p. 16–29, 2016. <https://doi.org/10.1016/j.jmarsys.2015.11.006>
- YING, C.; LI, X. LIU, Y.; YAO, W.; LI, R. Numerical study of water residence time in the Yueqing Bay based on the eulerian approach Numerical study of water residence time in the Yueqing Bay based on the eulerian approach. **IOP Conference Series: Earth and Environmental Science PAPER**, v. 153, n. 8, 2018.
- ZIMMERMAN, J. T. F. Mixing and flushing of tidal embayments in the western Dutch Wadden Sea part I: Distribution of salinity and calculation of mixing time scales. **Netherlands Journal of Sea Research**, v. 10, n. 2, p. 149–191, 1976. [https://doi.org/10.1016/0077-7579\(76\)90013-2](https://doi.org/10.1016/0077-7579(76)90013-2)